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Hybrid Modelling of Flow Processes in Underground Pump Storage Reservoirs

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ABSTRACT: Design and construction of pump storage reservoirs are influenced by land use conflicts and difficult to realize nowadays. Therefore, underground pump storage reservoirs (UPSR) are regarded as a possible alternative due to minor environmental impacts and less land use conflicts. However the feasibility of such a project needs to be analyzed from a technical, economic and legal point of view. In a first step, the hydraulic processes were investigated for different geometries by using a hybrid modelling approach as a key prerequisite for feasibility.

Keywords: Flow Processes, Underground pump storage reservoirs, Hybrid modelling, OpenFoam

1 INTRODUCTION

Pump storage reservoirs are of high importance for the German energy turnaround and the transition from the fossil fuel and nuclear energy age to volatile renewable energy sources. Renewable energies such as wind energy, solar energy and hydropower energy show high temporal and spatial fluctuations while the demand depends on human activities. The resulting difference between energy demand and energy supply requires new energy storage capacities in different time intervals from sub second to seasonal ranges.

Traditional pump storage reservoirs are often critically evaluated due to conflicts with nature conservation and population. Therefore, research is required for innovative and new pump storage concepts avoiding the aforementioned conflicts. Underground pump storage reservoirs are regarded as one promising alternative due to the possibility of subsequent use of old and abandoned mines (coal, ore or salt).

The hydraulic processes in these underground pump storage reservoirs (Fig. 1) are an important prerequisite apart from mining, technical, economic, approval and operational aspects. Consequently, the hydraulic processes in underground pump storage reservoirs are investigated in detail on the basis of an hybrid modelling approach using OpenFoam and a small scale physical model.

2 EXISTING CONCEPTS

The idea of using underground cavities for underground pump storage reservoirs is not new. First concepts were developed and discussed in the fifties of the last century (e.g. Issakson, 1968, Schumann, 1979) but were never realized in practice. The importance and possibilities of underground pump storage reservoirs increased due to the decrease of fossil energy resources, the retreat of nuclear energy (at least in Germany), the development of renewable energies and an increase of land use conflicts during the past years. Therefore, different implementation concepts are investigated in Germany by different working groups. Three different concepts are mentioned in the following even if the level of detail is still very different and a clear comparison is not possible so far. The energy research Centre in Lower Saxony investigates possibilities for the Harz mountains in Northern Germany by using old and abandoned ore mines (Beck and Schmidt, 2011). The University of Duisburg-Essen works on possibilities to use old coal mines in the Ruhr area (Niemann, 2013) and finally an underground pump storage reservoir is discussed as an alternative for a traditional pump storage reservoir in Forbach / Black Forest / Southern Germany (Achatz et al., 2011). Similar projects are also discussed in other countries such as the Wiscasset-Project in the US (Turgeon et al., 2011). The different concepts can be classified roughly into the following categories:

- Both or only one reservoir is in the underground
- Old or abandoned mines are re-used
- The lower reservoir is either a single cave or a branched system

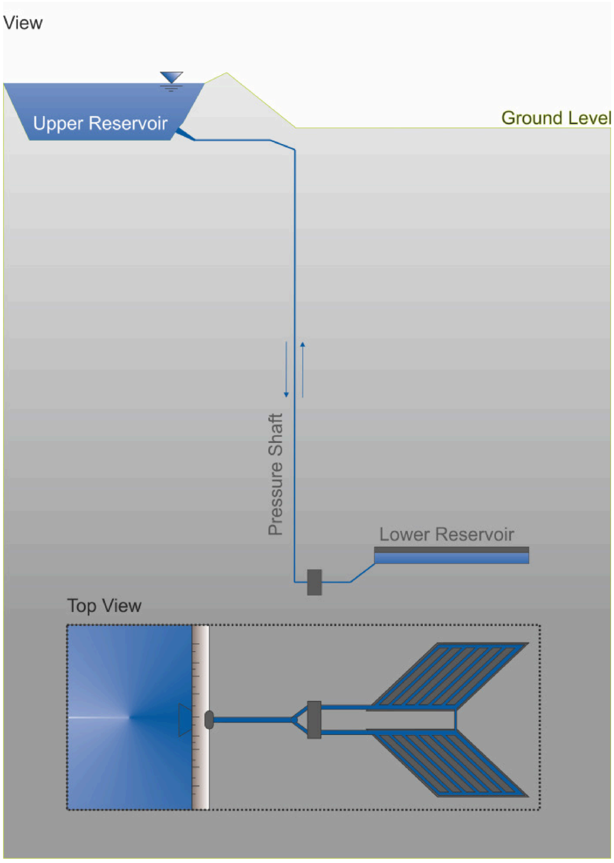

Figure 1. Concept of an underground pump storage reservoir

It is not known so far which of these systems can be realized due to different hydraulic, geotechnical, mechanical, financial, juridical and constructional aspects. Therefore, interdisciplinary investigations regarding the feasibility of UPSR are required and should be performed as soon as possible in times of energy transition, increasing electricity tariffs and uncertainties concerning the marketability of energy from pump storage reservoirs.

3 HYDRAULIC FEASABILITY

First systematic investigations concerning the hydraulic feasibility of UPSR are performed at the Institute of Hydraulic Engineering and Water Resources Management of RWTH Aachen in a hybrid model (here: hybrid = experimental und numerical) (Pummer and Schüttrumpf, 2013). First, a physical model of an underground storage reservoir (UPSR) was set-up in an approximate scale 1:100 to investigate the filling and emptying flow processes and to identify relevant factors influencing these processes (Fig. 2).

In a second step, the hydraulic processes in the underground pump storage reservoir were simulated by using 2D and 3D numerical models (OpenFoam, Flow3D, Telemac 2D). The numerical models were calibrated by the physical model and different model geometries (e.g. number of caves, length of caves) were investigated to find an hydraulically optimum geometry. The test programme was identical in the physical and numerical model simulations by considering the underground pump storage reservoir as a unit of the German energy network, Therefore, typical filling and emptying processes were given as in- and outflow boundary conditions. In this paper, only numerical results with OpenFoam are presented.

A comparison of the experimental and numerical results showed maximum differences in water depths in the order of 3% (Fig. 3).

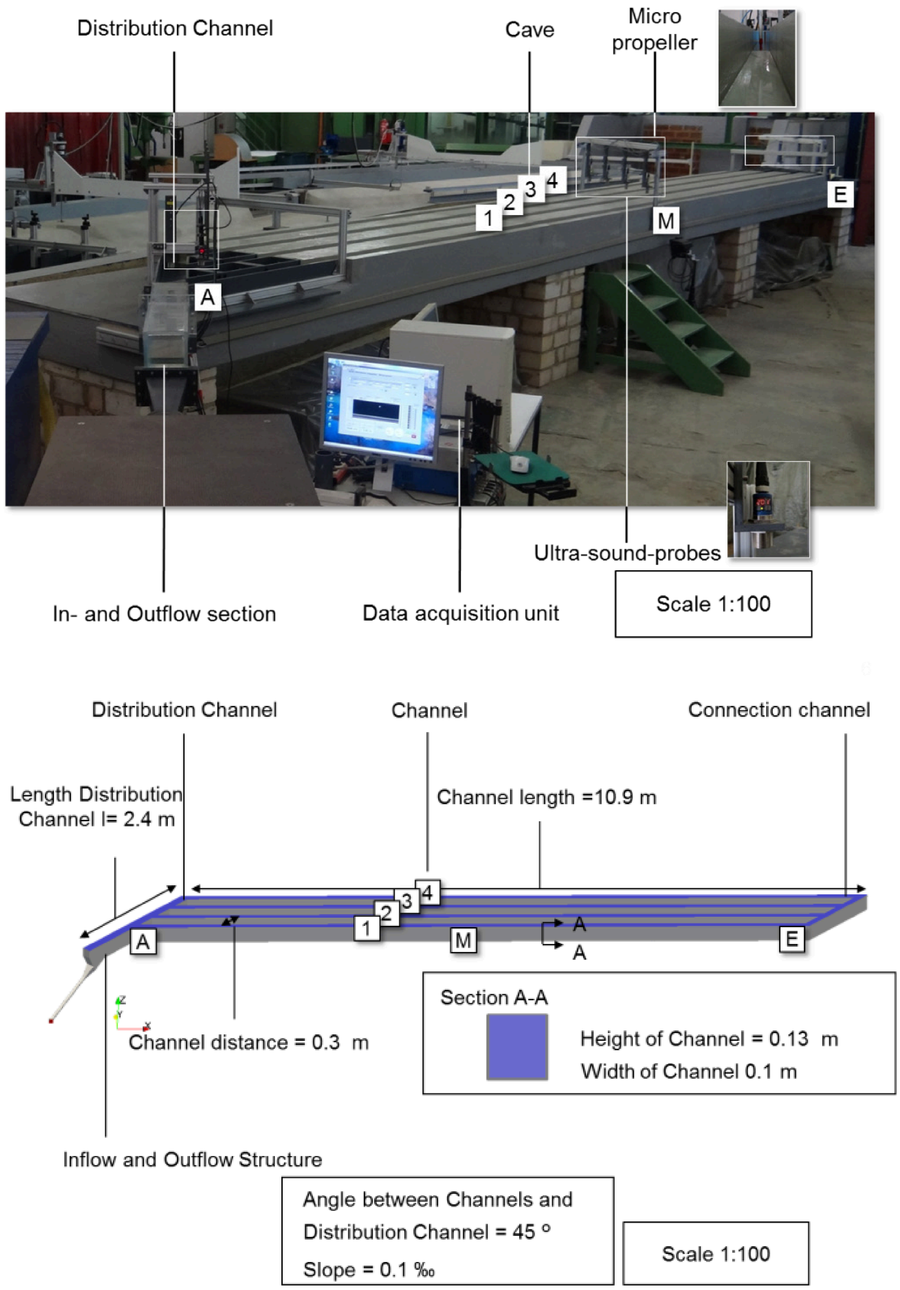

Figure 2. Experimental System (a) and numerical Model (b)

Objective of these investigations was to understand the local flow processes, the emptying and filling process, the influence of geometrical factors such as number, distance, slope, width and height of the caves to describe a flow optimized cave system. Therefore, it is of no importance in this context if the lower reservoir will be constructed in an old ore, coal or salt mine. It is of interest whether the caves can be filled or emptied in a given time interval. These investigations are also required to investigate the efficiency and working capacity, the freeboard and to determine the boundary conditions for soil-water interactions.

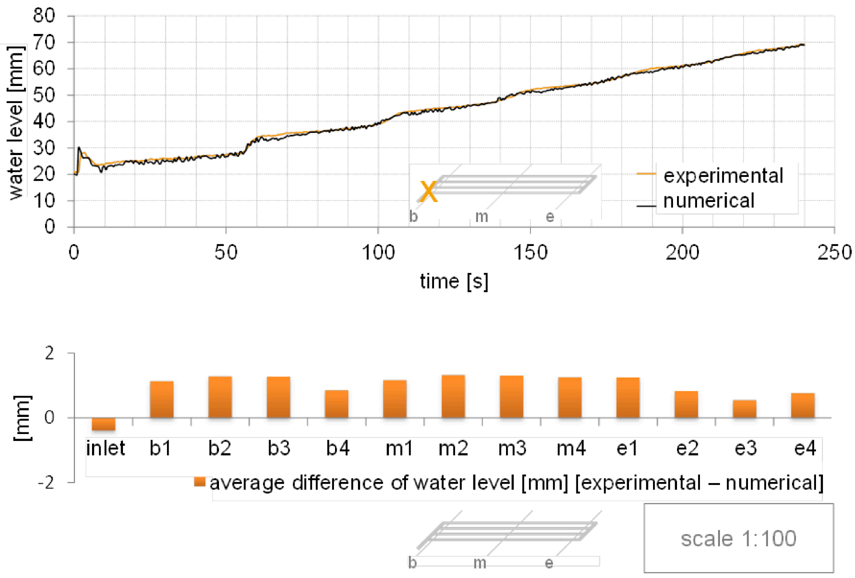

Figure 3. Comparison of experimental and numerical results

4 RESULTS

The experimental and numerical data were analyzed to get more information on the following aspects:

- Description of the emptying and filling process
- Global and local flow processes in an UPSR (Fig. 3)
- Optimum geometry of an UPSR
- Flow and pressure impacts on surrounding rock
- Suitability of 2D and 3D numerical models to assess flow processes in UPSR
- Energy storage in UPSR

It was important to distinguish between global and local processes during analysis of the experimental and numerical investigations. Global flow processes are related to the filling and emptying process and the influence of different geometrical properties of the underground caves. We were able to show:

- that an increasing number of caves is positive for the filling and emptying process
- the distribution of water is more efficient if the horizontal distance between the caves is small
- short caves can be filled and emptied in shorter times and are hydraulically more efficient,
- the bottom slopes of the caves influences the filling and emptying process

In addition, local flow processes are identified and described (Figs. 4 and 5):

- Hydraulic jumps and air intrusion due to fast filling and emptying processes
- Surge and down-surge waves
- reflections from the cave walls and cave ends

These effects were reduced due to adapted geometries of the caves. Therefore, we were able to increase the hydraulic performance of UPSR.

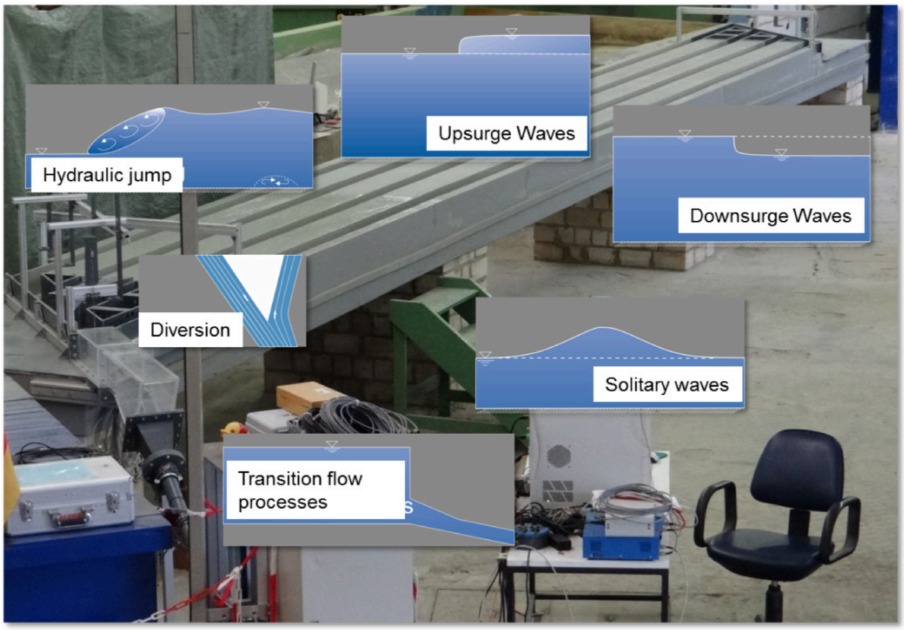

Figure 4. Local and global flow processes in an underground pump storage reservoir (UPSR)

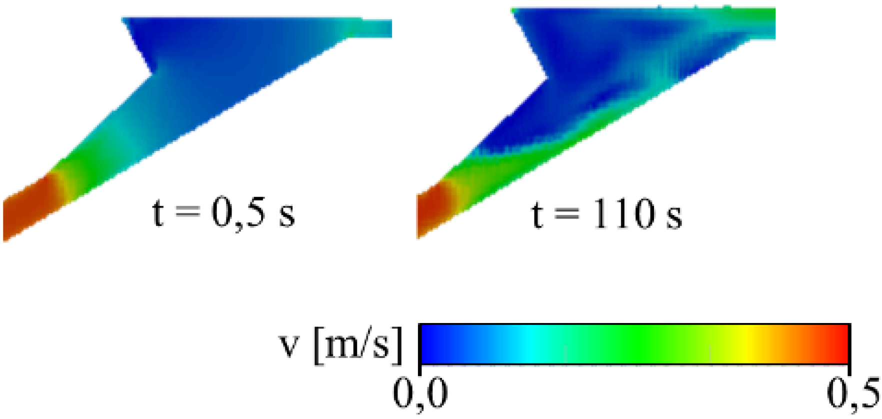

Figure 5. Local and global flow processes in an underground pump storage reservoir (UPSR)

5 CONCLUSIONS

The hydraulic feasibility of UPSR was investigated which could be a possible alternative to traditional pump storage reservoirs if other technical, juridical, economic and financial factors are proven. These pump storage reservoirs are very attractive due to low environmental impacts and less land use conflicts. Missing experience with these infrastructures requires more detailed investigations.

An hybrid modelling approach was found to be the most suitable way to investigate the aforementioned processes due to complexity of the turbulent and two phase processes on one hand and the need to investigate different geometries on the other side.

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