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Rock anchor pullout investigation for offshore renewable applications using G-PFEM

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Introduction

Rock anchors (RAs) are a cost-effective response to the increasing demand of offshore renewable energy anchoring. The proliferation offshore energy systems requires the development of novel anchoring systems suitable for challenging wave and tidal conditions. The Geotechnical Particle Finite Element Method (GPFEM) (Carbonell *et al*. 2022) is used here to investigate the effects of rock-anchor interface friction (*δ*) and embedment depth on pullout capacity (*H/D*). The results are rigorously compared with other numerical approaches highlighting the advantages of using advanced constitutive models and an FE based large strain formulation.

The Rock & the anchor

The RA examined is a novel self-drilling concept designed for offshore systems. The anchor is defined by an upper part, a shaft and a bottom drilling head (Figure 1a) and the GPFEM is used to simulate axial pull-out. The approach proposed is able to simulate large strain problems avoiding mesh distortion which can strongly affect brittle rocks (Monforte *et al.,* 2019). The non-local constitutive relationship for rocks was implemented in GPFEM and calibrated against experimental data on Berea sandstone from Wong *et al.* (1997). As shown in Figure 1b/1c the model nicely reproduces the complex experimental behaviour.

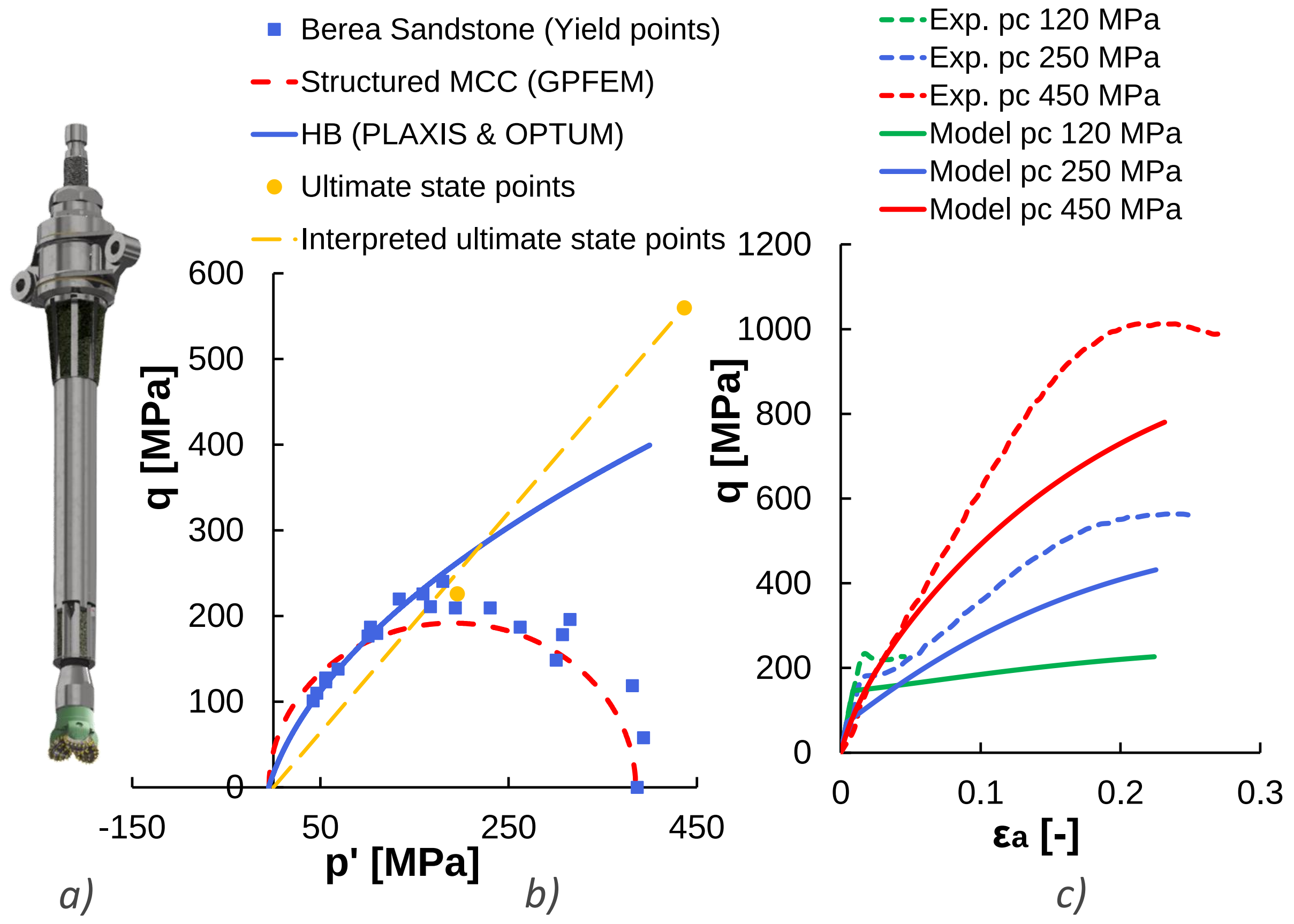


Figure 1. RA model definition: a) Rock anchoring system modelled b) yield surface calibration for HB and structured MCC model and c) variable confinement pressure simulations in q-ε_a

Numerical modelling

A set of 20 2D axisymmetric simulations to investigate the effect of the interface friction angle (*δ*) and embedment ratio (*H/D*) on the pullout capacity were performed (Table 1) following Cerfontaine *et al.* (2021). The same set of analyses was performed using both standard FE (with PLAXIS) and limit analysis (with Optum) simulations. The rock parameters were obtained from the calibration procedure shown in Figure 1b/c. For Plaxis and Optum a Hoek Brown failure criterion was used.

H/D [-]	δ [°]			
2	0	3	6	12
3	0	3	6	12
4	0	3	6	12
6	0	3	6	12
8.8	0	3	6	12

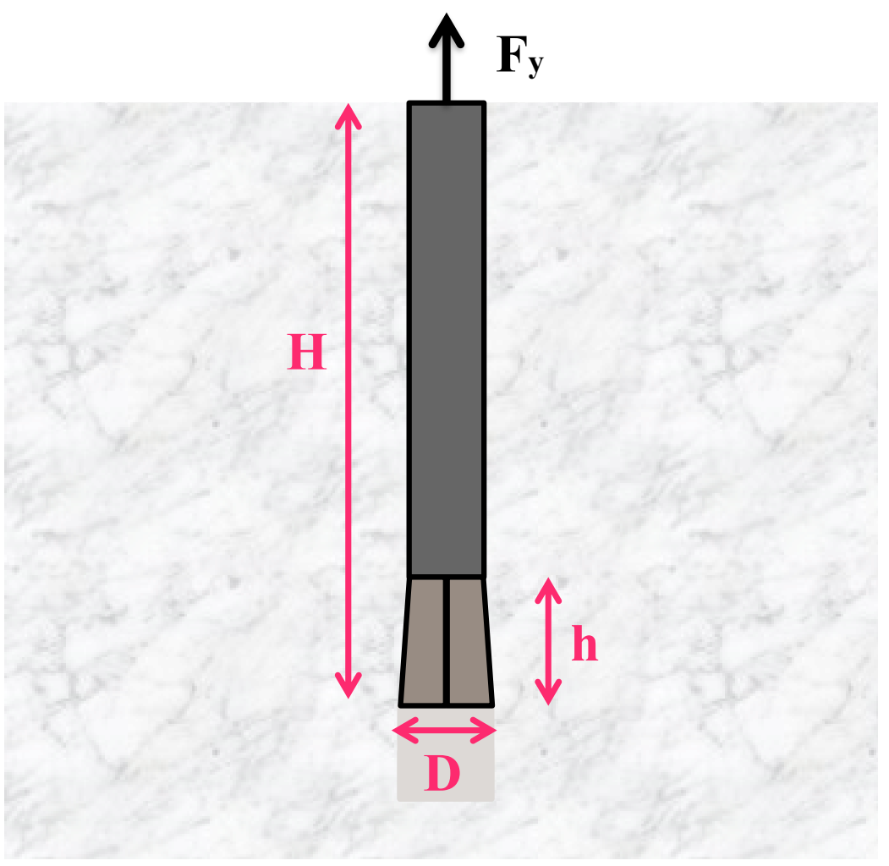
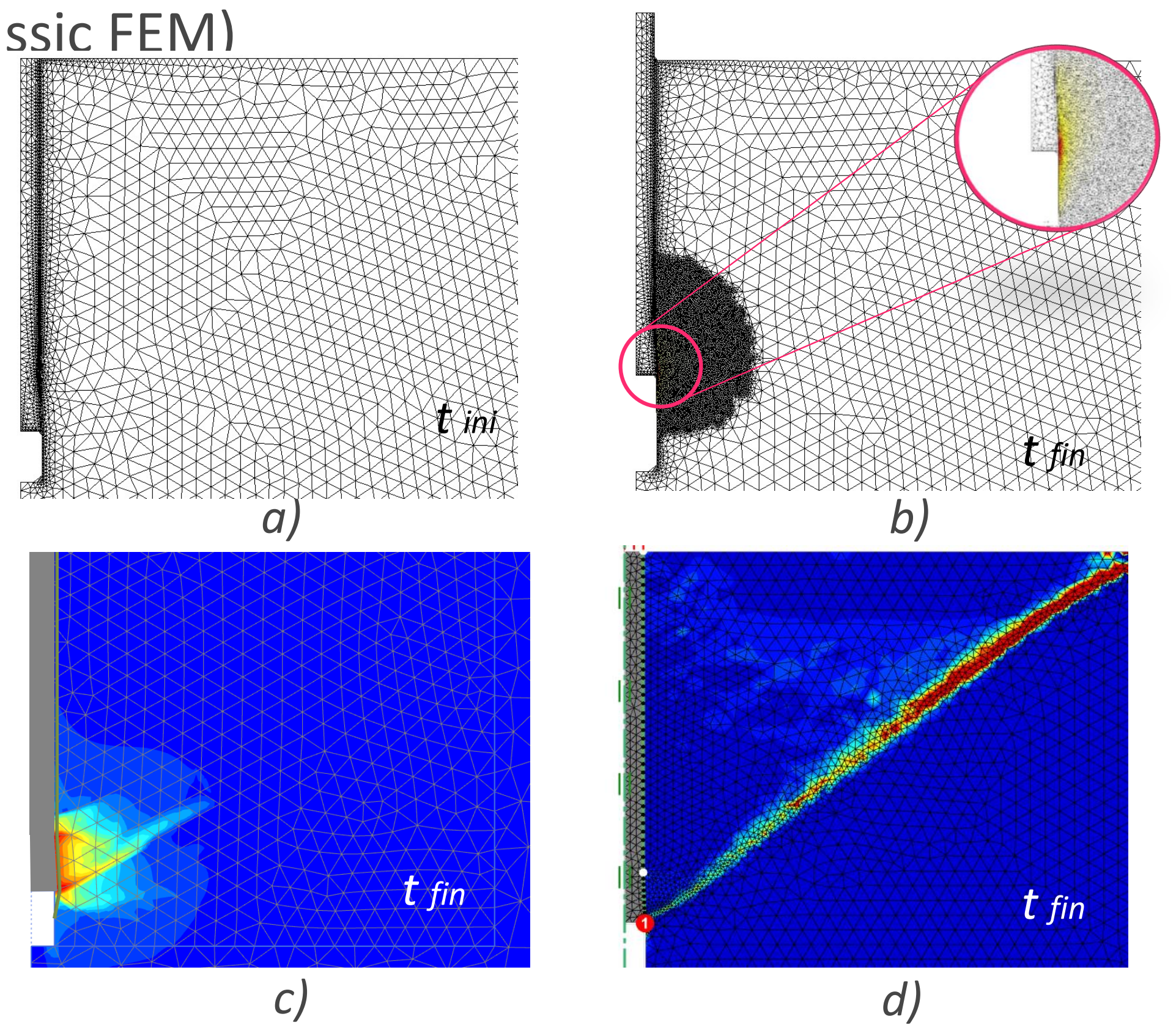


Table 1. Embedment ratio and delta values used for the set of simulations performed in PFEM with scheme of RA

For all models the RA pull-out is simulated by displacement control and the steel rock interface is modelled using a Mohr Coulomb criterion (interface friction of *δ*). Figure 2 compares the three models at RA failure. In the GPFEM a plastic deformation threshold is used to remesh. Following Oliynyk *et al.* (2021), the smallest mesh size is such that the elements are smaller than the characteristic length of the non-local model able to avoid mesh dependency issues (affected instead by classic FEM).



a) b) c) d)

Figure 2. RA numerical results: a) GPFEM Mesh distribution at the beginning of the analysis (u=0) and b) PFEM nonlocal deviatoric deformation at the end of the analysis (u=300 mm) c) deviatoric deformation for PLAXIS and d) Optum simulations

Parametric study

As expected the pull-out capacity is strongly dependent on both *δ* and *H/D* which affect the failure mechanism. Higher *δ* increase the RA influence zone whilst depending on *H/D* a deep or shallow failure mechanism develops (Figure 3a-b).

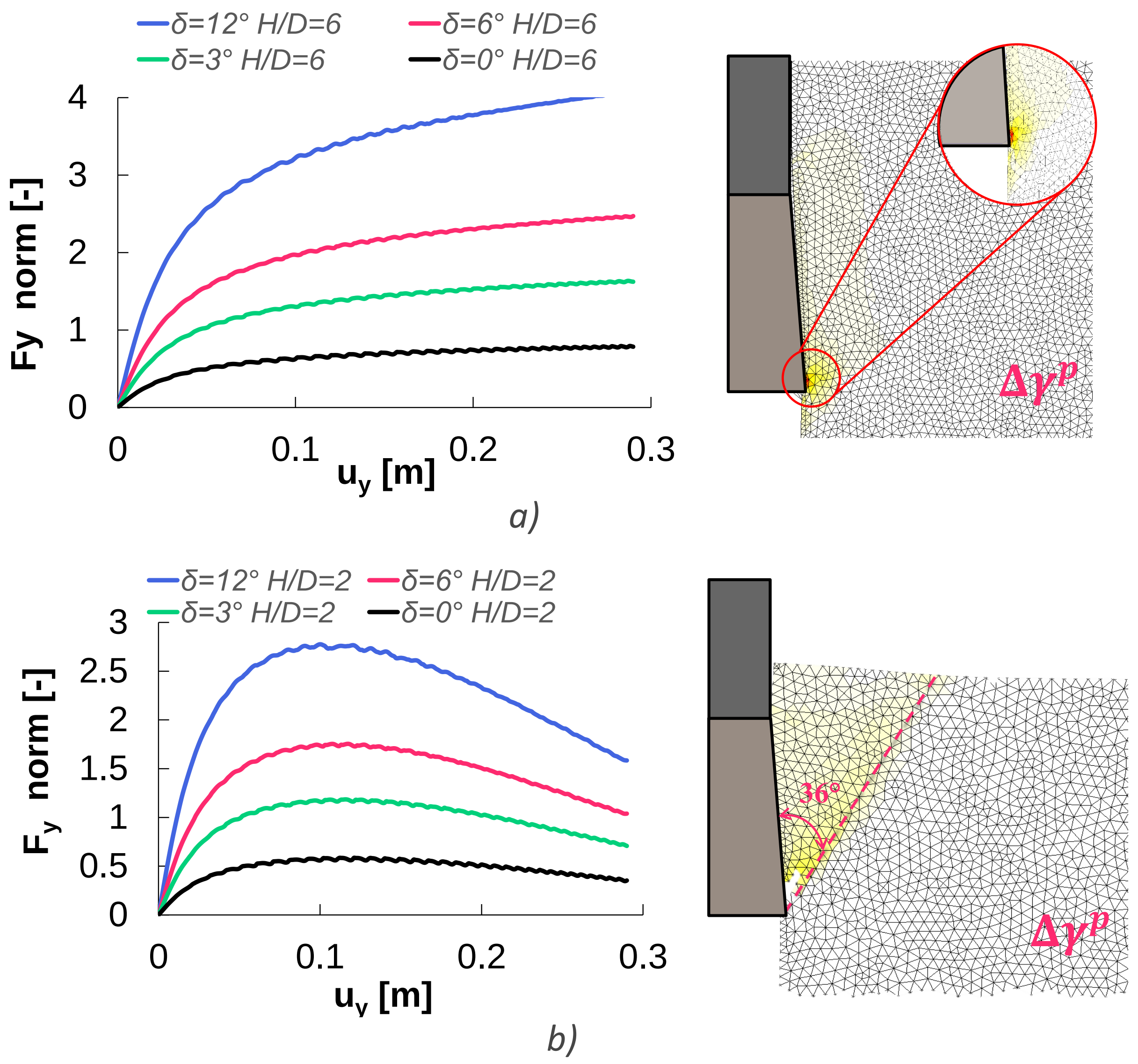


Figure 3. Influence of the interface friction angle and embedment ratio on uplift capacity with GPFEM: load displacement curves and failure mechanism via delta plastic strain schematic for a) H/D=6 and b) H/D=2 with different δ values.

Small strain FE (Plaxis 2D), LA simulations (Optum G2) and GPFEM simulation results are compared in Figure 4. The results suggest that LA overestimates the RA capacity compared then FEM and PFEM. The reason for this is the requirement of an associated flow rule and a resulting highly dilatant rock response. Using the Drescher and Detournay, (1993) approach to account for a non-associated flow rule slightly lowers the capacity. However, this still remains high compared to FE simulations.

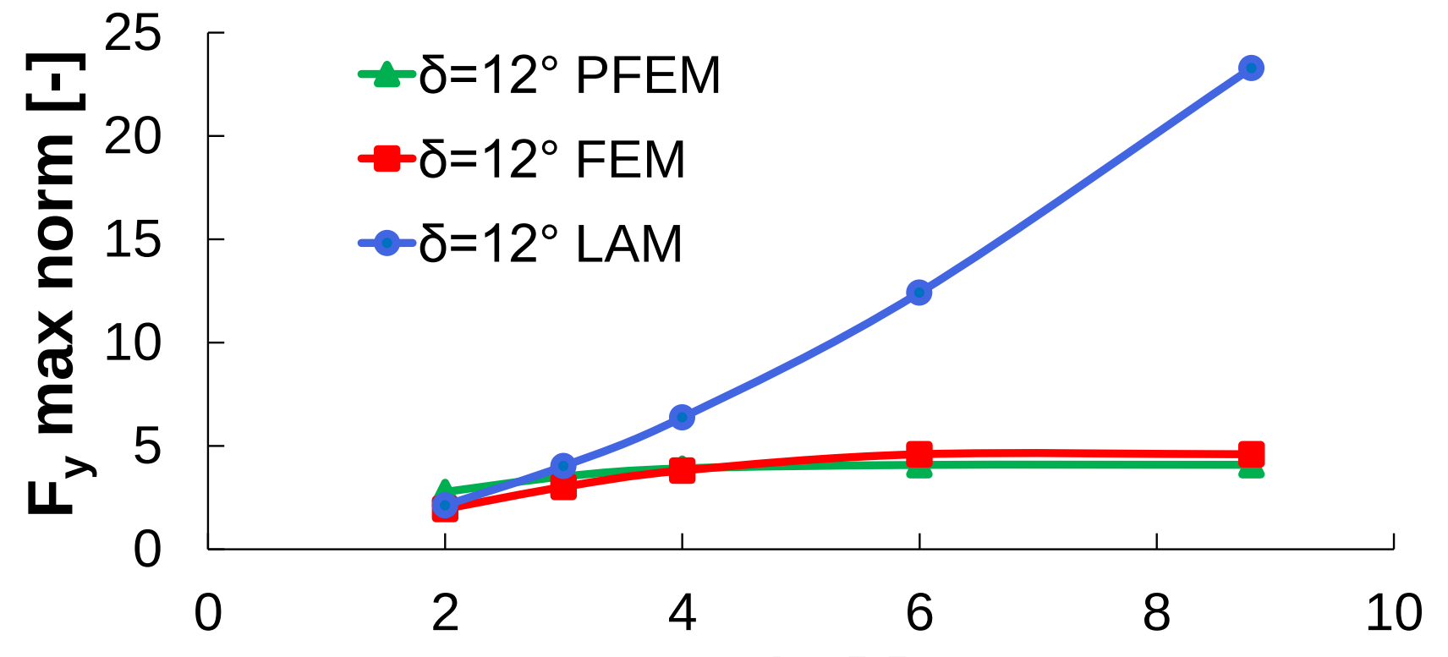


Figure 4. Normalised uplift capacity obtained using three different numerical techniques (GPFEM, FEM and LA)

Discussion

The GPFEM used for the simulations carried out is an affordable and reliable approach to tackle the large deformation pullout simulations of RAs. Thanks to the remeshing capabilities and a non-local formulation reliable results are obtained. The influence of geometry (H/D) and interface friction (δ) on pullout capacity has been ascertained (Figure 5).

- H/D values higher than 4 tend to a constant load capacity regardless of δ (Figure 5) because of a deep failure mechanism.
- The steel-rock interface friction plays a significant role on the capacity (Figure 5).
- The deep mechanism has a hardening type of behaviour whilst the shallow one is characterised by a brittle response that should be considered critical in design stages (Figure 3).

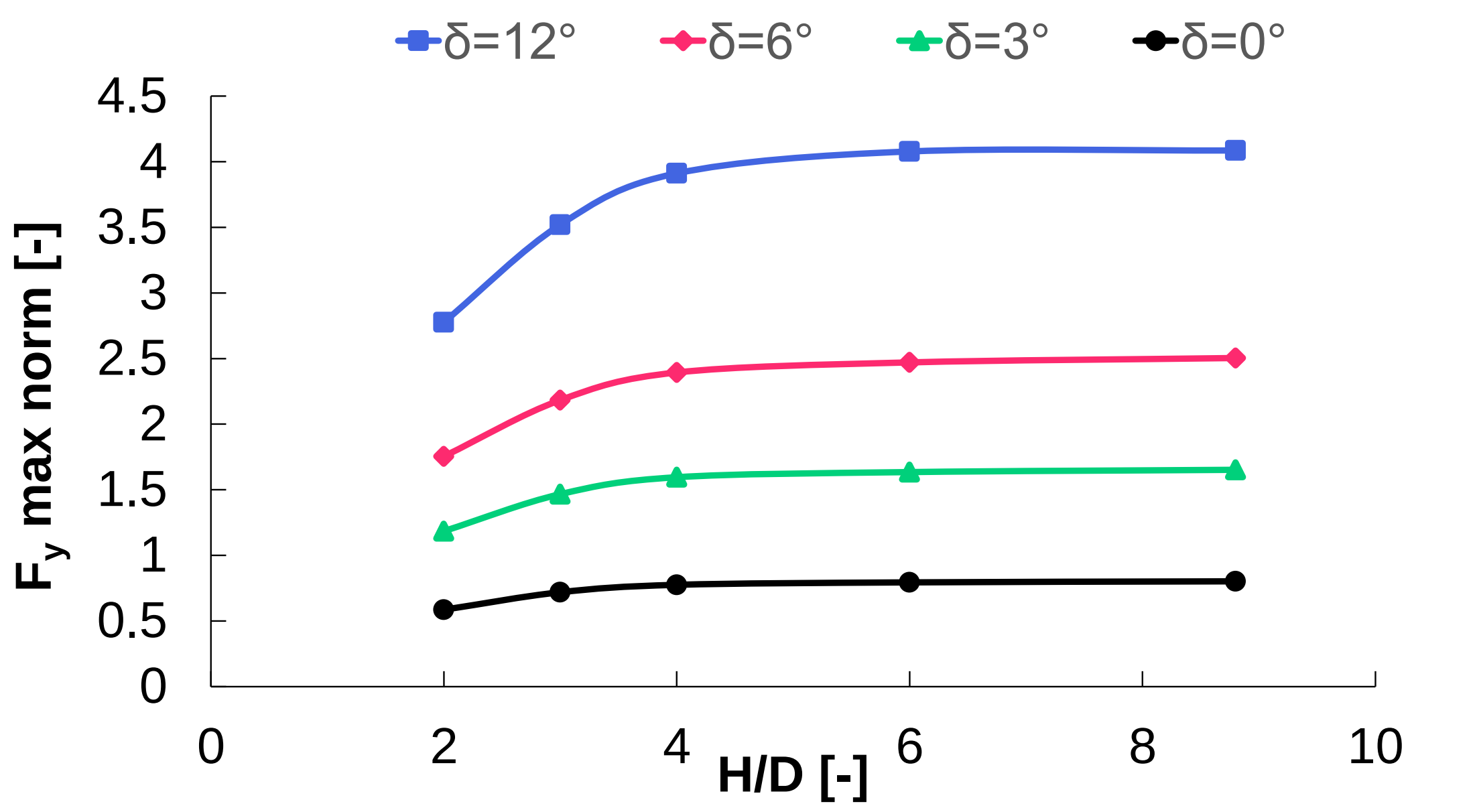


Figure 5. influence of δ on the normalised maximum pullout load capacity as a function of H/D

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