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Creep Processes Involved in the Maturation of Clay-isolated Highly Radioactive Waste in Very Deep Holes

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Abstract

The basic idea of concepts for disposal of highly radioactive waste deep in rock is that the heavy, saline, stagnant formational waters are unlikely to rise to contaminate shallow groundwater. A recent concept involves placement of the waste in the lower 2 km part of up to 4 km deep holes bored in granitic rock, and relies on the sealing capacity of engineered barriers in the form of concrete and clay in the upper parts of the holes. The parts located in fracture-poor rock are sealed with dense expandable clay, while concrete is cast where pre-grouted fracture zones are intersected. The holes will converge by creep and eventually exert the seals to radial compression. Using a new rheological model based on the Kelvin model in combination with a stochastic mechanical model, the predicted radial hole convergence causes a vanishingly small increase in pressure on the seals in the first 10,000 years. In a long time perspective they will be compressed and become less permeable. Parallel conversion of the clay minerals to become less expandable will, however, reduce this potential.

Keywords: Boreholes, Clay, Concrete, Convergence, Creep, Elasticity, Radioactive waste, Rheology, Stress, Viscosity

1 Scope of study

The case considered deals with the time-dependent change in the radius of up to 4 km deep boreholes intended for disposal of high-level radioactive waste (Figure 1). The very deep holes, generally known as DBD and represented by a concept called VDH here, are assumed to be bored with 0.8 m diameter and filled with soft

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bore mud in the excavation phase for the sake of stability in the boring phase and in the subsequent phase of installing supercontainers with waste canisters in the lower 2 km parts of the holes and placement of clay seals in the upper 2 km parts. The major sealing component consists of highly compacted, expandable clay where the rock is normally fractured and of concrete where the holes intersect fracture zones. The clay seals and clay-embedded waste canisters are contained in perforated tubes of copper, Navy Bronze, titanium or steel [1]. The clay generates, very early, a radial effective pressure of up to 4 MPa [2] on the borehole walls independently of the depth, while the surrounding rock exerts a counter-pressure that increases with time because of creep strain. The question to be answered is whether convergence of the holes will compress the clay radially and how the sealing effect of the clay is thereby altered.

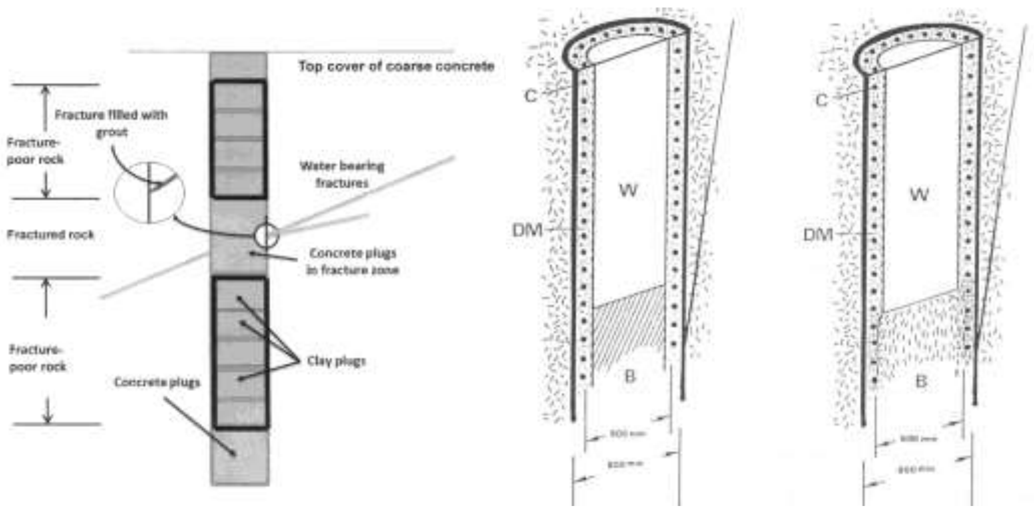

Figure 1. DBD version with 4 km depth. Left: Upper 2 km part of bored holes with clay seals in perforated "super-containers" and cast concrete depending on the degree of fracturing of the rock. Right: Evolution of lower 2 km casing-supported (C) hole hosting a perforated supercontainer with waste canister (W), and separating clay block (B), located in clay mud (DM); [3,4].

2 Evolution of clay barriers

2.1 Maturation of the clay seals in VDH

The dense core of the clay seals is not fully water saturated from start and expands by sorbing water from the initially soft boremud (1,100–1,300 kg/m^3 density). This process is associated with consolidation of the clay mud and softening of the expanding core (Figure 2). It sorbs water from the surrounding mud which becomes compressed under the swelling pressure exerted by the core. This process is of diffusive type and retarded by the redistribution of porewater in the mud and core that may take hundreds of years to be fully developed. For the assumed initial dry density of the core (1,450 kg/m^3) the swelling pressure can rise to 4 MPa in electrolyte-poor groundwater while in salt water the corresponding pressure is between 2 and 3 MPa. In the presently considered case we will assume that full swelling pressure, 4 MPa, is reached in less than one year [2].

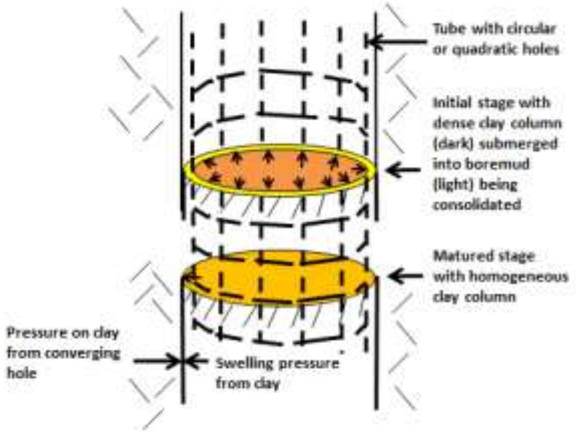

Figure 2. Schematic drawing of a clay seal that expands in conjunction with compression of the boremud in the initial stage. After consolidation of the mud the clay in the hole becomes largely homogeneous and impermeable under the prevailing very low regional hydraulic gradients.

2.2 The role of the rock

2.2.1 Stress conditions

The deep VDH holes will undergo changes in diameter because of the high rock stresses at depth. When the 0.8 m wide holes are being bored the hoop stress (σ_θ) and radial stress (σ_r) in the surrounding rock reach levels that can be calculated by using the theory of elasticity. One gets $\sigma_\theta=\sigma_h(1+a^2/r^2)$ and $(\sigma_r=\sigma_h(1-a^2/r^2)$, respectively, where the horizontal and intermediate principal stresses are σ_h, and a is the radius of the holes, r being the radial distance from the vertical symmetry axis. For the typical isotropic compressive horizontal rock stresses at 2 km depth, 60 MPa, the hoop stress at the periphery of the holes will be 120 MPa and the radial stress 0 MPa [5,6]. At 4 km depth, where the compressive horizontal rock stresses is estimated at 77 MPa, the hoop stress at the periphery of the holes will be 154 MPa and the radial stress 0 MPa [7]. Here, the stress constellation can begin to cause initiation of rock failure.

2.2.2 Strain evolution of VDH

The instantaneous deformation of the holes in the boring phase is small, elastic and negligible, while the time-dependent geometrical changes caused by creep strain can be of importance by leading to radial compression of the clay seals. Theoretically, the swelling pressure of the clay will counteract the movement of the walls of the holes and reduce the hoop stress in the rock around the holes. We will consider these matters here by making use of the Kelvin rheological model for the rock [6].

3 Creep strain models

Traditional rheological models like the classical Kelvin model in Figure 3 are useful in vizualising the basic principles of time-dependent shear or compressive strain of visco-elastic media as demonstrated by Pusch and Weston [8]. Comparison with a model, here termed "Eyring/Feltham", that is basically a thermodynamically founded creep model based on work made independently by Eyring et al, [9] and Pusch and Feltham [10], has shown that both are applicable to geological media like glacier ice, clay, and crystalline rock [8] provided that relevant material data are used.

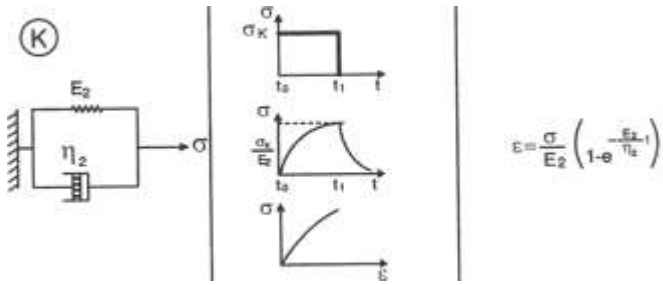

Figure 3. The original Kelvin rheological model [6].

We will make use of this model being basically the Kelvin model calibrated by the Eyring/Feltham model that implies, for moderate but not very low deviator stresses, that long time creep has a logarithmic time dependence. This has been shown by Feltham and Pusch [10,11], who proposed the following relationship for materials with a spectrum of interparticle bond energies:

$$\varepsilon = Bln(t + t_0) + A \qquad (1)$$

where B is a function of material properties and stress, and t_0 and A are integration constants. In our case we assume for various reasons[3] that t_0 and A equal zero. We choose to calibrate the Kelvin model by the Eyring/Feltham model, i.e. by putting:

$$\varepsilon = \frac{\sigma}{E}\left(1 - e^{-\frac{E}{\eta}t}\right) = Bln(t) \qquad (2)$$

Since B is solely a function of the stress σ and various material parameters, we conclude that B should be independent of time because no time-dependent

[3] t_o can be negative or positive, implying that the strain/time curve in a double-logarithmic diagram successively adapts to logarithmic strain [11].

material parameters were introduced, and hence that strain will be time dependent. A new modulus of elasticity derived from the equality in Eq.(2) gives the viscoelastic strain and hence makes it possible to solve the problem of mechanical interaction of rock and clay seals by calculating the radial movement of the borehole wall as a function of time after boring [8]. This, in turn, will show its impact on the density and physical properties of the confined clay by keeping in mind that:

- The stress changes caused by the boring will give a radial movement u that can be calculated by using the theory of elasticity: $u=pa(1-\nu)/E$ where E=σ/ ε and ν is Poisson's ratio, taken to be 0.2 here,

- For getting the time-dependent radial displacement of the borehole walls we will use the expression for strain of the Kelvin model, for which the modulus of elasticity of spring E2 in Fig.3 is taken as E4 MPa and the dashpot viscosity as η=E20 Pas for the basic case of granitic rock of ordinary quality [6,12,13,14,15]. The behaviour of weaker bedrock, represented by metamorphous or argillaceous rock, would imply a spring modulus of E3 MPa and η=E18 Pas [12]. The periods of time of interest are 1, 10, 100, 1,000 and 10,000 years after onset of creep. The assumed loading case implies that the internal pressure against the borehole walls is raised from an initially very low value when the dense clay is being inserted, to 4 MPa within a few months and to stay at this level until the convergence of the holes has gone on for at least 100,000 years. The axial hydraulic conductivity of the adjacent rock is thereby kept low [16].

3.1 Calculation of hole convergence

The calculation is made numerically using the upgraded Kelvin rheological model, which is mathematically straight forward, i.e.

$$\varepsilon(t) = \frac{\sigma}{E}\left(1 - e^{-\frac{E}{\eta}t}\right) \tag{3}$$

where σ is Hooke`s stress, $E$ is the Young`s modulus of the rock, η is the viscosity and t is the starting time of the creep. The idea here is to derive time-dependent values of ε and use these to calculate a corrected E −modulus, E', by imposing:

$$E'(t) = \frac{p}{\varepsilon(t)} \tag{4}$$

Here, p is the rock stress, which is related to the Hooke´s stress by:

$$\sigma = p\left(1 + \frac{a^2}{r^2}\right) \tag{5}$$

In our case, a equals the radius, r and, hence, $\sigma = 2p$. When the corrected Young´s modulus is at hand, we can calculate the time dependent displacement of the wall of the bored hole as:

$$u(t) = pr\frac{(1-\nu)}{E'(t)} = pr\varepsilon(t)(1-\nu) \quad (6)$$

One observes that use of Eq (2) is redundant, since $\frac{p}{E'(t)}$ equals $\varepsilon(t)$.

The calculated radial movement of the walls of 0.8 m diameter borehole in typical crystalline rock at 2 and 4 km depth using the proposed rheology model, is given by the graph in Figure 4.

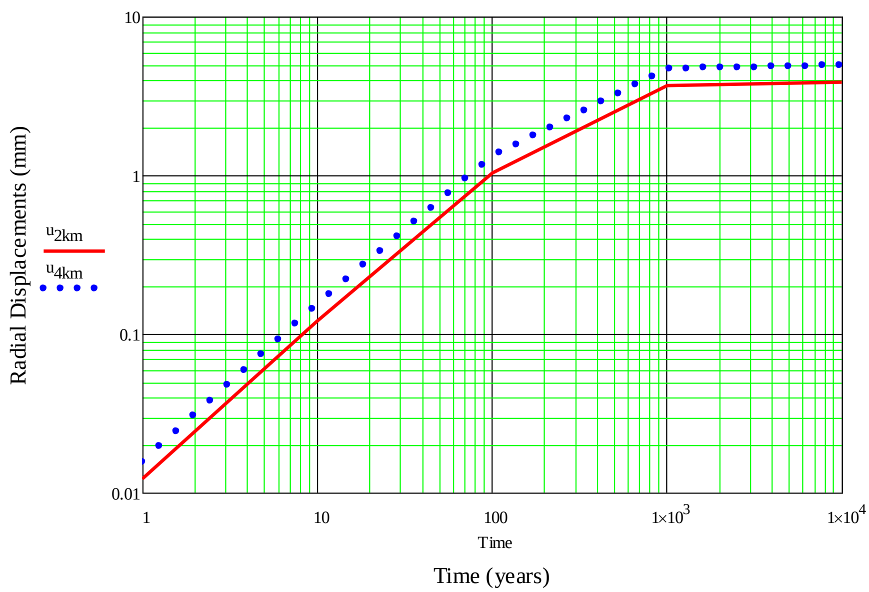

Figure 4. Calculated radial movement of the walls of 0.8 m diameter borehole in typical crystalline rock at 2 and 4 km depth by using the new rheological model.

The behaviour of somewhat softer rock with the estimated rheological parameters E_2=5E2 MPa and η_2=E17 Pas is illustrated by the graph in Figure 5, showing at least 60 times larger wall movement after 100 years and 20 times larger movement after 10,000 years.

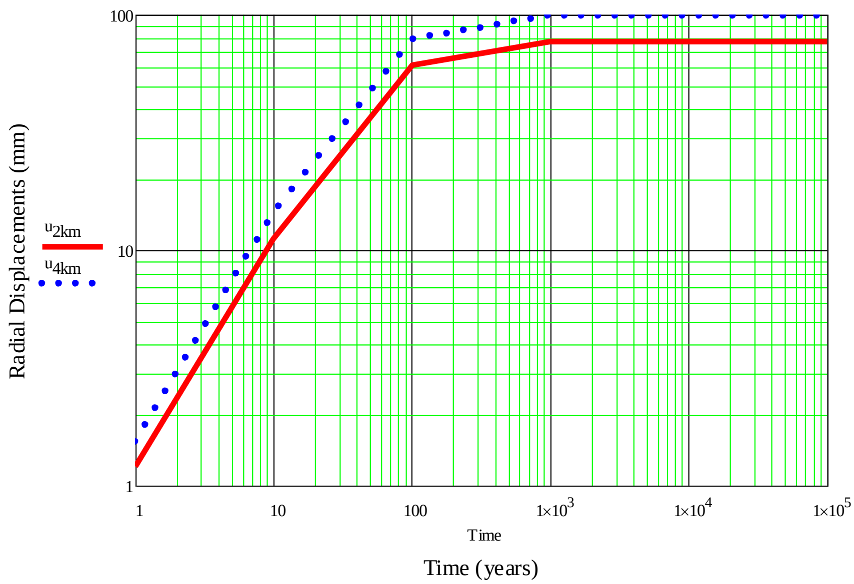

Figure 4. Calculated radial movement of the walls of 0.8 m diameter borehole in metamorphous or clayey sedimentary rock at 2 and 4 km depth by using the new rheological model.

4 Discussion and conclusions

Using the new rheological model based on the Kelvin concept combined with an Eyring/Feltham creep model based on stochastic mechanics for calculating the radial convergence of very deep clay-sealed holes located in crystalline rock, it is found that the very small convergence of the considered 0.8 m diameter holes causes a negligible pressure on the clay. Thus, it is realized that the maximum expected radial movement of the borehole wall in the first 500 years will be 2.5 mm at 2 km depth and 3 mm at 4 km depth, which will only cause an increase in dry density of the clay from 1,600 kg/m^3 (2,000 kg/m^3 at water saturation) to 1,620 kg/m^3. This will raise the effective pressure to 4.1 MPa and reduce the hydraulic conductivity from 4E-12 m/s to 2E-12 m/s [17]. In a 10,000 year perspective the wall of the holes at 4 km depth will have moved towards their centers by 5 mm and thereby increased the dry density to 1,620 kg/m^3, which will raise the swelling pressure to nearly 4.2 MPa and reduce the hydraulic conductivity to about E-12 m/s. None of the changes will significantly affect the sealing potential of the clay seals. In an even longer perspective, like a period of hundred thousand years, some further minor increase in density is expected, generating slightly better sealing function of the clay. However, parallel to this process chemically induced conversion of the smectite clay minerals to less expanding ones (illite) will take place and create an approximately tenfold increase in hydraulic conductivity and a strong reduction in swelling pressure [17,18].

Considering again holes bored in softer rock of metamorphic or argillaceous origin the displacement of the borehole wall would be on the order of 10 mm in 10 years and 60 mm in 50 years at 2 km depth. For this depth the convergence after 10 years would lead to an increase in clay dry density to about 1,682 kg/m^3 or 2,060 kg/m^3 for 100% water saturation, which will raise the clay pressure to about 10 MPa and reduce the hydraulic conductivity to E-13 m/s [17]. For the same depth the dry density would be 2,213 kg/m^3 after 50 years, causing an increase in pressure at the clay/rock contact to more than 50 MPa and a drop in hydraulic conductivity to around E-14 m/s, which is lower than the conductivity of the rock. The raised clay pressure in this time perspective will counteract the increase in hoop stress in the surrounding rock [16] and hence retard the movement of the borehole wall, which will come to a standstill beyond this moment.

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