Investigation of Potential Water Inflow into a Ventilated Tunnel of the Proposed Low/Intermediate-Level Waste Repository in Switzerland

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Abstract

Design calculations of two-phase flow phenomena associated with the construction and ventilation of a tunnel were investigated to estimate the potential water inflow through discrete **w**ater-**c**onducting **f**eatures (WCFs) into the tunnel. The physical processes that were considered in numerical simulations include the transient propagation of the pressure decline into the formation (Valanginian Marl, initially fully saturated, no dissolved gas) as a result of the tunnel construction. Ventilation of the tunnel results in a reduction in relative humidity of the tunnel air which, in turn, causes evaporation of water at the tunnel wall and the potential development of an unsaturated zone into the formation. The objective of this study is to investigate under what conditions the tunnel wall appears wet or dry, i.e. whether WCFs can be identified in a ventilated tunnel by mapping water inflow patterns.

The simulation results indicate that inflow to the tunnel decreases with time approaching steady state flow rates under single-phase flow conditions, which is lower than the evaporation rate. The water inflow rate decreased more rapidly for a first model scenario (WCF parallel to the tunnel axis), caused by linear flow through the WCF, than for a second model scenario (WCF perpendicular to the tunnel axis), characterized by radial flow toward the tunnel. Similarly, the desaturation zone extends farther into the WCF under linear flow than under radial flow.

1. Introduction

The following study is in connection with the safety assessment for the proposed repository for low/intermediate level (L/ILW) radioactive wastes at Wellenberg, Switzerland. The design of the proposed subsurface repository consists of a horizontally accessable cavern system in the low-permeability unit of the Valanginian Marl.

The access tunnel will yield hydrogeologic information on the host rock which is important for the safety assessment of the proposed repository. The objective of the numerical simulations are to assess if a WCF with a transmissivity of 1.E-9 m^2s^{-1} can be identified as a wet area on the tunnel wall. For this purpose, the following physical processes were simulated.

(i) The construction of the tunnel creates a transient pressure perturbation, which propagates into the formation.

(ii) Ventilation reduces the relative humidity in the tunnel air, resulting in a significant capillary suction pressure at the tunnel wall, thereby increasing the hydraulic gradient for water flow toward the tunnel.

(iii) The reduced air humidity in the tunnel results in the evaporation of inflowing water from the formation at the tunnel wall. The equivalent capillary suction pressure associated with the reduced air humidity causes a desaturation front to propagate into the formation creating two-phase flow conditions near the tunnel.

An illustration of the physical processes associated with the construction and ventilation of a tunnel is shown in Fig. 1.

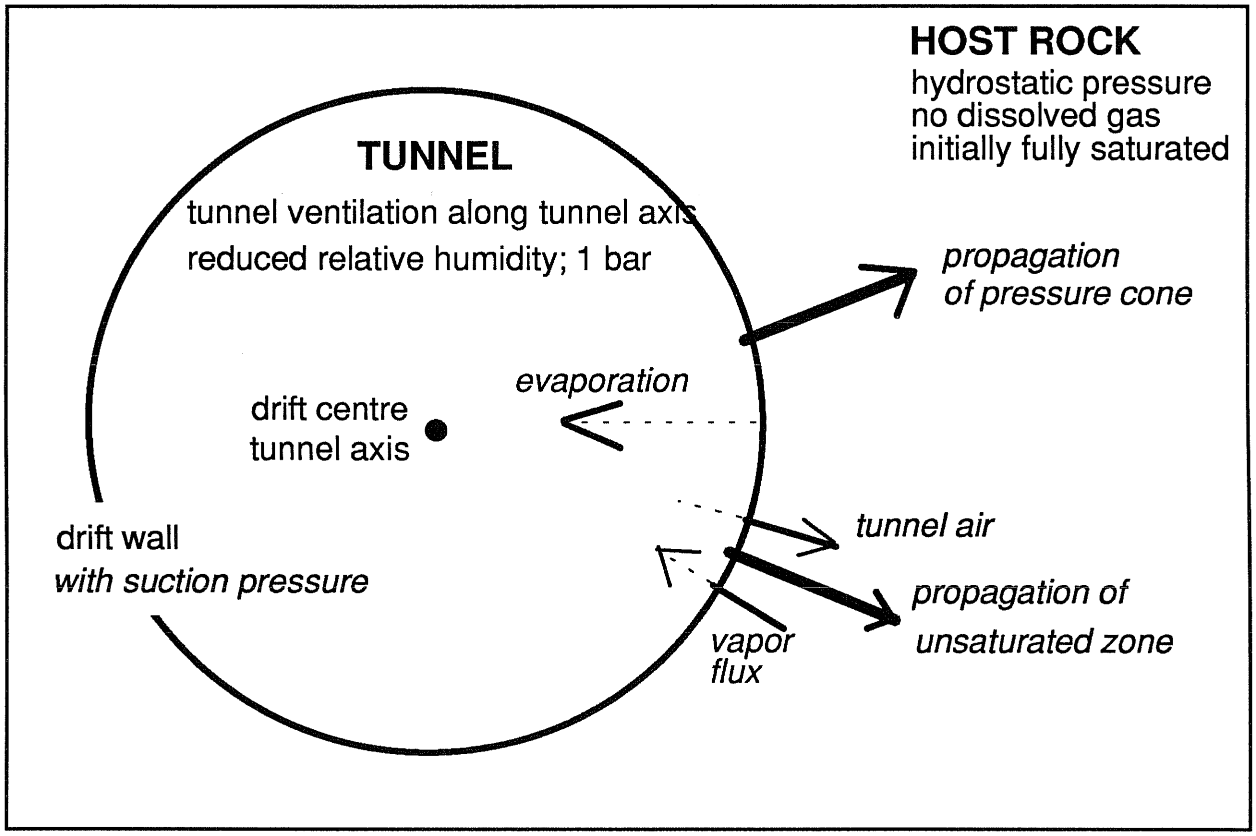

Fig. 1: Schematic description of physical processes associated with tunnel construction and ventilation

To determine whether the tunnel wall will appear wet or dry, the simulated water flow into the tunnel is compared to the potential evaporation rate that is computed as a function of reduced humidity and air velocity.

2. Model Geometry

A 2-D cross-sectional model perpendicular to the tunnel axis was used for the numerical simulations. In the first model scenario the WCF is parallel (type P) to the tunnel axis, represented by a 45 degree inclined, 1-m wide and about 400-m long zone (linear flow model) having at least two orders of magnitude higher permeability than the adjacent matrix. In the second model scenario (type Q), the plane of the WCF is perpendicular to the tunnel axis involving radial flow through the WCF toward the tunnel.

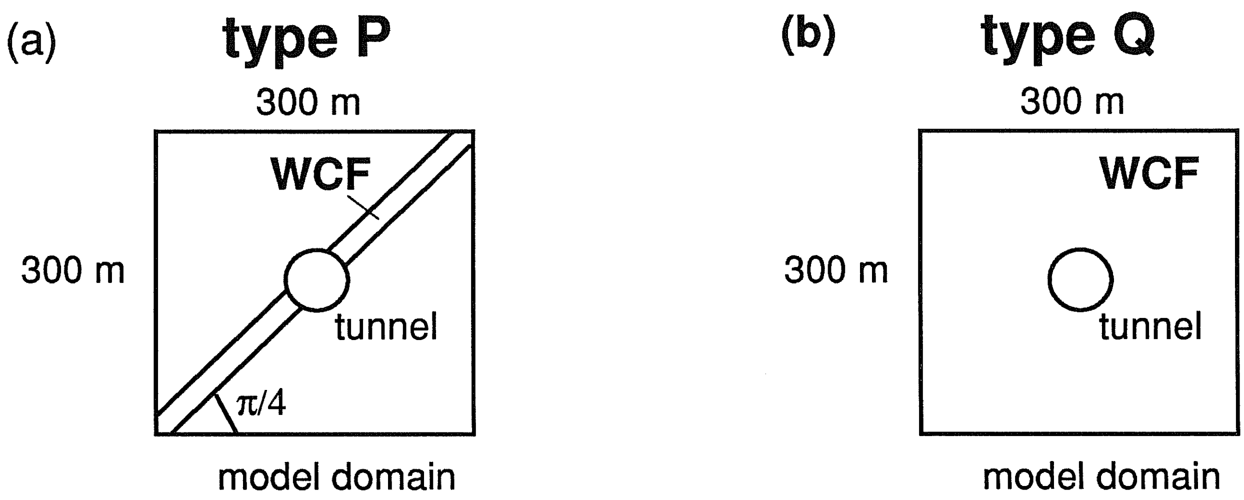

Fig. 2: Schematic representation of the model scenarios (a) WCF parallel to the tunnel axis (linear flow model) and (b) WCF perpendicular to the tunnel axis (radial flow model)

Initially hydrostatic pressures were assumed in the host rock and atmospheric pressure conditions in the tunnel. Transient water inflow into the tunnel was simulated with prescribed suction pressures at the tunnel wall as a function of the relative humidity and for a range of permeabilities of the WCF (sensitivity study). The simulated water inflow was compared with the potential evaporation rates that were analytically estimated from the relative humidity and wind velocity in the tunnel to determine, if and how long after tunnel excavation the tunnel wall appears wet or dry.

The following two analytical solutions are used to estimate the evaporation rate in the tunnel according to SVEDRUP (ref. in DRACOS, 1980)

$$E_v = 0.622 \cdot \frac{\rho_a}{p_a} \cdot \kappa^2 \cdot u \cdot (e1 - e2) \cdot \ln\left(\frac{z}{k}\right)^{-2} \tag{1}$$

and (WATANABE & BOSSART, 1992)

$$E_v = \frac{\Delta Q}{\Delta t} = -\frac{D}{\Delta x \cdot R} \cdot \left(\frac{\rho_{sb} \cdot h_b}{T_b} - \frac{\rho_{sa} \cdot h_a}{T_a}\right) \tag{2}$$

For more detailed information on the analytical and technical aspects of determination potential evaporation rates, the reader is referred to DRACOS (1980), WATANABE & BOSSART (1992) and EUGSTER & SENGER (1994).

Estimation of the evaporation rate is based on the assumption of a constant relative humidity in the tunnel and a linear decrease of humidity from 100% to a constant value within the first few centimeters away from the wall.

Tunnel ventilation is implemented in the numerical model as a prescribed boundary condition at the tunnel wall. This boundary condition is defined as an equivalent capillary suction pressure, corresponding to the reduced humidity according to the Kelvin equation (3) (EDLEFSON & ANDERSON, 1943). The capillary suction pressure increases the gradient of liquid flow toward the tunnel.

$$\phi_{suc} = \ln(h) \cdot \rho \cdot \frac{RT}{M_w} \tag{3}$$

3. Results

In order to answer the main question "wet or dry?" the results concerning water inflow vs. evaporation are illustrated in Fig. 3 and Fig. 4 for the base cases and in Tab. 1 for all simulated cases.

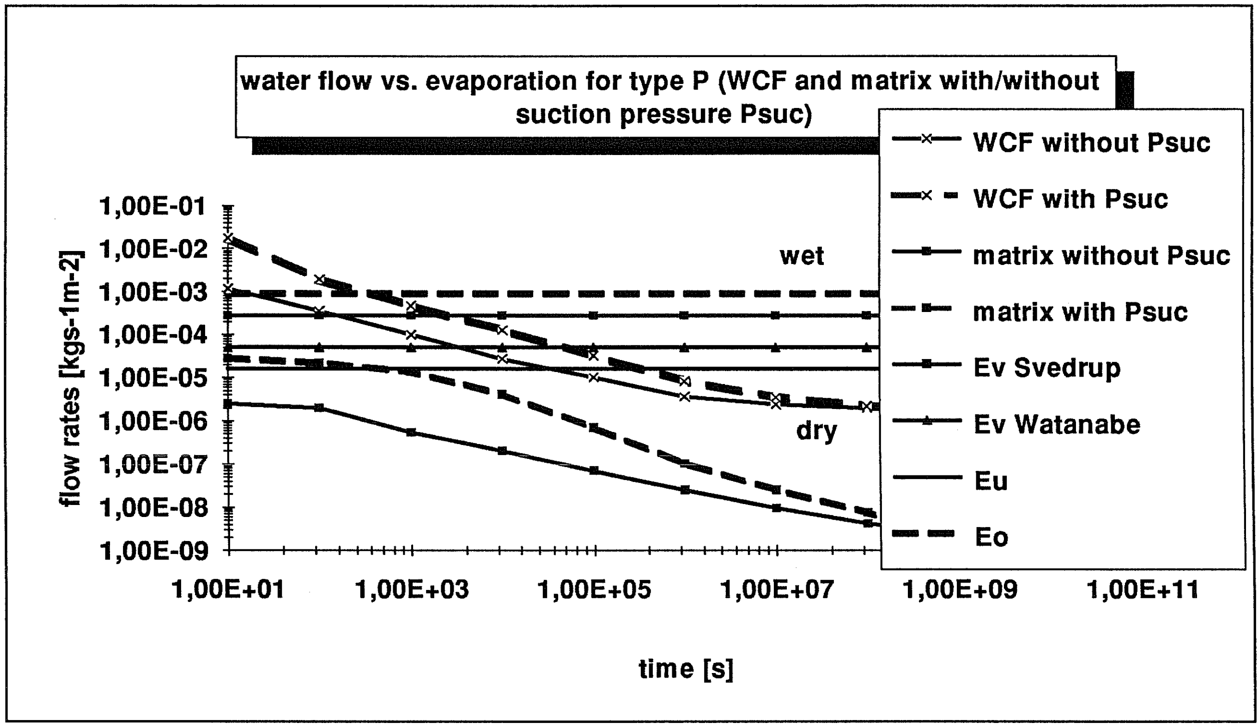

Fig. 3: Water inflow vs. evaporation rate as a function of time for the base case of type P (matrix and WCF)

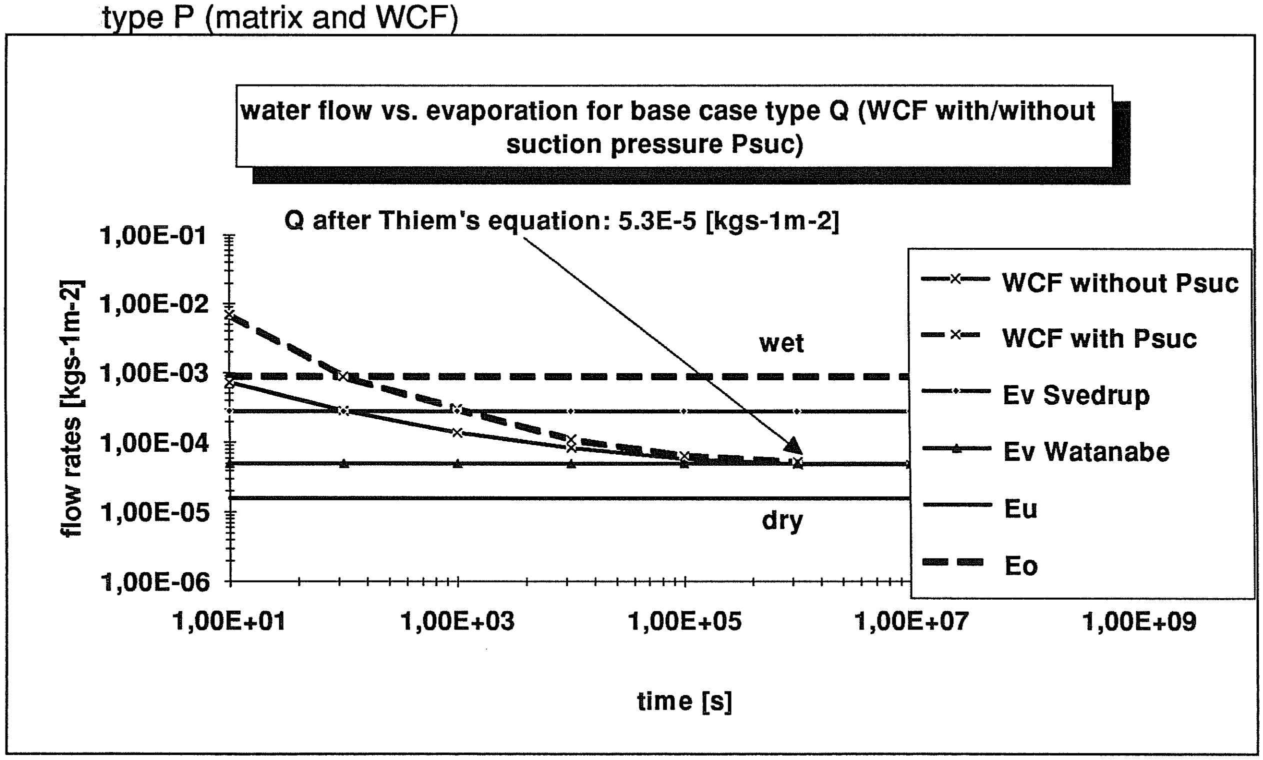

Fig. 4: Water inflow vs. evaporation rate as a function of time for the base case of type Q

The results indicate that inflow to the tunnel decreases with time approaching steady state flow rates under single-phase flow conditions, which is below the evaporation rates in the tunnel for type P (linear flow model) and about the evaporation rates for type Q (radial flow model). The equivalent suction pressure increases the water flow rate. A dry WCF can be observed if the evaporation rate (lower confidence bound Eu) is greater than the flow rate; this is reached after about 4 days in the example of Fig. 3. The flow behavior for the matrix also illustrated in Fig. 3 indicates dry conditions after a short time. Fig. 4 shows a steady state liquid flow rate that is about equal to the evaporation rate. In this case (type Q) it is not clear if the WCF is wet or dry at the tunnel wall.

The results of Table 1 indicate that for the linear flow model (type P), the WCF appears dry after a relatively short time for typical values of permeability and relative humidity. The WCF therefore cannot be identified at the tunnel wall. On the other hand, the results for the radial flow model (type Q) show a somewhat higher inflow. Therefore, it is not clear, whether the WCF can be identified or not. The desaturation zone extends farther into the WCF under linear flow than under radial flow (not illustrated).

Tab.1: A qualitative summary of all modeled cases for both scenarios type P and Q

evapo-ration rates **h** **T**	**ESv: 4.67E-04** **EWa: 8.38E-05** **Eu: 2.65E-05** **Eo: 1.48E-03** **50%**	**ESv: 2.80E-04** **EWa: 5.03E-05** **Eu: 1.59E-05** **Eo: 8.85E-04** **70%**	**ESv: 0.93E-04** **EWa: 1.68E-05** **Eu: 5.31E-06** **Eo: 2.94E-04** **90%**
1.E-8	**P dry after about 11 days** **Q never dry**	**P never dry** **Q never dry**	**P never dry** **Q never dry**
1.E-9	**P dry after about 1.5 days** **Q never dry**	**P dry after about 4 days** **Q never dry (see also Fig. 3 and 4)**	**P dry after about 25 days** **Q never dry**
1.E-10	**P dry after about 0.3 days** **Q dry after about 0.2 days**	**P dry after about 1 day** **Q dry after about 0.7 days**	**P dry after about 4.5 days** **Q dry after about 1 year**

ESv	evaporation rate after SVEDRUP [$kgs^{-1}m^{-2}$]	EWa	evaporation after WATANABE [$kgs^{-1}m^{-2}$]
Eu	lower confidence bound of evap. [$kgs^{-1}m^{-2}$]	Eo	upper confidence bound of evap.[$kgs^{-1}m^{-2}$]
T	transmissivity of WCF [m^2s^{-1}]	h	relative humidity in tunnel [-]

4. Discussion

Some points concerning the results have to be mentioned:

(i) The pressure decline due to tunnel construction was considered instantaneous. This leads, specially in the beginning, to an overestimation of water inflow.

(ii) No dissolved gas in the formation water was modeled. Potential degassing due to the induced pressure decline would lead to a smaller relative permeability for water. Neglecting this effect leads to an overestimation of water inflow.

(iii) "Enhanced binary diffusion" and "vapor pressure lowering" didn't have a significant influence on the water flow. A certain influence was observed for vapor and air flow which were not relevant in this study.

(iv) The linear flow model (type P) shows a preferential propagation of the unsaturated zone along the WCF. An unsaturated zone is developping from the desaturated part of the WCF into the matrix.

5. Summary

The results of the linear flow model (type P) show for typical values of permeability (WCF) and humidity (tunnel air) a dry surface for the WCF at the tunnel wall after a reasonable short time of about 1 week. For the radial flow model (type Q) it is not possible to predict whether the WCF is wet or dry at the tunnel surface. The extent of the unsaturated zone is larger for type P than for type Q.

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