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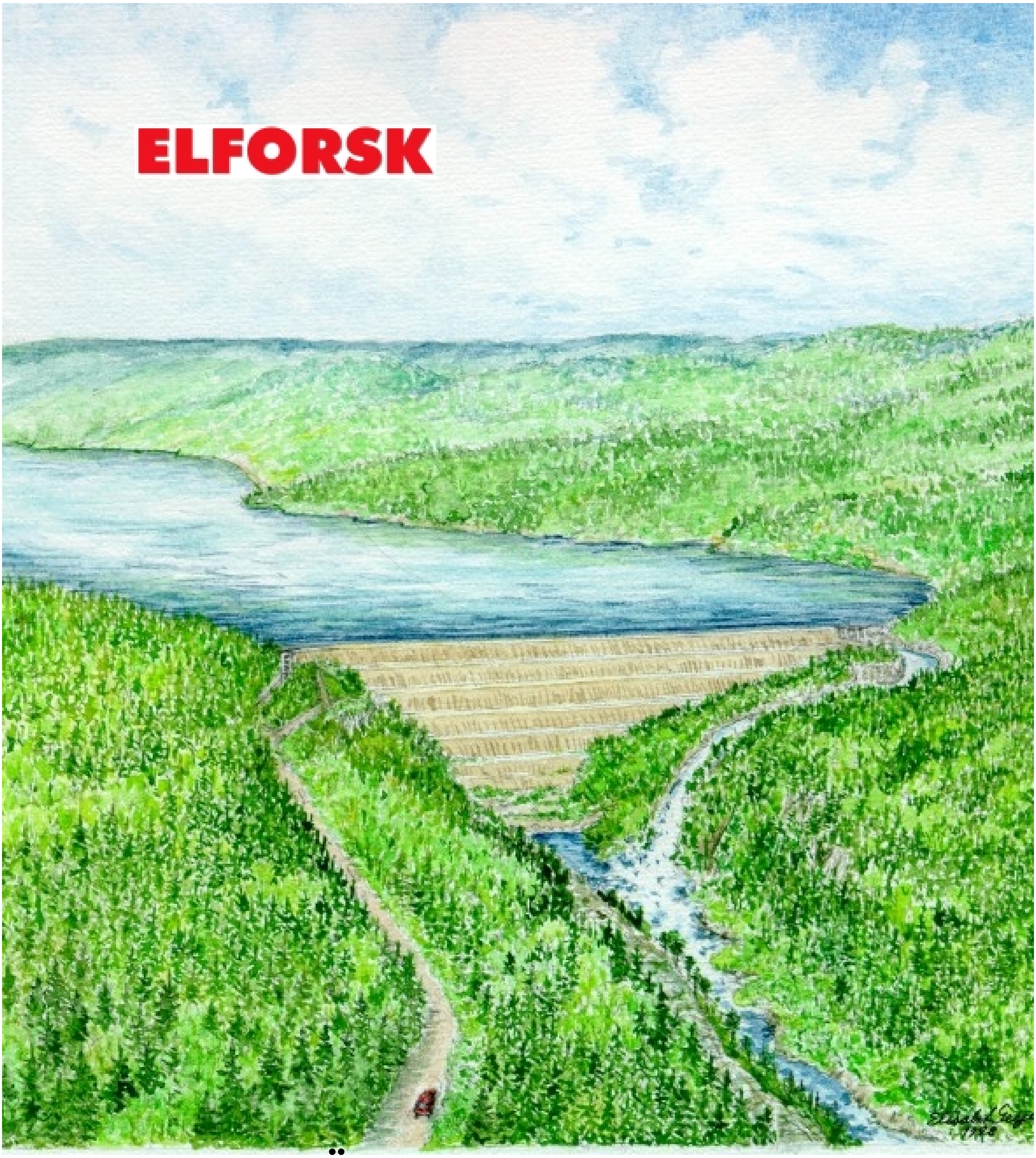

DAMMSÄKERHET

ON THE NON-LINEAR PRESSURE DISTRIBUTION IN EMBANKMENT DAMS.

Rapport 99:47

ON THE NON-LINEAR PRESSURE DISTRIBUTION IN EMBANKMENT DAMS.

- A FIRST STEP TOWARDS A NUMERICAL SIMULATION MODEL.

Elforsk rapport 99:47

Urban Svensson
Computer-aided Fluid Engineering AB

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Förord

BC Hydros W.A.C. Bennett damm i British Columbia, Kanada, är en 183 m hög och ca 2000 m lång jorddamm som dämmer upp en ca 30 mil lång sjö med en regleringsvolym av 70 miljarder m^3 vatten.

Två sjunkgropar uppstod under juni respektive september 1996 i Bennett-dammen. Man beslöt tillsammans med delstatens dammsäkerhetsmyndighet att magasinsnivån omedelbart skulle avsänkas. Därefter startade omfattande undersökningar av dammen både med mer beprövade metoder samt med nyare metoder som legat i forskningens framkant.

Hösten 1996, i anslutning till det inträffade, beslöts det att ett utvecklingssamarbete skulle starta mellan BC Hydro och svensk kraftindustri med inriktning på dammsäkerhetsfrågor kopplade till inre erosion, sjunkgropar och reparationsmetoder.

Utvecklingssamarbetet har varit mycket givande för båda parter. Det var ett unikt tillfälle att direkt kunna få tillgodogöra sig resultatet av de mycket omfattande utrednings-, undersöknings- och FoU-insatser på högsta internationella nivå. Genom detta utbyte har ett antal rapporter från svensk sida tagits fram, bl.a. den föreliggande. I detta samarbete har Urban Norstedt, Vattenfall Vattenkraft, och Gunnar Sjödin, Vattenregleringsföretagen, utgjort styrgrupp för VASO Dammkommitté och kraftindustrin och finansierande företag har varit alla medlemmar i Svenska Kraftverksföreningen.

Stockholm i december 1999

Elforsk AB

Innehållsförteckning

1 BACKGROUND

Higher than expected pressures are frequently measured in the cores of earth dams. For example, in the core of Benneth Dam the porewater pressure continued to rise for about three years after the filling of the reservoir 1972. After these three years the pressure decreased and after about twenty years the pressure had stabilised at values that can be expected in a homogeneous fully saturated dam core.

The higher than expected pressures are a consequence of a hydraulic conductivity that decreases in the flow direction. Several suggestions have been put forward, see St-Arnaud (1995), to explain what causes the decreasing hydraulic conductivity. In St-Arnaud (1995) it is suggested that air present in the voids of the dam could be responsible for the measured pressure distribution. The basic idea is as follows (see Figure 1):

- When the reservoir was filled air was entrapped, presumably in form of air-bubbles.
- As the filling continues the pressure on the upstream side, and progressively also inside the core, increases.
- Two effects can be expected to move the air downstream; as the pressure increases the bubbles will be compressed and the volume may be reduced with a factor of ten. The small bubbles may then move through the pores. However, as they approach the downstream boundary, with atmospheric pressure, the size increases and the bubbles get trapped again. The second transport mechanism is due to air dissolving in water. The amount of air that can go into solution increases with pressure (Henry's law). The air on the upstream side can thus go into solution, be transported by the water and evolve again at the downstream face due to the lower pressure (and hence lower air saturation in the water).
- The air bubbles on the downstream face cause a blockage for the water and hence a decreasing hydraulic conductivity in the flow direction.
- Eventually all air will be dissolved by the water and a fully saturated core with a linear pressure drop will be the final steady state.

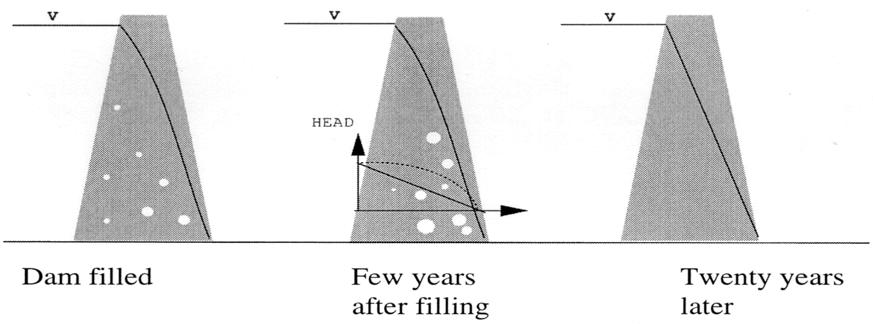


Figure 1. Schematic outline of problem considered.

The main objective of the present report is to evaluate if a mathematical/numerical model of the process described can be developed. It should be emphasised that it is a feasibility study and it is thus not part of the project to review and implement the best available physical laws and coefficients.

2 MATHEMATICAL FORMULATION

The problem will be treated as being one-dimensional and transient. Of the two phases, air and water, air will be assumed compressible while water is treated as incompressible. Some further details are given in Figure 2.

Within these assumptions the following set of equations can be formulated:

Momentum balance:

$$0 = -r_l \frac{\partial p}{\partial x} - r_l \rho_l \phi_l u_l ;$$

$$0 = -r_g \frac{\partial p}{\partial x} - r_g \rho_g \phi_g u_g ;$$

where p denotes pressure, r volume fraction, ρ density, ϕ a resistance factor and u the Darcy velocity. Index g and l stands for gas and liquid, respectively. As the momentum balance is between a pressure gradient and a linear resistance term, it is the Darcy law.

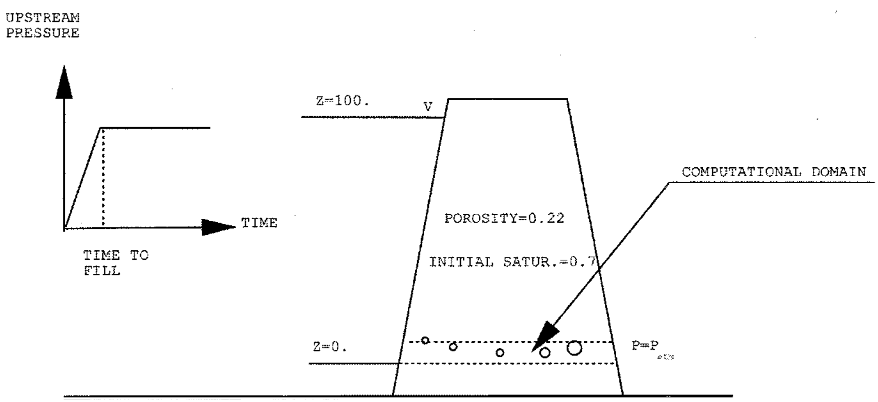


Figure 2. Computational domain, boundary and initial conditions.

Volume fractions:

$$\frac{\partial}{\partial t} r_l \rho_l + \frac{\partial}{\partial x} r_l \rho_l u_l = \dot{m}_{lg}$$

$$\frac{\partial}{\partial t} r_g \rho_g + \frac{\partial}{\partial x} r_g \rho_g u_g = \dot{m}_{lg}$$

where $\dot{m}_{lg}$ denotes mass exchange between the phases. An obvious constraint on the above equations is that the two phases should fill the space, i.e. $r_l + r_g = 1.0$

Liquid phase saturation: $$\frac{\partial}{\partial t} c_l r_l \rho_l + \frac{\partial}{\partial x} c_l r_l \rho_l u_l = \dot{m}_{cl}$$

where c_l is the saturation levels in the liquid and $\dot{m}_{cl}$ denotes transfer rates.

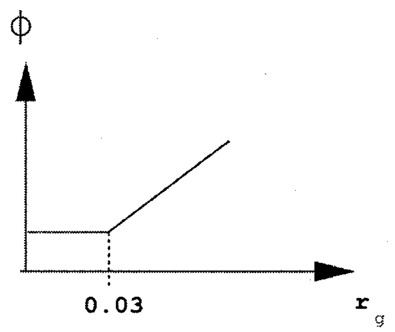
Source terms:

$$\dot{m}_{lg} = c_m \times (\psi_{int}(c_l) - c_l)$$

$$\dot{m}_{cl} = \left(f_{cl} + \dot{m}_{lg}\right) \times (\psi_{int}(c_l) - c_l)$$

where ψ_{int} represents the interface value of the variable in question. The above expressions give the convective and diffusive transport between the phases.

Resistance expressions:



General form:

It is thus assumed that low volume fractions of air will not influence the resistance, while a linear increase is assumed above this value.

Equation of state: $\rho_g = 1 + c(p - p_{atm})$

The air density will thus increase linearly with pressure.

The above set of equations is solved using the general equation solver PHOENICS (Spalding, 1981).

3 RESULTS

The computational domain, boundary conditions and some data were introduced in Figure 2. We will assume that the time to fill the reservoir, t_f, is three years and that the horizontal length of the domain is 100 metres. Time integration will proceed to 30 years, as we know that Benneth Dam shows a linear pressure distribution after about 20 years.

The mathematical model produces a lot of data worth studying in detail; one may for example study how air is dissolved in the water at the upstream boundary and evolves when the pressure decreases or one may study the transient behaviour of the permeabilities for air and water. In this report only the pressure distribution and air volume fraction will be discussed. Three cases are chosen to illustrate the effect of the transport of air:

- Air is allowed to be transported by the water phase according to Henry's law, but the Darcian transport is neglected, i.e. the permeability of the air is put to zero.

- Darcian transport is allowed but the exchange between the phases is neglected.

- Both Darcian transport and exchange between the phases are considered

The case without any transport of the air phase, i.e. no Darcian transport and no exchange, is of course also of interest. This situation can however, as will be shown below, be considered being covered by the first case above.

The case without any Darcian transport is first discussed. The time evolution of the pressure head and volume fraction of air is shown in Figure 3.

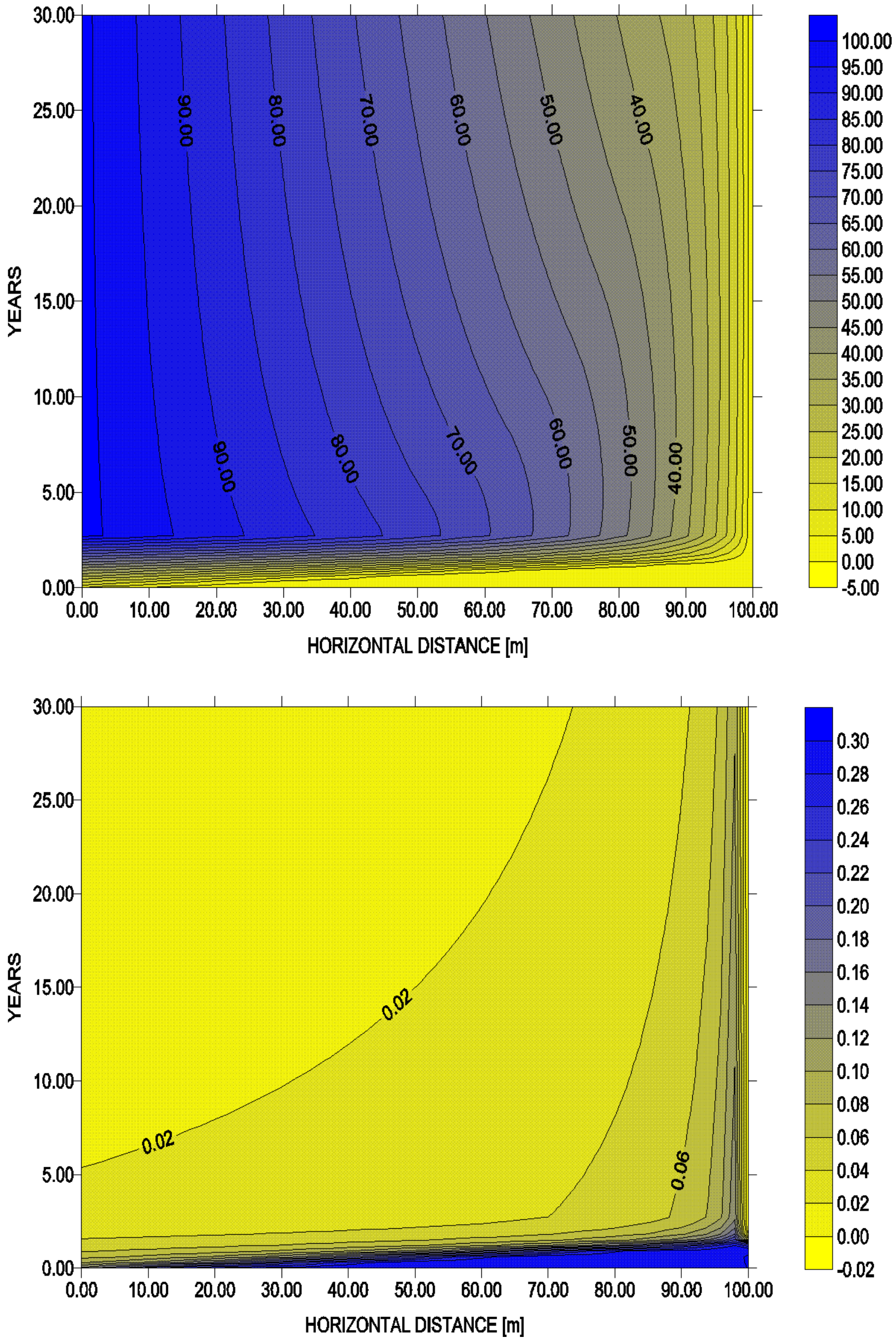


Figure 3. Time evolution of the pressure head and volume fraction of air, only Henry's law.

The pressure head is initially zero and increases to 100 metres in three years on the upstream side. As time goes on a more linear pressure distribution is approached, but still after 30 years the head is about 63 metres at x = 50 metres (should be 50 metres in a linear distribution). The explanation to the pressure distribution is given by the development of the air volume fraction, see Figure 3. After the filling the volume has decreased, according to Boyle's law, and at the upstream side the volume fraction is now only 0.03. Actually it is at this stage we can study the expected pressure distribution without any transport processes of air, as the dissolution is a slow process and has not yet influenced the pressure distribution. After 30 years there is still some air at the downstream side, which is the reason for the non-linear pressure distribution.

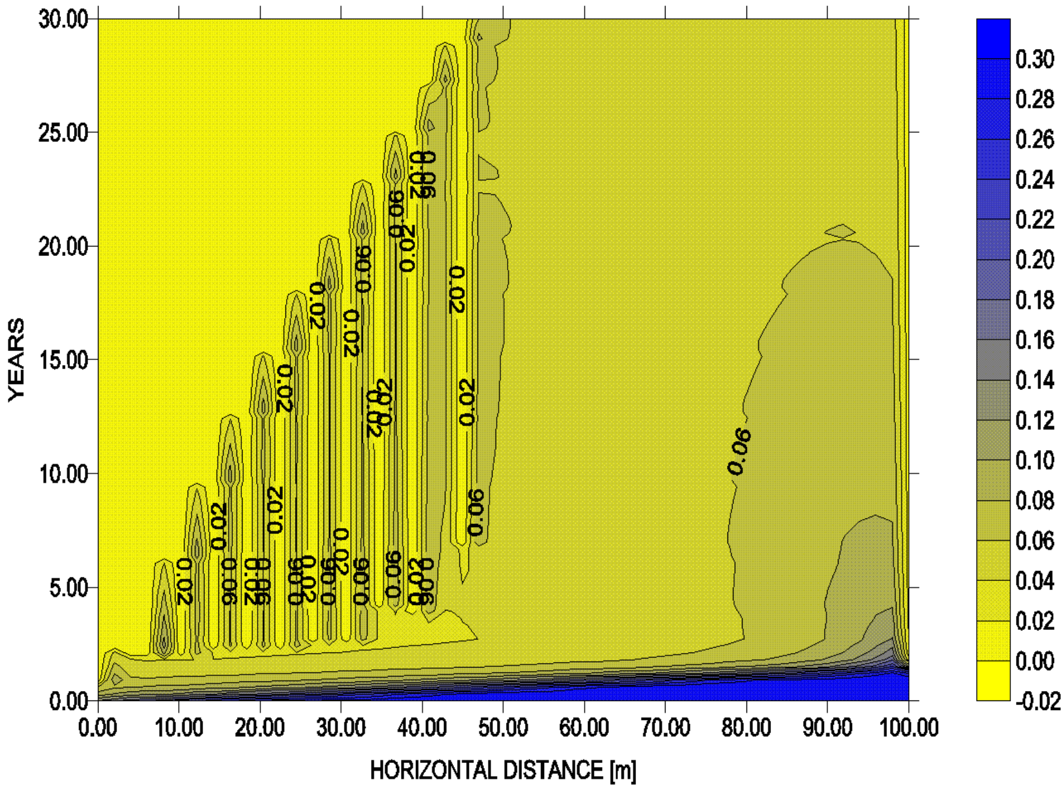


Figure 4. Time evolution of volume fraction of air, only Darcian transport

Next the case with Darcian transport but no phase exchange is discussed. The air volume fraction is shown in Figure 4. The pressure head after the time of filling, i.e. about three years, is found to be about 75 metres at x = 50 metres and the head increases with time at this position. There is thus no development towards a linear distribution. The air volume fraction at 30 years shows that no air is present in the first 50 metres while the rest has a volume fraction of about 0.07. The irregular distribution of the air is due to an instability in the one-dimensional situation studied; as it is assumed that small air bubbles move faster than larger ones, the small bubbles will catch up and merge with the larger ones and make these even slower. It is not clear if this process is present in "the real world" as the small bubbles can flow around the larger ones in the two- or three-dimensional case.

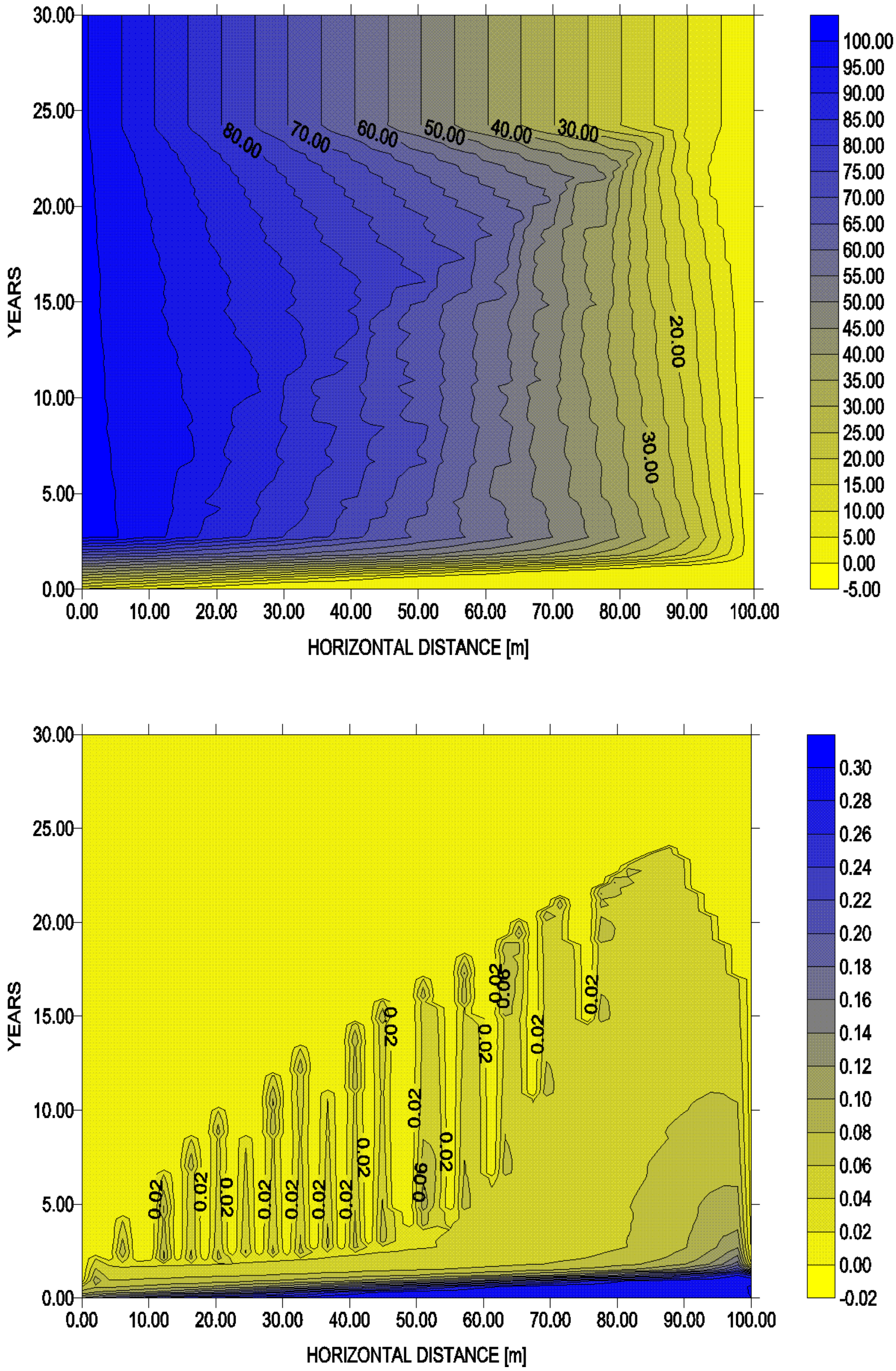


Figure 5. Time evolution of the pressure head and volume fraction of air, both Darcian transport and Henry’s law

The final case includes both modes of transport and is displayed in Figure 5. Now we find that the pressure distribution is linear and all air has left the domain after about 25 years. At x = 50 metres the head is about 65 metres when filling is completed and increases to almost 75 metres before it declines to the steady state value of 50 metres. The air distribution shows the same instability as discussed above, but the phase exchange now ensures that the air eventually leaves the domain.

4 CONCLUDING REMARKS

The main objective of this study is to evaluate if a mathematical/numerical model of the air-theory, as outlined in St-Arnaud (1995), can be formulated. It is the author's view that this has been demonstrated. The model is based on relevant physical laws and principles and produces results, see Figure 5, which are in qualitative agreement with observations. However, it should be emphasised that it is a feasibility study where some empirical relations have been tuned without considering possible experimental data or findings. If a more well-founded model is to be developed it is suggested that the following points are considered:

- Compile relevant information on permeabilities for the type of two-phase flow considered.
- Evaluate relevant laws and coefficients for the phase exchange.
- Verify simulations by comparisons with laboratory experiments, if available.
- Consider the two-dimensional situation.

5 REFERENCES

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St.-Arnaud, Guy (1995). The High Pore Pressures Within Embankment Dams: An Unsaturated Soil Approach. Canadian Geotechnical Journal, Vol. 32, No. 5, October.

Acknowledgement

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ELFORSK

SVENSKA ELFÖRETAGENS FORSKNINGS- OCH UTVECKLINGS – ELFORSK – AB

Elforsk AB, 101 53 Stockholm. Besöksadress: Olof Palmes Gata 31

Telefon: 08-677 2530. Telefax 08-677 2535

www.elforsk.se