A simple screening model for selecting CO2 sequestration sites using a semi-analytical model for calculating pressure buildup and phase front movement in thick and heterogeneous geologic settings

Whitney SARGENT, and Sally BENSON

Department of Energy Resources Engineering, Stanford University

Abstract

A semi-analytical solution developed by Kumar et al. (2009) has been updated to include multiple rock layers, an expanding constant pressure boundary, and an updated phase front definition. The two phase fronts that are calculated include a dry zone region detailed by Noh et al. (2004) and a two phase region. The semi-analytical model calculates the well pressure needed to inject CO2 at a constant rate at a specified time and the movement of the phase fronts. The updated semi-analytical model can be used for several applications; namely for complex sandstone layering formations, large storage reservoirs, and for quick and easy screening of potential CO2 storage sites.

Numerical solutions require significant reservoir characterization effort and simulation time to complete. The updated semi-analytical model can be used with limited reservoir data to estimate well pressure expectations and phase front movements. The algorithm developed by Kumar et al. (2004) can be implemented with transient, steady-state, and pseudo-steady state flow equations. The updated model assumes early-transient flow equations for initialization and steady-state flow equations for later time with a constant pressure boundary.

The updated semi-analytical model has been applied to a simplified CO2 storage reservoir and the results have been compared to a comparable TOUGH2 model. The pressure buildup results, defined as the difference between the well pressure and initial reservoir pressure, and two phase front movement and the dry zone front movement show reasonable agreement with some differences.

Input Data

Inputs		
CO2 Density	659.0	[kg/m3]
Water Density	998.4	[kg/m3]
Reservoir Pressure at Top of Perforations	14850611	[Pa]
Wellbore radius	0.10	[m]
Depth at top of perforation	1500	[m]
CO2 Viscosity	0.00005	[Pa*s]
Water Viscosity	0.00047	[Pa*s]
Target Flow rate	60.00	[kg/s]
Formation Compressibility	5.00E-09	[1/Pa]

Relative Permeability

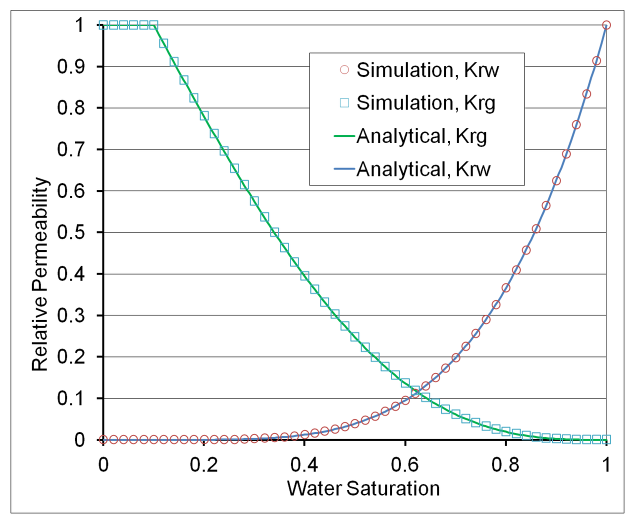
Corey Curve Equations in PetraSim

$$K_{rw} = S^{*4}$$

$$K_{rg} = (1-S^*)^2(1-S^{*2})$$

$$S^* = \frac{S_w - S_{wr}}{1 - S_{wr} - S_{gr}}$$

Saturations	
sgr	0
swr	0.1
D_BL_dry	1.0025
D_brine_BL	-0.07

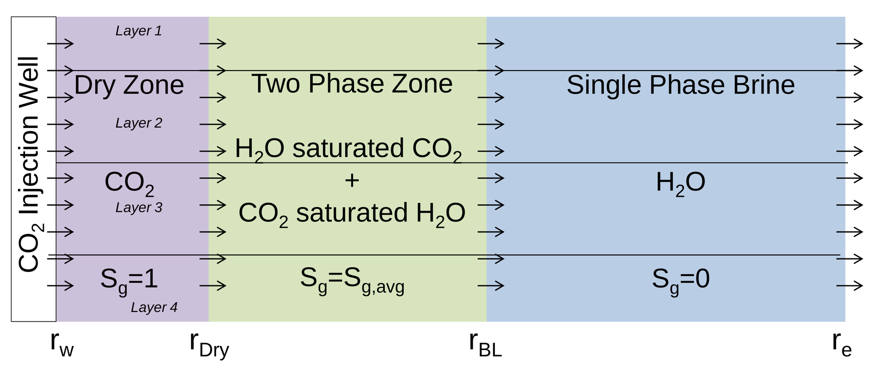


Other Information

- No Capillary Pressure Included
- Assumed 0.05 Solubility
- Compared pressure buildup values with PetraSim (TOUGH2) Model

Semi-Analytical Model Development

A semi-analytical model was developed originally by Kumar et. al (2009). This model calculates the injection pressure for a single homogeneous aquifer model. It assumed a constant pressure and a closed, no flow reservoir boundary and does not include gravity effects in the reservoir. This semi-analytical model has been updated to include heterogeneity, a new method of calculating CO2 phase traveling radii, and assumes a steady-state open flow boundary. The pressure buildup and CO2 saturation front movements calculated by the updated semi-analytical model is compared to the results of a simulation model run with TOUGH2.



Mobility and Fractional Flow (Kumar et. al.)

$$M_{avg,z}(t) = \ln\left(\frac{r_{e,z}(t)}{r_w}\right) * \left[\frac{\ln\left(\frac{r_{e,z}(t)}{r_{BL,z}(t)}\right)}{M_{brine}} + \frac{\ln\left(\frac{r_{BL,z}(t)}{r_{dry,z}(t)}\right)}{M_{BL}} + \frac{\ln\left(\frac{r_{dry,z}(t)}{r_w}\right)}{M_{dry}}\right]$$

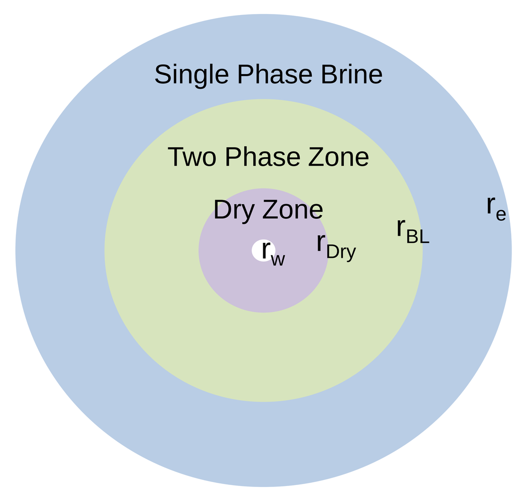
$$f_w(S_w) = \frac{1}{1+\frac{1}{M}}$$

$$f_{CO_2}(S_{CO_2}) = \frac{1}{M+1}$$

$$M_{dry} = \frac{k_{rg,S_g=1}}{\mu_g} \qquad M_{BL} = \left[\frac{k_{r,w}}{\mu_w}\cdot\frac{\mu_{CO_2}}{k_{r,CO_2}}\right]_{S_{g,avg}} \qquad M_{brine} = \frac{k_{rw}}{\mu_w} = \frac{1}{\mu_w}$$

Semi-Analytical Model Algorithm

1. Assume Pwt>Prt
2. Calculate the pressure profiles
   $$P_{wz} = P_{wt} + \rho_{CO2} g z$$
   $$P_{rz} = P_{rt} + \rho_w g z$$
   $$\Delta P = P_{wz} - P_{rz}$$
3. Calculate the flow rate
   A. Early Transient Flow Equation (Initialization)
   $$q_{co_2}(z) = \frac{4\pi k_z \Delta z}{\mu_w}\cdot\frac{\Delta P_z}{\ln\left(\frac{4k_z t}{\gamma\varphi_z\mu_w c_t r_w^2}\right)}$$
   B. Steady-State Flow Equation
   $$q_{co_2}(z) = \frac{k_z M_{avg}(z)}{\ln\left(\frac{r_e}{r_w}\right)} 2\pi\Delta P_z \Delta z$$
4. If $Q_T = \sum q_{co_2}(z)$ does not match the required flow rate, change Pwt.
   A. If $Q_T < Desired\ Q$, increase Pwt
   B. If $Q_T > Desired\ Q$, reduce Pwt



Radii Definitions (Updated)

$$r_{e,z}(t) = \sqrt{\frac{2k_z t}{(\varphi_z \mu_w c_t)}}$$

$$r_{dry,z}(t) = \sqrt{\frac{\frac{q_{g,z}(t_{i-1})\cdot t}{\pi\Delta z\varphi_z} + r_w^2}{1+\left(\frac{v_{BL}}{v_{dry}}-1\right)\left(\frac{\rho_w}{\rho_g}(1-S_{g,avg}-S_{wr})k + S_{g,avg}\right)}}$$

$$\frac{r_{BL}}{r_{dry}} = \sqrt{\frac{v_{D,BL}}{v_{D,BL}}}$$

$$r_{BL,z}(t) = \sqrt{\frac{\frac{q_{g,z}(t_{i-1})\cdot t}{\pi\Delta z\varphi_z} - \left(r^2_{dry,z}(t) - r_w^2\right)}{\frac{\rho_w}{\rho_g}(1-S_{g,avg}-S_{wr})k + S_{g,avg}} + r^2_{dry,z}(t)}$$

Retardation Factors

$$D_{brine\to BL} = \frac{C^{BL}_{CO_2,a}}{C^{BL}_{CO_2,a} - C^{BL}_{CO_2,g}}$$

$$D_{BL\to dry} = \frac{C^{dry}_{CO_2,g} - C^{BL}_{CO_2,a}}{C^{BL}_{CO_2,a} - C^{BL}_{CO_2,g}}$$

$$\downarrow$$

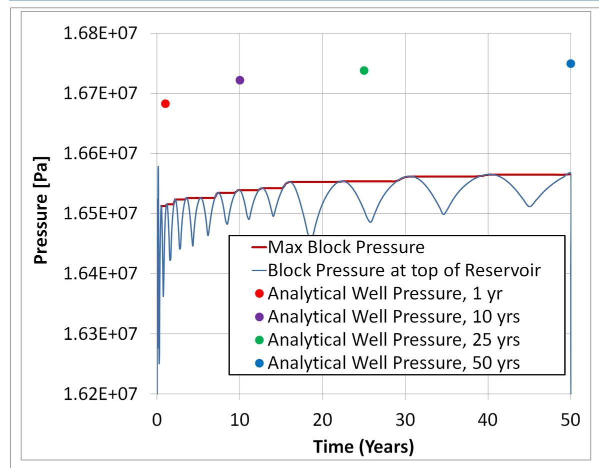
$$D_{brine\to BL} = \frac{Sol(1-\bar{S}_g)}{Sol(1-\bar{S}_g) - \bar{S}_g}$$

$$D_{BL\to dry} = \frac{1 - Sol(1-\bar{S}_g)}{\bar{S}_g - Sol(1-\bar{S}_g)}$$

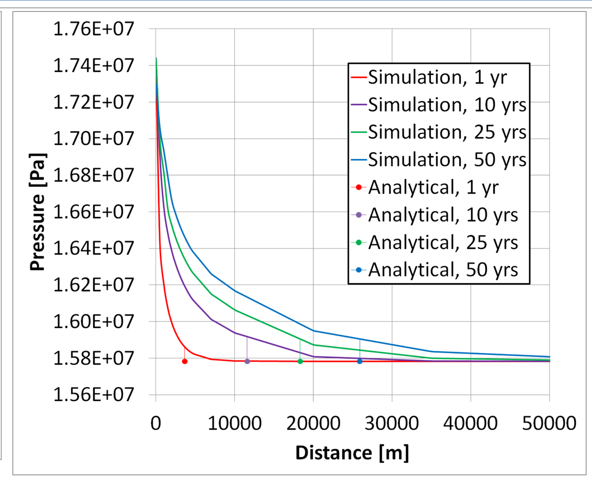
The retardation factors are described in detail by Noh et. al. and are used to determine the dimensionless velocity of the dry zone and the two phase zone. Essentially they describe a concentration percentage of difference in CO2 between two different zones and are used to expand the fractional flow curve where the dimensionless velocities are determined. By using the results provided in this paper our results for the front movement did not match, especially for the dry zone.

We investigated retardation factors further by using a simpler approach shown to the right using 5% mass solubility of CO2 in brine. We obtained a similar result for the two phase zone factor but not the dry zone. Thus, the results obtained in this presentation are by changing the D factors via trial and error.

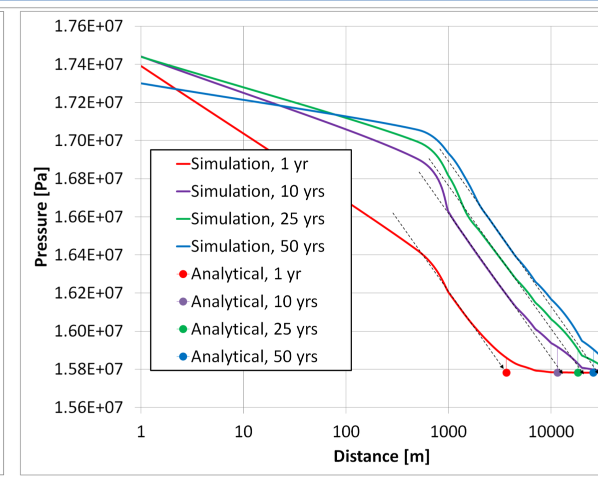
Validation Results with TOUGH2—Simple Model



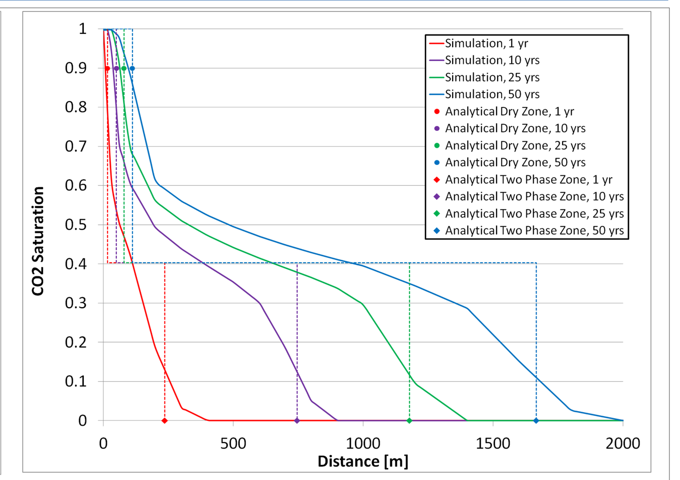
Semi-analytical model pressure results are 1.1% different from TOUGH2 results. The semi-analytical model is the "well pressure" and the TOUGH2 model pressure "block pressure" immediately next to the well location. The oscillation could be due to numerical stability from CO2 injection into those blocks.



This plot shows the TOUGH2 pressure from the well to the extent of the reservoir for 4 different times. The semi-analytical results for the pressure influence radius are shown as points. The pressure influence radius is defined as the point where the pressure change in the reservoir is zero. The plot to the right shows the effects of numerical dispersion.



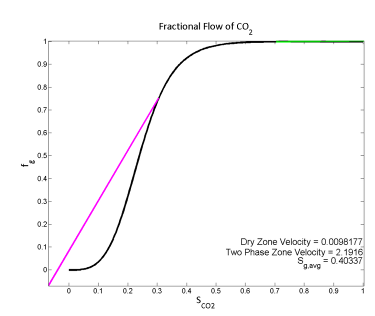
This plot shows the TOUGH2 pressure from the well to the extent of the reservoir for 4 different times on a semi-log axis. When the straight line of the pressure curve is extrapolated to the initial reservoir pressure (as shown by the black arrows) it is apparent that the semi-analytical model pressure influence radii is close to the results. The simulation results show large numerical dispersion in the results that make the previous plot hard to compare.



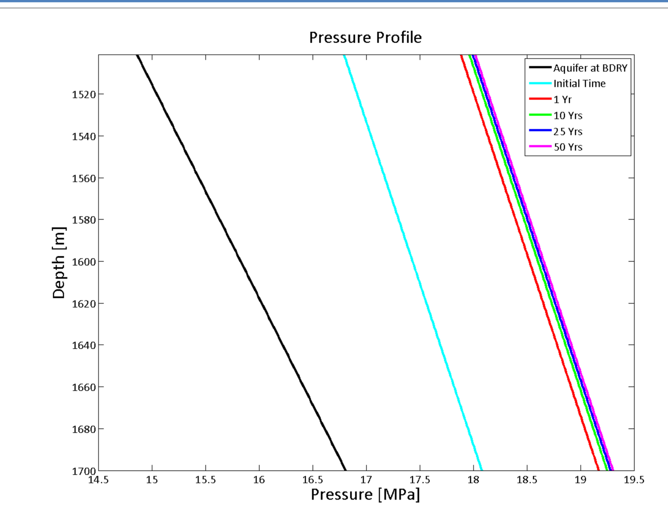
Semi-analytical model saturation fronts follow the trend of TOUGH2 results and are subject to numerical dispersion in simulation.

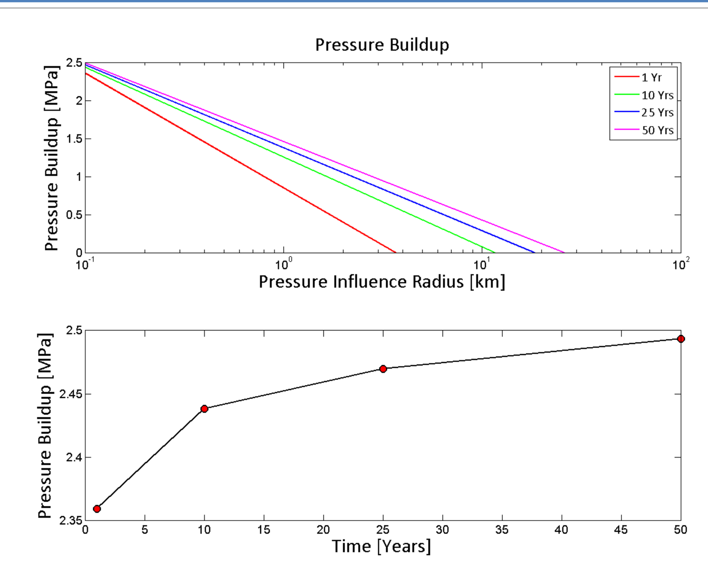
Semi- Analytical Multiple Layer Model Results

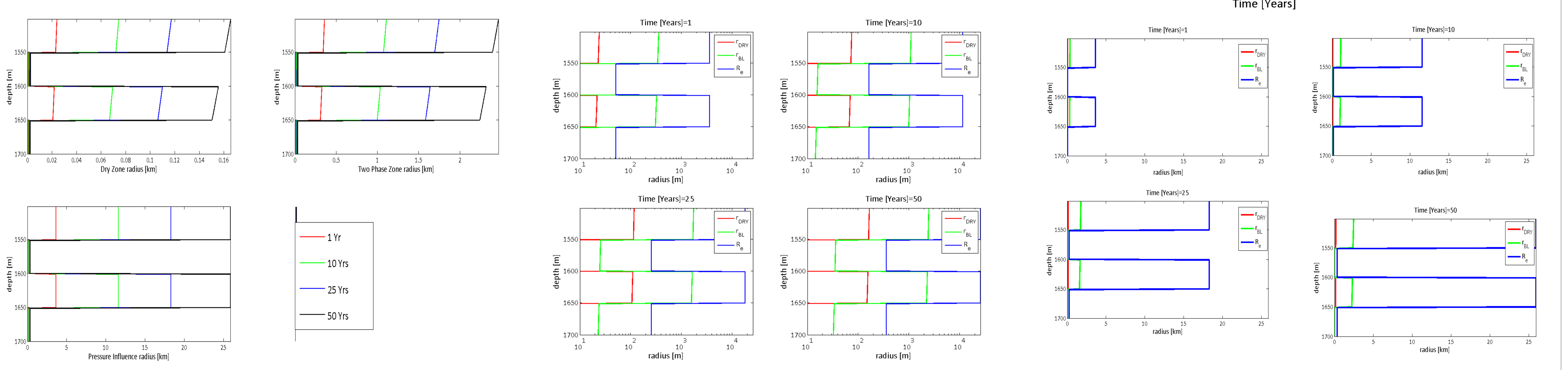
Layer Name	Layer Thickness, m	Layer Permeability, m^2	Layer Porosity
Layer 1	50	1.00E-13	0.2
Layer 2	50	1.00E-20	0.0001
Layer 3	50	1.00E-13	0.2
Layer 4	50	1.00E-20	0.0001



The results shown include pressure profile at the well, the pressure buildup, and zone front movement for a 4 layer system alternating properties to show how the layer heterogeneity is included in the model.







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EGU General Assembly 2012: April 22-27, 2012, Vienna, Austria

Contact: wsargent@stanford.edu; smbenson@stanford.edu