DISCUSSION

Authors' Reply to the Discussion by Crisci et al. (2021) on "Experimental Deformation of Opalinus Clay at Elevated Temperature and Pressure Conditions Mechanical Properties and the Influence of Rock Fabric"

Valerian Schuster[1,2] · Erik Rybacki[1] · Audrey Bonnelye[1] · Georg Dresen[1,2]

We thank Crisci et al. for their interest in our recently published work and appreciate the comments raised in their paper "Discussion on "Experimental Deformation of Opalinus Clay at Elevated Temperature and Pressure Conditions ¬ Mechanical Properties and the Influence of Rock Fabric" (2021). We are pleased to respond and use the opportunity to clarify issues related to testing procedures and interpretation in more detail.

Crisci et al. (2021) discuss three points, which may be relevant to the community dealing with experimental studies focused on mechanical properties of clay-rich rocks, 1) the effect of pore pressure generation during isotropic and triaxial loading as well as 2) the influence of strain rate on the strength of saturated samples, and 3) the effect of drying-induced microcracks on strength.

Crisci et al. (2021) discuss the unknown effective stress state of saturated samples in undrained and drained experiments before and during axial deformation. We agree with the authors that pore pressure plays an important role in the assessment of mechanical properties of saturated rocks. In addition to the initial unknown effective stress, Crisci et al. (2021) state that peak strength of saturated samples is further affected by the effective stress path experienced during loading. If deformation rate does not allow pore pressure to equilibrate, the resulting effective pressure is not uniform and may affect sample strength. We generally agree with

Crisci et al. and refer the reader to the discussion in Schuster et al. (2021). In particular, there we point at the potential effects of excess pore pressure on sample anisotropy, dilatancy and local effective pressures (cf., section 4.3).

The effect of strain rate on the generation of pore pressure during differential loading of saturated samples is important. As revealed in a plethora of studies of clay-rich fault gouges, deformation transients may cause elevated local fluid pressures leading to crack formation. During fast loading of samples with low permeability, high pore pressures may build up locally and pore pressure may not equilibrate in samples, both in drained and undrained conditions. Locally varying effective pressure will affect deformation behavior in addition to confinement, porosity and permeability and rate-dependent deformation processes such as shear-enhanced compaction, dilatancy hardening, or pressure solution (e.g., Geng et al. 2018). We estimated that applied strain rates in our experiments were above the critical strain rates required for pore pressure equilibrium (cf., section 4.3), so we expect that the deformation behavior of our samples probe the effect of local pore pressure transients. As correctly noticed by Crisci et al. (2021), we did not explicitly repeat the above calculation for undrained tests and the effect of non-equilibrium. The impact of strain rate on the mechanical behaviour of saturated samples was tested only for S-samples at 5×10^{-4} and 5×10^{-6} s^{-1} in the original paper. The S-sample tested at a strain rate of at 5×10^{-6} s^{-1} displays $\approx$30% higher strength than the samples deformed at 5×10^{-4} s^{-1} (see Fig. 8c and section 3.1.5), because pore pressure in the slow test may have been better equilibrated, resulting in a lower mean pore pressure, which increases the effective pressure and thus strength.

✉ Valerian Schuster
  valerian.schuster@gfz-potsdam.de

1   Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, 14473 Potsdam, Germany

2   Institute for Earth and Environmental Science, University of Potsdam, 14476 Potsdam, Germany

However, it is important to note here that the estimated critical strain rate for pore pressure equilibrium depends on several parameters and may be calculated with different approaches. For poorly consolidated rocks, consolidation theory can be used to predict the critical time, t_f, to maintain uniform pressure during loading until failure. For a sample length-diameter ratio of l:$d = 2$:1, t_f is estimated for drainage on top and bottom end from (e.g., Amann and Vogelhuber 2015).

$$t_{fd} = 1.667\frac{l^2}{c},$$

which is four times longer for drainage at one end only. This time is reduced to about,

$$t_{fu} = 0.400\frac{l^2}{c},$$

under undrained conditions, where c is the consolidation coefficient, which can be determined from consolidation tests or from hydraulic conductivity and bulk modulus (e.g., Bishop and Henkel 1962; Ewy and Stankovich 2000). For our samples with l = 20 mm, we obtain $t_{fd} = 3.3 \times 10^5$ s and $t_{fu} = 8 \times 10^4$ s, which correspond to an average strain to failure of about 3.5% to critical strain rates of about 1×10^{-7} and 4.4×10^{-7} s^{-1}, respectively. This is one to the three orders of magnitude lower than the applied strain rates in Schuster et al. (2021).

Another approach to calculate the critical strain rate for the transition from undrained to (single-end) drained conditions maintaining equilibrium of pore pressure is given by the characteristic time scale of,

$$t_c = l^2\frac{\eta\beta_s}{k}$$

where η is fluid viscosity, k is permeability, and β_s is storage capacity per unit volume, which might be approximated by $\beta_s \approx \beta\phi$ with β = compressibility of the pore fluid and ϕ = porosity (e.g., Fischer and Paterson 1989; Renner et al. 2000). The term $k/(\eta\beta\phi)$ is the hydraulic diffusivity D. For our samples and experimental conditions $k \approx 10^{-20}$ m^2, $\phi \approx 0.13$, $\eta \approx 0.28 \times 10^{-3}$ Pas, and $\beta \approx 4.2 \times 10^{-10}$ Pa^{-1}, which yields $D \approx 6.5 \times 10^{-7}$ m^{2}s^{-1}, corresponding to $t_c \approx 6.1 \times 10^2$ s for our sample geometry. Therefore, the critical strain rate with respect to the approximate strain at failure (0.035) is of the order of $0.035/(6.1 \times 10^2$ s$) = 5.7 \times 10^{-5}$ s^{-1}, which will be four times faster if both end surfaces are drained. This estimate is 2 orders of magnitude higher than that based on consolidation theory. Considering that significant volume changes associated with deformation, relevant for the hydraulic diffusivity, may occur up to a strain that is an order of magnitude lower than the failure strain (Duda and Renner 2012; Geng et al. 2018), the critical strain rate is also ten

times slower ($\approx 5.7 \times 10^{-6}$ s^{-1}), which is still one order of magnitude higher than the approach based on the consolidation coefficient. The different approaches above illustrate the difficulty in correctly estimating conditions for pore pressure equilibration. We do not know which method is more reliable and all approaches rely on assumptions that we were not able to test, for example potential changes of hydraulic diffusivity or conductivity during deformation by the processes mentioned above (compaction weakening, dilatancy hardening, solution-precipitation). It should be pointed out that the estimation of a critical strain rate for pore pressure equilibrium should be regarded with caution.

Crisci et al. (2021) also point at the potential strength reduction and reduced post-peak weakening of Z-samples caused by drying-induced micro cracks. Drying-cracks along bedding planes of clay-rich material is a well-known topic, especially for Opalinus Clay of the shaly facies (e.g., Houben et al. 2013). However, microstructural analysis of undeformed and dried sample material of the sandy facies of Opalinus Clay did not reveal the development of pronounced microcracks in clay rich layers. Instead, we identified localization in clay-rich layers with basal gliding of preferentially aligned phyllosilicates as major deformation mechanism in Z samples. Therefore, reduced strength and post-peak weakening is explained by increased contribution of gliding of basal planes as it presumably needs less stress compared to fracturing of clastic grains (e.g., Ibanez and Kronenberg 1993; Kronenberg et al. 1990; Mares and Kronenberg 1993), which may result in a stress drop after reaching peak stress as observed for P- and S-samples. At the applied confining pressures (50–100 MPa) the majority of microcracks are expected to be closed (e.g., Winhausen et al. 2020), suppressing dilatant frictional sliding along fracture planes.

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