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Hydro-mechanical simulations of well abandonment at the Ketzin pilot site for CO_2 storage verify wellbore system integrity

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Abstract

In geological underground utilization, operating and abandoned wells have been identified as main potential leakage pathways for reservoir fluids. In the scope of the well abandonment procedure currently carried out at the Ketzin pilot site for CO_2 storage in Germany, we implemented a hydro-mechanical wellbore model to assess the integrity of the entire wellbore system. Thereto, we investigated the impacts of stress changes associated with site operation and abandonment, including the final casing removal and cement backfill to be undertaken for well abandonment. Simulation results show a high unlikeliness of potential formation of fluid leakage pathways in the wellbore system.

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Keywords: Well integrity; well abandonment; CO_2 storage; hydro-mechanical modeling; numerical simulation

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1. Introduction

1.1. CO_2 storage at the Ketzin pilot site, Germany

The Ketzin pilot site for CO_2 storage is located near Berlin in the Federal State of Brandenburg, Germany. During the injection period from June 2008 to August 2013, 67 kt CO_2 were stored in the Stuttgart Formation formed by sandstone channels of fluviatile origin at 630 m - 650 m depth, embedded in a floodplain facies with a total thickness of about 74 m [1, 2]. A multi-barrier system of several caprock units as well the Ketzin anticline ensure structural trapping of gaseous CO_2. Beside the combined injection and observation well Ktzi 201, four additional wells (Ktzi 200, Ktzi 202, Ktzi 203, P300) were drilled to monitor CO_2 migration as well as reservoir and caprock integrity. Site-specific research activities at the Ketzin pilot site have been accomplished by 18 German and European projects so far and comprise of operational data acquisition, monitoring and modelling [3-6]. Long-term stabilization assessments for the post-operational phase were carried out by coupled numerical modeling [7-11], but numerical simulations on well integrity during site operation and well abandonment were not established so far.

1.2. Wellbore systems as potential leakage pathways

Wellbore systems are addressed as the main potential leakage pathways for CO_2 involving different leakage mechanisms [12-18]. In this regard, the cement-casing and cement-rock interfaces, which are suspect to stress changes and corrosion, are mainly emphasized for consideration in well integrity studies [19-21]. Stress changes are generally occurring during site operation, but also as a result of post-operational CO_2 migration, inducing spatial pore pressure changes within the reservoir. In this work, we focus on the impacts of stress changes at the Ktzi 201 injection well occurring during CO_2 injection in the operational phase and cement backfilling in the abandonment phase [22-24].

2. Model setup and parameterization

2.1. 3D model of the entire wellbore system

The implemented 3D model considers eleven geological formations from the Triassic to Quaternary including the major fluviatile sandstone channels within the Stuttgart Formation at 630 m - 650 m depth [2, 25]. Based on site operation reports [26], we integrated all wellbore system components such as cement sheaths, steel casings, tubing and packer elements as well as wellbore annuli for a detailed representation of the entire wellbore system (Fig. 1a).

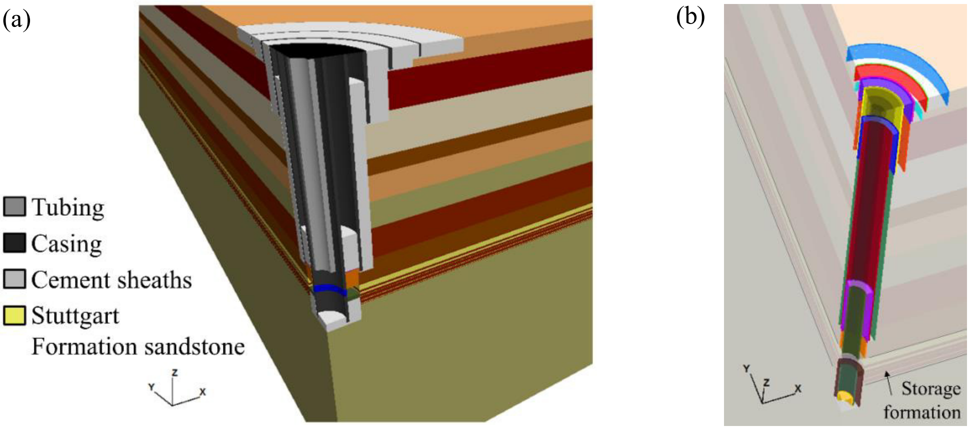

Fig. 1. (a) 3D hydro-mechanical model of the entire wellbore system, including casings, cement sheaths and tubing and all considered formations (not to scale); (b) Vertical cement-casing and cement-rock interfaces (not to scale).

The numerical model grid has a horizontal discretization of 5 m x 5 m to focus on near wellbore region, whereby element size increases with increasing distance from the wellbore. A tartan grid is used for vertical discretization over the entire model thickness of 1,500 m to ensure a sufficient resolution of all wellbore system elements as well as of the reservoir unit in the numerical model. At the vertical cement-casing and cement-rock interfaces, we added 21 numerical interfaces to observe normal and shear displacements during the simulation runs (Fig. 1b). The total number of elements used in the coupled hydro-mechanical model amounts to about 250,000.

2.2. Mechanical parameters

Geomechanical parameters assigned to the geological formations were derived from log-data [3, 27] and operational reports [25, 26], while well system parameterization was undertaken based on different sources [17, 28, 29]. The formations and cement sheaths were parameterized using a plastoelastic constitutive law, whereas the casing, tubing and packer elements were assumed to behave linear elastic. Tables 1 and 2 show the parameters that were assigned to the model, including density, Young’s modulus, Poisson’s coefficient, friction angle and uniaxial compressive strength.

Table 1. Mechanical parameters assigned to the geological formations implemented in the hydro-mechanical model.

Formation	Young’s modulus E (GPa)	Poisson’s coefficient ν (-)	Friction angle φ (°)	UCS C_0 (MPa)	Density ρ (kg/m³)
Quaternary	3.11	0.48	35.16	4.97	2,100
Rupelian	3.24	0.46	29.79	5.95	2,200
Pliensbachian	3.83	0.43	25.59	10.01	2,275
Sinemurian	3.78	0.41	25.77	11.54	2,314
Hettangian	4.45	0.42	29.48	12.68	2,198
Exter	5.07	0.37	26.16	17.80	2,250
Arnstadt	6.86	0.31	25.65	27.82	2,428
Weser	8.00	0.31	28.03	34.35	2,579
Stuttgart (floodplain facies)	7.83	0.35	29.57	36.73	2,464
Stuttgart (sandstone channels)	11.61	0.36	34.75	47.53	2,280
Grabfeld	6.12	0.34	26.96	29.88	2,508

Table 2. Mechanical parameters assigned to the wellbore system.

Elements	Young’s modulus E (GPa)	Poisson’s coefficient ν (-)	Friction angle φ (°)	Cohesion c (MPa)	Density ρ (g/m³)
Class G cement	8.3	0.10	17.10	2.60	1,850
EverCRETE cement	11	0.17	17.10	2.60	1,917
Casing / Tubing	210	0.30			7,800
Packer	0.006	0.48			1,100

Parameters not available in the references, such as the cohesion *c* and the tensile strength T_0 were calculated by the Equations 1 and 2 referred to Jaeger et al. [30], where μ is equal to *tan(φ)*, known as the coefficient of internal friction, and C_0 the uniaxial compressive strength (UCS).

$$c = \frac{1}{2}\frac{C_0}{\left(1+\mu^2\right)^{1/2}+\mu} \tag{1}$$

$$T_0 = \frac{C_0}{10} \tag{2}$$

The numerical interfaces were implemented and parametrized as described in [31] with a friction angle of 26.6° for cement-rock interfaces and 16.6° for cement-casing interfaces according to Topini et al. [32]. The required normal and shear stiffnesses (k_n and k_s) were assumed to be equal and expressed as the tenfold of the maximum stiffness of the adjacent materials. Bulk- (G) and shear moduli (K) were referred to the softer material with $\Delta z_{\min}$ representing the width of the smallest adjacent zone in Equation 3.

$$k_s = k_n = 10 \cdot \frac{K + \frac{4}{3}G}{\Delta z_{\min}} \tag{3}$$

2.3. Boundary and initial conditions

We assigned constant velocities of zero perpendicular to the lateral and bottom model boundaries, while the upper boundary was allowed to displace in any direction (Fig. 2). The normal faulting stress regime identified for the Ketzin pilot site was implemented by applying an initial stress regime with a horizontal to vertical total stress ratio of 0.85 and equal horizontal principal stresses [27]. A hydrostatic pressure gradient of 1 x 10^{-4} Pa/m was applied based on well log data [26].

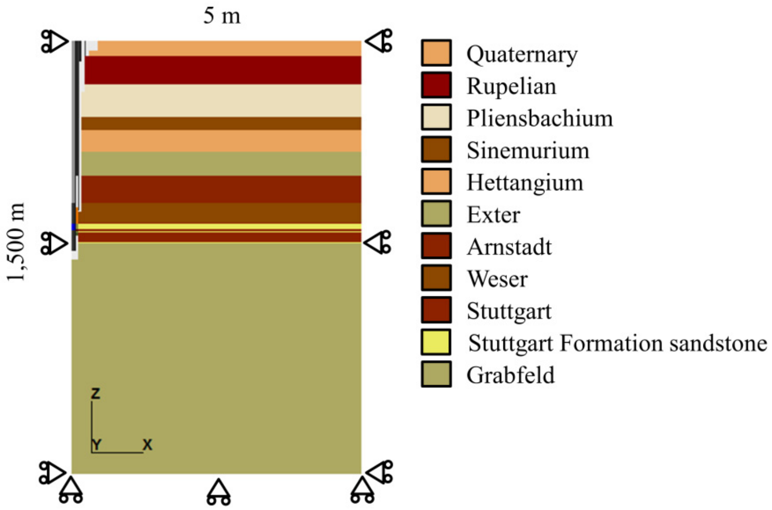

Fig. 2. 2D view of the hydro-mechanical model and its boundary conditions applied at the lateral and bottom model boundaries. The model setup considers eleven formations including the reservoir sandstone channels and floodplain facies within the Stuttgart Formation.

2.4. Simulation steps

The hydro-mechanical calculations were carried out in three simulation steps:

- Calculation of hydro-mechanical equilibrium prior to any CO_2 injection
- Simulation of operational phase based on available injection and post-injection bottomhole pressure data
- Simulation of abandonment phase using two backfilling steps

The first hydro-mechanical equilibrium computation considered the geological system before drilling any wells. After the implementation of the Ktzi 201 wellbore system with the numerical interfaces, a second hydro-mechanical equilibrium run was carried out. To simulate the operational phase, we selected 30 representative time steps from the observed Ktzi 201 bottomhole pressure for integration of the injection and post-injection phases at the Ketzin pilot site into the hydro-mechanical model (Fig. 3). Observed pressure and temperature data for each time step were derived from Moeller et al. [4]. A dynamic calculation of the CO_2 density was employed as a function of pressure and temperature to determine all required fluid pressures over the entire well length and reservoir depth using the Span and Wagner equation of state [33]. The bottomhole pressure determined in January 2015 was considered as reference pressure for the abandonment phase.

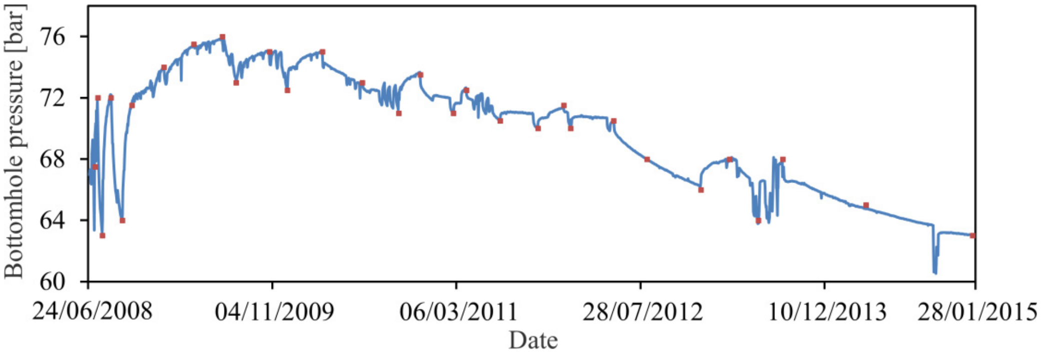

Fig. 3. Observed Ktzi 201 well bottomhole pressure at 550 m depth (blue line) from June 2008 to January 2015 [m]. Data selected as input for the hydro-mechanical simulations are marked by red squares..

The abandonment phase of the Ketzin pilot site wells is scheduled to be carried out in two steps (Fig. 4). After removing the tubing and casings located in front of any open well annulus, the lower 214 m of the borehole will be filled with Schlumberger EverCRETE cement. The second step considers backfilling of the remaining open borehole with a Class G cement up to the ground surface.

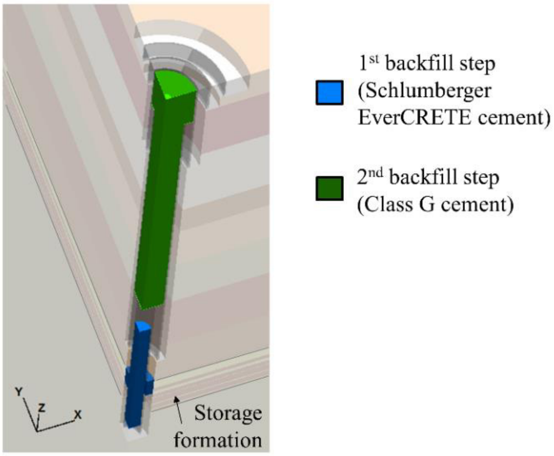

Fig. 4. 3D view of the two simulation steps representing the well abandonment phase: backfill with Schlumberger EverCRETE (blue) and Class G cements (green).

3. Results

Our simulation results demonstrate that the formation of potential fluid leakage pathways in the wellbore system is highly unlikely. Mechanical failure of casing or cement sheaths does not occur at any time of the simulation. Maximum shear displacements at the cement-casing and cement-rock interfaces are below 0.5 mm, and thus negligible in terms of shear fracture formation (Fig. 5a). Maximum interface normal displacements are compressive and below 0.005 mm, so that tensile fracturing cannot occur (Fig. 5b).

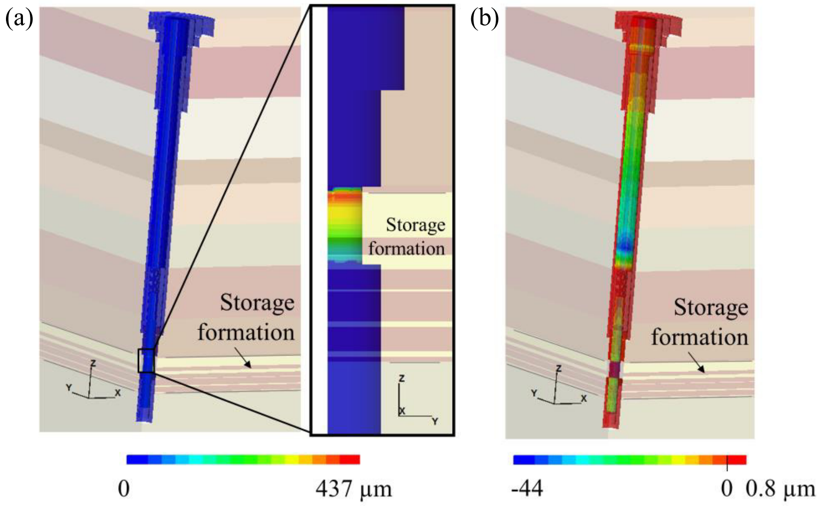

Fig. 5. Numerical simulation results demonstrate that relevant interface (a) shear displacements are only observed at the depth of the filter screen, while (b) relevant normal displacements are generally compressive and occur only between the inner casing and backfill cement (not to scale).

4. Conclusions

Our simulation results indicate that failure of the Ktzi 201 wellbore system is highly unlikely to occur at the Ketzin pilot site, taking into account the available site-specific data and observations at any time of site operation and well abandonment. Interface normal and shear displacements exhibit such low magnitudes that formation of potential fluid leakage pathways due to hydro-mechanical processes is also highly unlikely. The implemented hydro-mechanical model of the Ktzi 201 wellbore system can be further employed for investigation of different hypothetical failure scenarios and their impact on reactive transport by extending the hydro-mechanical coupling by hydro-chemical processes.

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