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Influence of volumetric boundary conditions on the water-retention behaviour of reconstituted and intact clay shales

Influence des conditions limites volumétriques sur le comportement de rétention d'eau des schistes argileux reconstitués et intacts

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ABSTRACT: Tunnelling in swellable soils is a challenging procedure with high risk of damage into the tunnel structure. To minimize the risk of damage to the tunnel support, a rigid or ductile principle of tunnel structure design are often applied to hinder or tolerate deformation in the ground upon swelling, respectively. Considering the coupled interactions between tunnel structure and the swelling rock, prediction of hydration process in swelling clay shales requires investigation of the water retention behaviour of shale under different tunnelling relevant boundary conditions. In this study, the main focus lies on the volumetric boundary conditions. For this purpose, the soil-water retention curves (SWCCs) of both intact and reconstituted Opalinus clay shale (OPA) were determined experimentally. This was carried out for each of the two materials under constant volume conditions in microcells, representing stiff tunnel lining, as well as without volumetric constraints, representing unsupported tunnels, where the intermediate states (deformation tolerant tunnel linings) can be fairly defined through interpolated. In contrast to bentonite that exhibits a noticeable influence of the volumetric boundary conditions, experiments on Opalinus indicated a rather smaller or eventually no influence in case of intact and reconstituted OPA, respectively. This phenomenon is believed to be attributed to mineralogy and fabric of samples.

RÉSUMÉ: Le creusement de tunnels dans des sols gonflants est une procédure difficile qui présente un risque élevé d'endommagement de la structure du tunnel. Pour minimiser le risque d'endommagement du support du tunnel, un principe rigide ou ductile de conception de la structure du tunnel est souvent appliqué pour entraver ou tolérer la déformation du sol en cas de gonflement, respectivement. Compte tenu des interactions couplées entre la structure du tunnel et la roche gonflante, la prédiction du processus d'hydratation dans les schistes argileux gonflants nécessite l'étude du comportement de rétention d'eau du schiste dans différentes conditions limites pertinentes pour le tunnel. Dans cette étude, l'accent est mis sur les conditions limites volumétriques. À cette fin, les courbes de rétention d'eau dans le sol (SWCC) des schistes argileux d'Opalinus (OPA) intacts et reconstitués ont été déterminées expérimentalement. Cette opération a été réalisée pour chacun des deux matériaux dans des conditions de volume constant dans des microcellules, représentant un revêtement de tunnel rigide, ainsi que sans contraintes volumétriques, représentant des tunnels non soutenus, où les états intermédiaires (revêtements de tunnel tolérants à la déformation) peuvent être assez bien définis par interpolation. Contrairement à la bentonite qui présente une influence notable des conditions limites volumétriques, les expériences sur l'Opalinus ont indiqué une influence plutôt faible, voire nulle, dans le cas de l'OPA intacte et de l'OPA reconstituée, respectivement. Ce phénomène serait attribué à la minéralogie et à la composition des échantillons.

Keywords: Swelling shale; soil-water retention behaviour; volumetric constraints.

1 INTRODUCTION

Underground construction in shales is of special interest not only because shales are considered as host rock for nuclear waste repository, but also several passageways as well as utility tunnels have been excavated in swellable clay shales. To assess the swelling evolution in shales, it is essential to properly evaluate the mechanical as well as hydraulic behaviours such as soil-water retention characteristics of the shale. However, the literature shows that the mechanical boundaries can dramatically impact the hydraulic behaviour as of Bentonite is a specific type of smectic clay. To address this phenomenon for tunnelling application, the new Belchen highway tunnel (Ziegler et al., 2022a) was chosen as the case study and the influence of tunneling-relevant boundary conditions on the SWCC of Opalinus clay shale which was the host rock in this project, was studied.

2 MATERIAL AND METHODS

This section gives a brief overview of the material studied, the sample preparation and the methods used to determine the water retention behaviour.

2.1 Material tested

Opalinus Clay (OPA) is a marine clay shale that was formed during the Jurassic period. The material consists of various types of facies, which are determined by the quantity of quartz, carbonates, and clay minerals. The studied OPA originates from the construction site of the new Belchen highway tunnel in the Jura Mountains in Northern Switzerland, which connects Basel and Lucern. Mineralogical studies revealed a composition that closely resembled the shaly facies of OPA at Mont Terri Underground Research Laboratory (Ziegler et al., 2022b).

The material was tested as intact rock, as well as in a reconstituted state as compacted powder. For the intact samples, the drilling cores were carved to a diameter of 3 cm on the lathe and then cut to a height of 8 mm using a diamond band saw. For the reconstituted samples, intact material was first ground to less than 0.25 mm grain size and then compacted to a dry density of 2.0 g/cm^3.

2.2 Soil-water characteristic curve

In this study, a total of four soil-water characteristic curves (SWCCs) for intact OPA and compacted OPA powder (each 2 samples) at an initial dry density ρ_d of 2.0 g/cm^3 were determined. In each case, one sample was used for SWCC at constant volume and one for free swelling conditions. Starting point for determined SWCCs were the preserved in-situ water content and suction of the intact OPA, and the hygroscopic water content of OPA powder and its resulting suction after compaction. From this state, the samples were both saturated and dried. These two states were selected as initial states as they are relevant most of geotechnical applications. The in-situ water content and the corresponding suction of the intact material form the initial state for the practical background of this study, i.e. swelling during mechanised tunnelling. The hygroscopic water content and the corresponding suction in the compacted state of the OPA powder are in turn the starting point for all experimental hydro-mechanical tests in the main project. Initial conditions are summarized in Table 1. Two values are given for intact OPA, as the initial states differ slightly for the two different volumetric boundary conditions. To ensure constant volume conditions, samples were installed in microcells as proposed by Seiphoori et al. (2014).

Since the vapor equilibrium technique (Delage et al. (1998), VET) is appropriate to use in combination with microcells, this experimental method was used in this study to determine SWCCs. By doing so, the suction range between 3 and 350 MPa was covered.

Samples for constant volume conditions were prepared according to Section 2.2. For free swelling conditions, compacts of powder or shards of intact OPA were directly stored in small plastic containers in desiccators. These desiccators contain oversaturated salt solutions in order to expose the samples to a defined suction. Nevertheless, the final suction of the samples was measured with a chilled mirror hygrometer (CMH). The void ratio needed to determine the degree of saturation (S_r) for the free swelling SWCC was determined via immersion weighing in paraffin oil (Christ et al., 2022). Experimental data was fitted with the van Genuchten equation (van Genuchten (1980), Equation 1):

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{[1+(\alpha\psi)^n]^m} \qquad (1)$$

where θ is the volumetric water content, θ_r the residual volumetric water content, θ_s the saturated volumetric water content, m, n, α are soil/fitting parameters and ψ the total suction.

The air-entry value (AEV) was determined according to the commonly used graphical construction method (Pasha et al., 2016), where the AEV is defined as the intersection of the tangent through the inflection point of the SWCC and the horizontal line of S_r=1. Here, this exact value was explicitly calculated corresponding to Soltani et al. (2021) via the first and second derivatives.

Table 1. Initial parameters of intact and reconstituted samples.

		Intact	**Reconstituted**
ψ_{init}	[MPa]	60-65	68
S_r	[%]	63-67	18

Another method to obtain information about the water retention behaviour of a soil is to derive it from the pore size distribution using MIP. The method associates the mercury intrusion with the drying path of a SWCC by considering the mercury intrusion at a given pressure p to be the same as the air intrusion at a matric suction ψ_m (Ferrari and Romero, 2019).

3 RESULTS AND DISCUSSION

Soil water characteristic curves (SWCCs) of compacted OPA powder and intact OPA for free swelling and volume constant conditions are shown in

Figures 1 and 2, respectively. Fitting curves were obtained by the least square method using the van Genuchten equation (Eq. 1), leaving out residual and saturated volumetric water contents or rather degrees of saturation. Fitting parameters are summarised in Table 2. It should be noted that these are not classic SWCCs, where a material is installed as a slurry and then dried (initial drying), rehydrated (main wetting) and dried again (main drying). The focus of the SWCCs in this study is on the initial state, which results from the in-situ state (intact material) or the initial state of all experimental tests in this study (powder).

Table 2. Van Genuchten fitting parameters and AEV of determined SWCCs in this study.

		Reconstituted		**Intact**
		free	VC	combined
n	[-]	1.503	1.558	2.132
m	[-]	0.335	0.358	0.452
α	[1/MPa]	0.290	0.211	0.019
ψ_{AEV}	[MPa]	1.49	2.07	26.34

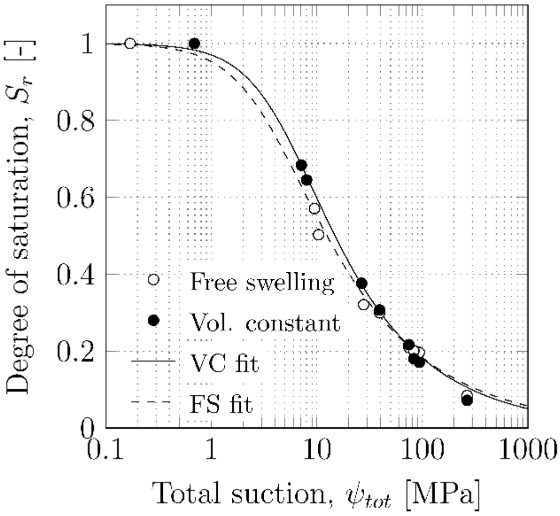

Figure 1. Soil-water characteristic curves of reconstituted OPA – experimental data and van Genuchten fit.

The derivation of the matric suction—saturation relationship should be limited to the low-suction range, in which capillarity dominates the water retention properties (Romero et al., 1999).

For OPA powder, the initial state corresponds to a suction of 68 MPa at a degree of saturation of 18%. A minor difference between volume constant and free swelling boundary conditions can be observed in the wetting branch. No difference can be seen in the drying branch, which is due to the fact that the applied volumetric boundary conditions are irrelevant for drying and the associated potential shrinkage of the sample. Microcells for the preservation of volume-constant boundary conditions were introduced in Seiphoori et al. (2014) as part of investigations into the water retention behaviour of compacted bentonite in the context of radioactive disposal.

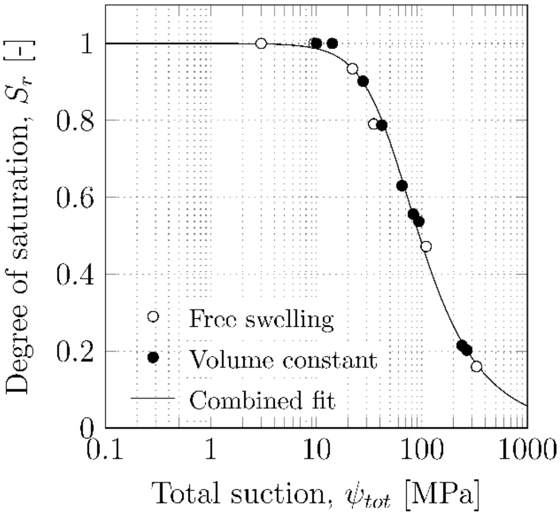

Figure 2. Soil-water characteristic curve of intact OPA – experimental data and van Genuchten fit.

In this study, a more evident influence of the volumetric boundary conditions on water absorption during hydration was observed. It was argued that further hydration is inhibited by the prevention of continued subdivision of the clay particles by the constant-volume boundary conditions, which in turn prevents further water absorption on and between the clay particles. In the present study, the SWCC of compacted OPA powder at constant volume boundary conditions shows a slightly higher degree of saturation at the same total suction than the SWCC without volumetric constraints. A look at the underlying data shows that this difference is due to the prevented expansion of the material. The water content is almost the same in both cases at the same total suction. With free swelling, however, the void ratio increases steadily as total suction decreases, whereas it remains the same for the constant-volume SWCC. The fact that the influences of the volumetric boundary conditions are not as pronounced in this case as in the study by Seiphoori et al. (2014) can be attributed to the mineralogy of the two materials analysed. While Seiphoori et al. (2014) investigated MX-80 bentonite, which has a smectite content of 85%, OPA consists of only 11-16% illite/smectite mixed layer minerals. Smectites are the clay minerals with the highest water absorption capacity. As a result, MX-80 has a significantly higher swelling capacity and therefore reacts more sensitive to restrictions in volumetric swelling. In view of the fact that the different volumetric boundary conditions for determining the SWCC were taken into account in order to consider the tunnelling relevant volumetric boundary conditions of *rigid lining*, *no lining* and *deformation-tolerant lining*, it can be concluded that a combined SWCC is sufficiently accurate given the minor deviations observed.

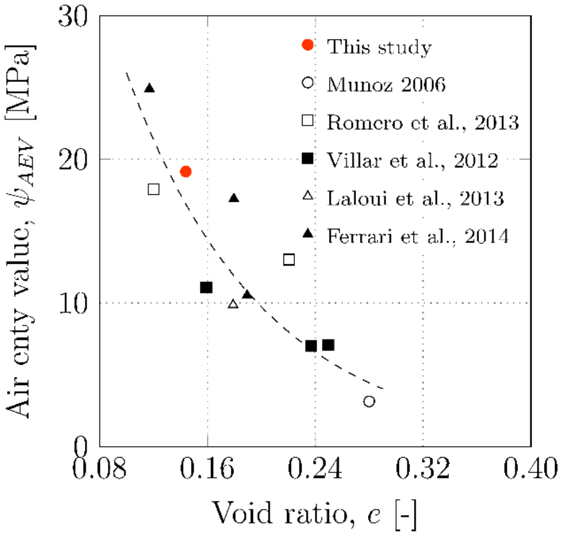

Figure 3. Air-entry value over void ratio from Ferrari et al. (2014) complemented with data from this study.

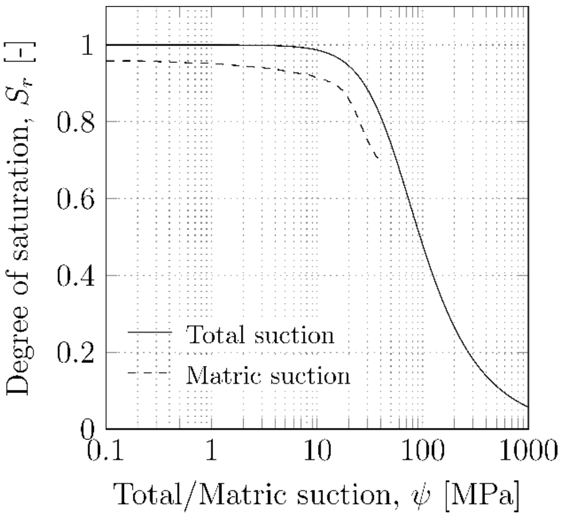

Figure 4. Separate consideration of matric and total suction in the context of the SWCC of intact OPA.

The initial state of intact OPA samples was at a total suction ψ_{tot} between 60 and 65 MPa and corresponding degrees of saturation between 63 and 67%. Experimental data of the SWCCs in Figure 2 show no difference for both volumetric boundary conditions considered. The points all appear to lie on the same scanning curve. Thus, no distinction was made in the fitting between the two different boundary conditions and all points were merged to derive a single combined parameter set. The fact that there is no recognisable difference between free and constant-volume swelling for the intact OPA in the SWCC can be attributed to a further point in addition to the influence of mineralogy already mentioned above. Diagenesis and the resulting structure play the decisive role here. As shown in Christ et al. (2023), the structure of the intact material acts as an additional attractive force and further reduces the swelling capacity. As OPA is ground, the swelling pressure and the water uptake capacity according to Enslin-Neff increase significantly. Both increase more with increasing grinding fineness. Due to the once again lower swelling capacity of the intact OPA compared to the OPA powder, the volumetric boundary conditions no longer play a significant role in the determination of the SWCC. An influence can no longer be identified from the data.

Air-entry values (AEVs) determined according to Equ. 1 are also summarised in Table 2. From a physical point of view, the AEVs are not actual air entry values, as they were determined using the wetting path and not the drying path. Nevertheless, they are considered here as characteristical values of a SWCC. It is noticeable that the AEV of the intact material is more than ten times the AEV of the powder. The magnitude of AEVs depend on different factors, like the density, grain size-distribution or aggregation (Nishimura et al., 2012), and thus factors that influence the size of the pore diameters. The smaller the pore diameter, the greater the suction required for air to penetrate into the pore space and thus to bring the sample into an unsaturated state. Due to the higher dry density of the intact material (ρ_d=2.3 g/cm^3) compared to the compacted powder (ρ_d=2.0 g/cm^3), the observed difference is plausible. This is also confirmed by the pore-size distribution of the two materials. The peak of the pores and thus the most common pore diameter is 300 nm for the powder, whereas it is only 10 nm for the intact OPA. Ferrari et al. (2014) summarised data from various studies on the water retention behaviour of intact OPA. The yielded exponential fit is plotted with available data from the literature in Figure 3. The AEV from this study shows very good agreement with the data and the corresponding exponential fit. Note: The value in Figure 3 from this study differs from the value in Table 2 because it is based on the definition of the AEV in Ferrari et al. (2014). There, the AEV is the suction that correlates to a degree of saturation of 95% in the SWCC. As mentioned before, the SWCC can also be derived from the MIP data. Thereby, pressure that must be applied to penetrate mercury into the pores of the sample is converted to a matric suction. Figure 4 shows both SWCCs for the intact material, the van Genuchten fit of the total suction and MIP data of the matric suction. The two curves fit together very well. The bend in the two courses runs almost parallel. Due to the upper limit of the MIP, the SWCC of the matric suction ends at approx. 40 MPa.

The difference between the two curves is due to the osmotic suction of the sample or rather the pore fluid. Ferrari et al. (2014) showed with a separate determination of the osmotic suction of OPA with the contact and non-contact filter paper method that this matches quantitatively well. In the current study, the proportion of osmotic suction decreases slightly as the degree of saturation increases, from 18.8 MPa at S_r=75% over 16.8 MPa at S_r=80% and 14.2 MPa at S_r =85% to 13.5 MPa at S_r =90%. This is attributable to the fact that the sample is saturated via the vapour phase, which lowers the ion concentration in the pore fluid and. thus the osmotic suction.

4 CONCLUSIONS

In this study, the soil water retention behaviour of intact and powder compacted Opalinus clay has been assessed in free and constrained volume conditions. The experimental results indicated no significant influence of volumetric boundary conditions on the SWCC of OPA. The air-entry value obtained form current experiments was found to be consistent with other measurements in the literature. Finally, the MIP-driven SWCC of the matric suction showed the same trend as the SWCC of total suction.

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