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Design considerations for deep caverns in Opalinus Clay

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ABSTRACT: The planned radioactive waste repository in Switzerland will be located within a *ca.* 900 m deep and 100 m thick layer of Opalinus Clay. Low- and intermediate-level waste will be emplaced in caverns with a diameter of 14 m. The great depth of cover and the rather low strength of Opalinus Clay (uniaxial compressive strength in the order of 3-5 MPa) are expected to result in squeezing conditions, which will be demanding to handle on account of the large dimensions of the cavern cross-sections. The paper investigates alterative concepts for the tunnel support, considering the uncertainties and peculiarities of the Opalinus Clay's response to tunnelling – *inter alia* its very pronounced time-dependency. The development of relevant deformations will not cease even after several decades, while in the presence of a stiff lining the rock pressure would reach very high values within the service life of the caverns (in the order of about 3-4 MPa within a period of 20-30 years after excavation).

1 INTRODUCTION

The Swiss National Cooperative for the Disposal of Radioactive Waste (Nagra) is planning the construction of a combined waste repository consisting of 14 m diameter caverns for low- and intermediate-level waste (L/ILW) and 3.5 m diameter tunnels for high level waste (HLW) (Figure 1). At the current project stage, the repository is planned to be located at a depth of 900 m, in the middle of a 100 m thick and fully saturated layer of Opalinus Clay. The present paper focuses on the conceptual design of the L/ILW caverns; for the HLW tunnels see the companion paper by Nordas *et al.* (2023).

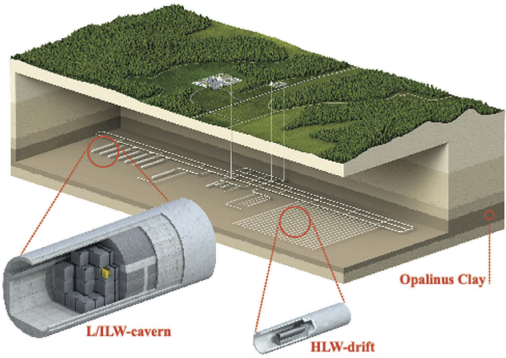

Figure 1. Schematic representation of the radioactive waste repository.

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The L/ILW caverns have a 13.6 m wide and 14.8 m high cross-section, and are planned to be constructed conventionally with full-face excavation. The paper discusses possible support concepts (Figure 2), considering the main features of the geomechanical behaviour of Opalinus Clay at the repository depth: squeezing conditions associated with the great depth and the rather low strength of Opalinus Clay (uniaxial compressive strength in the order of 3-5 MPa); extremely slow development of convergences and rock pressures over several decades due to the very low permeability of Opalinus Clay; and uncertainty about the behaviour of Opalinus Clay under negative pore pressures (suction), which are expected to develop due to excavation (see Section 3).

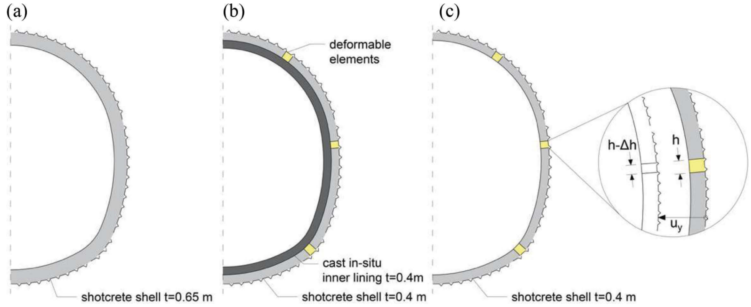


Figure 2. Evaluated support concepts: (a) single-shell shotcrete lining; (b) yielding support consisting of shotcrete shell with deformable elements followed by an inner lining; (c) yielding support throughout the entire life span.

2 THE HOST ROCK

Opalinus Clay is an argillaceous formation consisting of silty to sandy claystones. This type of rock is particularly suitable for long-term radioactive waste storage, due to its microscopic composition, its very low permeability and its moderate swelling behaviour. The latter ensures sealing of cracks generated by tunnel excavation, thus delaying seepage flow and radionuclide transfer through the ground.

The mechanical behaviour of Opalinus Clay has been investigated by means of consolidated drained and consolidated undrained triaxial compression tests on specimens obtained from deep boreholes in the repository sites under consideration (see, *e.g.*, Crisci *et al.* 2021). According to the experimental results, Opalinus Clay exhibits pronounced stiffness and strength anisotropy, practically brittle failure, and moderate stiffness dependency on the initial confining pressure.

The elevation of the water table corresponds to the ground surface, leading to a pore pressure of 90 bar at the repository level. As the Opalinus layer is embedded in high permeability limestones, it is expected that the full hydrostatic pressure of about 90 bar will act at the Opalinus-limestone interface, that is at a distance of just three diameters from the caverns.

3 DESIGN QUESTIONS AND COMPUTATIONAL MODEL

The investigated support types are based upon the so-called (Kovári, 1998) resistance principle (Figure 2a), the yielding principle (Figure 2c) or combinations thereof (Figure 2b). Depending on the support type and on the construction phase or time period, attention must be paid either to the rock pressures or to the rock deformations.

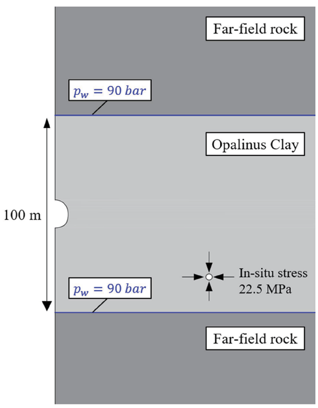
So, for example, in the case of Figure 2a, where the deformations are anyway small as long as the support does not fail, emphasis is placed on the rock pressure developing within the planned operation period of 25 years.

In the case of Figure 2c (yielding principle), the convergences that will occur within the service life of the structure stay in foreground, because they may violate the clearance profile or impair the serviceability of the caverns during the storage operations. A reliable estimation of the deformations is important for the selection of an adequate excavation radius and for the structural detailing of the support.

Finally, for a support combining the yielding and the resistance principle (Figure 2b), emphasis is placed on the time-development of convergence until inner lining installation, and on the time-development of rock pressure afterwards.

Since rock pressures and deformations develop slowly over time in the case of Opalinus Clay, and the time-dependency is due to the seepage flow around the openings (consolidation), coupled hydraulic-mechanical computations have been performed for addressing the aforementioned questions. Specifically, a two-dimensional plain strain hydraulic-mechanical finite element model has been developed in Abaqus® (Dassault Systèmes 2019) to estimate the instantaneous ground response to the excavation of the caverns and the evolution of the consolidation-induced rock deformations and pressures (Figure 3). The model takes account of the construction and operational phases through a series of computational steps (Table 1).

(a)



(b)

Opalinus Clay	
Young's modulus parallel to bedding *Ep*	13.6 GPa
Poisson's ratio v_{pp}	0.2
Young's modulus orthogonal to bedding *Eo*	4.5 GPa
Poisson's ratio v_{op}	0.1
Shear modulus G_{op}	2.1 GPa
Matrix cohesion *c*	1.0 MPa
Matrix friction angle φ	27.5°
Matrix dilatancy angle ψ	4°
Bedding cohesion c_b	1.0 MPa
Bedding friction angle φ_b	21.5°
Bedding dilatancy angle ψ_b	2°
Permeability *k*	10^{-13} m/s
Far-field rock	
Young's modulus *E*	5 GPa
Poisson's ratio *v*	0.2
Shotcrete shell and inner lining	
Young's modulus *E*	30 GPa

Figure 3. (a) Part of the computational domain; (b) assumed material constants (after Anthi *et al.*, 2022).

The constitutive model considers Opalinus Clay as an anisotropic, linearly elastic and perfectly plastic material obeying the Mohr-Coulomb failure criterion (see Nordas *et al.*, 2023). The computations have been performed with residual strength parameters. The assumed material constants are given in Figure 3b.

A source of relevant analysis and design uncertainty in the present case is associated with the behaviour of Opalinus Clay under high negative pore pressures: Tunnel excavation in weak rock at great depths results in plastic yielding of the rock and a decrease in the rock stresses within a zone around the opening ("plastic zone"). The stress relief in combination with the rock loosening that accompanies yielding generally results in an increase in the pore volume and – if the rock is saturated as in the present case – in an increase in the water content. The latter cannot occur instantaneously because it presupposes that water will seep from further away towards the plastic zone, which – if the rock exhibits a low permeability as in the present case – needs considerable time. Instead, pore water experiences a pressure drop in the short term and the pore pressure may even become negative ("suction"; see blue line in Figure 4). The suction increases the effective stresses and the frictional shear resistance of the rock, and is, therefore, favourable for the short-term behaviour of the ground, provided that the latter remains saturated. This is quite possible, but not certain beyond doubt for argillaceous materials. Under suction, air may enter into the

Table 1. Computational steps.

Step	Figure 2a	Figure 2b	Figure 2c
1	Complete undrained unloading of the excavation boundary. (a)	Computation of the short-term rock deformations by means of an undrained unloading of the excavation boundary to the yield pressure of the support, considering the deformable elements as rigid - perfectly plastic. (b)	
2	Activation of the shotcrete shell and computation of the time-development of the sectional forces in the shell by means of a transient analysis for 25 years	Computation of the additional, time-dependent convergences of the yielding support by means of a transient analysis for 1 or 3 years.	As step 2 of the analysis of the support concept of Figure 2b, but the transient analysis extends over the entire service life of the cavern.
3		Activation of the inner lining and computation of the section forces that develop during its service life by continuing the transient analysis for 25 years.	

(a) This is a favourable (non-conservative) simplifying assumption which was made in order to show that the solution of Figure 2a is unfeasible even under favourable assumptions.
(b) This step provides the total short-term rock deformations, including the pre-deformations, that is the deformations occurring ahead of the tunnel face and between tunnel face and location of support installation. In order to determine the necessary deformation capacity of the yielding support, only the rock deformations occurring after support installation are relevant. They are obtained by subtracting the pre-deformations from the total rock deformations. The pre-deformations have been computed by means of a preliminary 3D undrained analysis.

rock, with the consequence that the rock desaturates and the high negative pore pressures largely disappear (red line in Figure 4), whereby their stabilizing effect gets lost. In summary, the short-term behaviour of the rock can be more or less unfavourable depending on whether or not the rock desaturates under negative pore pressures.

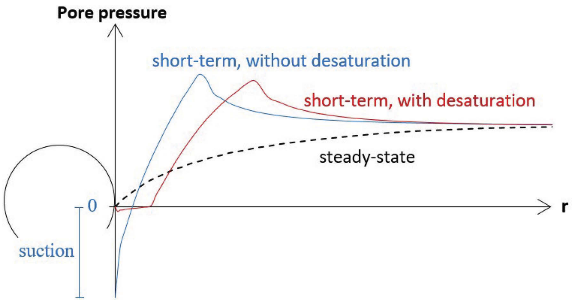


Figure 4. Radial pore pressure distribution around a circular tunnel (schematically).

Rock desaturation has the opposite effect (it is favourable) with respect to long-term behaviour. The negative pore pressures that develop in the short term if the rock remains saturated (blue line in Figure 4) dissipate over the course of time (the dashed line in Figure 4 shows the long-term pore pressure distribution) and cause additional time-dependent deformations. It can be said that desaturation accelerates rock deformation, resulting in less favourable short-term behaviour, but more favourable long-term behaviour. As we will see later, this is a very relevant aspect from the practical engineering viewpoint. For the support type of Figure 2b, desaturation results in greater deformations of the primary (yielding) support, but in lower loadings of the inner lining.

Due to uncertainty about the rock behaviour under suction, two borderline cases will be considered: (i) the rock remains 100% saturated even under very high negative pore pressures; (ii) rock completely desaturates as soon as pore pressure drops below zero.

4 SHOTCRETE LININGS BASED ON THE RESISTANCE PRINCIPLE

Initially a top heading and bench excavation was envisaged, with a 65 cm thick single-shell shotcrete lining completed within four tunnel diameters behind the tunnel face (Figure 2a). The transient geomechanical analyses outlined above revealed that the rock pressure developing within the service life of the cavern might be prohibitively high.

Figure 5 shows the axial force distribution in the shotcrete shell under the simplifying non-conservative assumption that the short-term loading of the shell is negligible. According to this model, the shell is subjected only to the rock pressure developing over the course of time, because the shell prevents time-dependent (consolidation-induced) convergences. The latter would be considerable if the rock remained saturated under the suctions developing in the short term, and therefore the prevention of the deformations by the shell would result in considerably higher (by a factor of 6 higher) axial forces and concrete stresses (blue line) than in the case with rock desaturation (red line). In the former case, the stresses exceed the strength of a good quality shotcrete; in the latter case, the stresses are very low and would allow a much thinner lining. These results illustrate that the insufficient knowledge about rock behaviour under negative pore pressures is a source of relevant design uncertainty.

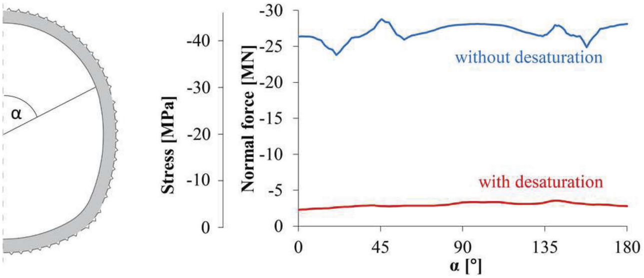


Figure 5. Structural concept of Figure 2a: Normal force and axial stress distribution in the shotcrete shell 25 year after installation (before installation of inner lining).

In conclusion, even if neglecting the short-term loading of the shell, even without considering force eccentricity (bending moment) and even without any material and load safety factors, a support based on the resistance principle does not appear reasonable under the conditions of the deep repository. A yielding support will be studied in the next section.

5 SHOTCRETE LININGS BASED ON THE YIELDING PRINCIPLE

The yielding support considered consists of a shotcrete shell that contains six 30 cm wide longitudinal slots (marked yellow in Figure 2b) with "highly deformable concrete" elements (Kovári 2005, 2009). These elements yield almost perfectly plastically under a high yield strength (10 MPa, or even higher depending on the concrete composition), thus offering a high support pressure (0.5 MPa for the planned 14 m diameter cross-section) during the deformation phase, which is advantageous from the structural point of view (Cantieni and Anagnostou, 2009). Elements of this type have been successfully applied *inter alia* in the Lötschberg Basetunnel (Keller, 2005) and in the St. Martin La Porte access tunnel to the Lyon-Turin Tunnel (Barla *et al.*, 2008).

The deformable elements mitigate the risk of shotcrete overstressing because they limit the shotcrete stresses to their yield strength. This presupposes however that their deformation capacity suffices to accommodate the reduction in the circumference induced by convergences, which raises questions as to the rock deformations developing in the period up to the installation of the lining.

Figure 6 shows the deformations of the opening (total ground displacements minus ground displacements at the point of installation of the lining) that are predicted under the two assumptions about rock desaturation within 3 years. Rock desaturation would result in loss of the stabilizing effect of suction and thus to larger short-term convergences (up to 100 mm according to Figure 6), in a bigger decrease in the circumference of the opening (up to $2\pi \cdot 100$ mm = 628 mm) and in bigger compression of the deformable concrete elements. In the case of six 300 mm wide slots, each deformable concrete element would experience a compression of up to 628/6/300 = 35%, which is less than the usual deformation capacity of such elements (40%). So, a yielding support would be effective even in the case of desaturation, which is the most unfavourable assumption with respect to the short-term displacements ("with desaturation").

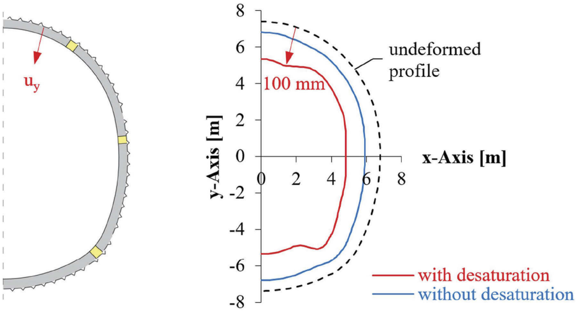


Figure 6. Structural concept of Figure 2b: Displacements of the yielding support 3 years after excavation (latest time instance of inner lining installation).

The installation of the inner (practically rigid) lining prevents further deformation. Instead, a rock pressure develops over time. Figure 7 shows the numerically predicted axial forces and bending moments, 25 years after lining installation. Each marker corresponds to another concrete section of the inner lining. The diagram also shows the moment - normal force interaction curves for two concrete qualities and lining thicknesses, considering material safety factors after the SIA (2004). Rock desaturation results in larger displacements in the period before lining installation (compare the red with the blue line in Figure 6), but to considerably lower rock pressures in the period after lining installation (compare the red with the blue points in the interaction diagram of Figure 7).

The axial forces predicted under the assumption of desaturation are about 3.5 MN (red crosses in Figure 7), which points to a rock pressure of about 3.5/7 = 0.5 MPa (considering the cavern radius of about 7 m). So, the rock pressure developing upon the lining is low, even if the lining is installed early (1 year after cavern excavation). The corresponding sectional forces can easily be sustained by a 0.4 m thick lining made of concrete C25/30.

However, as previously discussed, the critical case is the one without desaturation, where the high excess pressures developing short-term dissipate slowly over time, but the lining prevents the developments associated with this process. A delay in the lining installation (three years instead of one year after excavation) does not help much in this respect (compare triangular markers with blue crosses in Figure 7). Regardless of the lining installation time, the load developing upon the stiff lining within 25 years is about 3-4 MPa. Such a high and slowly developing load is not typical for squeezing rock and reminds us of the conditions experienced in tunnels

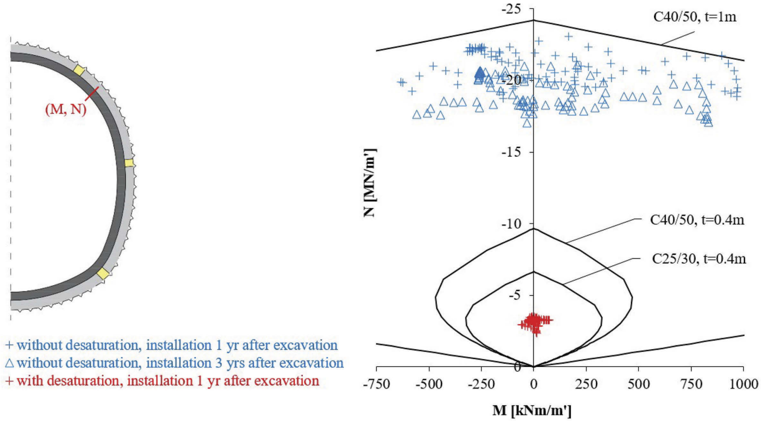


Figure 7. Structural concept of Figure 2b: Normal force – moment interaction in the cast-*in-situ* inner lining 25 years after installation.

in heavily swelling Gypsum Keuper (Anagnostou, 2007). In the present case, an inner lining according to the resistance principle would have to be at least 1 m thick and made of higher quality concrete.

6 YIELDING SUPPORT THROUGHOUT THE ENTIRE SERVICE LIFE

As an alternative to an extraordinary thick inner lining according to the resistance principle, it is worth to investigate the option of a yielding support over the entire service life of 25 years (Figure 2c), because in the present case the loads developing upon a stiff support are high (due to the great depth), but the displacements developing with a light support are rather moderate (Figure 6), and therefore possibly acceptable from the serviceability viewpoint.

This is evident from Figure 8, which shows the development of the convergence over time when refraining from an inner lining. Under the assumption that the rock remains saturated under the suction developing short-term (blue line), the convergence would increase from 30 to 50 mm within 25 years, which does not appear to be problematic for the serviceability. In the case of rock desaturation (red line), the convergence would be greater in the short term, but would increase much more slowly over time; the 25-year convergence (105 mm) is only slightly greater than the 3-year convergence (100 mm), which must anyway be foreseen for the yielding support, and can be easily materialized.

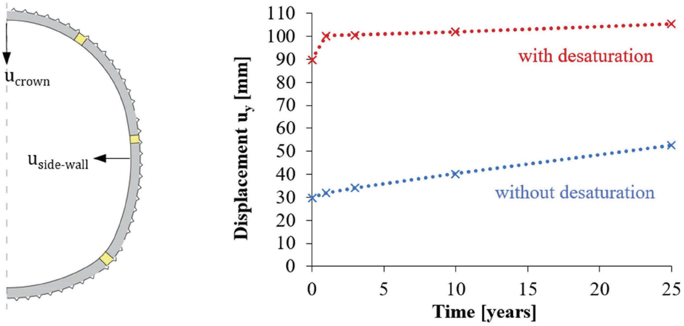


Figure 8. Structural concept of Figure 2c: Tunnel convergence over time (average between crown and side-wall).

7 CONCLUSIONS

A support based on the resistance principle (Figure 2a) is not feasible for 900 m deep, 14 m diameter caverns in Opalinus Clay. In order to avoid support overstressing, one must allow deformations to occur in a controlled manner at least for the primary support (Figure 2b). This can be achieved using proven techniques. Incorporating highly deformable concrete elements in the shotcrete shell fulfils the requirements of safety and convergence control. The uncertainty about rock behaviour and saturation under negative pore pressures results in a prediction uncertainty about the magnitude of convergence that must be accommodated by the primary support, but this uncertainty is irrelevant from the design viewpoint because even the worst-case convergence is within the feasibility limits.

One might expect that the additional deformations occurring in the case of a yielding primary support would result in a significant decrease in the load developing later upon the stiff inner lining. This is true only if the rock desaturates under the suctions developing immediately after excavation. In this case, the loading of the inner lining is easily manageable. In the other borderline case, with the rock remaining saturated in the short-term in spite of the negative pore pressures, the stabilizing effect of the suctions results in smaller deformations of the primary support and in higher long-term loading of the inner lining, thus necessitating a lining of extraordinary thickness and strength. Consequently, the uncertainty about rock saturation is relevant with respect to the inner lining.

The effect of this uncertainty can nevertheless be mitigated by abandoning the resistance principle and selecting a yielding support for the entire service life of the caverns (Figure 2c). A yielding support with only slightly higher deformation capacity than the one anyway required in the primary phase would suffice for the 25-year-long service life. The serviceability aspects of such a solution are under investigation.

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