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Discussion on "Coupled effective stress analysis of insertion problems in geotechnics with the Particle Finite Element Method" by L. Monforte, M. Arroyo, J.M. Carbonell, and A. Gens

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Abstract

Addressed here is the Particle Finite Element Method (PFEM) modelling of undrained CPTu penetration with regard to a reference analytical solution based on the Spherical Cavity Expansion Method (SCEM). Also discussed is the choice of the soil model and its parameters. The effect of cone interface friction on CPTu simulation is analyzed in a series of penetration tests using Arbitrary Lagrangian-Eulerian (ALE) and Updated Lagrangian (UL) methods. The results of the simulations are compared with the Authors' proposal.

KEYWORDS: Cone penetration test, Cone resistance, Friction sleeve, Large deformation finite element methods (LDFEM), Large strains, Pore water pressure

1. Introduction

Monforte et al. [1] have presented a valuable and comprehensive research on the numerical modelling of CPTu penetration using PFEM. They analyzed the cone penetration at different rates and compared the results qualitatively with the studies of Sheng et al. [2] using UL and Ceccato et al. [3,4] using Material Point Method (MPM). The Authors performed a detailed parametric study concerning the influence of interface friction on net cone resistance (q_n), the friction sleeve (f_s) and pore water pressures at different filter locations (u_1, u_2, u_3). However, in the Discussers' opinion, the main shortcoming of this study is the fact that the results of the simulations are not compared with an analytical solution for undrained CPTu penetration using SCEM. In undrained conditions, further analysis is also necessary concerning the interface friction effect on the CPTu penetration. As a contribution to the discussion, we would like to present some results of numerical analyses as well as a review of the literature data. The numerical simulations in this discussion are conducted using ALE and UL formulations for the same set of Modified Cam Clay (MCC) parameters as given in Table 2 of the manuscript.

2. Model Parameters selection

The Authors state they mimicked the solution presented by Sheng et al. [2] and used it as a reference. Why did the Authors use a hyperelastic model instead of a poroelastic model? How were the hyperelastic parameters selected to provide a soil response compatible with Sheng et al. [2]? This raises the question as to how accurately the hyperelastic model simulates soil behavior in the elastic regime of the reference solution [2]. The application of constant Poisson's ratio in poroelasticity (as used by Sheng et al. [2]) allows for shear modulus change with volumetric strains according to the formula:

$$G = \frac{3 \times (1 - 2\upsilon') \times (1 + e_0)}{2 \times (1 + \upsilon') \times \kappa} \times p' \times \exp\left(\varepsilon_v^e\right) \tag{D1}$$

where G = shear modulus, υ' = effective Poisson's ratio, e_0 = initial void ratio, κ = swelling slope, p' = effective mean stress and ε_v^e = elastic volumetric strains. For the parameters presented in Table 2, G=887.32kPa. During undrained CPTu penetration, the volumetric strains are close to 0, and, according to Eq. (D1), G should basically remain unchanged. Similar soil behaviour in undrained conditions also should be expected using hyperelasticity [5]. According to Eq. (13) and using the constants assumed by the Authors, the calculated G equals 1306.32kPa, which is significantly larger than the G=887.32kPa obtained from poroelasticity. Consequently, The PFEM calculated cone resistance may be overestimated in comparison to Sheng et al. [2].

3. SCEM solution

The Authors compared the simulation of CPTu penetration with the solution presented by Cecatto et al. [4] (MPM) and Sheng et al. [2] (UL). However, in Discussers opinion, a more appropriate reference solution can be obtained using SCEM. Chen and Mayne [6] derived the relationships for u_1, and u_2 using MCC material and a frictionless interface. This solution is in agreement with field observations [7] and, in the Discussers' opinion, it can form a satisfactory reference when undrained CPTu penetration is performed. The pore water pressure (PWP) in the cone vicinity can be calculated with SCEM as [6]:

$$u = \Delta u_{oct} + \Delta u_{shear} + \Delta u_{TSP} + u_0 \tag{D2}$$

$$\Delta u_{oct} = \frac{4}{3} c_u \ln I_R \tag{D3}$$

$$\Delta u_{shear} = p'_0 - \frac{2c_u}{M} \tag{D4}$$

$$\Delta u_{TSP} = s\left[2c_u - \left(1 - K_0\right)\sigma'_{v0}\right] \tag{D5}$$

where: u = pore water pressure around the cone, Δu_{oct} = octahedral component of pore water pressure, Δu_{shear} = shear-induced component of pore water pressure, Δu_{TSP} = total stress path dependent component of pore water pressure, s = total stress path coefficient (s=4/3 for u_1 and s=0 for u_2 [6]), u_0 = initial pore water pressure, K_0 = earth pressure at rest coefficient, σ'_{v0} = initial effective vertical stress. Using compatible parameters (G=877.32kPa, c_u=17.78kPa) and initial conditions assumed by the Authors (weightless soil, p'_0=38.57kPa, K_0=0.5), one can calculate the corresponding components of the mobilized excess pore water pressure: Δu_{oct}=92.70kPa, Δu_{shear}=3.01kPa, Δu_{TSP}=8.84kPa (only for u_1) and u_0=0kPa (due to weightless soil). Consequently, the water pressures at the filter positions are u_1=104.55kPa and u_2=95.71kPa. With G=1306.32kPa, one obtains Δu_{oct}=101.86kPa, Δu_{shear}=3kPa, Δu_{TSP}=8.84kPa, u_1=113.71kPa and u_2=104.86kPa. These values are significantly lower than those presented by the Authors in Table 4. In Discussers' opinion, this could be attributed to high oscillations and variability of PWP distributions around the cone obtained with LDFEM, such as UL, ALE, MPM or PFEM. Examples of such non-uniform distribution can be seen in the Authors' papers (Fig. 8b in [2], and Fig. 2 in [8]). In Fig. D1, the Discussers present the PWP distributions around the cone from the ALE model (frictionless interface) and the corresponding SCEM solutions for u_1 and u_2. The concentration of generated PWP is observed at the cone tip and just behind the cone. The Discussers predominantly used the average PWP value from the u_1 area (see Fig. D1). For the u_2 position, the Discussers mainly considered the PWP values close to the actual filer position or the average value from nearby points, see Fig. D1. However, due to high PWP fluctuations in this area, it is difficult to determine the actual u_2 value. This high variability is also observed for field registered u_2 measurements (e.g., Fig. 2 in [9]) or lab tests (e.g., Table 2 in [10]). To sum up, due to uncertainty in determining u_2, the unique reference SCEM solution may facilitate the

interpretation in the cone vicinity. Discussers would like to ask the Authors for their opinion regarding the reliability of u_2 output in PFEM.

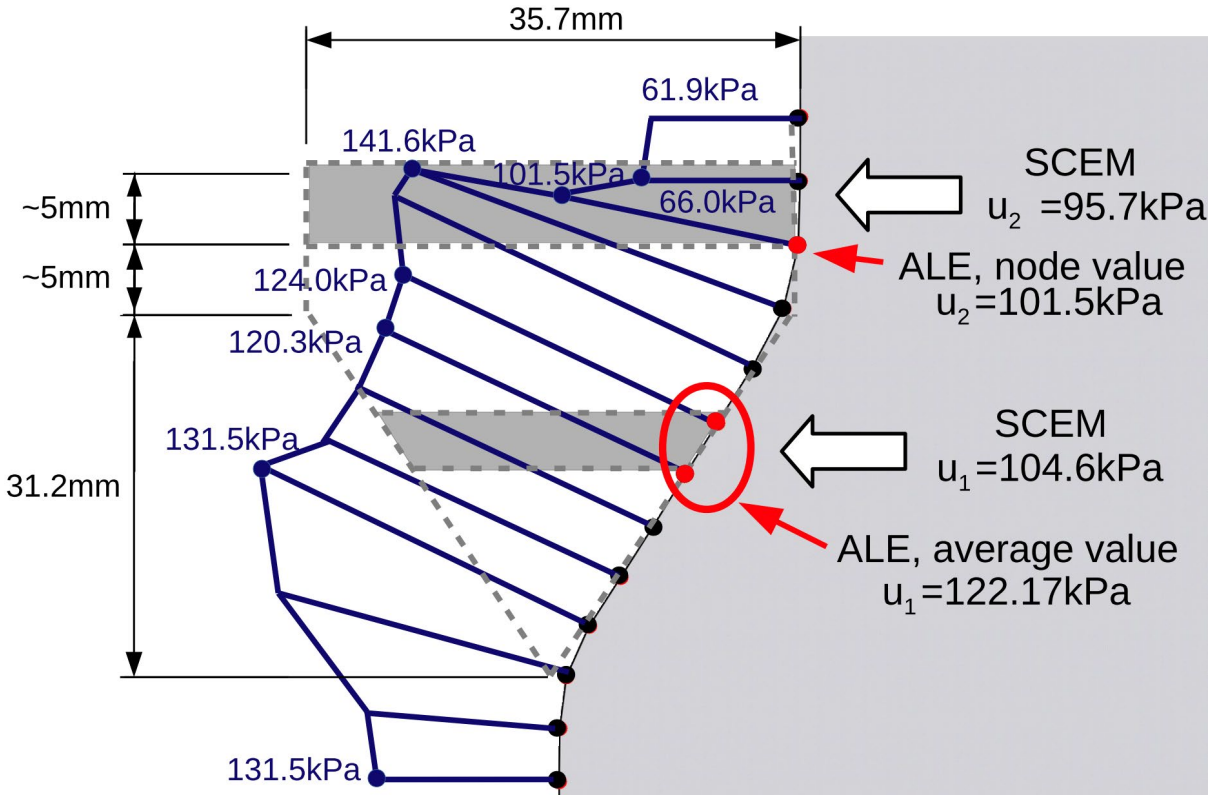

Fig. D1. PWP distribution around the piezocone: ALE model (frictionless interface) and corresponding SCEM results. [no colour]

4. Influence of interface friction on CPTu readings

In this section, the influence of interface friction on cone resistance, sleeve friction, and pore water pressures will be investigated and compared with the Authors' results. The UL and ALE formulations have several drawbacks, as was rightly noticed by the Authors. One of them results from the very high interface friction angle in the numerical penetration simulation. In our study, an interface friction angle higher than δ=20º for ALE and δ=15º for UL caused an abrupt termination of the calculations.

4.1 Cone resistance

The q_n increase with interface friction is presented in Fig. D2a. The numerically simulated q_n obtained using ALE and UL is up to 40% higher than for the corresponding smooth cone and

considerably higher than the PFEM solution. The Authors suggest that PFEM and MPM give similar results when there is an increase in interface friction. They link the discrepancies with the performance of contact algorithm, although both formulations use the contact penalty method. The ALE and UL calculation results presented by the Discussers are closer to the MPM solutions [3] referred by the Authors. This may suggest that the friction component of the cone resistance is underestimated in the PFEM.

4.2 Sleeve friction

Fig. D2b presents sleeve friction increase in relation to interface friction. Here, UL, ALE, and PFEM give almost the same results. However, this to some extent contradicts the cone resistance results (Fig. D2a) and the Discussers would like to ask the Authors for their opinion regarding the contact algorithm performance.

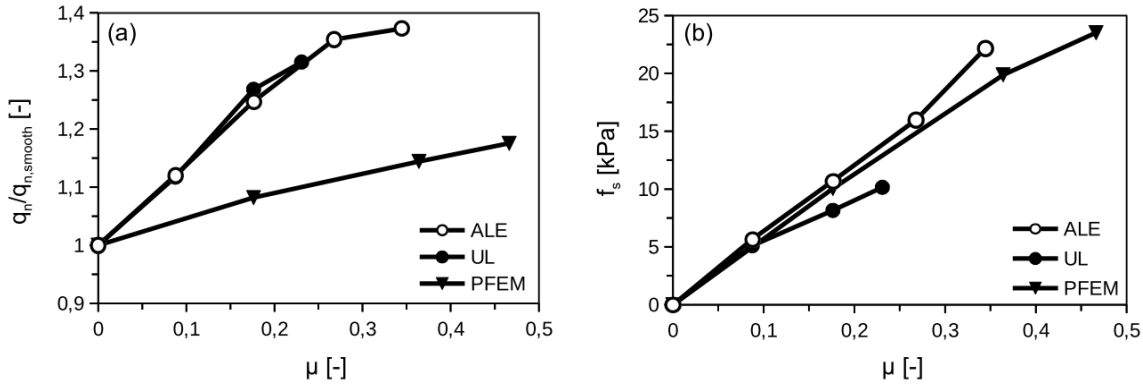

Fig. D2. Effect of interface friction on (a) cone resistance and (b) sleeve friction. [no colour]

4.3. Pore water pressure u1, u2, u3 readings

The Authors' analysis of pore water pressures developed around the cone due to different interface friction seems to be incomplete. Of the provided values u_1, u_2 and u_3 (in Table 4), only the results of u_2 position are discussed. A comparison between the Authors' and the Discussers' results is presented in Fig. D3. The discrepancies for the u_2 position may be related to the PWP nodes used in the analysis. This issue was already addressed in section 2. The PWP around the cone (in u_1 and u_2) seems to be independent of the interface friction. The

research shows that only the u_3 position seems to be slightly influenced by interface friction when μ<0.2. For higher μ values, this effect is more important.

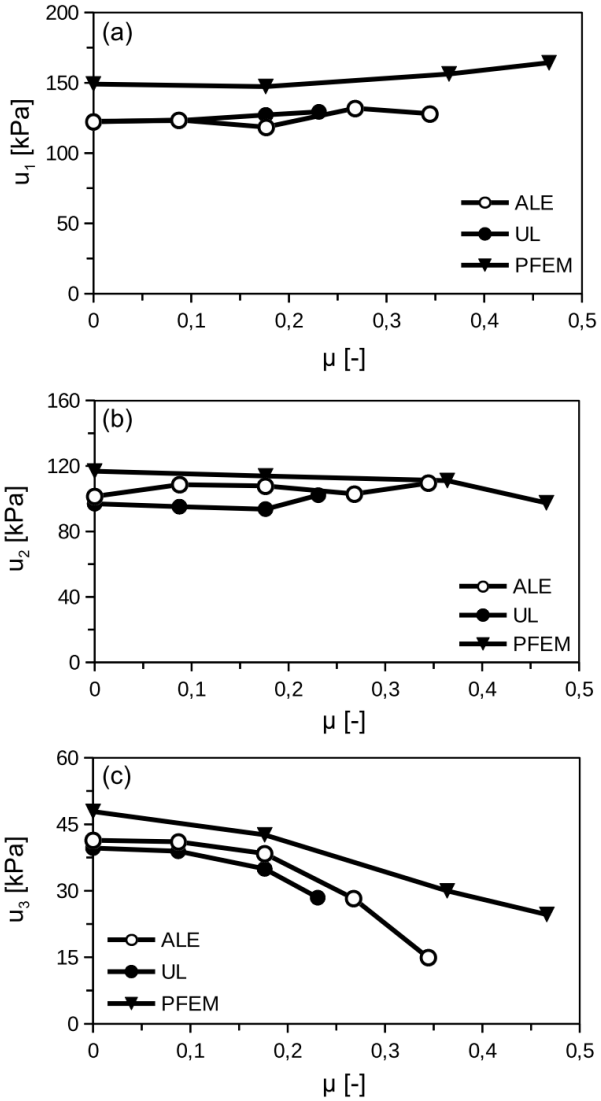

Fig. D3. Effect of interface friction on PWP at (a) u_1, (b) u_2 and (c) u_3. [no colour]

5. Conclusions

The Discussers would like to draw attention to the effect of interface friction in numerical simulations of CPTu penetration. The Discussers found that cone resistance determined using ALE and UL was more influenced by interface friction than in the case of the Authors' PFEM tests. In case of sleeve friction modelling, the obtained results were more similar. In all the cases, PWP in u_1 and u_2 was relatively unaffected by interface friction.

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