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A sensitivity study on the mechanical properties of interface elements adopted in finite element analyses to simulate the interaction between soil and laterally loaded piles

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ABSTRACT: An increasing number of offshore energy structures have been built recently on driven piles, ranging from jacket piles with typical length-to-diameter (*L/D*) ratios of 10-40 to monopiles with far lower *L/D* ratios. The load-displacement behaviour of these foundations can be investigated by means of Finite Element (FE) analyses, for instance following the design methodology developed by the PISA Joint Industry Project (JIP). A challenging aspect of the modelling, for piles loaded either axially or laterally, is the simulation of the behaviour at the soil-pile interface with the adoption of suitable formulations for the interface elements and with representative mechanical properties. This paper presents a sensitivity study conducted on both the elastic and plastic properties of interface elements adopted in FE analyses of laterally loaded piles driven in chalk. The study benefited from the extensive field and laboratory test results collected during the ALPACA JIP and the corresponding pile tests. The aim of the paper is to provide guidance for numerical modelling on the selection of the most appropriate mechanical properties of interface elements to be used in the analyses of soil-pile interaction under lateral loading.

Keywords: soil-pile interaction; finite element modelling; interface elements

1 INTRODUCTION

In recent years, the geotechnical community has made significant efforts to optimise the design of foundation systems for offshore renewables. For instance, the PISA (PIle Soil Analysis) Joint Industry Project (JIP) developed a new design methodology for laterally-loaded large-diameter piles (Burd et al., 2020; Byrne et al., 2020) that was validated against field testing conducted at clay and sand sites.

The PISA design methodology involves the use of advanced 3D Finite Element (FE) modelling (Taborda et al., 2020; Zdravkovic et al., 2020a), that allows for a detailed characterisation of the soil-pile interaction. Such an interaction was simulated satisfactorily by including, in the FE models, appropriate interface elements (Day and Potts, 1994) at the contact between the outer pile shaft and the surrounding soil. These elements can be assigned mechanical properties that are representative of the pre- and post-yield behaviour at the soil-pile interface. A tension cut-off can be also introduced, to allow for the interface elements to open and simulate the potentially highly influential gapping that may form behind piles under lateral loading.

A numerical modelling approach similar to the one proposed in the PISA JIP has been adopted during the ALPHA (numerical Analysis of Laterally loaded Piles driven in cHAlk) research project, that studied piles driven in fractured chalk (Pedone et al., 2023). ALPHA benefited from extensive field and laboratory characterisation conducted for the ALPACA JIP (Jardine et al., 2019; Vinck et al., 2022; Liu et al., 2023) as well as multiple axial and lateral, monotonic and cyclic tests on instrumented piles that provided a database for developing new design methods (ALPACA AWG, 2022).

Following the template established by the PISA JIP, 3D FE analyses were undertaken for ALPHA to investigate the interaction between laterally-loaded driven piles and the surrounding chalk (Pedone et al., 2023). These analyses included a sensitivity study conducted on both elastic and plastic properties of interface elements used for modelling the mechanical behaviour at the pile-chalk interface. The present paper summarises the key findings of this sensitivity study, with the aim of providing guidance to numerical analysts for the selection of the most appropriate mechanical properties of interface elements to be used in the modelling of soil-pile interaction under lateral loading.

The article first reports the geometry of the boundary value problem analysed and its discretisation, together with the boundary and initial conditions employed. The constitutive model parameters are subsequently summarised, including the mechanical properties assigned to the interface elements as part of the sensitivity study. Results and conclusions are discussed and presented at the end of the paper.

2 3D FE MODEL DESCRIPTION

2.1 *Modelled geometry and discretisation*

One set of the ALPACA field loading tests is taken as a reference for the numerical simulations described in this paper. These concerned tubular 20.6 mm wall thickness X80 steel 508 mm outside diameter (D) driven piles with 3.05 m embedded length (L), giving $L/D=6$. While sets of similar piles were subjected to multi-directional, axial and lateral, cyclic and monotonic loading, only uni-directional monotonic lateral loading is considered in this article.

Due to the symmetric nature of the problem under investigation, only a half-pile was modelled, as shown in Figure 1, where the mesh adopted in the FE analyses is illustrated. The 4.5 m deep and the 6 m radial extent of the soil domain was discretised using 20-noded displacement-based hexahedral elements, while the pile was discretised using 8-noded shell elements (Schroeder et al., 2007). 16-noded zero-thickness interface elements (Day and Potts, 1994) were introduced between the outer pile shaft and the surrounding chalk.

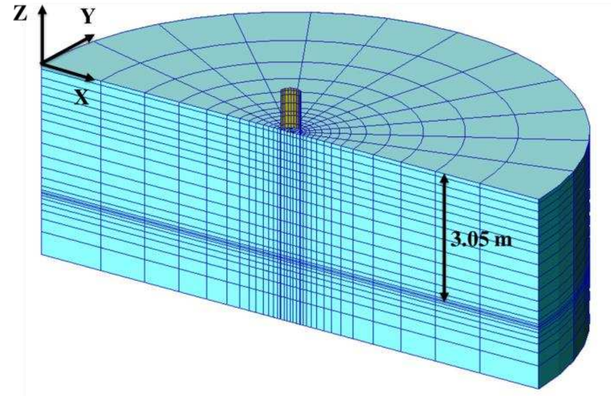

Figure 1. Mesh generated for the 3D FE analyses

2.2 *Boundary and initial conditions*

During the analyses, the displacements orthogonal to the vertical boundaries were restrained, as well as all the displacement components of the nodes located at the base of the mesh. In addition, given that the shell elements used for modelling the pile have both displacement and rotational degrees of freedom at the nodes, rotations about the X and Z axes were set to zero for the shell nodes located on the symmetry plane. Following the procedure adopted on site, pile lateral loading was imposed by applying horizontal displacements in the X-direction at 0.95 m above ground level.

The 3D FE analyses were carried out with ICFEP (Potts and Zdravkovic, 1999, 2001). The fractured nature of chalk gives it high mass hydraulic conductivity (expected to be 10^{-5}-10^{-3} m/s after Lord et al., 2002), so the analyses were considered fully drained. Pore pressures were kept constant, with ground water table at ≈6 m below ground surface following the near-hydrostatic distribution measured by Vinck et al. (2022).

The initial vertical effective stresses were calculated considering an average saturated bulk unit weight of ≈19.5 kN/m^3. The initial horizontal effective stresses were determined based on a representative coefficient of earth pressure at rest, $K_0=0.6$ (Vinck et al., 2022). Such an assumption neglects the complex pile driving effects on the near shaft local effective stress regime.

As shown by Buckley et al. (2018), pile driving causes the formation of: (i) an annulus of weak putty chalk around the pile, whose size is comparable with the pile wall thickness; (ii) a second annulus, located around the weak putty chalk annulus, where chalk with greatly increased fracturing is found. While Jardine et al. (2023) and Pedone et al. (2023) highlighted the importance of accounting for the above when modelling axially and laterally-loaded piles driven in chalk, these aspects were not accounted for in the sensitivity study presented in the paper, which focussed on the mechanical properties at the pile-chalk interface.

2.3 *Soil and pile modelling*

Pedone et al. (2023) describe how to model the complex behaviour of intact chalk accurately. While the intact chalk's pre-yield behaviour is only moderately non-linear, it exhibits significant softening post-yield when sheared from low confining pressures, and its large strain behaviour is markedly pressure dependent (Vinck et al., 2022; Liu et al., 2023). However, a simple, linear-elastic perfectly-plastic model that employed a non-softening Mohr-Coulomb model was considered sufficient for the sensitivity analyses.

All the simulations were performed assuming: (i) a drained Young's modulus, $E'=1.25$ GPa, and a drained Poisson's ratio, $\mu'=0.2$; (ii) an effective angle of shearing resistance, $\phi'=26°$, an effective cohesion intercept, $c'=176$ kPa, and a dilation angle, $\psi=0°$. The elastic parameters were based on the ALPACA chalk characterisation data (Vinck et al., 2022). The plastic parameters were defined based on the post-peak chalk behaviour, assumed to be representative of the average fractured chalk strength (Pedone et al., 2023). It is important to note that the plastic parameters adopted in this paper were derived from the limited laboratory data that was available at the time the sensitivity study was undertaken. However, Pedone et al. (2023) used additional data (Liu et al., 2023) for more accurate model parameter derivation as this became available.

The modelled piles developed unambiguous field geotechnical failures before their steel walls yielded during testing (ALPACA AWG, 2022), so the shell elements representing the piles were assumed to be linear elastic, with E=210 GPa and μ=0.3.

2.4 *Modelling soil-pile interface*

Zero-thickness interface elements (Day and Potts, 1994) were used to simulate the pile-chalk interaction. The stress-strain formulation of these elements refers to 'strains' that are defined as relative displacements between the nodes of the interface elements shared with the pile (i.e. with the shell elements) and those shared with the soil (i.e. with the hexahedral elements).

A linear-elastic perfectly-plastic Mohr-Coulomb-type model was used for the interface elements. The elastic behaviour was defined through a normal stiffness, K_N, and a shear stiffness, K_S, whose units of measurement are defined as force/length^3, due to the definition of 'strains' adopted in the formulation (Day and Potts, 1994). The sensitivity study discussed in Section 3 refers to a *Baseline case* in which K_N=K_S=10^8 kN/m^3 was assumed. The starting assumption of K_N=K_S was adopted following Taborda et al. (2020) and Zdravkovic et al. (2020a).

The interface element Mohr-Coulomb failure criterion is formulated in terms of effective stresses (Day and Potts, 1994) and therefore defined in terms of ϕ', c' and ψ. For the *Baseline case*, ϕ'=34°, c'=1 kPa (nominal), and ψ=0° were assumed. These reference values were selected based on chalk-steel interface laboratory tests conducted by Vinck (2021) and were also adopted by Pedone et al. (2023).

The interface element formulation (Day and Potts, 1994) implemented in ICFEP (Potts and Zdravkovic, 1999, 2001) also allows elements to open if the normal tensile stresses exceed the threshold value $c'/tan\phi'$. When the interface is open, the normal (tensile) stress remains equal to the prescribed threshold value and the shear stress is zero. Gap opening was therefore allowed to take place in the analyses discussed below.

3 SENSITIVITY STUDY RESULTS

Table 1 summarises the 3D FE analyses conducted as part of the sensitivity study (and the corresponding mechanical parameters that were varied).

3.1 *Variation of interface elastic properties*

3.1.1 *Normal and shear stiffnesses*

A first set of analyses, referred to as *Sensitivity study 1*, was conducted by varying the interface elastic properties. Variations were applied to both K_N and K_S, keeping K_N=K_S to follow the PISA JIP modelling approach. Five analyses were considered as part of the *Sensitivity study 1* (including the *Baseline analysis, NS1-NS4*), varying K_N=K_S in the range 10^5-10^9 kN/m^3 (Table 1).

Table 1. Summary of 3D FE analyses and corresponding parameter variations considered in the sensitivity studies

Study	**Analysis**	**K_N (kN/m^3)**	**K_S (kN/m^3)**	**ϕ'**
1	Baseline	10^8	10^8	34°
	NS1	10^5	10^5	34°
	NS2	10^6	10^6	34°
	NS3	10^7	10^7	34°
	NS4	10^9	10^9	34°
2	S1	10^8	10^6	34°
	S2	10^8	10^5	34°
	S3	10^8	10^4	34°
	S4	10^8	10^2	34°
3	F1	10^8	10^8	31°
	F2	10^8	10^8	28°

The load-displacement curves referred to as *Sensitivity study 1* are shown in Figure 2, in comparison with: (i) the range of measurements collected on two laterally-loaded D=508 mm and L=3.05 m piles reported by ALPACA AWG (2022); (ii) the numerical predictions obtained with a Mohr-Coulomb perfectly-plastic model by Pedone et al. (2023), who modelled the same piles but accounting for pile installation effects (and adopting K_N=2.4·10^6 kN/m^3 and K_S=3·10^5 kN/m^3). The loads in Figure 2 correspond to the reactions in the X-direction extracted at the top of the pile while imposing lateral movements, and the displacements correspond to the average displacements in the X-direction around the pile perimeter at ground level.

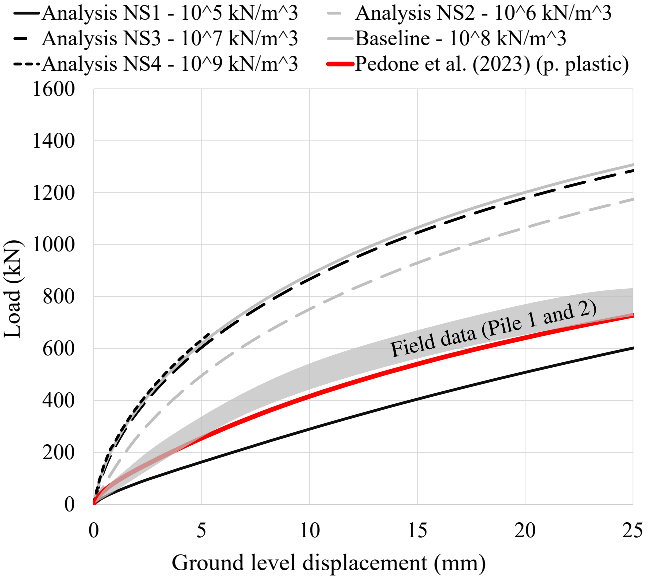

Figure 2. Load-displacement curves (Sensitivity study 1)

The pile response in *Analysis NS1* (K_N=K_S=10^5 kN/m^3) appears 'soft', even if the soil stiffness is relatively large (E'=1.25·10^6 kPa and μ'=0.2).

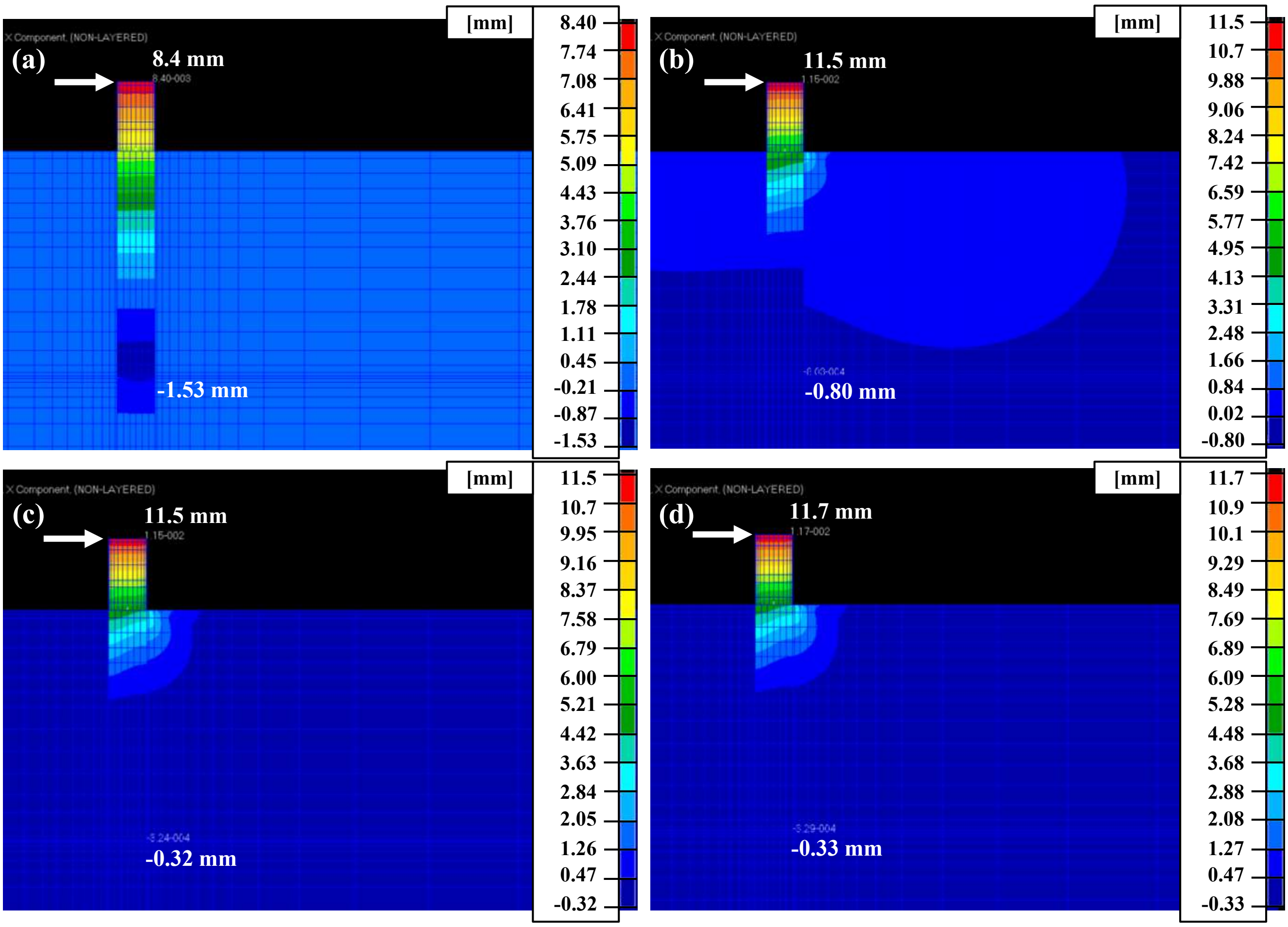

Figure 3. Horizontal X-displacement contours for Analysis NS1 (a), NS2 (b), NS3 (c) and the Baseline analysis (d)

Analysis NS2 (K_N=K_S=10^6 kN/m^3) shows a much stiffer response, probably because the interface stiffness is comparable with the soil stiffness (even though a direct comparison is not possible due to the different units of measurement). A slightly stiffer response is observed in *Analysis NS3* (K_N=K_S=10^7 kN/m^3), when the interface stiffness exceeds the soil one. The *Baseline analysis* (K_N=K_S=10^8 kN/m^3) gives results very similar to those of *Analysis NS3* and *Analysis NS4* (K_N=K_S=10^9 kN/m^3). However, convergence was poor in *Analysis NS4*.

To better understand the load transfer mechanism between the pile and the soil, the horizontal displacement contours of the *Baseline analysis* and *Analysis NS1-NS3* are reported in Figure 3. The results refer to the stage at which pile displacements at ground level are ≈5 mm (maximum and minimum displacements, observed at the top and bottom of the pile, respectively, are also shown).

The *Analysis NS1* results (Figure 3(a)) do appear unreasonable, as the displacements applied to the pile are not transferred to the surrounding soil. The interface elements, which appear too soft compared to the pile and soil elements on either sides, dominate the pile response and allow it to move without inducing any significant ground movements at this stage (the latter were only observed when much larger pile displacements were applied). The remaining three analyses produce much more reasonable results, those from *Analysis NS3* (Figure 3(c)) and the *Baseline analysis* (Figure 3(d)) being practically identical.

The results of *Sensitivity study 1* imply that, when modelling laterally-loaded piles, the interface stiffness should be of similar order of magnitude or higher than the Young's modulus, *E'*, of the soil. This requirement derives from the need to transfer lateral loads from the pile to the soil, and, hence, is likely to be more relevant to the normal rather than to the shear stiffness. In order to clarify this aspect, a second sensitivity study was performed by varying only the K_S.

3.1.2 Shear stiffness only

Sensitivity study 2 was conducted by keeping K_N=10^8 kN/m^3 (*Baseline analysis*) and reducing K_S from 10^8 to 10^2 kN/m^3 (Table 1), hence assuming $K_S \leq K_N$. The load-displacement curves of this second study are shown in Figure 4. It is interesting to observe that even a 2 orders-of-magnitude reduction in shear stiffness (*Analysis S1*) does not induce any major lateral pile capacity variations. Some sizeable differences are observed with K_S=10^5 kN/m^3 (*Analysis S2*), and even bigger pile capacity variations are predicted when K_S=10^4 kN/m^3 (*Analysis S3*). A further K_S reduction was attempted in *Analysis S4*, where K_S=10^2 kN/m^3, but the results appear similar to those obtained from *Analysis S3*.

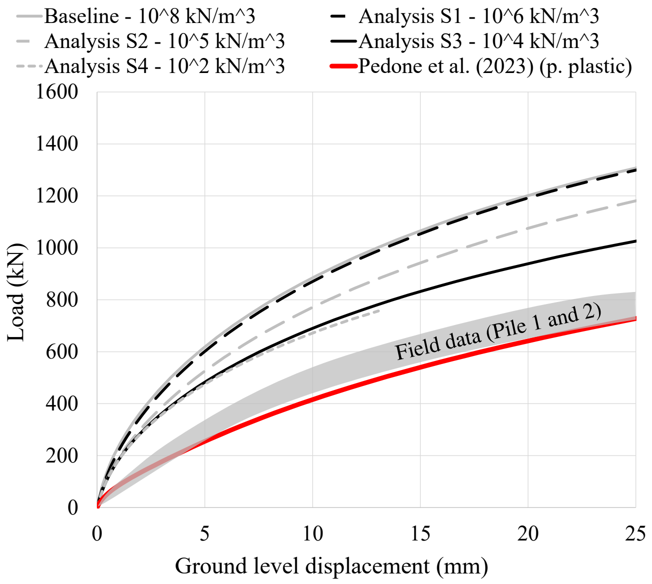

Figure 4. Load-displacement curves (Sensitivity study 2)

The results of *Sensitivity study 2*, obtained under the assumption that $K_S \leq K_N$, confirm the postulate that the impact of interface shear stiffness variations is limited in comparison with that of interface normal stiffness. Inappropriate choices for the latter can lead to unreasonable predictions for laterally-loaded piles. Nevertheless, unreasonably small K_S values (e.g. $K_S=10^2$ kN/m^3) are likely to affect the outcomes of the analysis. For this reason, following the PISA approach (Taborda et al., 2020; Zdravkovic et al., 2020a), it is reasonable to assume $K_S=K_N$ (with K_N at least comparable with the soil stiffness E').

However, more accurate K_S estimates can be obtained from soil-steel interface tests (based on the shear stresses and the corresponding displacements at the interface). The pre-yield behaviour observed during tests by Vinck (2021) between St Nicholas at Wade putty chalk (after aging for 25 days) and steel (including X80 steel) led Pedone et al. (2023) to adopt $K_S=3 \cdot 10^5$ kN/m^3 when making best-estimate simulations of the interface interactions between X80 steel piles and aged putty chalk.

3.2 *Variation of interface plastic properties*

The plastic properties adopted in the *Baseline analysis* correspond to $\phi'=34°$, $c'=1$ kPa (nominal) and $\psi=0°$. These values were interpreted and employed by Pedone et al. (2023) based on Vinck's (2021) interface tests. While these values are considered representative of the post-yield chalk-pile interface behaviour, a third parametric study was conducted to explore the potential impact on the lateral pile loading predictions of varying the plastic interface properties.

In particular, a reduction in ϕ' was accounted for in two additional FE analyses, named *Analysis F1* and *F2*, in which ϕ' values of 31° and 28° were considered, respectively (Table 1), as these covered the range indicated by Vinck's (2021) chalk-steel interface tests. The results of *Sensitivity study 3* are reported in Figure 5, indicating that ϕ' variations within the interval 28°-34° are likely to have only a limited impact on pile lateral capacity predictions. Similar results were reported by Zdravkovic et al. (2020b) in relation to monopile capacity in dense Dunkirk Sand.

While it is possible that interface dilation angle variations might impact the results of the analyses, this was not investigated in the present study, as the available laboratory test data indicated that taking $\psi=0°$ was representative for the problem under investigation.

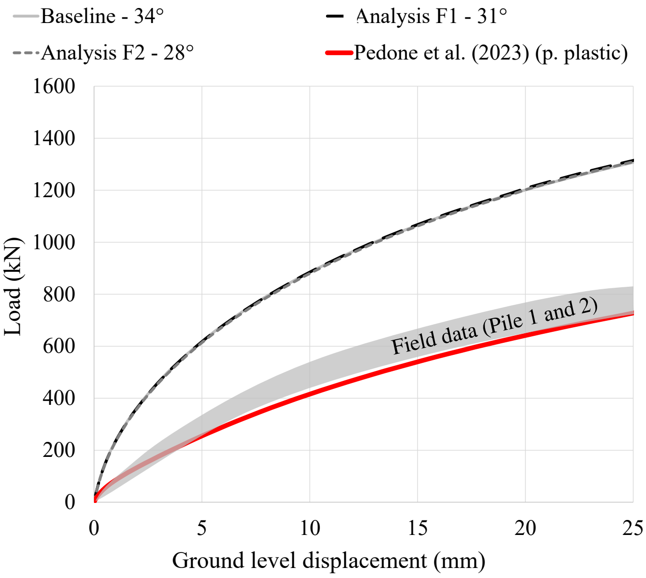

Figure 5. Load-displacement curves (Sensitivity study 3)

4 CONCLUSIONS AND FINAL REMARKS

The paper reports the results of a sensitivity study performed to provide guidance for the selection of the mechanical properties of zero-thickness interface elements adopted in FE analyses to simulate the soil-pile interaction under lateral loading. The study was performed as part of the ALPHA project and was conducted taking as a reference one set of ALPACA JIP pile tests. Selected field and laboratory data collected as part of the ALPACA JIP were also used to derive initial ground conditions and model parameters.

Three sets of 3D FE analyses were performed, as reported in Table 1, and the main conclusions drawn are:

- Lateral pile movements are realistically transferred from the pile to the soil if the interface normal stiffness, K_N, is comparable to the soil stiffness E'. When K_N is significantly smaller, the chalk located in front of the pile does not seem to be engaged, leading to unrealistic estimates of the lateral pile capacity. On the other hand, if relatively high K_N values are adopted in comparison to the soil stiffness, convergence issues may arise.

- A second sensitivity study was conducted under the assumption that $K_S \leq K_N$. The results of this study allowed to observe that the impact of interface shear stiffness variations on the capacity of laterally-loaded piles is limited in comparison with that of changing normal stiffness. Nevertheless, unreasonably small values (e.g. $K_S=10^2$ kN/m^3) are likely to affect the outcomes of the analyses. Confirming earlier studies, it appears reasonable to assume $K_S=K_N$. However, K_S values can be estimated more reliably from chalk-steel interface laboratory tests.
- The impact of ϕ' variations on lateral pile capacity was limited over the 28°-34° range considered based on laboratory interface shear tests.

Finally, it is important to observe that relatively thin elements have been adopted to model the soil adjacent to the pile, to achieve accurate soil-pile interaction predictions. As reported by Day and Potts (1994), the size of these elements might have an impact on the numerical performance of the interface elements located next to them. It is also important to recognise that the interface properties could have different impacts on the piles' response to axial loading, and that this would require investigation through a separate sensitivity study.

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