Numerical Study of CO_2-Injection Borehole Integrity with Consideration of Thermo-mechanical Effects

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Abstract. Underground storage of CO_2 is one efficient solution to reduce CO_2 emissions and to slowdown the greenhouse effect. The objective of the CLEAN project is to investigate the feasibility of CO_2 storage in a depleted oil and gas reservoir. For this purpose, one part of the onshore-gas field "Altmark gas field" has been provided for the research. The objective of this paper is to verify the integrity of the research borehole during cooler CO_2-injection and to validate the closure of the injection induced cracks in cement due to salt creep by using numerical simulator FLAC3D. After numerical simulation, the critical value of the decreasing temperature in different segments was indicated. It was also proved that, the creep behavior of salt rocks can indeed close the cracks in the cement which leads to the recovery of borehole integrity.

Keywords: Altmark gas field, Borehole integrity, CCS, Borehole Sealing.

1 Introduction

CO_2 emission is one of the most dominant reasons for the greenhouse effect. Different technologies have been developed to reduce the CO_2 emissions. Underground storage of CO_2 is one such efficient solution. The second largest European on-shore gas field Altmark has been provided by Gaz De France-Suez Germany Ltd. for the research. The injecting borehole is constructed with casing and cement, which is located at a depth between ca. 2600 m and 3500 m surrounded by rock salt and sandstone. After 30 years of gas production, the temperature field in the casing, cement and rocks has reached equilibrium. When the cooler liquid CO_2 is injected through the casing into the reservoir, the

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temperature field will be disturbed and the equivalent stress increased, which will induce shear failure of the steel and damage the borehole integrity. Moreover, the temperature interruption will cause different shrinkage of the steel (casing), cement and rocks, there may be cracks building in the casing and cement, especially at the contact areas between casing and cement or between cement and rock mass. However such cracks might be closed due to the creep of salt rock.

2 Numerical Simulation

Wellbore ITE1, through which gas was produced for 30 years, was constructed in 1984. As shown in Figure 1 the reservoir sandstone layer and bedding salt rock layer were simulated with FLAC3D from -2790 m to -3470 m. The sandstone section is located from -3310 m to -3470 m, while salt rock is located from -2790 m to -3310 m. The parameters for the wellbore construction and mechanical and thermal properties are listed in Tables 1, 2 and 3.

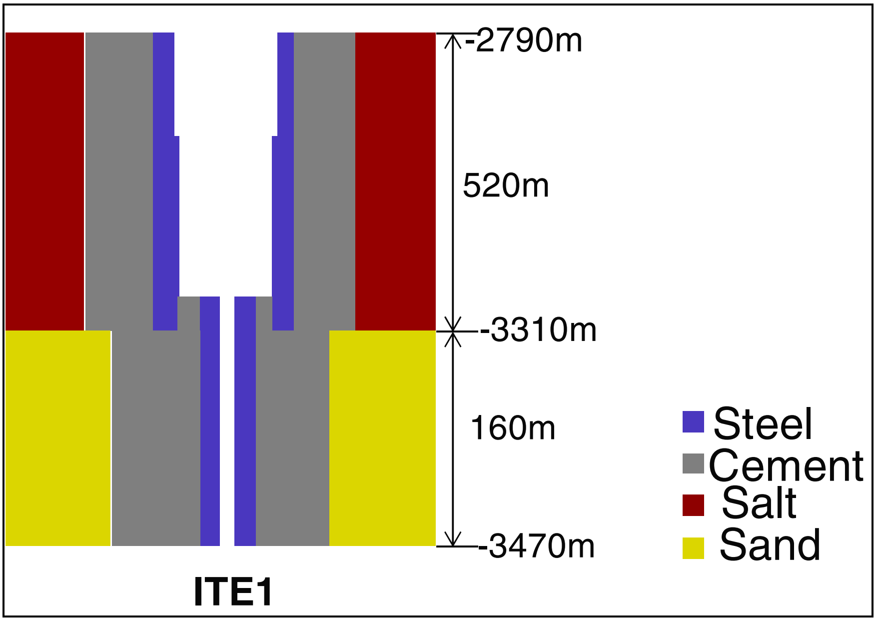

Fig. 1 Construction of wellbore ITE1

Before CO_2-injection the wellbore was used as a production borehole for about 30 years. Therefore, the production phase must be simulated first and the injection phase should be simulated based on the results of the production phase. Because of limited hardware only the three segments shown in Figure 2 were numerically simulated. Detailed geometry is presented in Figure 3. Moreover, because of the radial symmetry of the wellbore only three 5 ° sectors were simulated. The salt rock, sandstone, steel and cement were characterized with LUBBY2, Strain-Softening, von-Mises and Mohr-Coulomb's constitutive model respectively.

According to the project partner's study, the temperature inside the casing will decrease by about 22 ℃ within the first day of CO_2-injection. If the injection rate is constant, the temperature field should stay constant. However, there may be perturbation during the injection, which will cause an immediate decreasing temperature [2]. Therefore, two concepts for the decreasing temperature were simulated: one is immediate decrease by more than 22 ℃ in the inner surface of steel pipe (temperature boundary condition) on the first day; the other one is the stepwise decrease of 22 ℃ in the inner surface of steel pipe (temperature boundary condition) on the first day followed by an immediate decrease of 1-10 ℃ (22+x ℃). The vertical primary stress is equal to the integration of density along the depth. The two horizontal stress components are identical and equal k multiplied by the vertical stress (k is assumed to be 0.5). By analyzing the numerical simulations, the critical value of the interruption in the temperature due to the two decreasing concepts is likely to maintain the borehole integrity.

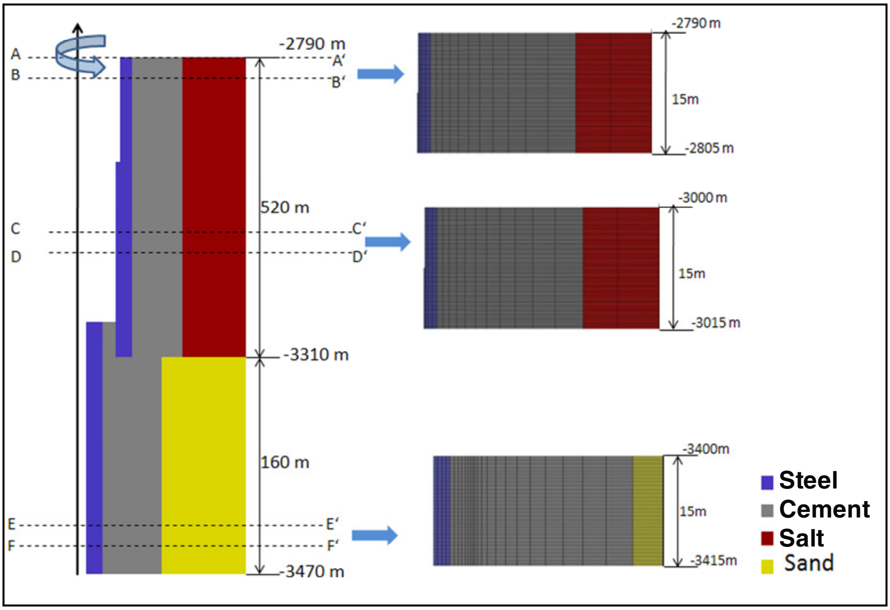

Fig. 2 Three segments for simulation (ordered from the top down: segment 1, 2, 3)

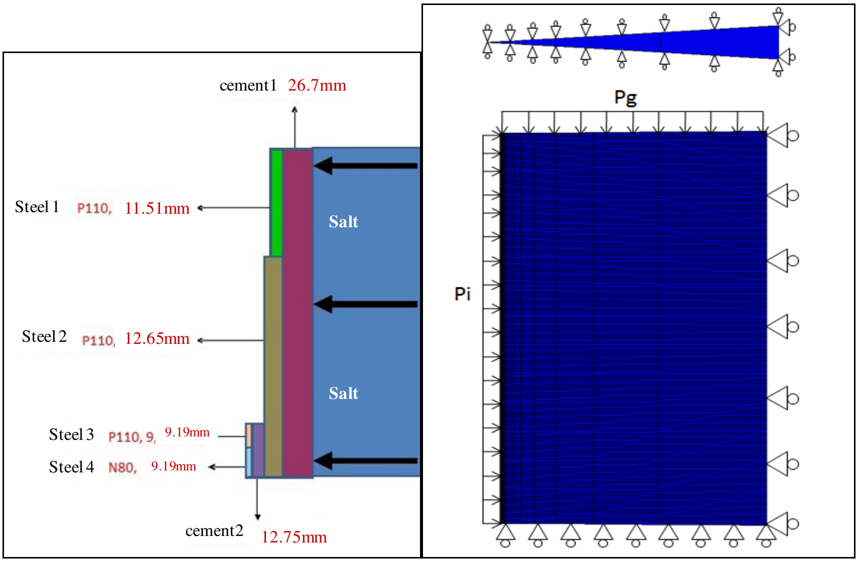

Fig. 3 Detail geometry and boundary conditions of the simulated model

Table 1 Geometrical parameters of borehole construction

	outer diameter [mm]	range [m]	width [mm]
Casing string	177.8	2770-2900	11.51
Casing string	177.8	2900-3310	12.65
Liner	127	3250-3275	9.19
Liner	127	3275-3470	9.19

3 Indicating the Critical Value of the Decreasing Temperature

To indicate the critical value of the decreasing temperature, the equivalent stresses around the borehole were recorded and compared with the steel shear strength. After simulation of the two temperature decreasing concepts, the stress distributions at the three segments were recorded. As an example Figure 4 shows the equivalent stress distribution at depth 2800 m under different conditions. It shows that, the more the temperature decreases, the bigger the equivalent stress (σ_1-σ_3) is. When the immediate decreasing temperature reaches 29 °C, the equivalent stress exceeds the steel shear strength (shown with a red dash), which means a shear failure. The stress distributions were recorded for all three segments, so that the critical value of the decreasing temperature for each of the three segments can be detected. Figure 5 shows the shear failure for segment 1

Table 2 Mechanical parameters of steel, sandstone, rock salt and cement

parameter	symbol	unit	steel	Sandstone	rock salt	cement
compression modulus	K	[MPa]	1.75e5	5.376e3	-	4.7619 E3
Shear modulus	G	[MPa]	8.0769e4	3.702e3	-	4.3478E3
Young's modulus	E	[MPa]	2.1e5	9032	23363	1E5
inter friction angle	ϕ	[°]	-	37.5	-	29
density	ρ	[kg/m^3]	7900	2260	-	2400
Poisson value	ν	[-]	0.3	0.22	0.3	0.15
strength	F	[MPa]	861.5(P110*)/655(N80*)	3.69**	-	-
cohesion	C	[MPa]	-	17.28	-	-
Kelvin-shear module	$\bar{G}_k^*$		-		1.4e04	-

* P110 and N80 are the two different types of steel; the value is the compression strength of steel** tensile strength

Table 3 Thermal parameters for steel, cement and rock salt

	Temperature [°C]	heat capacity [J/kg·K]	thermal [[W/mK]	thermal expansion coefficient [K^{-1}]
steel	-	480	48	1.2e-4
cement	-	1880	0.87	1.6e-4
rock salt	25	826	5.51	4.2e-5
	50	867	5.1	
	100	876	4.26	
	180	890	3.33	

immediately after a decreasing temperature of 30 °C. For the second decreasing temperature concept (step by step plus an immediate decrease of 22+x °C), the critical value is higher than that of the first concept for segment 1, and reaches 32 °C. The equivalent stresses are shown in Figure 6.

It is found that, in the 3 segments there were already 3 failures after the first day of injection (temperature decreasing by 22 °C). Therefore, the simulation of the second decreasing concept was not performed for segment 3. The critical value of two decreasing temperature concepts in segment 1 and 2 are listed in Table 4.

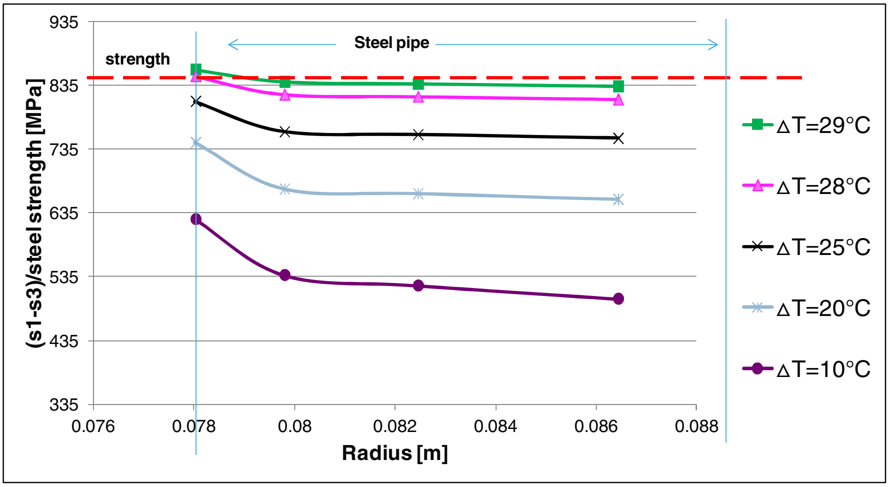

Fig. 4 Equivalent stresses after different decreasing temperatures in the steel pipe (immediately)

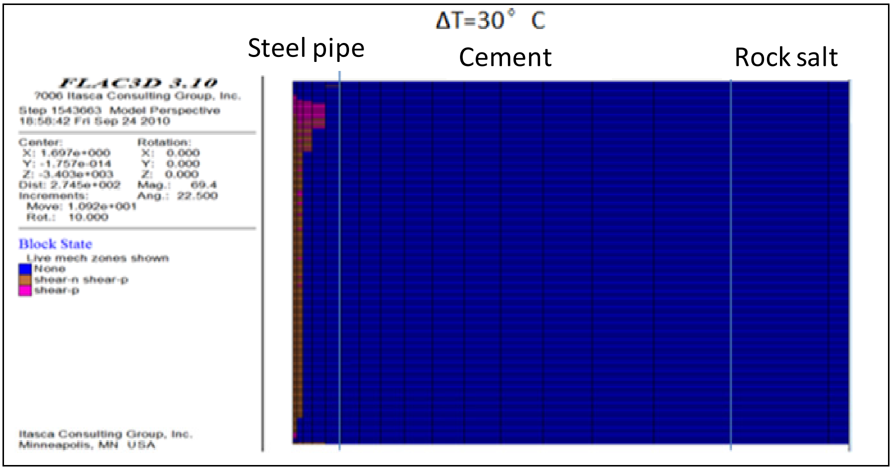

Fig. 5 Shear failures in segment 1 after decreasing temperature of 30 °C

4 Analyzing the Influence of Salt Creep Behavior on Borehole Integrity

Another objective of this paper is to the find the reason for the closure of the CO_2 injection induced cracks. During the decreasing temperature process, the steel and cement shrink differently and induce cracks in the casing and cement, especially at

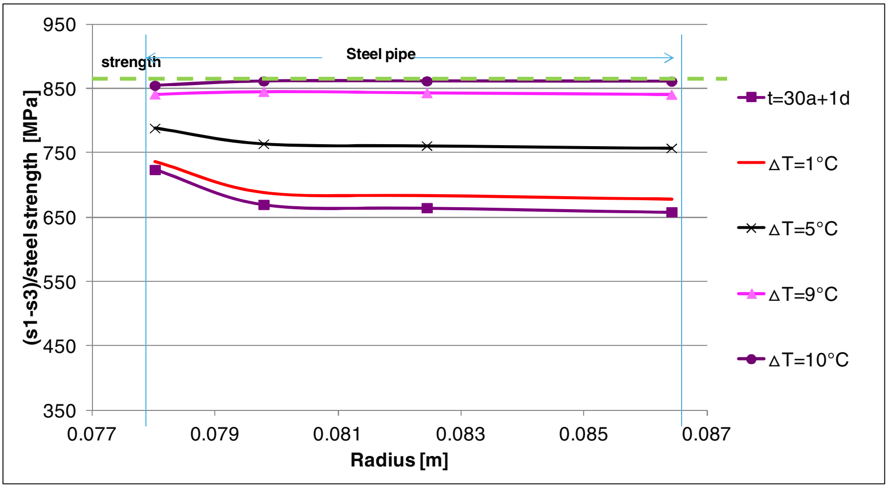

Fig. 6 Equivalent stresses after one day step by step decreasing plus further immediate decreasing in the steel pipe (segment 1)

Table 4 Critical value of decreasing temperature

	step by step +immediately	Immediately
Segment 1	32 °C	28 °C
Segment 2	30 °C	31 °C

the contact areas between casing and cement or between cement and rock mass. After the temperature decreases the salt rocks creep and push the cement in the steel direction. Therefore, it is possible that the cracks are closed due to the pushing effect. This question can be answered by analyzing the displacement in salt rock, cement and steel. Segment 1 was analyzed to find the reason for the closure of the cracks. After detecting the critical temperature, it is known that the integrity is damaged when the value of the decreasing temperature reaches 29 °C in segment1. Therefore, the displacement caused by the immediate decreasing temperature of 29 °C was analyzed (see Fig. 7). Generally, the nearer the point is to the steel, the bigger the displacement is. However, Figure 7 shows that the displacements of points 1, 2, 3 are different from each other. Point 2 has the greatest displacement, which is an anomaly (the displacement in the borehole direction is negative). This phenomenon can be explained by the creep behavior of salt rock.

The displacement of point 2 consists of two components, displacements induced by cooling and creep. To better understand the effect of creep behavior, another simulation using an elastic model is performed for comparison. The displacement differences of the two simulations are shown with Figure 8. The difference between point 1 and 2 means the displacement of point 1 minus the displacement of point 2. Therefore, if the displacement of point 2 is bigger than point 1, the displacement different between point 1 and 2 should be positive, because the displacement in borehole direction is negative. That means the bigger the different is, the greater the creep behavior is.

Comparing the difference between point 1 and 2, it is found that the displacement difference decreases at the beginning when using the visco-plastic model, which means that point 1 moves further than point 2 at the beginning because of the cooling effect. Then the increase difference slows, which means that point 2 moves further than point 1 because of the creep behavior. Compared with the result when using an elastic model for steel, sand and rock salt, the difference between point 1 and 2 is smaller than using the visco-plastic model while the difference between point 2 and 3 is bigger which indicates that point 2 moves more in the direction of the borehole so the cracks could be closed by this movement. The situation of the step by step decreasing temperature is different. The displacement of the situation (22+10 °C) in segment 1 is shown in Figures 9 & 10. It shows that all three points move fast into the borehole on the first day due to the shrinkage of the steel. Then the three points move slowly into the borehole until the fifth day. As in the first concept, the displacement of point 2 is bigger than point 1, which proves that the cracks can also be closed by the creep behavior of rock salt under the second decreasing temperature concept.

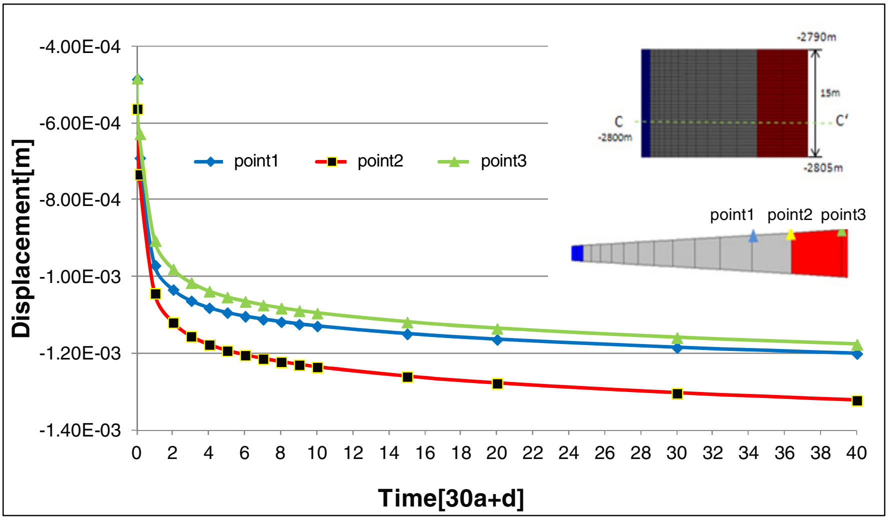

Fig. 7 Radial displacement vs. time (Segment 1, ΔT=29 °C, imediately)

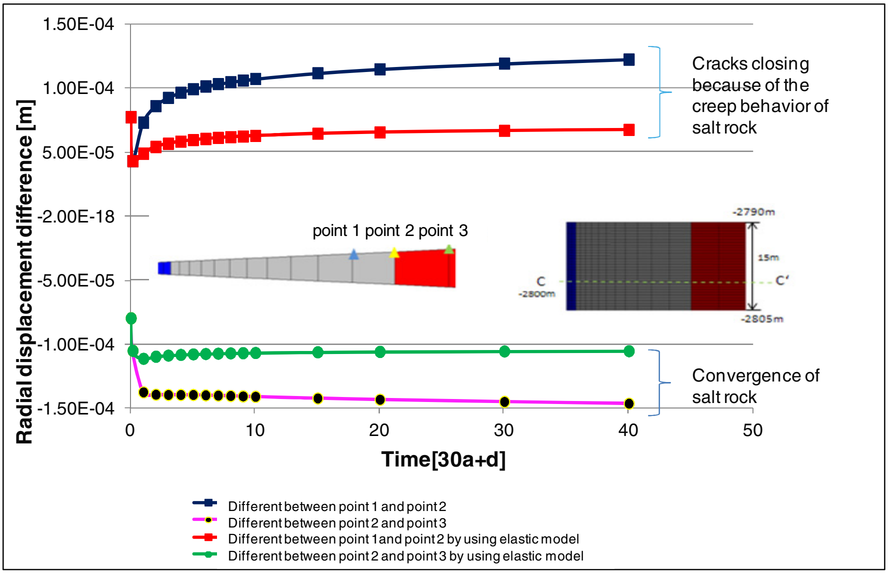

Fig. 8 Radial displacement difference vs time (Segment 1, ΔT=29 °C, immediately)

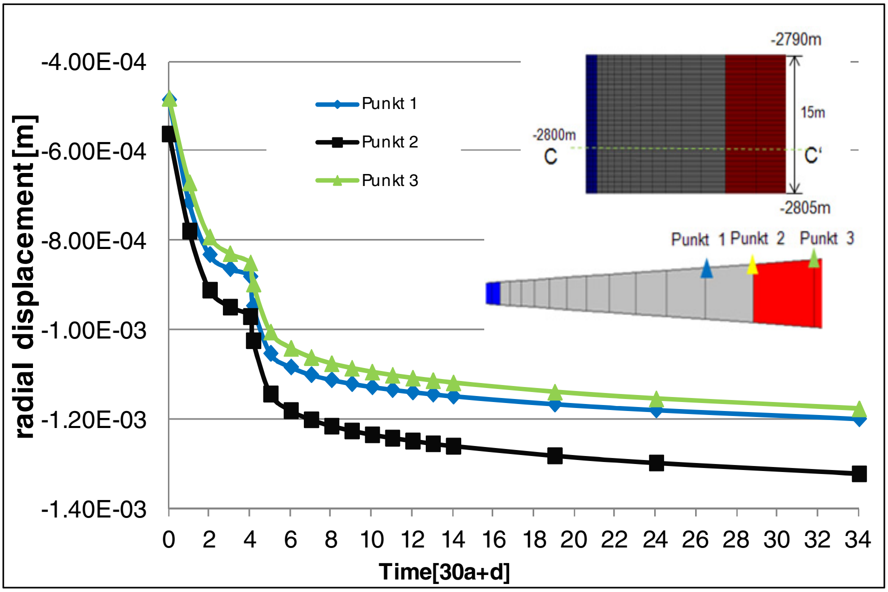

Fig. 9 Radial displacement vs. time (ITE1, ΔT=22+10 °C)

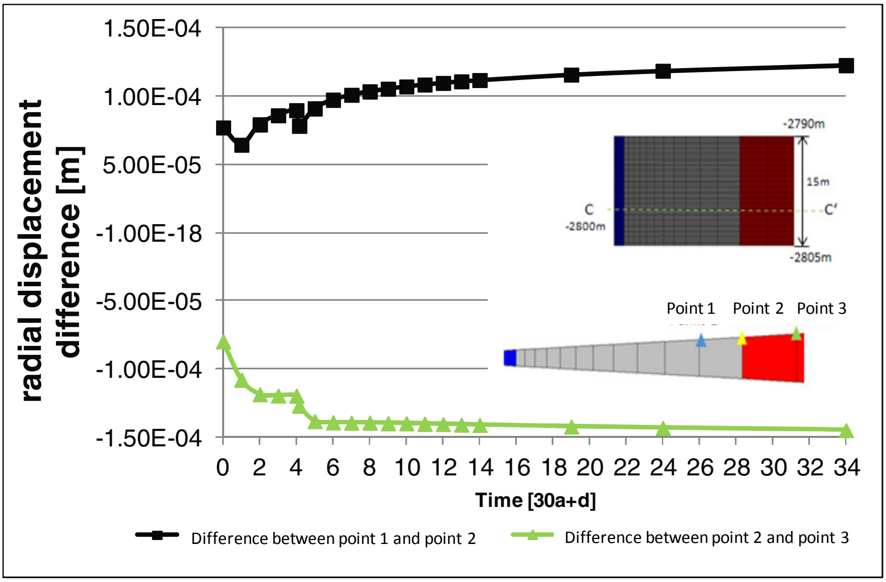

Fig. 10 Radial displacement vs. time (Segment 1, ΔT=22+10 °C)

5 Conclusions

The numerical simulation of the CO_2 injection process verified that the borehole integrity can be maintained if the injection induced decreasing temperature is not too big. The critical value of the decreasing temperature is indicated under a different concept for a different segment by using the numerical simulation, even though controlling the temperature of steel during or after CO_2 injection is still challenging. By analyzing the displacement after simulation using the elastic and visco-plastic model, it is found that cracks are induced due to different shrinkages of steel, cement and rock, which can be closed by the creep movement of rock salt. The borehole integrity is recovered by the creep behavior of rock salt after several days.

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