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THE EFFECTS OF FLUID DENSITY VARIATIONS DURING OILFIELD WASTEWATER DISPOSAL

Ryan M. Pollyea, Richard S. Jayne, Hao Wu

Virginia Polytechnic Institute and State University
Department of Geosciences
Blacksburg, Virginia 24061, USA
e-mail: rpollyea@vt.edu

ABSTRACT

Oilfield wastewater injections have been implicated in the rapid increase of earthquake occurrence in the midcontinent United States. Injection-induced earthquakes occur when pore pressure accumulation on optimally-aligned faults decreases effective normal stress below the Mohr-Coulomb failure threshold. As a result, numerical models of pressure diffusion have been implemented to explain and/or quantify the relationship between induced seismicity and pressure diffusion away from saltwater disposal (SWD) wells, and there have been several recent studies that incorporate pressure diffusion models into probabilistic earthquake hazard forecasts. Inspection of these SWD groundwater models reveals that investigators uniformly assume that fluid density is constant throughout the geological system. In this study, we test the robustness of the constant-density assumption by comparing variable- and constant-density SWD simulations within a synthetic model domain with characteristics of the Anadarko Shelf geologic province in northern Oklahoma and southern Kansas. Results show that far-field pressure diffusion is relatively insensitive to fluid density during SWD operations; however, near-field pressure accumulation and recovery curves exhibit substantial variability. Specifically, our results show that the advective transport of high density brine into the seismogenic zone may sustain elevated pore fluid pressure long after injection operations cease. In light of the hundreds of closely spaced SWD wells on the Anadarko Shelf, these results have important implications for injection-induced earthquake hazard.

INTRODUCTION

Earthquake frequency in the midcontinent U.S. has increased dramatically since 2009 owing in large part to the rapid proliferation of salt water disposal (SWD) wells that are used to discard produced oilfield wastewater (Ellsworth, 2013). During SWD operations, highly brackish produced waters are reinjected into deep underground geologic formations, the result of which increases fluid pressure and decreases effective stresses in the affected regions (NRC, 2013). As a consequence, injection-induced earthquakes occur when the effective stress on optimally-aligned faults decreases below the Mohr-Coulomb failure threshold (Walsh and Zoback, 2015). Injection-induced earthquakes are known to occur at depths of 4 – 8 km below ground surface (Keranen et al., 2013), where pore-fluid pressure is largely unknowable. As a consequence, the linkage between earthquake swarms and SWD operations relies largely on statistical correlations (e.g., Pollyea et al., 2018; Weingarten et al., 2015) and physics-based groundwater models that match pressure migration from SWD wells with earthquake hypocenter locations (e.g., Keranen et al., 2014). As groundwater modeling methods become increasingly relevant in the context of SWD earthquake hazard prediction (Langenbruch et al., 2016), it is important know whether the most salient fluid system characteristics are being considered. For example, model uncertainty is generally assessed by testing a range of geologic properties (e.g., permeability, porosity, etc.), while the effects of variable fluid properties are considered negligible. Our review of the literature finds that groundwater models developed in the context of injection-induced earthquakes uniformly assume constant fluid properties throughout the geologic system. This implies that no compositional or temperature differences exist between wastewater and fluids within the seismogenic zone; however, SWD operations occur over km scales and affect depth intervals in which fluid properties are known to vary substantially due to thermal and geochemical differences. This study tests the robustness of the constant-density assumption by comparing variable- and constant-density

SWD simulations within a synthetic model domain with characteristics of the Anadarko Shelf geologic province in northern Oklahoma and southern Kansas.

METHODS

The region of interest for this study is Alfalfa County, Oklahoma, which is located within the Anadarko Shelf geologic province. Alfalfa County experienced rapid growth in oil and gas production between 2010 and 2015 as unconventional recovery methods unlocked previously inaccessible resources from the Mississippi Lime formation. This region is particularly interesting in the context of injection-induced earthquakes because there were no magnitude-2.5 or greater (M2.5+) earthquakes before 2013, but the annual M2.5+ earthquake rate increased dramatically between 2013 and 2015 due to increasing SWD volume (Fig. 1). Since 2015, the M2.5+ earthquake rate has been declining due to the combination of decreasing production and mandated SWD volume reductions. The United States Geological Survey (USGS) Produced Waters Database (PWD) indicates that brine produced from the Mississippi Lime in Alfalfa County is characterized by mean total dissolved solids (TDS) concentration of 207,142 ppm (σ = 31,487 ppm, N=8) (Blondes et al., 2017). If we assume that the reported brine concentration is representative of modern oilfield wastewater then the average brine density for SWD fluid in Alfalfa County is 1,123 kg/m^3 +/- 15 kg m^{-3} at temperature (40°C) and pressure (21 MPa) conditions typical of the Arbuckle formation (Mao and Duan, 2008). Unfortunately, data for geochemical composition of Precambrian basement fluids in Oklahoma are neither publicly available or reported in the literature. Nevertheless, the USGS PWD includes 10 records for Precambrian basement fluids in central Kansas; the mean TDS concentration for these records is 107,226 ppm (σ = 48,346 ppm) (Blondes et al., 2017), which corresponds with mean fluid density of 1,068 kg/m^3 +/- 30 kg/m^3 at 21 MPa and 40°C (Mao and Duan, 2008).

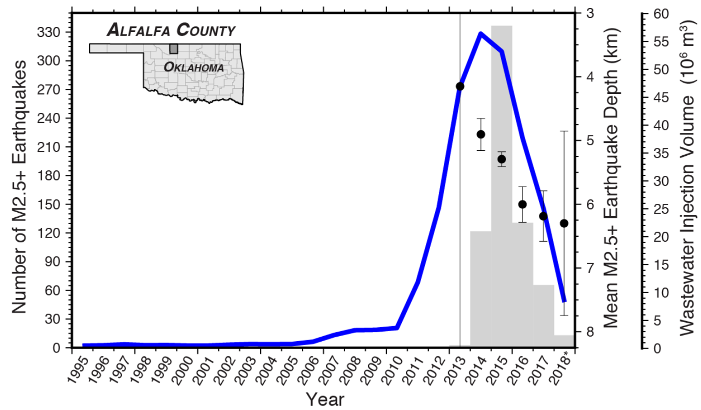

Figure 1: Number of M2.5+ earthquakes (gray bars), annual SWD injection volume (blue line), and error-weighted mean annual hypocenter depth (black circles) in Alfalfa County, Oklahoma during the period 1995 – 2018. Error bars correspond with two standard errors of the mean. SWD volume data from Oklahoma Corporation Commission (OCC, 2018) and earthquake data from USGS Comcat database (USGS, 2018). SWD and earthquake data are current through 31 May 2018.

To understand how fluid density affects pressure migration from SWD operations into the seismogenic zone, we develop an SWD model with characteristics of Alfalfa County, Oklahoma. The conceptual model represents the Arbuckle formation from 1,900 – 2,300 m depth overlying the Precambrian basement from 2,300 m – 10,000 m depth. The model domain comprises a 200 km × 200 km lateral extent; however, we invoke 4-fold symmetry to reduce the simulation grid to a lateral extent of 100 km in each direction (Fig. 2A). As a result, the 100 km × 100 km × 8.1 km volume is modeled as a 3-D unstructured grid comprising 1,278,613 grid cells with local grid refinement near the SWD wells. The Precambrian basement is discretized as a dual continuum (2 vol. %

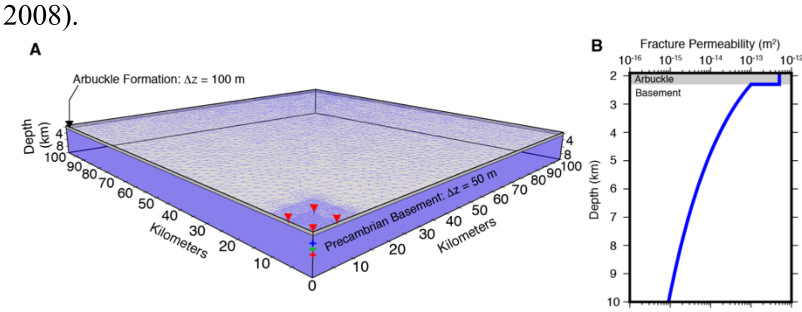

Figure 2: Schematic illustration of model domain (A) and permeability distribution for the Arbuckle and basement fracture domains (B). Well locations in A are denoted by red triangles. Blue, green, and red + symbols denote timeseries pressure monitoring locations at 4, 5, and 6 km depth, respectively, and color corresponds with timeseries curves in Fig. 2.

fracture domain) to separately account for fracture and matrix flow. Basement fracture permeability (k) decays with depth (z) according to the Manning and Ingebritsen (1999) equation: $k(z) = k_0 (z/z_0)^{-3.2}$. For this model, z_0 corresponds with the depth of the Arbuckle-basement contact, where permeability is estimated to be 1×10^{-13} m^2 (Fig. 2B). The remaining hydraulic parameters are listed in Table 1. We simulate SWD within a well field comprising nine SWD wells on a regular grid with 6 km spacing, injection interval from 1,900 – 2,100 m depth, and individual injection rates of 2,080 m^3/day (13,000 bbl/day). Two fluid composition scenarios are considered: (1) non-isothermal with SWD fluids comprising TDS concentration of 207,142 ppm and density of 1,123 kg m^{-3}, and basement fluids with TDS concentration of 107,226 ppm and density of 1,068 kg m^{-3}, and (2) isothermal with uniform fluid composition throughout, i.e., constant density. The code selection for this study is TOUGH3 (Jung et al., 2017) compiled with EOS1 and EOS7 for the constant and variable density models, respectively. Initial conditions for all model scenarios comprise a hydrostatic gradient, which is calculated separately for the isothermal and variable density models. For the variable density models, the initial temperature distribution is calculated on the basis of a 40 mW/m^2 heat flux across the bottom of the domain, which results in a geothermal gradient of 18 °C/km. Boundary conditions for both simulations comprise (1) constant pressure (and temperature for the variable density model) in the far-field, (2) no-flow boundaries across the top and bottom of the domain, and (3) a 40 mW/m^2 heat basal heat flux for the variable density simulations. No flow boundaries are also specified in the *xz*- and *yz*-planes through the origin to facilitate the symmetry boundaries.

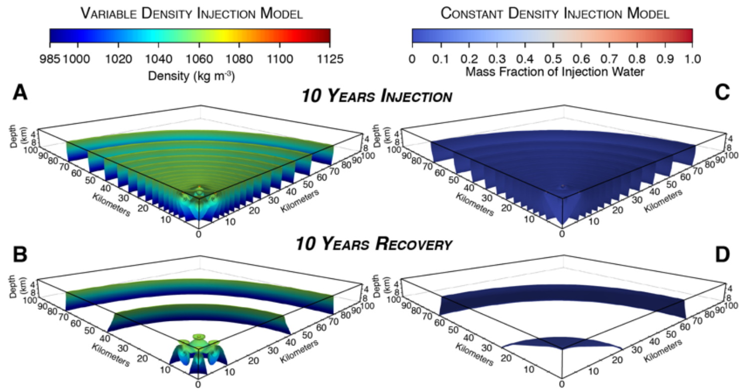

Figure 3: Results of variable (left) and constant density (right) simulations as isosurface contours of pressure accumulation (ΔP_f) after 10 years of injection (upper) and 10 years of recovery (lower). Isosurface contours are at 10 kPa intervals.

Table 1. Model Parameters

	k-matrix m^2	k-fracture m^2	Porosity -	Density kg m^{-3}	β Pa^{-1}	k_T W m^{-1} °C^{-1}	c_p J kg^{-1} °C^{-1}	D m^2 s^{-1}
Arbuckle	5×10^{-13}	-	0.1	2,500	1.7×10^{-10}	2.2	1,000	-
Basement	1×10^{-20}	Fig. 2A	0.1	2,800	4.5×10^{-11}	2.2	1,000	-
Brine	-	-	-	1123†	-	-	-	1.14×10^{-9}
Water	-	-	-	-	-	-	-	2.30×10^{-9}

† Reference density for EOS7. β – compressibility. k_T – thermal conductivity. c_p– heat capacity. D – diffusion coeff.

RESULTS & DISCUSSION

Fluid pressure accumulation as low as 10 kPa (0.1 bar) has been implicated in earthquake triggering, and our results show that just nine SWD wells each operating at 2,080 m^3/day (13,000 bbl/day) can drive a 10 kPa (0.1 bar) pressure front to ~75 km over 10 years (Fig. 3). Interestingly, these results also indicate that long range pressure diffusion is generally independent of fluid density despite the additional load imposed by high density SWD fluids. In the vicinity of individual SWD injectors, our results show that the effects of fluid density appear after ~4 years of injection when fluid pressure accumulation (ΔP_f) at 4 km depth begins increasing more rapidly than at 5 and 6 km depth (Fig. 4A, blue line). This rise in fluid pressure results from the downward, advective transport of high density wastewater, which displaces lower density basement fluids. When SWD operations cease after 10 years of injection, our results show that continuing downward, advective flow of high density wastewater delays fluid pressure recovery (Fig. 4A). This result is in stark contrast to pressure recovery curves in the constant-density scenario, which show pressure recovery by exponential decay (Fig. 4B). In the context of regionally expansive SWD operations, these results explain a number recently reported phenomena, including (1) measurements of increasing fluid

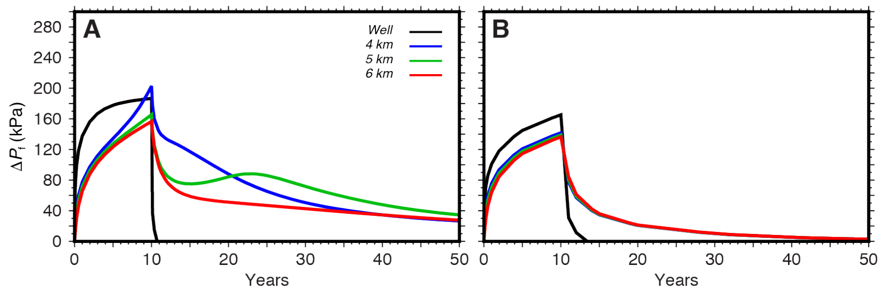

Figure 4: Timeseries of fluid pressure accumulation below the central SWD well for variable density (A) and constant density scenarios (B).

pressure within Arbuckle wells located 90+ km from high-rate injectors in northern Oklahoma and southern Kansas (Peterie et al., 2018), (2) the 40 km distance separating SWD wells and a number of earthquakes in the 2016 Fairview sequence in north-central Oklahoma (Goebel et al., 2017), (3) the 125 km geospatial correlation range between SWD volume and earthquake occurrence in Oklahoma (Pollyea et al., 2018), and (4) systematically deepening mean annual hypocenter depths in northern Oklahoma (Fig. 1). In conclusion, the results of this study suggest that fluid density variations are an important component of injection-induced earthquake hazard, and should be accounted for in model predictions when there is evidence that such density variations exist.

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