Journal of Earth Sciences and Geotechnical Engineering, Vol. 9, No. 3, 2019, 275-295
ISSN: 1792-9040 (print version), 1792-9660 (online)
Scientific Press International Limited

Time-Dependent Physical Interaction of Clay and Rock in HLW Repositories

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Abstract

Disposal of canisters with Highly Radioactive Waste (HLW) in boreholes in crystalline rock can be made by use of "supercontainers" with waste and clay seals, moved down in clay mud which undergoes consolidation under the swelling pressure exerted by the dense clay seals. The concept can be used for disposal in mined repositories at a few hundred meters depth and in very deep boreholes (VDH) with saline, stagnant formational waters that are unlikely to rise to contaminate shallow groundwater. For disposal in mined repositories the supercontainers are suitably placed in 8-10m long inclined boreholes with 1,900mm diameter. The concept for disposal of HLW in the lower halves of 4 km deep holes relies primarily on the sealing capacity of engineered barriers, clay and concrete, in the upper halves of the holes. The parts of a VDH that are located in fracture-poor rock are sealed with dense, expandable clay, and by concrete cast where pre-grouted fracture zones are intersected. The deep holes will undergo convergence and eventually expose the clay, concrete and waste packages to radial compression. Using the Kelvin rheological model for predicting the radial convergence of the holes these components will be subject to a small pressure increase in the first 10,000 years. In a longer time perspective, they will be compressed by the slowly increasing confining pressure causing improved sealing ability of the clay.

Keywords: Highly Radioactive Waste (HLW), boreholes, crystalline rock, clay seal, disposal, deep hole concept (VDH), supercontainer.

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Article Info: *Received:* June 5, 2019. *Revised:* August 23, 2019.
Published online: September 10, 2019.

1. Introduction - Concepts

This paper deals with the interaction of clay and rock in mined repositories at about 400 m depth and in 4 km deep boreholes, with focus on the evolution of clay seals. Figure 1 shows the first mentioned concept and Figure 2 the deep hole concept, called VDH [1,2]. These holes are bored with 600-800 mm diameter and filled with soft bore mud in which "Supercontainers" are submerged.

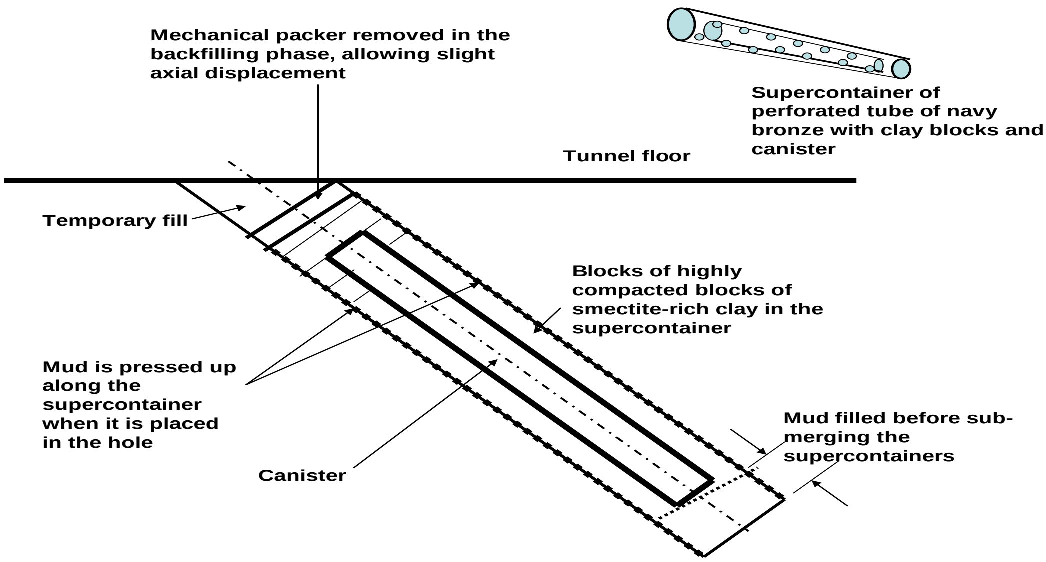

Figure 1: Supercontainer with clay-lined waste canister in mud-filled inclined borehole [1].

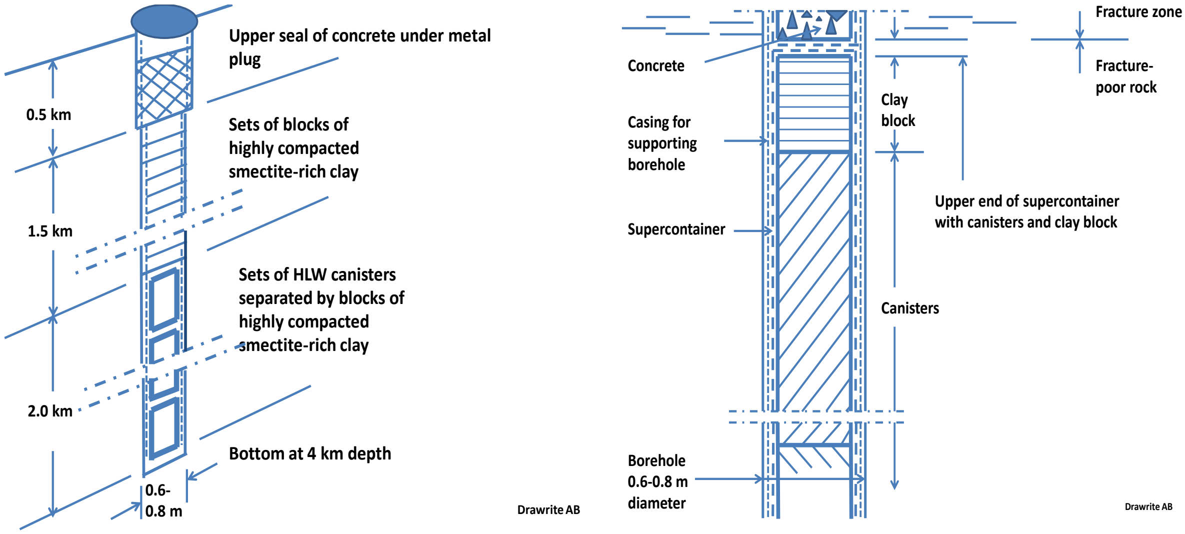

Figure 2: VDH with 4 km depth. Left: Clay seals and concrete in upper 2 km part and HLW in the lower part. Right: Components in the lower, "deployment" part. The same type of supercontainers filled only with dense clay blocks is used in the upper 500-2000 m part.

Perforated "supercontainers" make the placement of clay seals and waste canisters safe and quick and give the clay uniform access to water for generating a uniform clay "skin" around the containers. This process takes place by expansion of clay from a dense clay core through the perforation (Figure 3). Finite element calculations have shown that the optimal degree of perforation is about 50 %. The supercontainers are proposed to be made of copper, bronze, titanium or steel.

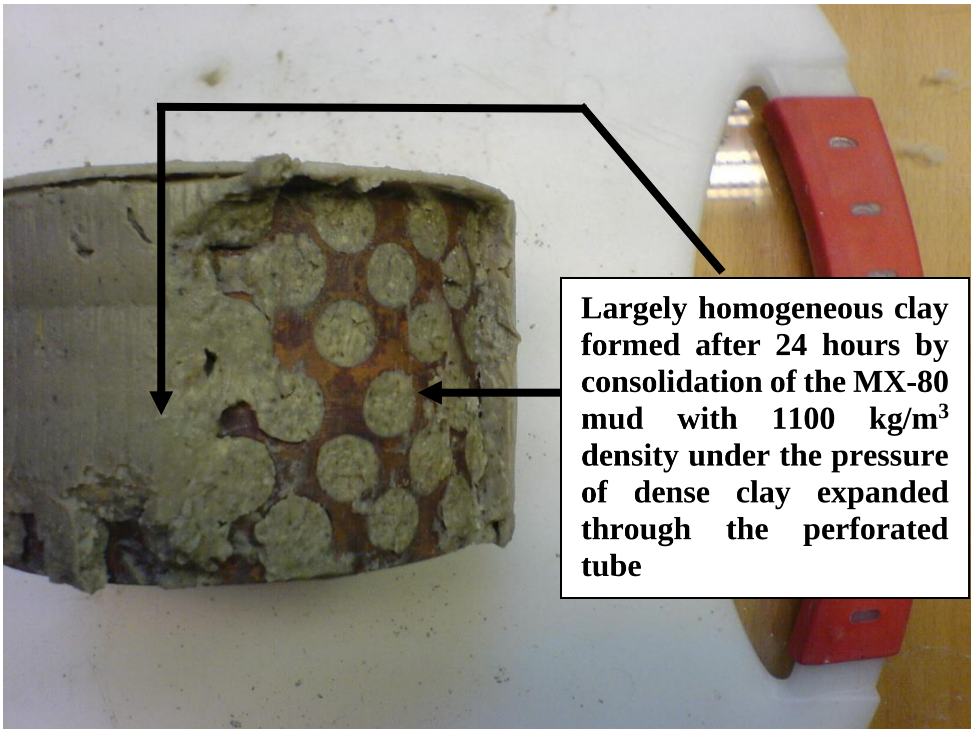

Figure 3: Supercontainer submerged in clay mud for 24 hours. Part of the clay skin formed by clay migrated through the perforation removed for determination of water content and density.

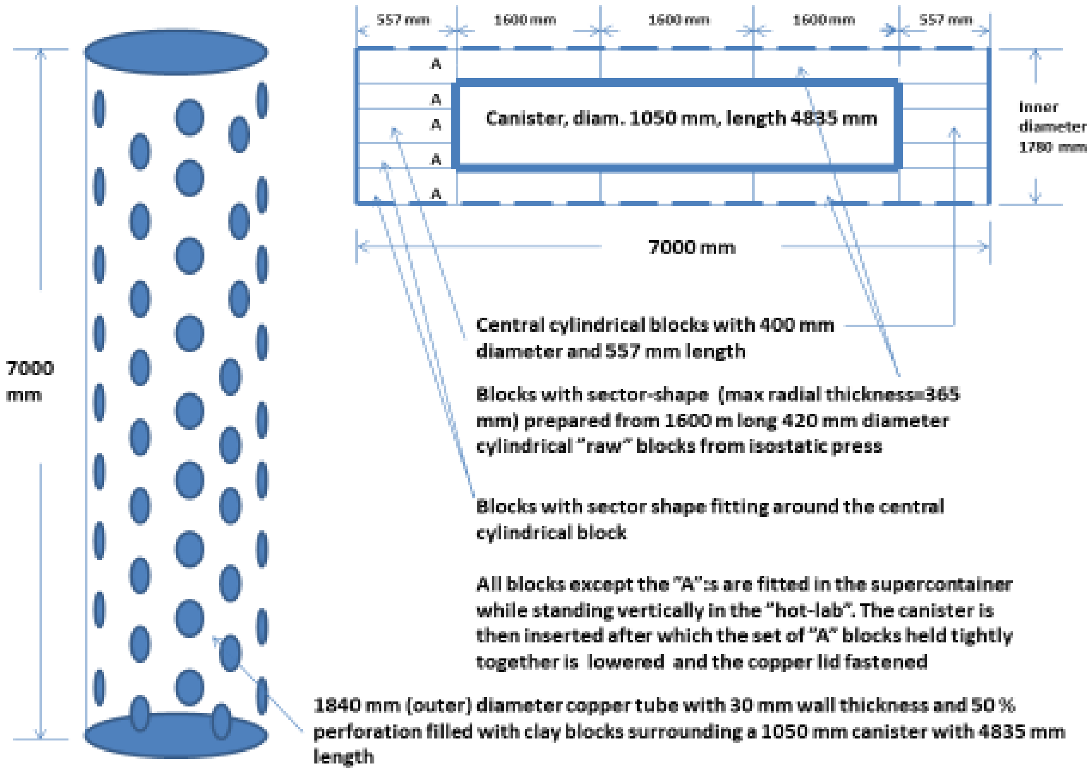

Figure 4: Schematic picture of supercontainer with HLW waste canister and dense expandable clay for installation in a mined repository with 1,900 mm diameter deposition holes.

The major sealing component of the supercontainers consists of highly compacted, expandable clay placed where the rock is normally fractured, and of concrete cast on site where the holes intersect permeable and weak fracture zones. Big boreholes generate high hoop stresses in the rock and slight convergence of the holes. The two clay components, i.e. the dense clay confined in the supercontainer and the clay mud in which it is submerged, interact hydraulically driven by the different hydrophilic potentials of the soft mud and the dense clay, by which water is given off from the mud to the dense clay which expands. The process leads to successively increased density of the mud and reduced density of the clay in the supercontainer.

2. Maturation of clay components

2.1 Definitions

The dense clay in the supercontainers and the clay mud interact hydraulically and successively form a clay skin with uniform density around the supercontainers (Figure 5). The hydraulic gradient considered in the model is created as a consequence of differences in hydration potential: the high hydration potential of the dense clay causes water in the soft mud to move into it, which will thereby contain more water and undergo a drop in density, which lowers its hydration potential. All the ring-shaped neighboring elements in the clay core will be less dense while all mud elements will become denser. The hydration/dehydration process is a function of the position of the clay elements and of time. The elements are subject to one-dimensional consolidation or swelling, implying only radial water flow and clay migration.

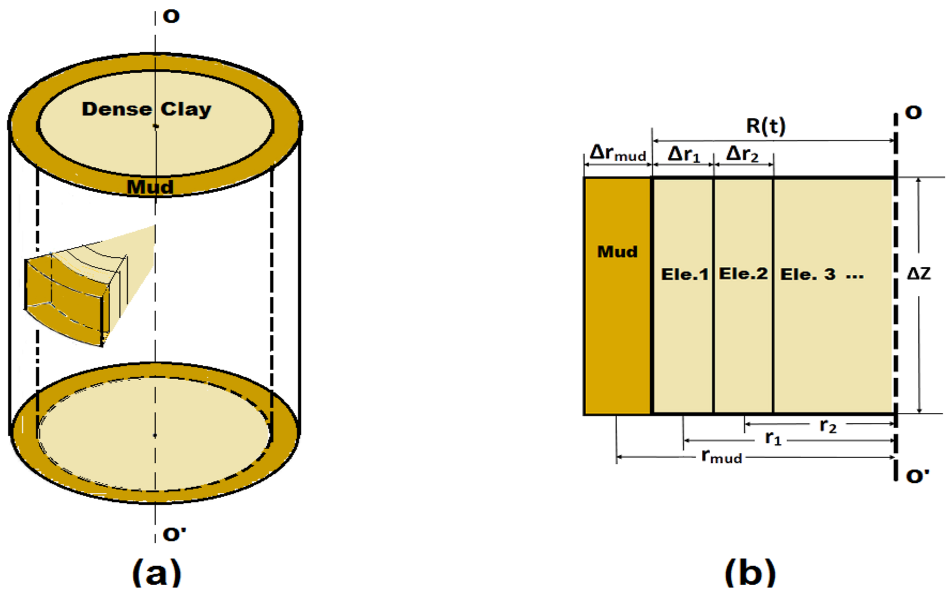

Figure 5: The clay seal system. a) Dense smectite clay core surrounded by soft smectite clay mud; b) Partition into elements for calculation of the maturation.

We will follow here the principle of evolution of the maturation process derived by Ting Yang [3], starting by defining the permeated fluid volume Q in time interval Δt using Darcy's law.

$$Q = \frac{2\pi KH}{ln\frac{R_2}{R_1}}(h_2 - h_1) \cdot \Delta t \tag{1}$$

where H is the height of the cylindrical specimen,

R_1 and R_2 represent flow paths in radial direction

and $(h_2 - h_1)$ is the hydraulic head difference, which drives the process.

The fluid flux across a cross-sectional area *A* of the soil is q per time unit under the prevailing hydraulic gradient *i*, denoting the hydraulic conductivity as *K*, is calculated by applying the numerical code described below.
The elements are subject to one-dimensional consolidation or swelling, implying only radial water flow and clay migration.

The permeated fluid volume Q in time interval Δt is:

$$Q = \frac{2\pi KH}{ln\frac{R_2}{R_1}}(h_2 - h_1) \cdot \Delta t \tag{2}$$

where H is the height of the cylindrical specimen,

R_1 and R_2 represent coordinates of flow paths in a radial direction

and $(h_2 - h_1)$ is the hydraulic head difference.

The fluid flux across a cross-sectional area *A* of the soil is q per time unit under the prevailing hydraulic gradient *i*, denoting the hydraulic conductivity as *K*, is calculated by applying the numerical code described below.
The hydraulic interaction of rock and clay will proceed until the difference in effective stress in the mud and dense clay is evened out. Since we are considering extreme periods of time it can be questioned whether the radial pressure caused by creep-generated convergence of the holes can balance the swelling pressure exerted by the ultimately consolidated mud/clay and if convergence can cause consolidation of it. If this is the case radial compression of the clay can be expected to reduce its hydraulic conductivity and thereby improve its sealing potential. The hydraulic/mechanic interaction of the two clay components, which drives the maturation process, has been modelled as will be briefly described in the last part of the paper.

2.2 Clay phases

The swelling pressure of the clay seal system should eventually bring the hoop and radial rock pressures around the VDH back to the original levels for preserving the natural hydraulic properties. The pilot model test reported in the preceding section showed that the mechanisms involved in the early maturation of the clay seal system are known. Subsequently, further maturation will be caused if the convergence of the deep holes is sufficient to consolidate the clay system (Figure 6).

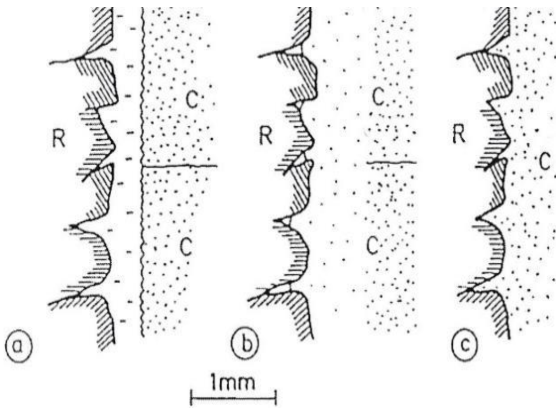

Figure 6: Integration of smectite-rich clay mud and dense clay blocks associated with mud penetration into boring-disturbed rock. Left: a) Clay block ("c") in supercontainer placed in clay mud; b) Early stage of block expansion; c) Ultimate block expansion and self-injection of mud in the rock [4]. Right: Smectite mud prepared with electrolyte-poor water to a dry density of 200kg/m^3 [5]. 200x optical micrograph.

Before considering further the processes involved in clay maturation one needs to consider the impact of temperature, which is relatively moderate (60-70^{o}C) in the upper 2km part of VDH with no waste, but significant in the lower 2km part. Table 1 shows the temperature at the canister surface, in the clay and in the rock at different distances and times after placement of waste generating initially 200W per meter canister length, dropping to 100W after 12 years, to 30W after 60 years and to 5W/m canister length after 1,000 years. The ambient natural temperature 4 km below the ground surface is estimated to range between 65 and 80^{o}C, and between 40 and 55^{o}C at 1.5 km depth. The temperature determines the porewater viscosity and thereby the rate of homogenization of the clay system. It also determines the vapour pressure and thereby the physical stability of the clay seal system as well as the chemical/mineralogical constitution.

The impact of temperature on the function of clay and rock in mined repositories at 400-500m depth is of less interest in the present context since the maximum canister temperature is stated to be lower than 90^{o}C and its duration much shorter than in VDH.

Table 1: Assumed temperature conditions at 0.5, 2 and 4 km depth in and around a VDH 50 years after placement of waste, the value being the sum of ambient temperature and the increase related to the radioactive decay. There are no waste packages in the upper 2,000m part [6].

Depth [m] And Ambient temperature [°C]		Increase in temperature in clay beyond ambient [°C]	Increase in rock temperature at 10m horizontal distance [°C]	Increase in rock temperature at 100m horizontal distance [°C]	Estimated max temperature in clay [°C]
500 m	15	15	15	15	15
1,000 m	20	20	20	20	40
2,000 m	35	40	45	25	85
3,000 m	55	70	65	10	135
4,000 m	80	70	80	0	150

2.3 Evolution of clay barriers

The dense core of the clay seals can either have a low initial degree of water saturation (40-50%) or be fully water saturated from start. In either case it adsorbs water until its hydration potential is fully utilized. In mined repositories and in the upper half of VDH temperature is lower than 90°C and it is deemed preferable to use clay that is fully water saturated from start in order to reach a high thermal conductivity. For the lower part of VDH this matter is of less importance since the dense clay in the supercontainers will anyhow be quickly water saturated because of the high water pressure. This process is associated with consolidation of the clay mud under such pressure and with expansion of the dense clay core which softens by absorbing water from the surrounding mud. The basic process of redistribution of porewater takes place whenever saturated contacting smectite clay elements have different densities but is retarded by the long flow paths when the clay seals have large dimensions. A high degree of homogeneity of the clay seal system in VDH with 600-800mm borehole diameter can take several decades or even centuries to be reached. A high initial dry density of the clay core is naturally desired since it will give a high swelling pressure and thereby very tight contact between rock and clay seal system, eliminating leakage of possibly radioactively contaminated water flow along the contact.

3. Pilot model study

3.1 Test arrangement

The study comprised experiments with the physical model shown schematically in Figure 5. It comprised a permeable vessel for simulating a mud-filled borehole in which a perforated 100mm diameter model supercontainer was placed. The mud was prepared by mixing finely ground Danish smectite-rich Holmehus clay of Tertiary age with distilled water to a dry density of 222kg/m^3. It was filled in the vessel into which the supercontainer, tightly filled with pre-compacted and pre-saturated blocks of Holmehus clay with 1,600kg/m^3 dry density was submerged. The arrangement allowed water to migrate into or from the mud. The aim was to extract the supercontainer at selected time intervals for determining the water content and density of clay samples.

3.2 Clay material

Danish pre-Quaternary clay named Holmehus clay exploited by the Danish mineral company Dantonite A/S (Roskilde) was used for the tests. It is a mixed-layer clay consisting of two kinds of mixed layer phases that are fully expandable to 17Å by ethylene glycol saturation (IS-ml and diVS-ml). The ratio of smectite layers (S%) of IS-ml is 60%, and 20-25% of diVS-ml. Figure 7 shows typical XRD spectra.

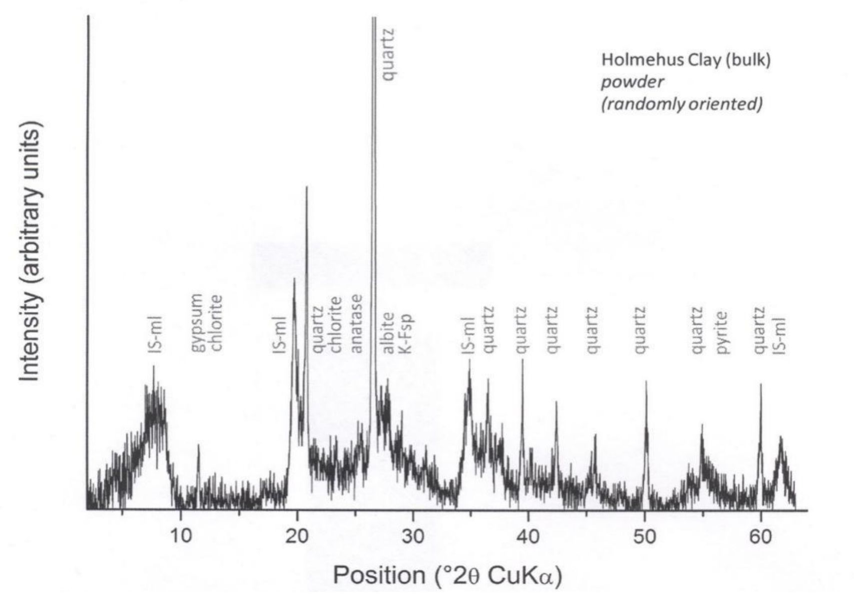

Figure 7: Holmehus bulk material (analysis by Kasbohm, Greifswald University, Germany).

Table 2: Main geotechnical data of virgin Holmehus clay for saturation/percolation of distilled water (A) and 3.5 % $CaCl_2$ solution (B). Results shown as A/B.

Dry density [kg/m^3]	Hydraulic conductivity for percolation with distilled water (A) and 3.5% $CaCl_2$ solution (B) [m/s]	Swelling pressure for saturation with distilled water/3.5% $CaCl_2$ solution [kPa]	Approximate undrained shear strength of clay saturated with 3.5% $CaCl_2$ solution at the contact with rock [kPa]
225	>E-9/-	<50/0	0
450	>E-9/-	85/0	5
750	1.0E10/E-9	155/0	10
1,070	1.0E-10/1.0E-9	400/50	25
1,270	1.5E-11/3.0E-11	1,300/600	300
1,430	2.5E-12/7E-12	2,400/1,500	750
1,750	E-12/3E-12	>3,000	1,500

3.3 Numerical model for predicting the evolution of the dry density

According to basic soil physics, the hydraulic gradient, created as a consequence of the lower hydration potential, i.e. negative porewater pressure, in the mud than in the dense clay, drives porewater from the mud to the dense clay, which causes stiffening of the mud and softening of the dense clay. Following Yang [3] the hydration/dehydration process is a function of the position of the clay elements and time. The elements are subject to consolidation or swelling, implying only radial flow and clay migration. On dividing the clay column in Figure 5 with height ΔZ and initial radius R into N elements (N being a positive integer), the parameters of each element with the subscript n $(n = 1, 2, 3 \ldots N)$ are specified, n-1 representing the mud.

Application of the model means that the computation is performed stepwise and repeated iteratively using the same time steps. If T is the total computation time and the maturation time for each time step is Δt, the time steps t are hence equal to $[\frac{T}{\Delta t}]$. The operation begins with derivation of the relationship of flow volume and hydraulic conductivity defined by Darcy's law. By rearranging and integrating the functional relationships of this law, the percolated fluid volume Q in time Δt becomes:

$$Q = \frac{2\pi KH}{ln\frac{R_2}{R_1}} \cdot \frac{U_e}{g_{water}} \cdot \Delta t \tag{3}$$

Water migration in the clay elements implies water transport from the boundary of the clay cell in Figure 5, $r_{(n-1)}(t)$ to the adjacent one $r_n(t)$. The hydraulic conductivity is taken here to be the weighted average value $\bar{k}_n(t)$ of the clay. Substituting the conductivity, the flow path $r_{(n-1)}(t)$ to $r_n(t)$, and the difference in suction (negative water pressure) into Equation (2), one obtains:

$$Q_n(t) = \frac{2\pi \frac{\bar{K}_n(t)}{r_{(n-1)}(t) \rightarrow r_n(t)} \Delta Z}{ln\frac{r_{(n-1)}(t)}{r_n(t)}} \cdot \frac{\Delta U_{e_{(n)}}(t)}{g_{water}} \Delta t \tag{4}$$

For each element, water flows both into the element in equation and out from it into the adjacent ones during each time step.

The model was implemented assuming that the solid parts of both mud and dense clay are conserved throughout the maturation process [3]. For each time step, the change in width of clay and mud elements by swelling/shrinking are computed, requiring that all material and geometric parameters, like the radius, change in radius, dry density, hydraulic conductivity and porewater suction have to be updated for the computation in the next time step. The parameters are iteratively computed for the respective time steps until total time has passed.

3.4 Test results

Table 3 summarizes the results from numerical calculations ("Theor") and measurement ("Exper") of the true dry density [3,5].

Table 3: Dry density [kg/m^3] and swelling pressure of the clay system in simulated 100mm diameter hole as a function of time. A is the radial distance in mm from the symmetry axis [5].

Time, from start	Dry density for *A*=25 mm Theor/Exper. [kg/m^3]	Dry density for *A*=40 mm Theor/Exper. [kg/m^3]	Dry density for *A*=50 mm Theor/Exper. [kg/m^3]	Swelling pressure [MPa] for *A*=50 mm after 1 year (distilled water/3.5% $CaCl_2$ solution)
8 min.	1590/1590	1100/1300	200/200	0.020/0.000
5 hours	1200/1420	1220/1150	1300/600	0.100/0.010
1 year	1200/1250	1240/1200	1220/1150	0.950/0.900

Figure 8 shows graphs of the predicted and measured dry density at various distances from the symmetry axis of the test cell determined 8 minutes and 310 minutes after deployment of the model supercontainer [3].

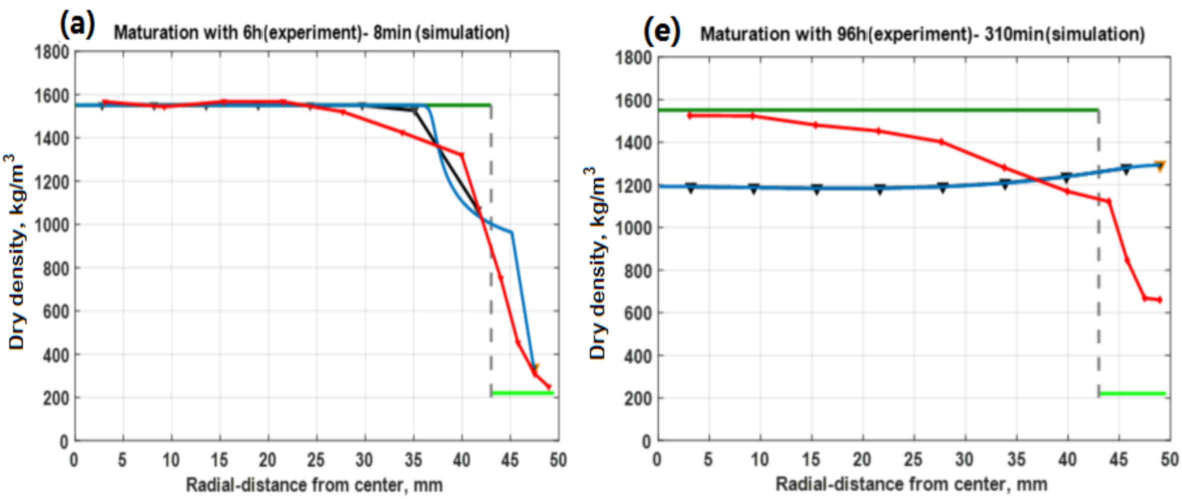

Figure 8: Predicted and actual dry density. a) Determination after 6 h and prediction for 8 min. e) Determination after 96 h and prediction for 310 min. Green represents the conditions at start.

3.5 Conclusive remarks concerning homogenization of clay components

One concludes from the model study that the expected successive homogenization of the clay/mud system took place but that the actual maturation was much faster than predicted [3,5].

The experiments showed that the swelling pressure rose from very low values to such a high level in less than half a day that it was difficult to axially extrude the clay from the confinement. In a full-scale VDH with 600-800mm diameter the clay is expected to mature slower than in the model tests because of the longer pathways for porewater flow while the swelling pressure exerted on the walls of the borehole will grow nearly as quickly as in the model test since only the outermost part of the dense clay core will be involved in the earliest phase of maturation.

A lesson learned is the need to plan and carry out placement of supercontainers in deep boreholes such that they come on site before the shear resistance ("wall friction") becomes too high to bring them down to the desired positions. If one fears that the operation may be significantly delayed one has to use a high-capacity drill rig and a heavy vibratory pile-driver for execution. It is estimated that one of the first placements of supercontainers in a 4km deep borehole may require 1 full day. For avoiding difficulties with bringing them down, which is not a problem for mined repositories in which the tunnel roof can be used as support and the placement of supercontainers will be quick. For VDH the supercontainers can be coated with talc/clay paste just before installing them [7].

4. Role of rock

4.1 Large-scale migration of radionuclides from buried HLW

For reaching the required state of no radionuclides from leaking canisters in a repository reaching biosphere one needs to identify and assess migration paths and mechanisms for bringing such ions up to a defined level that is commonly taken to be several times deeper than the depth to which wells for drinking water are expected to be bored, i.e. around 1,000m. Ruling out artesian conditions, which would have been found in the site investigation process, large-scale convection of contaminated deep groundwater driven by temperature gradients caused by the disposed waste, and flow of such water via the boring-disturbed zone in the walls of tunnels, shafts and deep boreholes, is predictable. Such convection can take place in mined repositories because of the high transmissivity of rock at small depth, while for VDH, hydraulic gradients are negligible from the start of boring the holes to the end of the operational period, meaning that the driving force for migration of possibly released radionuclides can be neglected. Diffusive migration can also be ruled out because of the low diffusion coefficient (<E-9m^2/s) and the long migration distance, i.e. at least 1,500m.

4.2 Stress conditions

The deep VDH holes will undergo changes in diameter because of the high rock stresses at depth. When the holes have been bored the hoop stress (σ_θ) and radial stress (σ_r) in the surrounding rock have reached 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 compressive horizontal rock stresses at 2 km depth, 60MPa, the hoop stress at the periphery of the holes will be 120MPa and the radial stress 0MPa [8]. At 4 km depth, where the compressive horizontal rock stresses are estimated at 77MPa, the hoop stress at the periphery of the holes will be 154MPa and the radial stress 0MPa. Here, the stress constellation can begin to initiate rock failure.

4.3 Strain evolution in VDH

The instantaneous deformation of the holes in the boring phase is small and elastic 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 [8].

4.4 Creep strain models

Traditional rheological models like the classic Kelvin model in Figure 9 are useful in visualizing the basic principles of time-dependent shear or compressive strain of visco-elastic media. For practical use the Kelvin model can be coupled to those appearing in modern creep theory and in this paper we will use a model here termed "Eyring/Feltham" that is basically a thermodynamically founded creep model worked out by Feltham and colleagues at Brunel University, U.K., in the seventies [9,10], and which has turned out to be applicable to geological media like glacier ice, clay, and crystalline rock.

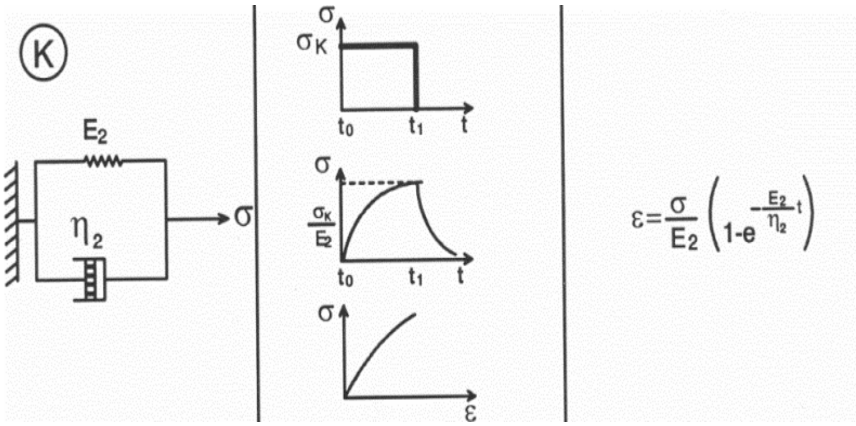

Figure 9: The original Kelvin rheological model.

In this paper we will make use of the traditional version of the Kelvin model and treat the problem of mechanical interaction of rock and clay in VDH repositories by calculating the radial movement of the borehole wall as resulting from creep in rock generated by rock pressure, counteracted by the pressure generated by clay seals that undergo consolidation. The following steps are taken in application of the model:

- The stress changes caused by creating deep holes by boring give a radial movement u that can be calculated by using the theory of elasticity: $u=pa(1-\nu)/E$ where $E=\sigma/\varepsilon$ and ν is Poisson's ratio, taken to be 0.2 here,
- For finding the time-dependent radial displacement of the borehole walls we will use the expression for strain of the Kelvin model, where the modulus of elasticity of spring E2 in Figure 9 is taken as E4MPa and the dashpot viscosity as η=E20Pas for crystalline rock of ordinary quality, and assuming an E-modulus of E3MPa, and a dashpot viscosity of η=E17Pas for argillaceous rock [8]. The periods of time for creep to develop are taken as 1 to E4 years. The assumed loading case implies that the pressure against the borehole walls is raised from an initially very low value when the dense clay is just being inserted in clay mud in the holes, to 4MPa within a year when the clay system

has largely matured and stays so until the convergence of the holes has lasted for up to E5 years.

4.5 Calculation of hole convergence

Calculations have been made numerically using the Kelvin rheological model, which is mathematically straight forward, i.e.

$$\varepsilon(t) = \frac{\sigma}{E}\left(1 - e^{-\frac{E}{\eta}t}\right) \tag{5}$$

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

$$E'(t) = \frac{p}{\varepsilon(t)} \tag{6}$$

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

$$\sigma = p\left(1 + \frac{a^2}{r^2}\right) \tag{7}$$

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

$$u(t) = pr\frac{(1-\nu)}{E'(t)} = pr\varepsilon(t)(1-\nu) \tag{8}$$

One observes that use of Equation (6) is redundant, since $\frac{p}{E'(t)}$ equals $\varepsilon(t)$.

The calculated radial movement of the walls of an 800mm diameter borehole in typical crystalline rock at 2 and 4km depth using the Kelvin rheology model, is given by the graph in Figure 10.

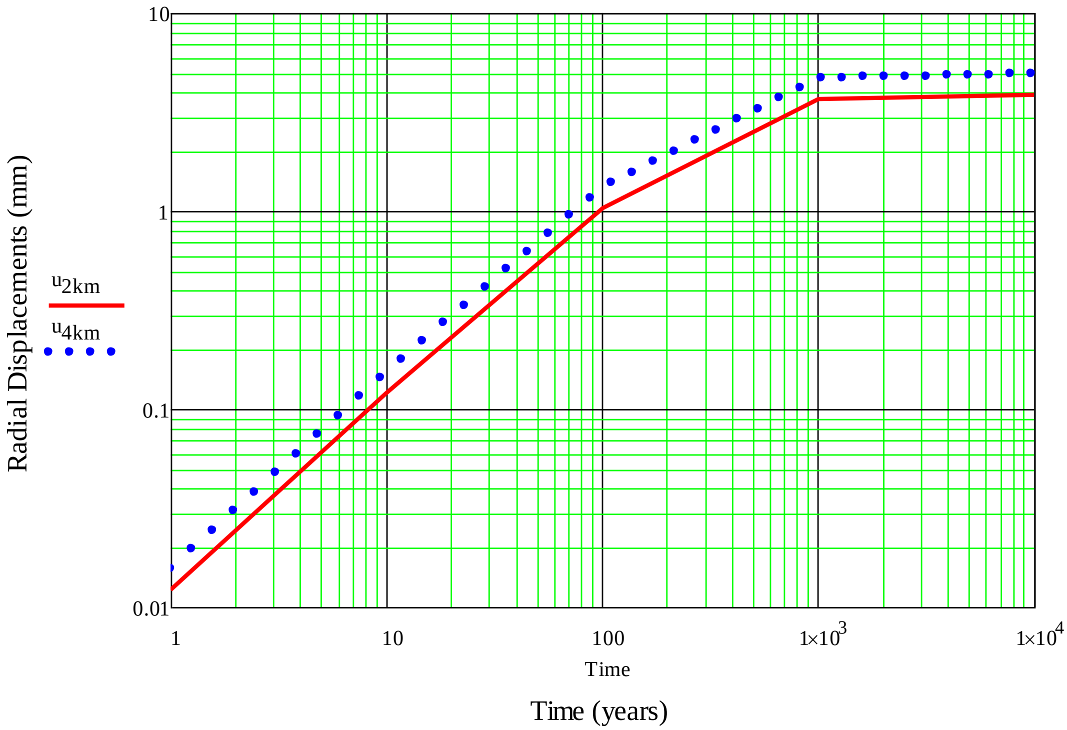

Figure 10: Calculated radial movement of the walls of an 800 mm diameter borehole in typical crystalline rock at 2 and 4 km depth by using the Kelvin rheological model. Temperature and counter-pressure from the clay are not considered.

One finds that for VDH in crystalline rock of granitic type the radial inward movement of the lower, waste-bearing part of the 800mm hole after E2 years will be about 1.5mm, 5mm in E3 years, and 6mm in E4 years. For the upper part of the hole, where the rock pressure is lower, the corresponding movement will be about 1 mm after E2 years, 3.5mm in E3 years and 4mm in E4 years neglecting the impact of the clay. The temperature rise to around 150°C in the lower part will increase the strain by about 0.1% to be of the order of 1mm in the first hundred years after which further impact of heat becomes negligible [9].

For argillaceous rock with the assumed rheological parameters E_2=5E2MPa and η=E18Pas one obtains the graph in Figure 11 of the radial, inward movement of the walls of the hole. The lower, waste-bearing part of the hole will have moved by about 100mm after E4 years, tending to increase further. After 100 years, the displacement is already very significant, i.e. 60mm. For the upper part of the hole the movement will be about 60mm after 100 years and about 75mm after E3 to E5 years. These data are very uncertain because of lack of laboratory and field measurements and unknown influence of temperature.

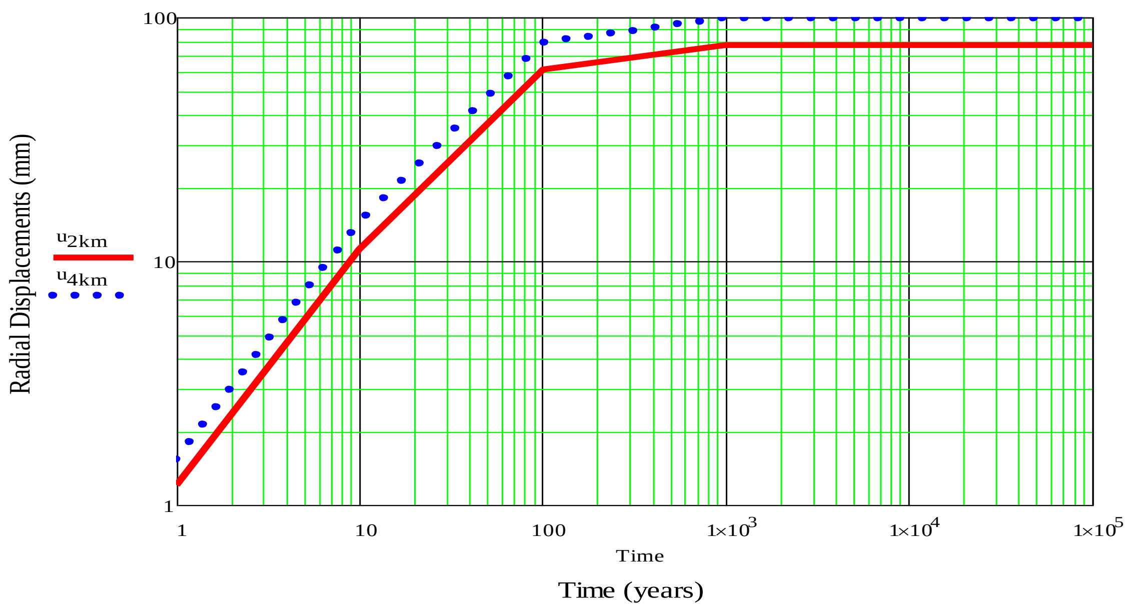

Figure 11: Predicted radial movement of the walls of an 800 mm diameter borehole in argillaceous rock, neglecting impact of temperature.

4.6 Conclusive remarks concerning hole convergence

Using the Kelvin rheological model 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 800mm diameter holes causes a negligible pressure on the clay. Thus, the calculations show that the maximum expected radial movement of the borehole wall in the first 500 years will be 2.5mm at 2km depth and 3mm at 4km depth, which will only cause an increase in dry density of the clay from 1,600 kg/m^3 to 1,620kg/m^3. This will raise the swelling pressure from the assumed 4.0MPa to 4.1MPa and thereby reduce the hydraulic conductivity from 7E-12m/s to 4E-12m/s. In a 10,000-year perspective, the wall of the holes at 4 km depth will have moved towards their centers by 5mm and thereby increased the dry density to 1640kg/m^3, which will raise the swelling pressure to nearly 4.2MPa and reduce the hydraulic conductivity to about 2E-12m/s. Neither of the changes will significantly affect the sealing potential of the clay seals. In an even longer perspective, like a hundred-thousand-year period, 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 permanent increase in hydraulic conductivity and a strong reduction in swelling pressure [10].

Considering instead holes bored in argillaceous rock the displacement of the borehole wall would be on the order of 10mm in 10 years and 60mm in 50 years at 2km depth. For this depth the convergence after 10 years would lead to an increase in clay dry density to about 1682kg/m^3 or 2060kg/m^3 for 100% water saturation, which will raise the clay pressure to about 10MPa and reduce the hydraulic conductivity to E-13m/s [11]. For the same depth the dry density would be 2213kg/m^3 after 50 years, causing an increase in clay pressure to more than 50MPa and a drop in hydraulic conductivity to around E-14m/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 and hence retard the movement of the borehole wall, which will come to a standstill beyond this time.

5. Discussion and conclusions

The paper describes two important cases of time-dependent physical interaction of rock and clay seals:

Maturation of clay components

- Yang's model for numerical calculation of the maturation process was successfully applied for quantifying the homogenization of mud and dense clay by considering the process to involve transport of porewater from the softest material with low hydration potential to the densiest having the highest hydration potential,
- For both mined repositories and deep holes for disposal of HLW supercontainers can be used. They contain clay-lined waste containers and will be submerged in soft clay mud. The two clay components, i.e. the clay surrounding waste canisters and the mud in which the supercontainers are placed, are both smectite-rich and hence expandable and strongly hydrophilic,
- Pilot tests validate the predicted maturation implying that the clay mud becomes denser while the dense clay become softer, and that the clay system

becomes largely homogeneous. However, the numerical model overrates the rate of density change which can be explained by scale factors.

Impact on the sealing ability of clay components in VDH by convergence of the holes

- Logically, the very deep holes will undergo convergence because of the high rock pressure at depth. The convergence can be estimated by combining the Kelvin rheological model and Feltham's a thermodynamically founded creep rate model. Application of the resulting model indicates insignificant convergence of the large-diameter waste-deposition holes in mined repositories at about 400-500m depth because of the low rock pressure, as well as in the upper part of VDHs, while at 4km depth the radial convergence of VDH with 800mm diameter located in crystalline rock can be of practical importance by causing consolidation of the clay components after more than 3,000 years. However, parallel to this process chemically induced conversion of the smectite clay minerals to less expanding ones (illite) will take place and largely erase it.
- Considering VDH in argillaceous rock the displacement of the wall of 800mm boreholes would approach half a decimeter in 50 years at 2km depth and raise the clay pressure to more than 50MPa, reducing the hydraulic conductivity to be lower than that of the rock.

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