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Impact of CO2 injection in deep saline aquifers: study on pressure response in stratified formation of Qianjiang depression area, China

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Abstract—**In order to mitigate the adverse impacts of climate change, CO_2 captured from carbon emitters like coal-fired power plants may be stored in deep saline aquifers. This action may cause pressure changes, which affect subsurface volumes. The main purpose of this study is to evaluate the pressure changes during CO_2 sequestration in CO_2 storage formation embedded in a sequence of aquifers and aquitard of the Qianjiang depression area, China. In order to demonstrate the transient pressure, we have conducted TOUGH2 modeling of CO_2 injection into closed formations of different thicknesses assuming impermeable boundaries. A 2-D radially symmetric model was developed to represent a CO_2 storage site in the Qianjiang depression area. The storage formation into which CO_2 is injected is 120 m thick and located at a depth of about 1380m below the ground surface. The CO_2 injection thickness was 15m from the bottom of the storage formation. Carbon dioxide is injected into a zone of 77 m radial extent representing a few distributed wells. Injection occurs at an annual rate of 2.488 * 10^7 tonnes of CO_2 representing 16 times the CO_2 rate captured from a medium-size-coal-fired power plant. The simulation runs cover a time period of 100 years altogether, comprising the 30-year injection period and a 70-year post-injection period. The pressure buildup results after one year never attains 50% of initial pressure (maximum tolerable pressure buildup). Our simulation results indicate that interlayer pressure propagation through a sequence of aquitard/aquifer will not affect the top aquifer. Moderate pressure increases occur in top aquifer only in case when pore compressibility was reduced by one order of magnitude.**

Keywords: Qianjiang depression area, TOUGH2, Pressure buildup, aquitard/aquifer

I. INTRODUCTION

Geologic carbon sequestration in deep formation has drawn increasing consideration as a promising method in order to mitigate the adverse impacts of climate change [1], [2], [3], and [4].

Generally, CO_2 sequestration is defined as the removal of gas that would be emitted into the atmosphere and its subsequent storage in a safe, sound place [5].

Data used during the present research are from the Wangchang oil field. The Wangchang oil field is located in the northern part of Qianjiang depression area where the Qianjiang depression covers 2500 km^2 and it has most of the current petroleum production [6]. The rock type in the study area consists mainly of feldspar quartz sandstone and quartz sandstone debris, in addition to small amounts of feldspar sandstone and feldspar lithic sandstone. Quartz content is generally 60 to 90%, Feldspar content occupies about 5 to 25% and debris content of about 5 to 15 % mainly in acid volcanic rocks [7].

The main aim of this research is the demonstration of pressure change during CO_2 injection in CO_2 storage formation embedded in a sequence of aquifers and aquitard of the Qianjiang depression area.

In order to demonstrate the transient pressure, we have conducted TOUGH2 modeling of CO_2 injection into closed formations of different thicknesses assuming impermeable boundaries. The whole work was done using the TOUGH2/ECO2N simulator [8],[9].

II. CONCEPTUAL MODEL AND MODEL SETUP

A 2-D radially symmetric model was developed to represent a CO_2 storage site in Qianjiang depression area. The storage formation into which CO_2 is injected is 120 m thick and located at a depth of about 1380m below the ground surface. The CO_2 injection thickness was 15m from the bottom of the storage formation. The storage formation is bounded at the top by a sealing layer of 30 m (see fig. 1), followed by a sequence of aquifers with various thicknesses and sealing layers with various thicknesses. The bottom of the storage formation is formed by a layer considered in the present study as impermeable base rock with thickness of about 100 m. Altogether; the model domain includes four aquifers and five aquitards. The lateral extent boundary at 300 km, which corresponds to a footprint area of about 282,743 km^2. The large lateral extent was chosen in order to ensure that the boundary condition would have minimal effect on the simulation results.

Carbon dioxide is injected into a zone of 77 m radial extent representing a few distributed wells. Injection occurs at an annual rate of 2.488 * 10^7 tonnes of CO_2 representing 16 times the CO_2 rate captured from a medium-size-coal-fired power plant. The simulation runs cover a time period of 100 years altogether comprising the 30-year injection period and a 70-year post-injection period. Notice that the results shown about pressure buildup in this work were the results obtained after one year injection period.

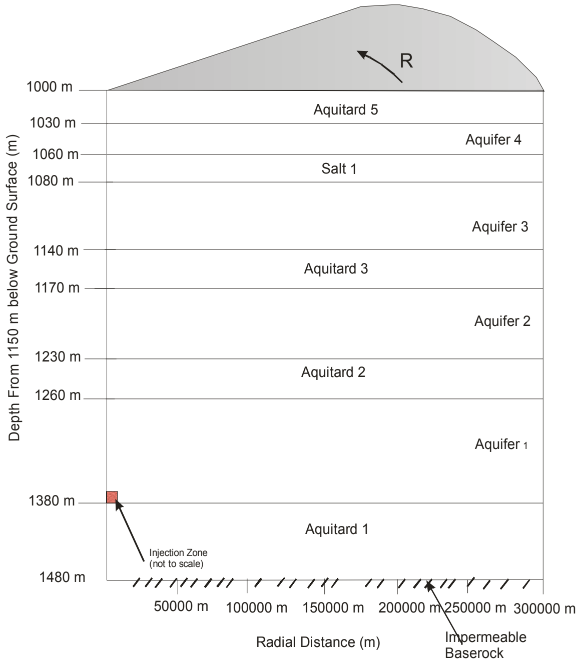


Figure 1. Schematic showing a vertical cross-section of the radially symmetric model domain with deep brine formation CO_2 storage and overlying aquifer/aquitard sequence.

TABLE 1.THE COMBINATION OF RESERVOIR, COVER LAYER OF QIANJIANG DEPRESSION AREA

System	Series	Formation		Thickness (m)	Lithology Character
Eogene	Oligocene	Qian 1	Upper	120～450	Referred to as “mud-gypsum layer”; consists of gray to dark mudstone, gypsum-mudstone, oil shale with intercalated salt
			Middle		Intercalation of gray mudstone and siltstone
			Lower		Intercalation of gypsum, salt, sandstone and mudstone, with some oolitic marlite
	Eocene	Qian 2		110～700	Consists of 24 rythmic units, each composed of salt, gypsum-mudstone, glauberite mudstone, oil-bearing mudstone, marlite occasionaly, silty fine-grained sandstone occurs at the bottoms of the units
		Qian 3	Upper	150～640	Gray to dark-gray mudstone, siltstone and oolitic marlite; three rhythmic units and two suites of sandstone
			Lower		Consists of 14 rhythmic units,each composed of dark-gray mudstone, gypsum mudstone and salt, with some silty fine-grained sandstone
		Qian 4	Upper	100～700	Gray and dark gray mudstone, glauberite mudstone, salt, oil-bearing mudstone and silty fine-grained sandstone
			Lower	600～1000	Gray and dark-gray mudstone, glauberite-mudstone, salt, oil-bearing mudstone

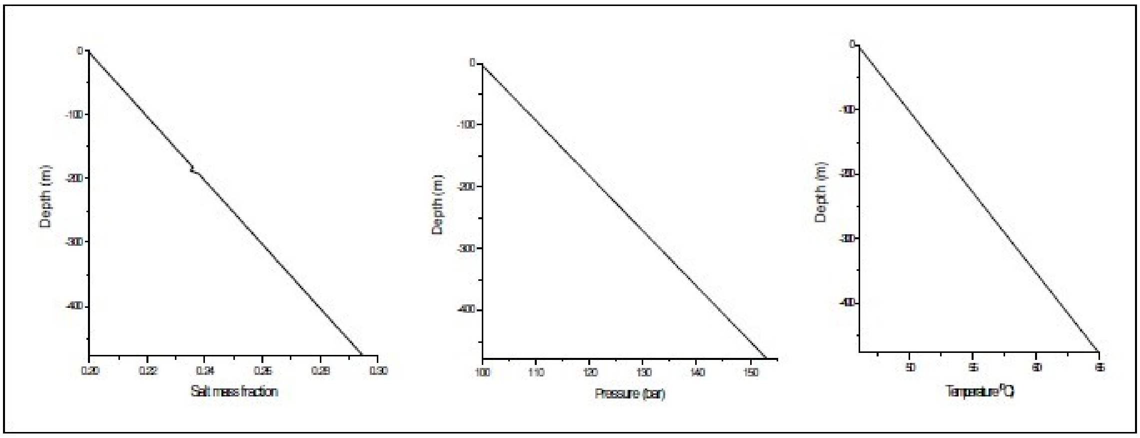


Figure 2. Vertical Profile of initial pressure, salt mass fraction and temperature from the top aquifer to the storage formation

Fig.2 shows the initial conditions used for the simulations in a vertical profile. There are no lateral variations, meaning that the system is stagnant prior to injection of CO_2, this explains that regional groundwater flow is neglected. Initial pressure is hydrostatic. Temperature varies linearly with depth, within the Qianjiang depression area, in sandstone and mudstone, the gradient is high, 3 to 4^0 C/100m and in salt layers the geothermal gradient is low compared to sandstone and mudstone units. In salt, the geothermal gradient is comnly 2.3 to 3.0^0 C/100 m [10]. Salt mass fraction vertical profile was prepared based on the idea that in Qianjiang depression area, salinity increases with the burial depth, deeper than 1250 m, the salinity varies from 250,000m/l to 340,000 mg/l. The vertical salinity profile represents an equilibrated sysyem where no density-driven flow occurs at the initial state.

III. MODEL PARAMETRS

The hydrogeologic properties chosen for the aquifer-aquitard sequence are given in Table 1. For a given porosity, mudstone permeability varies over a range of 2–5 orders of magnitude [11], During our work we have varied seal permeability over a wide range : ks = $9.0 * 10^{-17}$ to $9.0*10^{-21}$ which fall in the range of sealing layers, in the previous research where [12] used shale as sealing layer, he varied seal permeability over a wide range: ks =$1.0 * 10^{-16}$ to $1.0 * 10^{-21}$ m^2 based on shale permeabilities reported in [13], [14] [15],and Hart et al. [16].

Apart from the seal permeability variations, pore compressibility which is another parameter defining the pressure response to CO_2 injection was considered. In the first case, the compressibility of all layers is considered to vary linearly with depth, starting with the values given in Table 1 for the deepest aquifer and aquitard, respectively, and assuming a one-order-of-magnitude increase over the entire vertical sequence (to account for the fact that shallower units are often less consolidated and thus more compressible than deep units). In the sensitivity cases, we have reduced/increased the base-case compressibility values by one order of magnitude. The different cases reflect the range of pore compressibilities measured over a wide range of subsurface materials (e.g., [17], [14], [18],[19]. Note that the compressibility of the fluids (i.e., CO_2 and water) is intrinsically taken into account in TOUGH2/ECO2N in terms of density variations with fluid pressure. The sensitivity cases addressing pore compressibility have all been conducted using a seal permeability of $9*10^{-17}$ m^2 (seal permeability considered in base case).

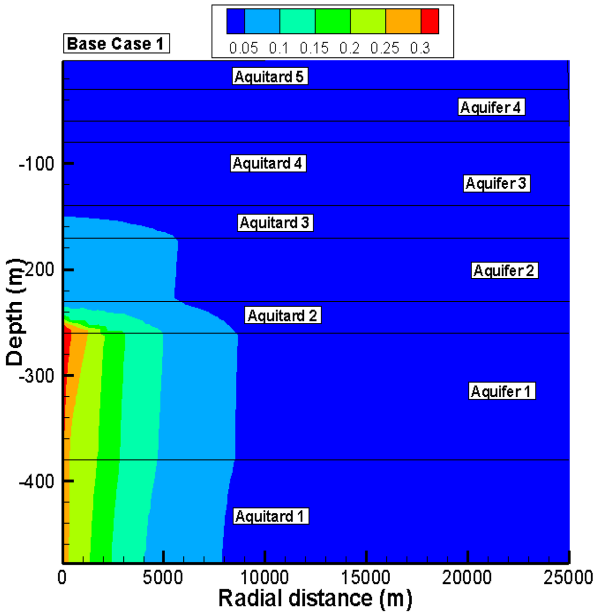
TABLE 2.THE COMBINATION OF RESERVOIR, COVER LAYER OF QIANJIANG DEPRESSION AREA

Properties		Aquifer	mudstone	salt
Permeability, k（m^2）	Horizontal	9.0×10^{-13}	9.0×10^{-17}	9.0×10^{-17}
	Vertical	9.0×10^{-13}	9.0×10^{-17}	9.0×10^{-17}
Porosity		0.16	0.10	0.10
Pore compressibility（Pa^{-1}）		4.5×10^{-10}	9.0×10^{-10}	
Rock grain density (kg m^{-3})		2600		
Formation heat conductivity under fully liquid-saturated conditions (W/m ^oC)		2.51		
Rock grain specific heat (J/kg ^oC)		920		
Temperature（^oC）		46		
Pressure（bar）		Refer to the fig.2		
Salinity（mass fraction）		Refer to the fig.2		

k_{rl}: Liquid relative permeability	$k_{rl} = \sqrt{S^*}\left\{1-(1-\left[S^*\right]^{1/m})^m\right\}^2$, $S^* = (S_l - S_{lr})/(1-S_{lr})$		
S_{rl}: Residual water saturation	$S_{rl} = 0.20$	$S_{rl} = 0.20$	$S_{rl} = 0.20$
k_{rg}: Gas relative permeability	$k_{rg} = (1-\hat{S})^2(1-\hat{S}^2)$, $\hat{S} = (S_l - S_{lr})/(S_l - S_{lr} - S_{gr})$		
S_{gr}: Residual gas saturation	$S_{gr} = 0.05$	$S_{gr} = 0.05$	$S_{gr} = 0.05$
P_{cap}: Capirally pressure	$P_{cap} = -P_0(\left[S^*\right]^{-1/m} - 1)^{1-m}$, $S^* = (S_l - S_{lr})/(1-S_{lr})$		
m : Van Genuchten	$m = 0.46$	$m = 0.46$	$m = 0.46$

IV. SIMULATION RESULTS AND DISCUSSIONS

In this section, we evaluate the pressure perturbation in the subsurface in response to CO_2 injection. Fig.3 shows the contours of pressure buildup in a vertical cross-section that expands from the injection zone up to a lateral radius of 100 km and includes the entire vertical sequence of strata, from the deep storage formation up to the uppermost aquifer. Results are given after 1 year CO_2 injection. Seven simulation cases are considered and the difference among them is the seal permeability (ks) values (for the base case ks = $9*10^{-17}$ m^2, case 1 ks = $9*10^{-18}$ m^2, case 2 ks = $9*10^{-19}$ m^2, case 3 ks = $9*10^{-20}$ m^2, case 4 ks = $9*10^{-21}$ m^2, case 5 means the pore compressibility was increased by one order of magnitude and finally the case 6 means the pore compressibility was reduced by one order of magnitude).



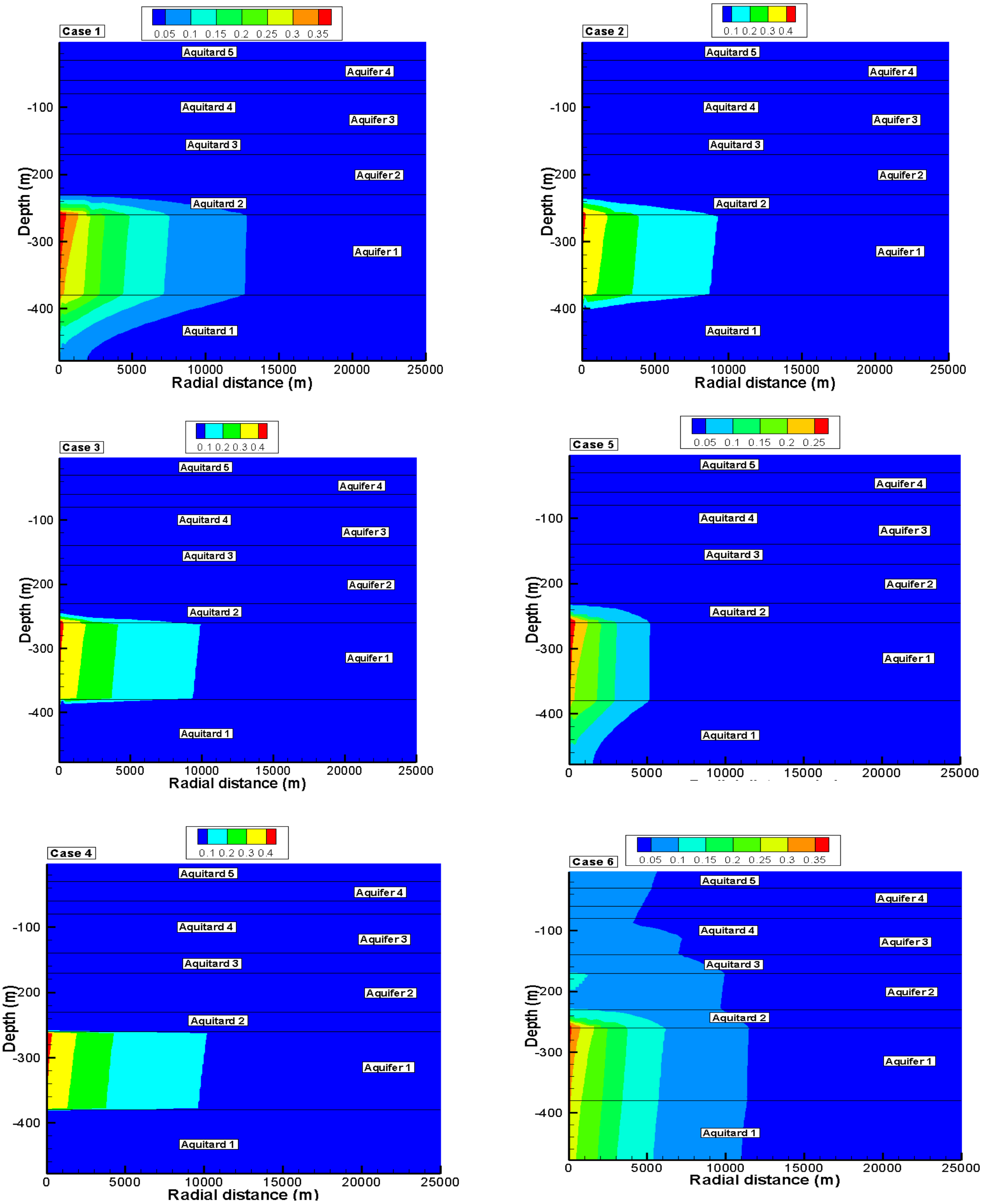
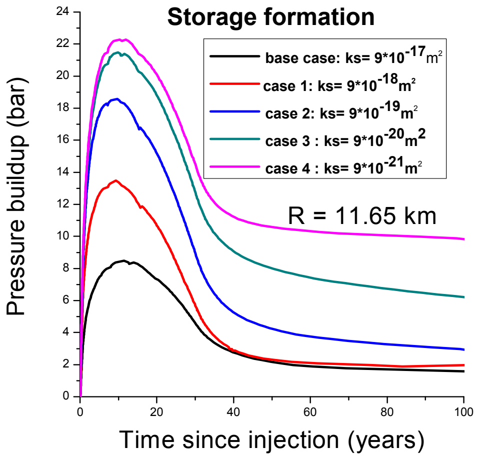
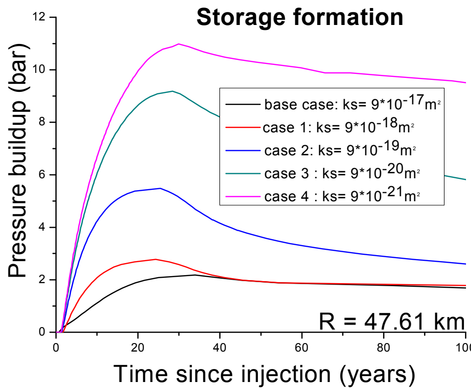
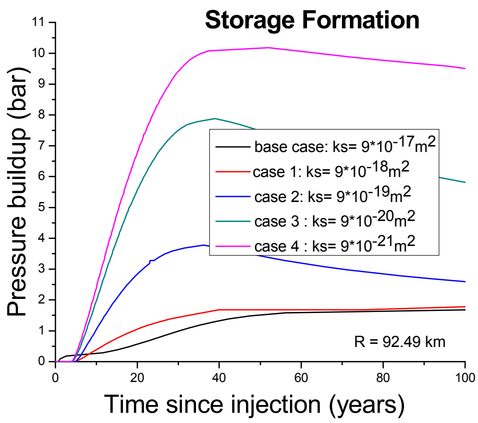

Case 1
Case 2
Case 3
Case 4
Case 5
Case 6
0.05 0.1 0.15 0.2 0.25 0.3 0.35
0.1 0.2 0.3 0.4
0.05 0.1 0.15 0.2 0.25
Aquitard 5
Aquifer 4
Aquitard 4
Aquifer 3
Aquitard 3
Aquifer 2
Aquitard 2
Aquifer 1
Aquitard 1
Depth (m)
-100
-200
-300
-400
0
5000
10000
15000
20000
25000
Radial distance (m)

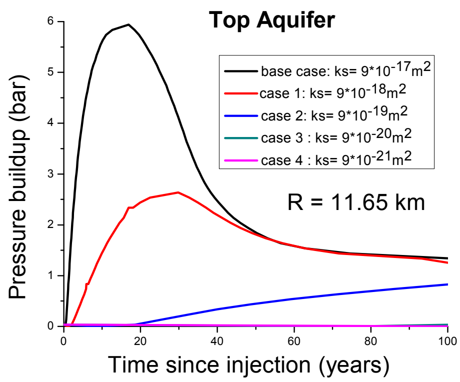
Figure 3. Contours of pressure buildup (change in fluid pressure from the initial hydrostatic condition) after 1 year of CO_2 injection, for different values of seal permeability and different pore compressibility values

Fig.3 shows that the permeability of the sealing layers has a strong effect on both the vertical and the lateral pressure propagation. After 1 year of CO2 injection (comparing case 2 (ks = $9*10^{-19}$) to the base case), when the seal permeability changed by two orders of magnitude the pressure buildup became 20% of the initial pressure whereas for the base case the pressure build up was 5% of the initial pressure. Note that when the seal permeability changed by two orders of magnitude the distance within the storage formation was 9 km, corresponding to the area of influence covering more than 254 km^2. In the vertical direction, the region of pressure buildup of about 10% extends up to 150 m from the top aquifer for base case whereas for all simulated cases the pressure buildup propagation of about 10% stops at aquitard 2 except for the case 6 (Pore compressibility reduced by one order of magnitude) where the pressure buildup of about 10% reaches the top of the top aquifer. When the seal permeability decreases, the pressure buildup increases horizontally.









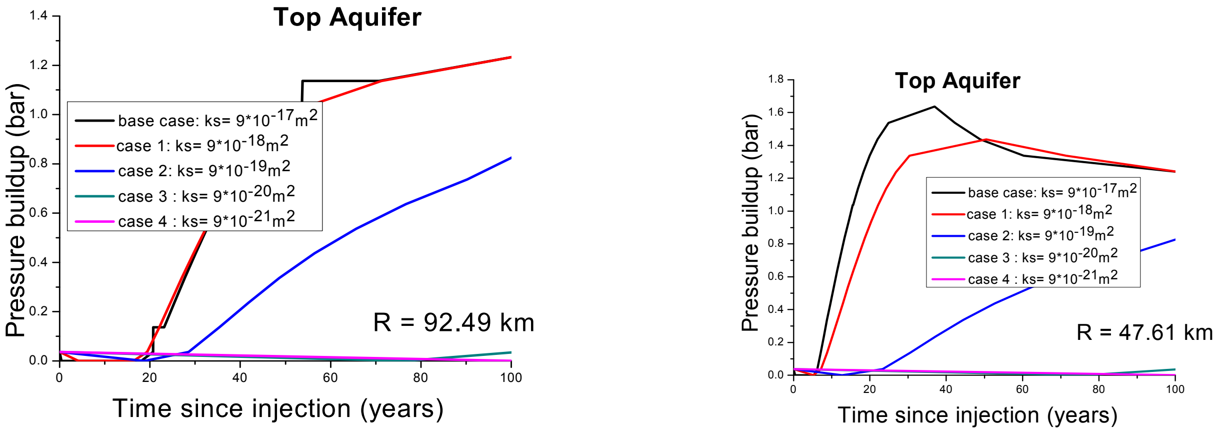


Figure 4. Sensitivity of pressure evolution to seal permeability. Pressure results are plotted at different radial locations and in different aquifers (storage formation and the top aquifer.

V. CONCLUSION

Through numerical modeling of the Qianjiang depression area subsurface formations with a single injection zone, we have demonstrated pressure response to the CO_2 injection in the mentioned formations. The characteristics of pressure buildup and their magnitude depend on the radial location and seal permeability.

The pressure buildup never attains 50% of initial pressure (maximum tolerable pressure buildup) in all aquifers, we may conclude in saying that the pressure buildup in all cases is tolerable.

The maximum pressure increases-about 6, 2.5, 1.3 bar, respectively at R = 11.65 km (the top aquifer) –are much smaller than those measured in the storage formation.

In case of R = 47.61 m, maximum pressure increases-about 1.7, 1.5.

In all considered cases, for the top aquifer the highest ks gives the maximum pressure buildup which is not the case for storage formation where the smallest ks gives the maximum pressure buildup.

Our simulation results indicates that interlayer pressure propagation through a sequence of aquitard/aquifer will not affect the top aquifer. Moderate pressure increases occur in the top aquifer only in case when pore compressibility was reduced by one order of magnitude.

Note that after one year CO_2 injection (Fig.3), the case 2 (ks = $9*10^{-19}$ m^2)shows a pressure increases of 0.1 bar extending about 9 km laterally within the storage formation, corresponding to the area of influence covering more than 254 km^2.

In the vertical direction, the region of pressure buildup of about 10% extends up to 150 m from the ground surface whereas for all simulated cases the pressure buildup propagation of about 10% stops at aquitard 2 except for the case 6 (Pore compressibility reduced by one order of magnitude).

When the seal permeability decreases, the pressure buildup increases horizontally.

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