Geophysical monitoring of brine and air leakages in groundwater from deep energy storages

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ABSTRACT

Injected compressed air energy storage (CAES) and brine may seep from deep reservoirs along weak zones upwards into shallow groundwater aquifers. These CAES and fluid phase leakages cause changes in the electrical resistivity, density and elastic moduli of the aquifers, and justify applications of various geophysical techniques. Applied geophysical techniques can resolve and monitor these brine and CAES anomalies of a sufficient size and contrast inside the aquifer. Our sensitivity study shows that an investigation depth of conductive brine anomalies is at least twice that of resistive CAES anomalies. Based on sensitivity contrasts, seismic and gravity techniques are more sensitive to CAES leakages whereas electric and electromagnetic to brine intrusions.

INTRODUCTION

Renewable energy resources are intermittent and need a buffer storage to bridge the time-gap between production and demand peaks. The North German Basin has favourable conditions and a very large capacity for compressed air/gas energy storage (CAES) in porous saltwater reservoirs and salt caverns. However, the injected CAES and even saltwater can seep along weak zones and fractures upwards and migrate into shallow groundwater aquifers. These gas and fluid phase leakages cause changes in the electrical resistivity, density and elastic moduli of these aquifers, and justify applications of various geophysical techniques. Our current interdisciplinary project ANGUS+ deals with impacts of using geologic subsurface as a thermal, electric or material reservoir in context with alternative energy resources. Our main task is to develop an integrative geophysical monitoring strategy for this geologic CAES and its possible leakages for almost realistic scenarios.

Using numerical simulations of almost realistic scenario we study the applicability of techniques of elastic full wave inversion (FWI), electric resistivity tomography (ERT), transient electromagnetic induction (TEM) and gravity in monitoring these leakages in shallow groundwater aquifers.

HYDROGEOLOGICAL SIMULATION

We simulated two scenarios (Fig. 1). The first is a saltwater intrusion of 4.2 g/s with different salinities for 10 years due to pressure increase into a near surface potable aquifer. In the model the aquifer is homogeneous with a thickness up to 40 m. The salt water is transported with natural groundwater flow.

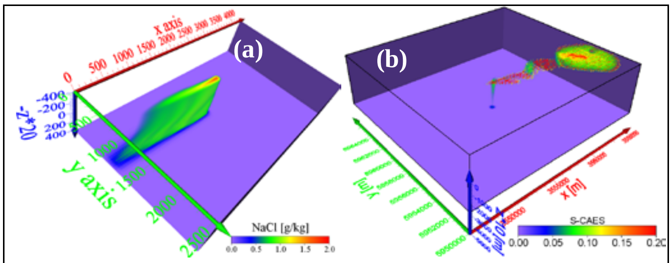

Figure 1: 3D saltwater and CAES leakages into shallow groundwater. After 10 years of leakage the density change of water is up to 4 kg/m^3 for saltwater intrusion (salinity 4 g/l, a) and -340 kg/m^3 for CAES (saturation 0.654, b).

The second is a leakage of 1 kg/s compressed air for 10 years into a 500 m thick Quaternary aquifer with alternating layers of different sands, silt and clay. The geological structure has been determined by the State Agency for Agriculture, Environment and Rural Areas. It was imported into the simulation code TOUGH2-MP (EOS3) with help of the user interface PetraSim. The air migrates buoyancy driven upwards, but accumulates below low permeable layers and searches its way upwards through better permeable areas.

GEOPHYSICAL MODELLING

Table 1: Petrophysical laws, and forward and inversion codes applied in this study.

Method	Petrophysical law	Forward - inverse codes	References
ERT	Archie	RES2DMOD - RES2DINV	Archie 1942, Loke et al 2003, Christiansen & Auken 2009, Tarantola 1986, Gassmann 1951, Köhn et al. 2012, Batzle & Wang 1992, Götz & Lahmeyer 1988
TEM	Archie	EM1DINV	
FWI	Gassmann, Patchy	DENISE	
Gravity	Mixing law for multiphase media	IGMAS+	

These hydrogeological leakage models, among others, are transferred in geophysical models (electric resistivity, seismic P and S-wave velocities and density) using almost realistic parameterization and adequate petrophysical laws (Table 1). Typical values for petrophysical parameters (e.g., porosity, density, TDS, elastic parameters) are considered from publications (e.g. Kunkel et al. 2002, Hese 2012). Using codes of Table 1, the forward modelling of this scenario generates synthetic datasets which in turn are inverted to reproduce the underground models. Surveys using optimized setups are conducted on land, in the air and in boreholes (e.g. Hagrey 2012). Data inversions are conducted without and with posing constraints on the initial model outside the leakage. We present here a part of the geophysical results for the sake of brevity.

GEOPHYSICAL MONITORING SALTWATER INTRUSION

Results reflect a varying sensitivity of the different applied techniques to resolve and monitor this saltwater intrusion (Figs. 2-3). ERT and TEM techniques are well capable to detect and monitor this intrusion already 0.5 year after intrusion. Gravity and FWI are unable to detect the anomaly of this saltwater intrusion with salinity contrasts up to 3.721 g/l (density up to 3.721 kg/m^3, averaging 0.045

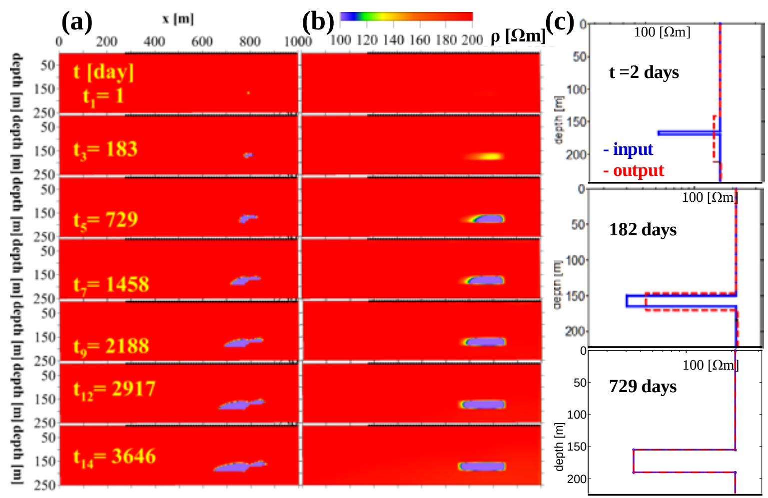

Figure 2: Monitoring of brine intrusion with increasing time after seepage begun by 2D ERT (a: input, b: output models) and 1D TEM (c), showing a high spatiotemoral resolution down to 160 m depth.

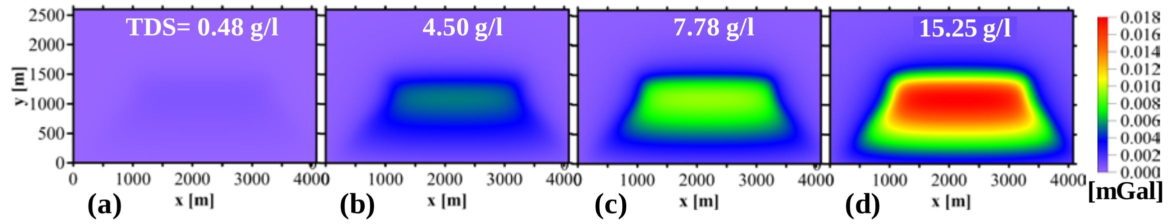

Abb. 3: Sensitivity of vertical gravity anomalies (Δg_z) resulting from brine leakage of varying salinities (TDS). Applied TDS intrusion (a) is undetectable by modern micro-gravimeters (3-5 μGal precision) and the detectability starts for TDS ≥ 4.5 g/l (b-d).

kg/m^3). Sensitivity analyses show that a plume as in figure 1 yields a measurable vertical gravity anomaly Δg_z (i.e. > 5 µGal) when the density contrast approaches ≥4.5 kg/m^3, i.e. TDS contrast ≥ 4.5 g/l. Hence, only salt water intrusions with a TDS 10 times higher than in the presented scenario can be detected by gravity. Seismic sensitivity analyses using reverse time migration (RTM) show that a plume detection is possible with a TDS contrast is 50 times larger than in the scenario (not shown).

GEOPHYSICAL MAPPING CAES LEAKAGE

Reconstructed ERT models (Fig. 4) show the technique capability (of different surveys and inversion constraints) to resolve the resistive anomalies of the CAES leakage within the conductive aquifer. The inverted model resolution is enhanced by applying a combined surface-borehole survey (instead the single surface or borehole survey alone, cf. Figs. 4d and 4e) and by considering a constrained inversion (instead of no constraints, cf. Figs. 4d and 4f). We can see that the resolution of the surface survey decreases with increasing depth where the deep anomaly shows a smeared oversize and reduced amplitude.

Inverted 1D aero-TEM models show the technique capability to resolve these shallow and deep resistive anomalies. The shallow resistive anomaly is better resolved than the deep anomaly. Obviously, both ERT and TEM techniques can resolve these CAES anomalies. However, the resolution of resistive air plumes in conductive medium is governed by the equivalence principle of the transverse resistance (ρh= constant, h= layer thickness), where the smearing effect increases the thickness on expenses of the resistivity amplitude. i.e. the amplitude is underestimated.

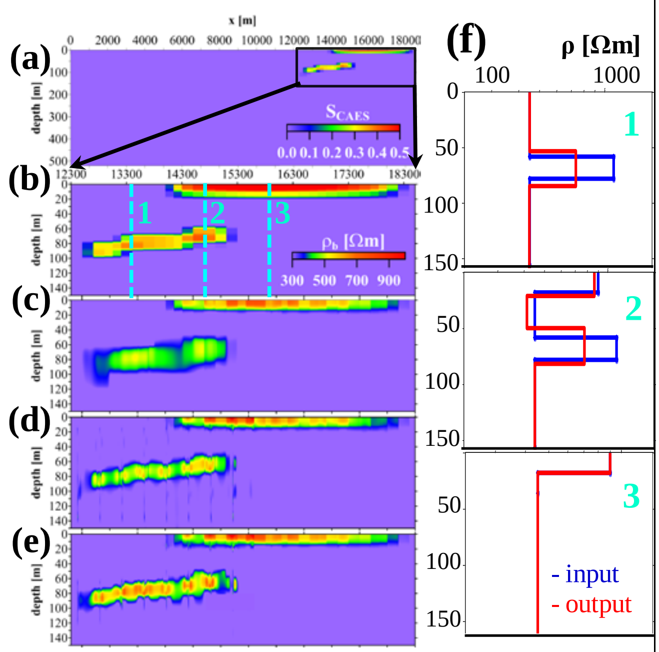

Fig. 4: Vertical section of CAES leakage (a) with the 2D ERT forward (b) and inverted resistivity models from surface (c) and surface-borehole surveys (d-e), and 1D TEM sounding models (f) at three locations (see b). The resolution is enhanced for models of surface-borehole and constrained inversion compared to their other corresponding models.

Moreover, the 3D gravity technique applied here (not shown?) shows a high sensitivity to this shallow leakage in groundwater. For this leakage a negative anomaly approaches an amplitude of >140 µGal which is far higher than the least measurable value of 5 µGal using micro-gravimeters.

Applying Gassmann eq. yields changes of the elastic material parameters of V_p, V_s and bulk density d_b (Fig.5a-c). Due to the free surface boundary condition the data of synthetic reflection seismic is dominated by the Rayleigh wave, which highly increases the nonlinearity of the inverse problem (Brossier *et al.* 2009). The synthetic seismic sections are the input data for the FWI. The initial model for the time-lapse waveform inversion at each time-step is the true elastic baseline model before the CAES leakage. No constraints to the time-lapse data, like sequential frequency/offset filtering or time windowing, are applied and all elastic model parameters are inverted simultaneously. The seismic inversion results (Fig. 5d-f) are compared with the true changes (Fig. 5a-c). Due to the dominance of the Rayleigh wave in the time-lapse data only V_s model variations could be recovered with some success, while the changes in V_p and d_b are underestimated.

CONCLUSION

Applied geophysical techniques are capable to detect and monitor saltwater or CAES leakage. A comparative interpretation of results for both leakages may facilitate the sensitivity evaluation of the single techniques applied to each of these leakages. The CAES leakage is characterized by its resistivity highs and mass deficit, and the saltwater intrusion by its resistivity lows and mass excess. The lower boundary value of detectability has been determined. FWI technique can map the CAES plume better than the saltwater plume based on impedance contrasts. Applied integrative techniques complement each other. Gravity and FWI methods are more sensitive to CAES plumes yielding stronger density contrast than saltwater intrusions, whereas ERT and TEM are more sensitive to the conductive saltwater than the resistive CAES. Also the investigation depth for the resistive CAES plume is far shallower than that for the conductive saltwater intrusion.

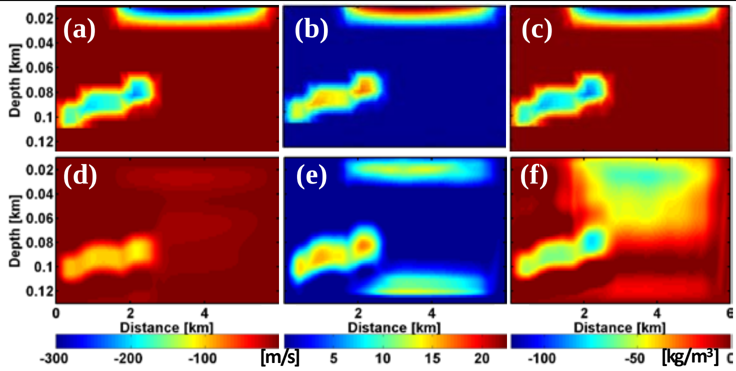

Fig. 5: Changes of the elastic material parameters P-wave velocity (a, d), S-wave velocity (b, e) and bulk density (c, f) for the true model of the CAES leakage in the groundwater aquifer (a-c) and that resulting from FWI (d-f), respectively.

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