

Two-phase flow simulation of water sealing of compressed air storage under cyclic pressure change in an unlined rock cavern

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Abstract Numerical simulations of two-phase flow through a porous medium were performed to understand the dynamic behaviour of the air that seeped out of an unlined cavern adopted for CAES (Compressed Air Energy Storage) in a saturated rock mass. In some cases, the pressure in the cavern is expected to change periodically due to daily or weekly usage of the compressed air. When the pressure is lowered, the amount of groundwater flowing into the cavern increases. If the water supply is insufficient, the air leakage might be induced. This study also investigated the effects of the periodic change in the air pressure on the water sealing of compressed air. It was found that the air which had seeped into the porous rock mass was trapped in a definite zone around the cavern when the pressure in the cavern was lowered.

INTRODUCTION

Compressed Air Energy Storage (CAES) (EPRI, 1989) is a means of storing off-peak surplus energy for subsequent use during peak periods. Air is compressed and stored in a cavern during periods of low demand for power. When power is needed, the compressed air is withdrawn from the cavern to drive electric generators. An operational effectiveness of compressed air storage can be expected only when the stored-air pressure can be raised to as high as 50–100 atmospheres (Nakayama *et al.*, 1993).

The adaptation of existing rock caverns, such as mined caverns, for CAES is one profitable use of underground spaces. The massive structural rigidity of a rock mass has the advantage of supporting large air pressures. However, under such high pressure, air often leaks out of unlined rock caverns through fissures and/or fractures in the rock mass. The cost of the CAES can be relatively low if no lining is required.

It is expected that groundwater will prevent the air in the cavern from leaking when the groundwater pressure is higher than the air pressure. Numerical simulations of two-phase flow through porous media are performed to understand the dynamic behaviour of the air that seeps out of the cavern into a saturated rock mass. This study investigates the necessary conditions for sealing the air with groundwater, and the effects of the periodic changes in the air pressure on the sealing.

NUMERICAL SIMULATION

The following governing equations for two-phase flow of air and water through porous medium (Meiri, 1981) are used for generating the finite element model in this study.

$$n \frac{dS_w}{dp_c} \left(\frac{\partial p_a}{\partial t} - \frac{\partial p_w}{\partial t} \right) = \frac{\partial}{\partial x_i} \left\{ k_{ij} \frac{k_{rw}}{\mu_w} \left(\frac{\partial p_w}{\partial x_j} + \rho_w g \frac{\partial x_3}{\partial x_j} \right) \right\} \quad (1)$$

$$n \left\{ (1 - S_w) \frac{d}{dp_a} \left(\frac{1}{\beta_a} \right) - \frac{1}{\beta_a} \left(\frac{dS_w}{dp_c} \right) \right\} \frac{\partial p_a}{\partial t} + \frac{n}{\beta_a} \left(\frac{dS_w}{dp_c} \right) \frac{\partial p_w}{\partial t} = \frac{\partial}{\partial x_i} \left(k_{ij} \frac{k_{ra}}{\mu_a \beta_a} \frac{\partial p_a}{\partial x_j} \right) \quad (2)$$

where k_{ij} is the intrinsic permeability tensor; k_{ra} and k_{rw} are the relative permeabilities of air and water, respectively; p_a and p_w are the pressures in air and water, respectively; p_c is the capillary pressure; S_w is the saturation of water; n is the porosity of the porous medium; β_a is the formation volume factor of air; ρ_w is the density of water; μ_a and μ_w are the viscosities of air and water; g is the acceleration of gravity; t is the time; and x_i are the Cartesian coordinates (x_3 being the vertical coordinate oriented positive upward). The boundary conditions are described as the prescribed pressure and/or the prescribed flux.

The expressions proposed by Brooks & Corey (1966) or by van Genuchten (1980) are employed to describe the relationships between the capillary pressure, the degree of saturation and the relative permeabilities.

Figure 1 depicts the flow domain simulated in this study. The simulations are performed in both small-scale and large-scale domains. A small-scale domain is expected to ensure the accuracy of the simulation in which the functional relationships between the relative permeabilities, the capillary pressure and the saturation have to be adapted. The air leakage under periodic pressure change in the cavern is investigated by comparison with the air leakage under constant pressure. The attenuation of the periodic pressure change with a distance, and its influence on the air leakage, are studied by comparing the simulation results in small-scale and large-scale domains.

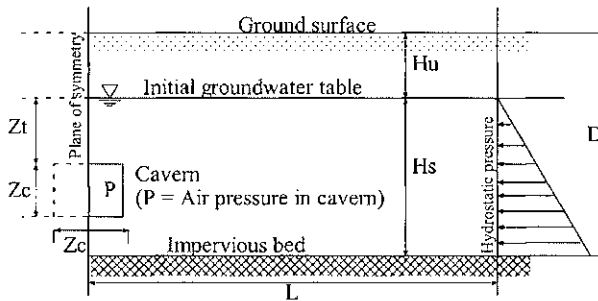


Fig. 1 Flow domain for simulation.

RESULTS AND DISCUSSION

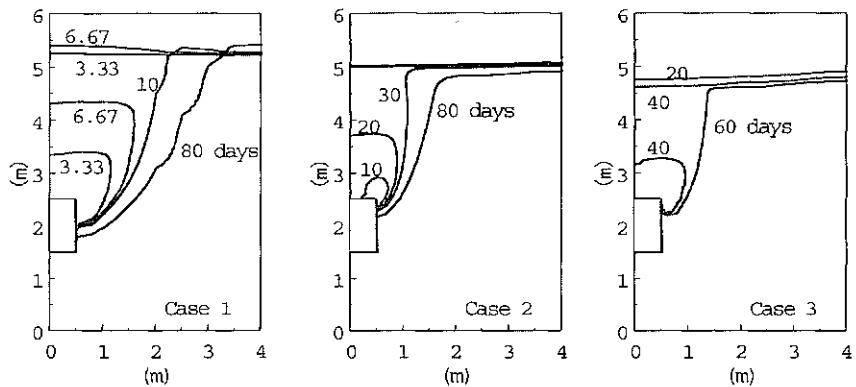
Three cases are simulated in a small-scale domain. The dimensions of the domain shown in Fig. 1 are $L = 10$ m, $D = 7$ m, $Hu = 2$ m, $Hs = 5$ m, $Zt = 2.5$ m and $Zc = 1$ m. The relative permeabilities and the capillary pressure as a function of the saturation in these simulations are based on the expression proposed by Brooks & Corey (1966). The air pressure in the cavern for each case is given in Table 1.

Table 1 Air pressure in the cavern.

	P (hPa)	Pressure head in m H_2O	Remarks
Case 1	353	3.6	Constant
Case 2	226	2.3	Constant
Case 3	167–226	1.7–2.5	Periodic (sine curve, period of one day)

Note: the initial pressure head of water on the top of the cavern is 2.5 m H_2O .

In the following, the water surface is defined as the surface of $S_w = 99.9\%$. In other words, the water surface is the boundary between the saturated and unsaturated zones. The displacements of the water surface and the water table are depicted in Fig. 2.

**Fig. 2** Displacements of water table and water surface.

In Case 1 where the air pressure in the cavern is larger than the initial water pressure around the cavern, the air leaking out of the cavern begins to break through the groundwater table at $t = 9$ days. It is observed that the water is raised as high as 0.5 m before the breakthrough.

In Case 2, although the air pressure in the cavern is less than the initial water pressure, the air breaks through the water table at $t = 26$ days. The reason for this is as follows. Since the pressure in the cavern is less than the outside water pressure, the groundwater flows into the cavern. To supply the water flowing into the cavern, the groundwater table declines towards the cavern and then the water pressure around the upper part of the cavern becomes less than the air pressure in the cavern. Thus, the air begins to leak out. Figure 3 shows the flows of air and water at $t = 10$ days in Case 2. The air leaks from the upper part of the cavern while the water flows into the cavern from its bottom.

In Case 3, the pressure change in the cavern follows a sine curve with the period of one day. Since the maximum pressure in the cavern in Case 3 is equal to the pressure in Case 2, the minimum pressure in Case 3 is less than the pressure in Case 2. Therefore, the amount of water flowing into the cavern in Case 3 is more than that in Case 2 and the decline of the water table is larger. As shown in Fig. 2, the drawdown of the water table above the cavern from its initial level is about 40 cm at $t = 40$ days. The air begins to break through the water table at $t = 50$ days. Figure 4 shows the water flows at $t = 19.5$ days when the pressure in the cavern is maximum and at $t = 20$ days

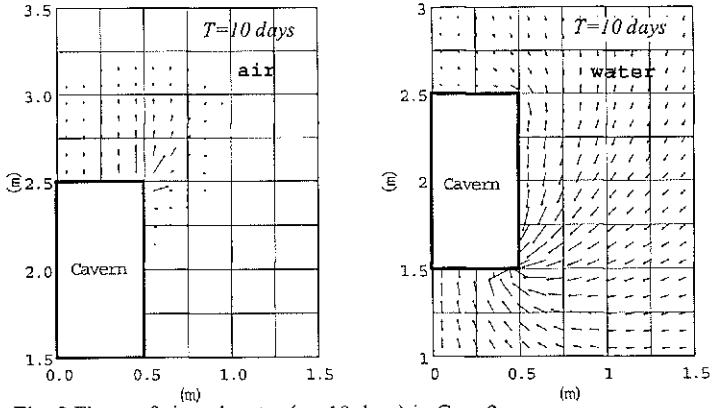


Fig. 3 Flows of air and water ($t = 10$ days) in Case 2.

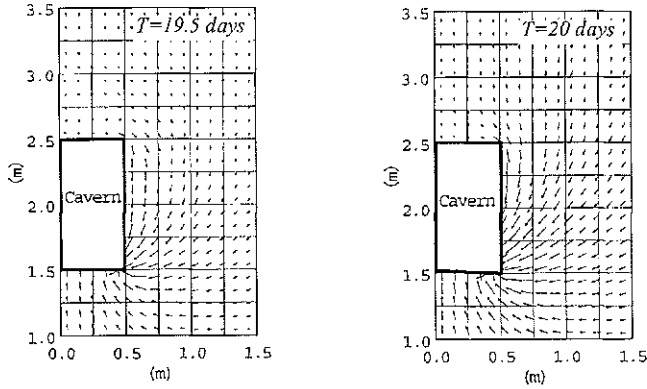


Fig. 4 Flows of water ($t = 19.5$ and 20 days) in Case 3.

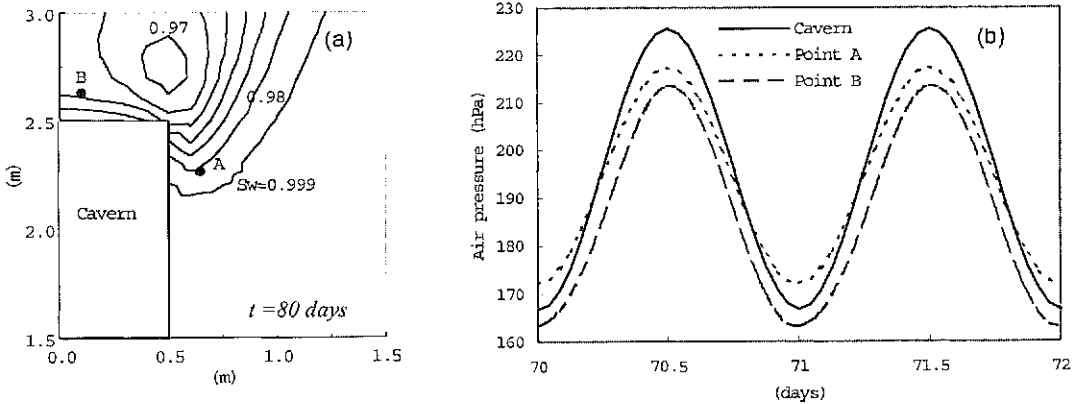


Fig. 5 (a) Saturation around cavern, and (b) air pressure changes at points A and B, and in cavern in Case 3.

when the pressure is minimal. Figure 5 shows the saturation distribution near the cavern at $t = 80$ days and the air pressure changes at the points A and B, shown together with the pressure in the cavern. No phase difference is observed among these

pressure changes. The pressure at the point B is always less than that in the cavern. On the other hand, the pressure at the point A becomes larger than the pressure in the cavern when the latter is reduced. This indicates that the air which has seeped into porous rock mass around the point A is trapped there when the pressure in the cavern is lowered. The reason for this is speculated as follows. The saturation around the point A is quite high although it is less than 100%, while the saturation around the point B is less. It is noted for reference that the ratio of k_{ra} for $S_w = 0.99$ to k_{ra} for $S_w = 0.97$ is about 0.14. Thus, the relative permeability of air around the point A is quite small compared with that around the point B. Therefore, the air which has seeped into the rock mass under the large pressure gradient cannot flow back to the cavern under a small pressure gradient. On the other hand, the relative permeability of the air around point B is always large enough for the air to move back and forth.

The simulations in the large-scale flow domain are performed for four cases. The dimensions of the domain are $L = 1000$ m, $D = 480$ m, $H_u = 40$ m, $H_s = 440$ m, $Z_t = 360$ m and $Z_c = 10$ m. The expression proposed by van Genuchten is used to evaluate the relative permeabilities and the capillary pressure as a function of the saturation for these simulations. The air pressure in the cavern for each case is given in Table 2.

Table 2 Air pressure in cavern.

	P (MPa)	Pressure head in $\text{m H}_2\text{O}$	Remarks
Case 4	4.9	500	Constant
Case 5	3.53	360	Constant
Case 6	4.51–4.9	460–500	Periodic (sine curve, period of one day)
Case 7	3.53–4.9	360–500	Periodic (triangular, period of one week)

Note: the initial pressure head of water on the top of the cavern is 360 $\text{m H}_2\text{O}$.

Figure 6 shows the displacement of the water surface (or the surface of $S_w = 99.9\%$) in Case 4 where the pressure in the cavern is about 1.4 MPa larger than the initial water pressure on the top of the cavern. The water table is pushed up as high as 20 m from its initial location by the air at $t = 955$ days and up to the ground surface at $t = 1915$ days.

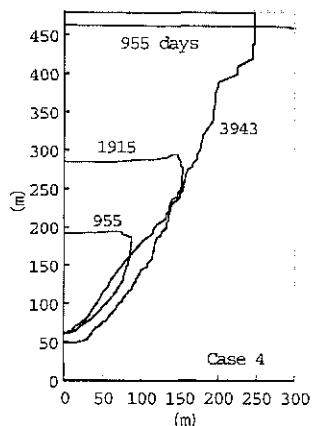


Fig. 6 Displacements of water table and water surface (Case 4).

In Case 5, the pressure in the cavern is kept equal to the initial water pressure on the top of the cavern. The water surface which started from the cavern rises only to less than 100 m above the cavern after 4195 days (or nearly 11.5 years). Because the amount of water flowing into the cavern is supplied with only a small decline of the water table, the water pressure on the top of the cavern decreases little from its initial value.

In Case 6, the change of pressure in the cavern follows a sine curve with a period of 1 day and the maximum pressure is equal to the pressure in Case 4 where the pressure is kept constant. No sensible difference between the displacements of the water surface in Case 4 and Case 6 is observed. The air leaks out of or into the cavern according to the pressure in the cavern. The amount of air leakage at the maximum pressure is twice as much as that in Case 4. On the other hand, when the pressure in the cavern is reduced, part of the air that has seeped into the rock mass flows back into the cavern though the minimum pressure is larger than the initial water pressure around the cavern.

In Case 7, the pressure in the cavern linearly increases from 3.53 Mpa to 4.9 Mpa for 2 days and then linearly decreases to 3.53 Mpa for 5 days. The minimum pressure in this case is equal to the initial water pressure on the top of the cavern. Figure 7 shows the potential distribution of water around the cavern at $t = 259$ days when the pressure in the cavern is minimum. A high potential zone appears around $z = 120$ m above the cavern. Because of this, the water flows into the cavern even from its ceiling. This suggests that the air is trapped there for the same reason as discussed in Case 3. This is a distinctive process of air leakage when the pressure in the cavern changes periodically.

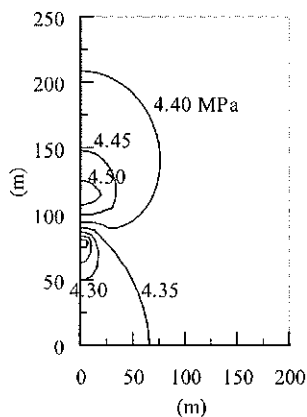


Fig. 7 Potential distribution of water (Case 7).

CONCLUSION

Even if the air pressure in the cavern is less than the pressure of groundwater around the cavern, the air leakage might be induced when the amount of water flowing into the cavern is not compensated. When the pressure in the cavern changes periodically, the air appears to be trapped in a specific zone around the cavern where the saturation

is relatively large. When the flow domain is small compared with the cavern, the periodic pressure change has a great influence on the dynamic behaviour of air leakage. On the other hand, this influence is attenuated in the case where the flow domain is large enough to supply the water flowing into the cavern.

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