DOE-ARRA Geologic Sequestration Training and Research 2011 Yearly Review Meeting

Project: DE-FE0001836 Numerical modeling of geomechanical processes related to CO_2 injection within generic reservoirs

Missouri University of Science & Technology
Presenter: Dr. Andreas Eckert, Department of Geological Sciences & Engineering

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Project Participants

- Dr. Andreas Eckert: PI
- Dr. Runar Nygaard: Co-PI
- MingYen Lee (ML): PhD student; Petroleum Engineering
- Matthew Paradeis (MP): Masters student; PE
- Nevan Himmelberg (NH): Undergraduate assistant

Introduction

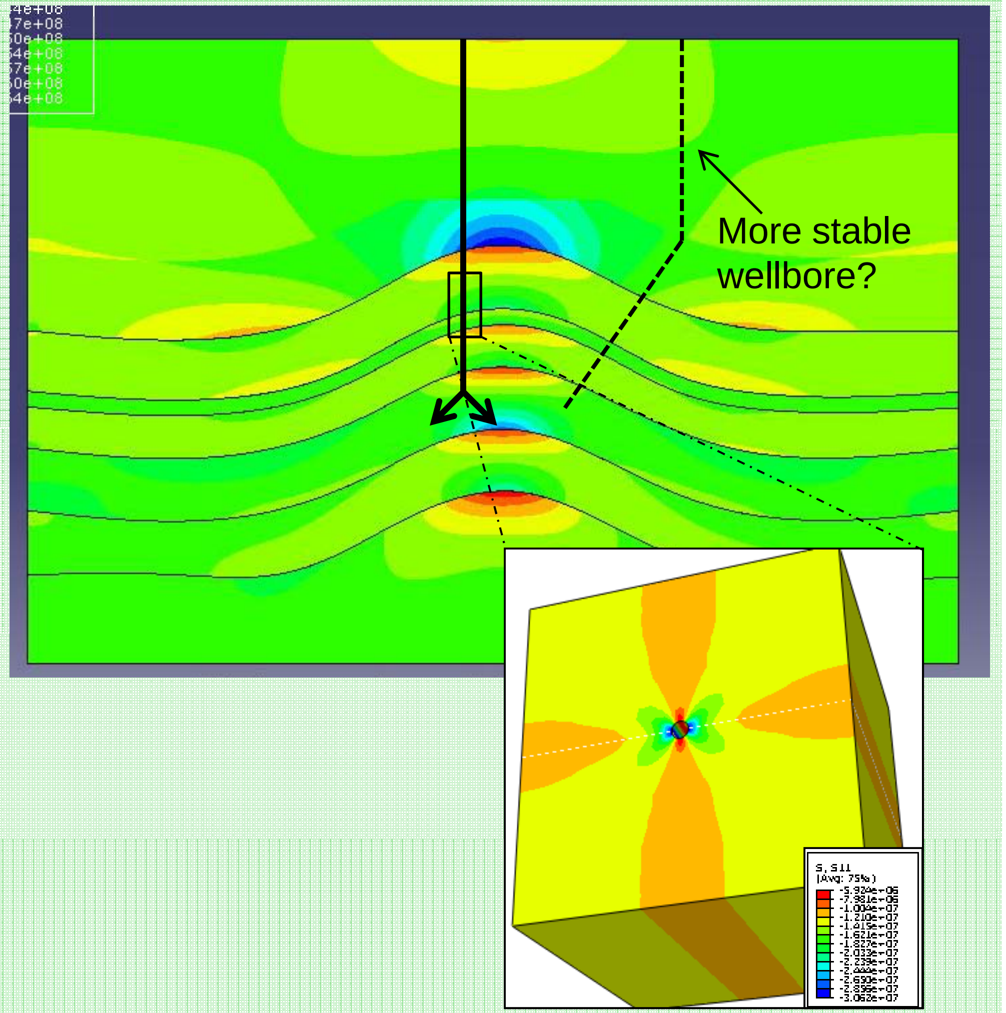
- Find suitable geomechanical conditions for generic CO_2 sequestration sites: Anticline
- CO_2 injection affects:
  - cap rock stability (fracture generation and reactivation)
  - wellbore integrity
- Benefits: Numerical database for stress changes dependent on site geometry and pore pressure changes

Project Objectives

- Train graduate students to develop multi-scale Finite Element models of different geological settings for sequestration sites in order to address:
  - How does fluid pressure induce rock deformation?
  - How do faults and fractures affect fluid migration?
  - Critical wellbore placement
  - Wellbore integrity
- Gain understanding of how reservoir geometry affects cap rock, fault and wellbore stability.
- Insights for future site selection.

Methodology

- Multi-scale modeling to study influences of large scale models on borehole
  - Optimal wellbore trajectory
  - Optimal wellbore design



Project Funding

- Total Project Cost: $317,937.00
- DOE Share: $299,113.00
- Non-DOE Cost Share: $18,825
- Cost Share Provider: Missouri S&T

Highlights of Project to Date

- Accomplishment 1: *Initialization of in-situ stress states for anticline reservoir setting*
- Accomplishment 2: *Calculation of maximum sustainable pore pressures in the reservoir; recommendations on injection location*;
- Accomplishment 3: Wellbore scale models: *Influence of discretization parameters (model size, element density, element type) and boundary conditions on model results.*

Tasks – Overview

Task No.	Task Description	Task Duration	Task Funding
1	Project Management and Planning	12/01/2009 – 11/30/2012	$0
2.1	CO_2 sequestration lecture	01/01/2010-06/30/2010	$19,069
2.2	Introduction and literature research	01/01/2010-06/30/2010	$19,069
3.1	2D FE model construction and results verification	01/07/2010-12/31/2010	$33,900
3.2	CO_2 injection related pore pressure modeling	01/10/2010-03/31/2010	$16,950
3.3	Re-modeling of fractured regions	01/01/2011-06/30/2010	$21,188

Tasks – Overview

Task No.	Task Description	Task Duration	Task Funding
4	Initial model of wellbore section	01/07/2010-03/31/2011	$42,375
5.1	Pre-stressed 3D model	01/07/2011-12/31/2011	$25,425
5.2	CO_2 injection related pore pressure modeling	01/01/2012-12/31/2012	$38,138
6.1	Integrate BCs for optimal drilling location	04/01/2011-12/31/2011	$38,138
6.2	Integrate BCs for optimal wellbore integrity	01/01/2012-12/31/2012	$50,850
7	Documentation	10/01/2012-12/31/2012	-

Project Schedule

Technical Tasks	Year 1				Year 2				Year 3				Year 4
	Q1	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**
1.0 Project Management, Planning and Reporting													
2.0 Introduction and literature research													
2.1 CO_2 sequestration lecture													
2.2 Literature research													
3.0 2D Finite Element study													
3.1 2D model construction and result verification													
3.2 Result analysis of CO_2 injection related pore pressure modeling													
3.3 Re-modeling of fractured regions													
4.0 Initial model generation of 3D borehole section													
5.0 3D FE study of reservoir settings													
5.1 Pre-stressed 3D model													
5.2 CO_2 injection related pore pressure modeling													
6.0 3D wellbore placement & integrity analysis													
6.1 Integrate BCs for optimal drilling location													
6.2 Integrate BCs for optimal wellbore integrity													
7.0 Documentation of results and final report to DOE													
Project reports				**AR**				**AR**				**FR**	

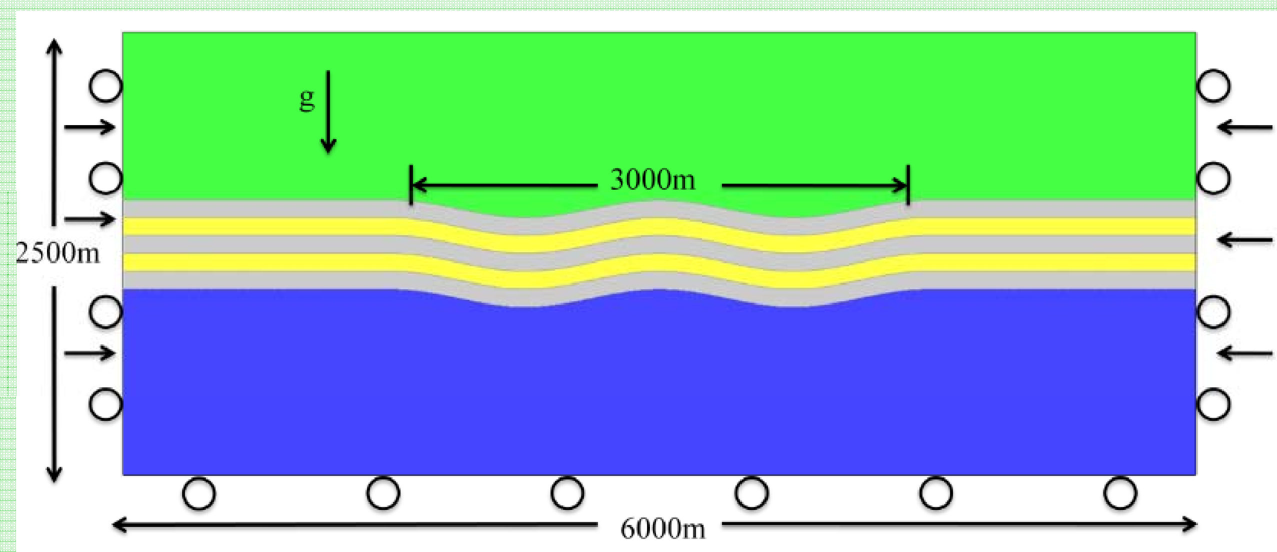
AR: Annual report; FR: Final report

Discussion – Task 2

- **<u>Task 2.0:</u>** Introduction and literature research
- ***<u>Subtask 2.1:</u>*** Student Selection and Introduction (PI)
  - Introduce selected graduate students to CO_2 sequestration by 400 level CO_2 sequestration lecture. Topics: Carbon Capture, Transport, Sequestration, CO2 sequestration risks, reservoir geomechanics, wellbore geomechanics, structural geology and applied numerical modeling.
- ***<u>Subtask 2.2:</u>*** Literature research (ML, MP)
- ***<u>Subtask 2.3:</u>*** Software introduction (Abaqus and HyperWorks); PI
- **<u>Task 2:</u>** ***100% complete***

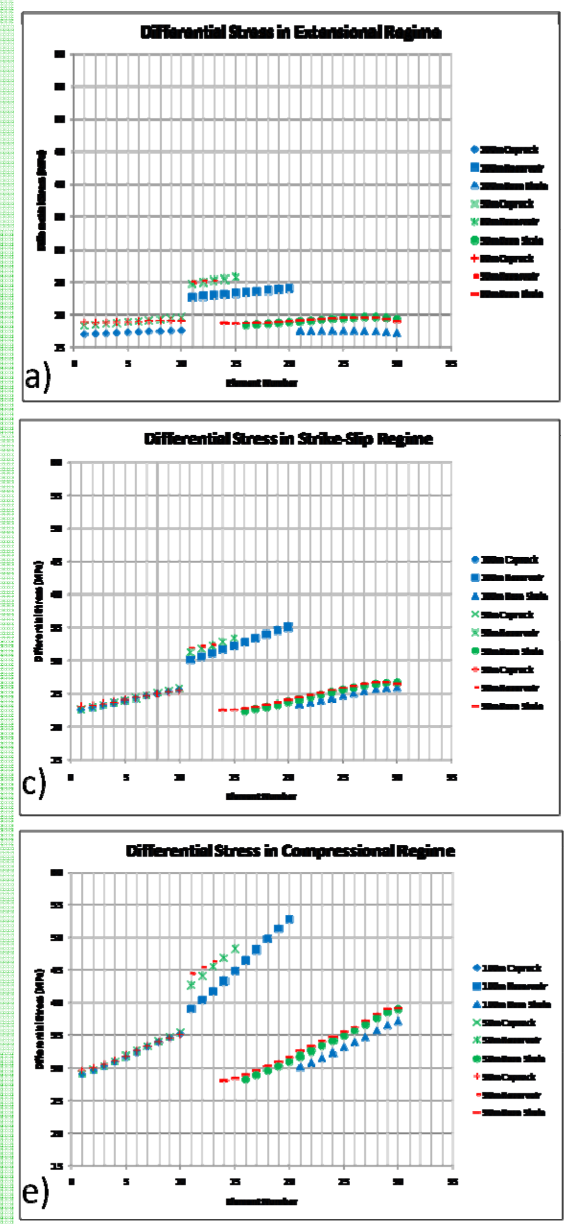
Discussion - Task 3

- **Task 3.0 :** 2D Finite Element study (PI, MP)
- ***Subtask 3.1:*** 2D Model Construction and Result Verification (***100% complete***)
  - Provide stress results under varying loading scenarios (extensional, strike-slip, and compressional);

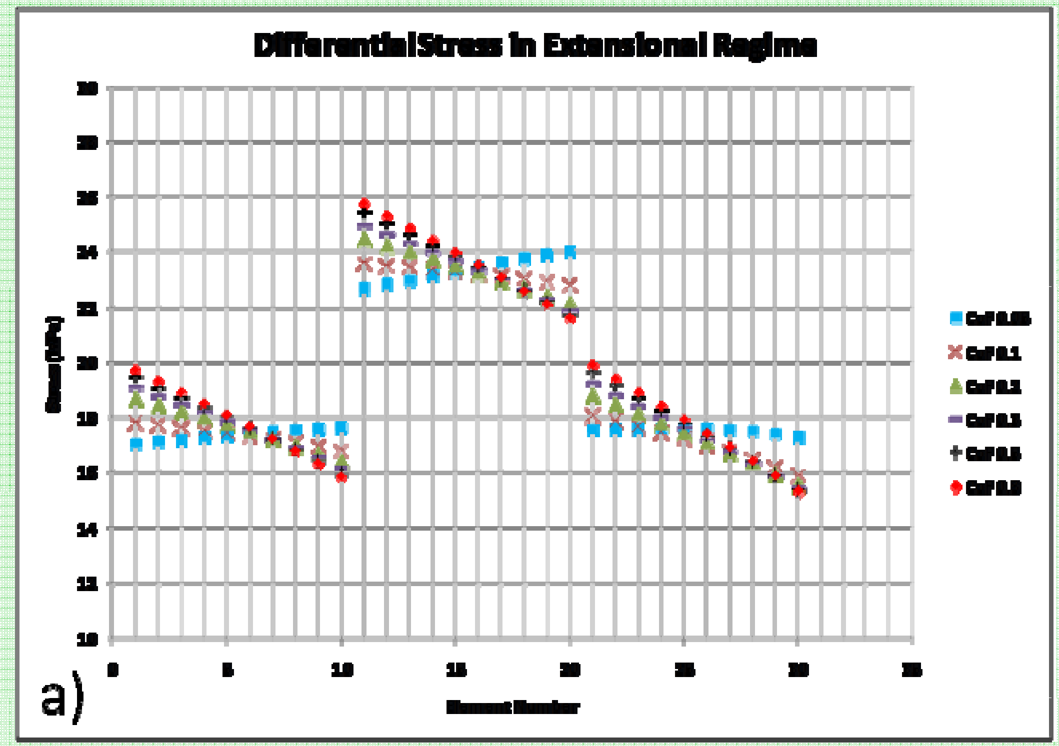


Influence of reservoir thickness and stress regime:

- Differential stress increases as thickness decreases
- Higher differential stress in reservoir versus shale layers
- Thicker reservoirs make better injection targets (not just because of the volumetrics)



Influence of inter-bedding slip



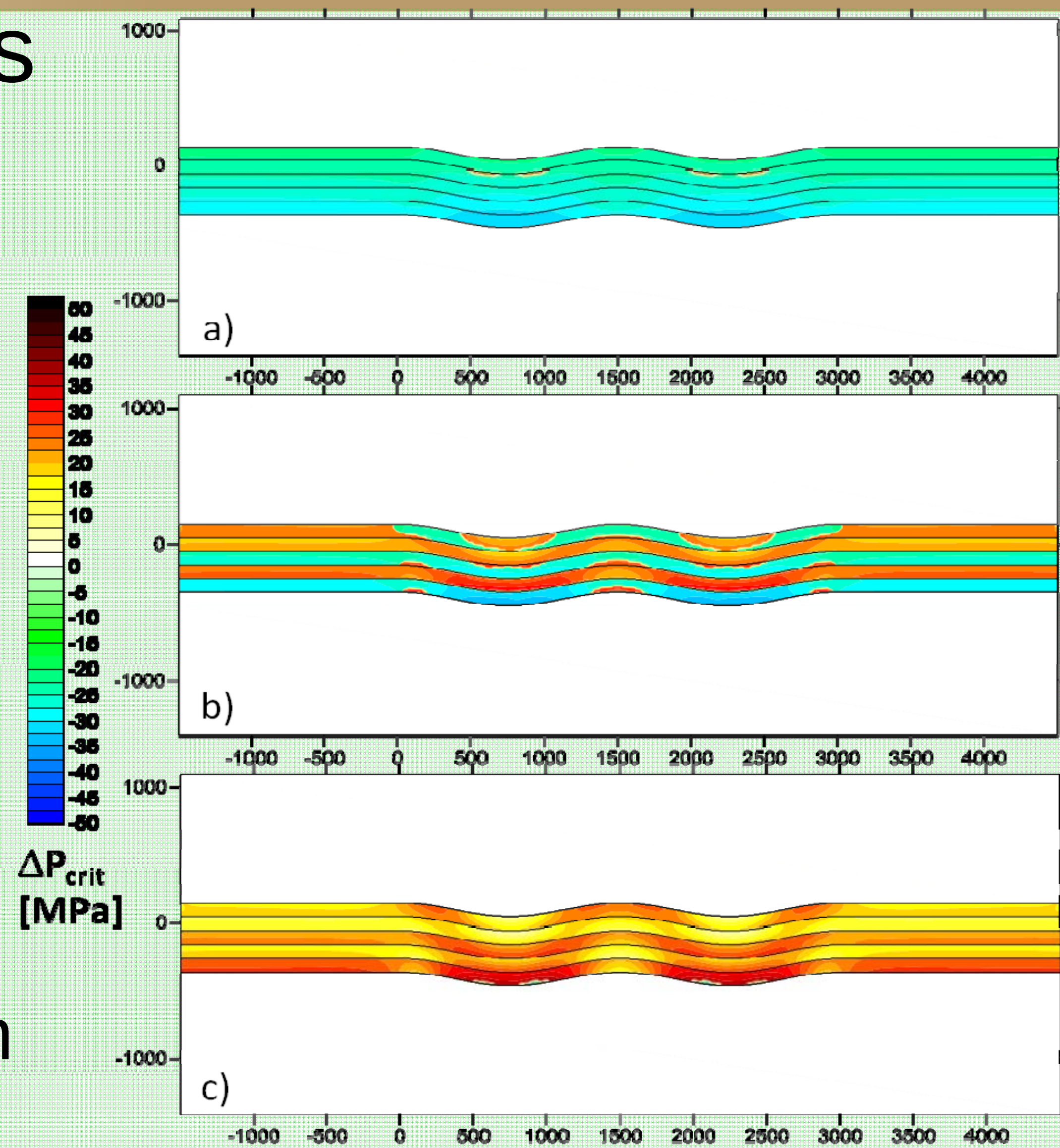
- Low values produce increasing differential stress with depth,
- high values produce decreasing differential stress with depth.

Discussion - Task 3

- ***Subtask 3.2.:*** CO_2 Injection Related Pore Pressure Modeling
  - Analyze geomechanical risk on reservoir scale: maximum sustainable pore pressure; (***100% complete***)
  - Inject CO2 using reservoir simulator and transfer pore pressures to FE models; analyze occurrence of fractures; (***20% complete***)

Influence of stress regime on ΔP_{crit}

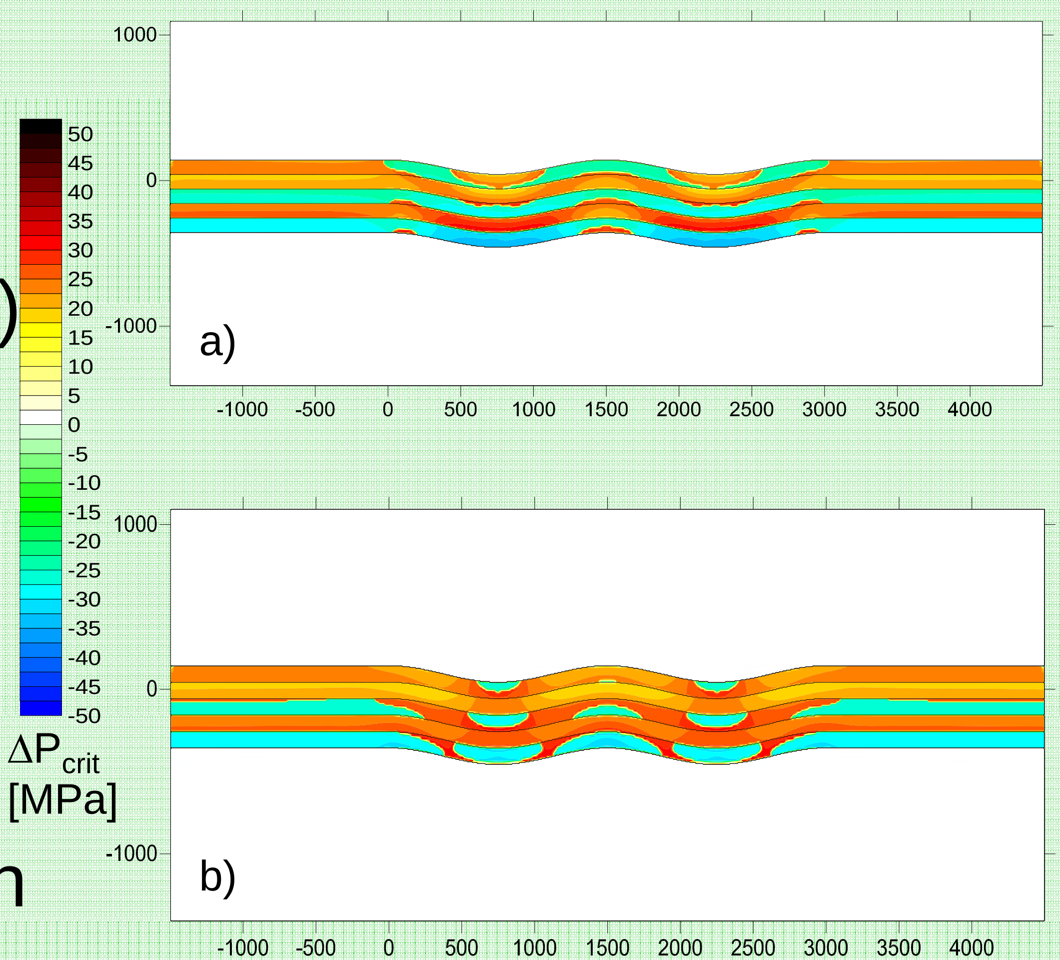
- Extensional regime: almost exclusively tensile fracture risk
- Strike-slip: mix of shear and tensile risk
- Compression: nearly all shear fracture risk
- Highest risk for reservoir-caprock is in bottom of reservoir layer at crest



Contours of critical pore pressure difference for extensional (a), strike-slip (b), and compressional (c) regimes. The scale shows tensile critical pressures as negative values

Influence of Intra-bed slip on ΔP_{crit}

- Low friction: Almost entirely tensile risk in caprock (~20-30 MPa)
- High friction: highest risk in caprock is shear (~20 MPa)
- More of the model is at risk of shear failure (vs. tensile) in the high friction case



Contours of critical pore pressure difference for strike-slip regime for coefficients of friction 0.05 (a) and 0.8 (b). The scale shows tensile critical pressures as negative values

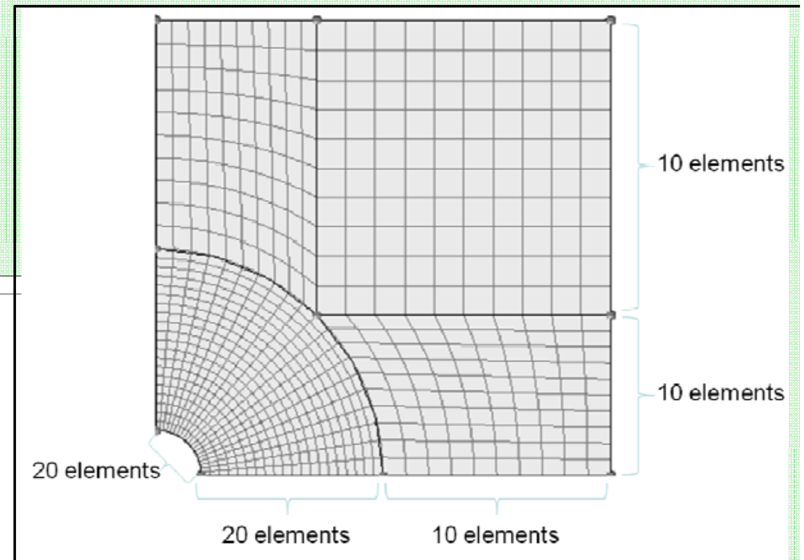
Discussion - Task 3

- ***Subtask 3.3.:*** Remodeling of Fractured Regions (PI, MP)
  - Re-modeling of failed regions from 3.2 as fractures with associated fracture permeability to study the effect of fractures on fluid migration pathways. (0% complete)

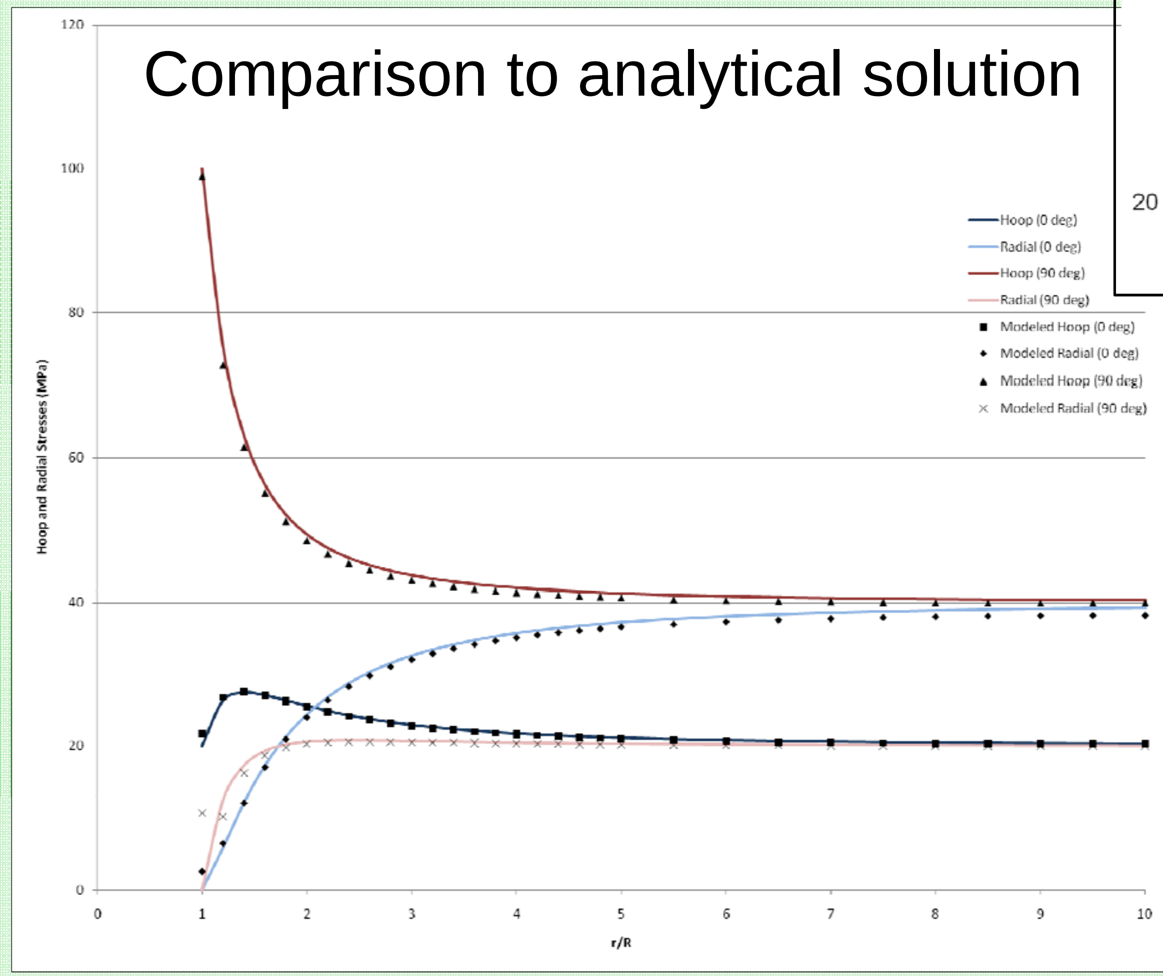
Discussion - Task 4

- **<u>Task 4.0:</u>** Generation of Borehole Model for Validation Purposes (Co-Pi, ML) (***100% complete***)
- ***<u>Subtask 4.1:</u>*** Generate geometry for 3-D model
  – mesh construction, quality assessment of the Finite Element mesh and the assessment of boundary conditions. Verify the stress results against the analytical solution.
- ***<u>Subtask 4.2:</u>*** Include Pore Pressure & Mud Weight
- ***<u>Subtask 4.3:</u>*** Wellbore stability implications
  – conduct sensitivity analysis of various pore pressure and mud pressure scenarios under different stress regimes to study their effects on wellbore integrity.

Base model



Comparison to analytical solution



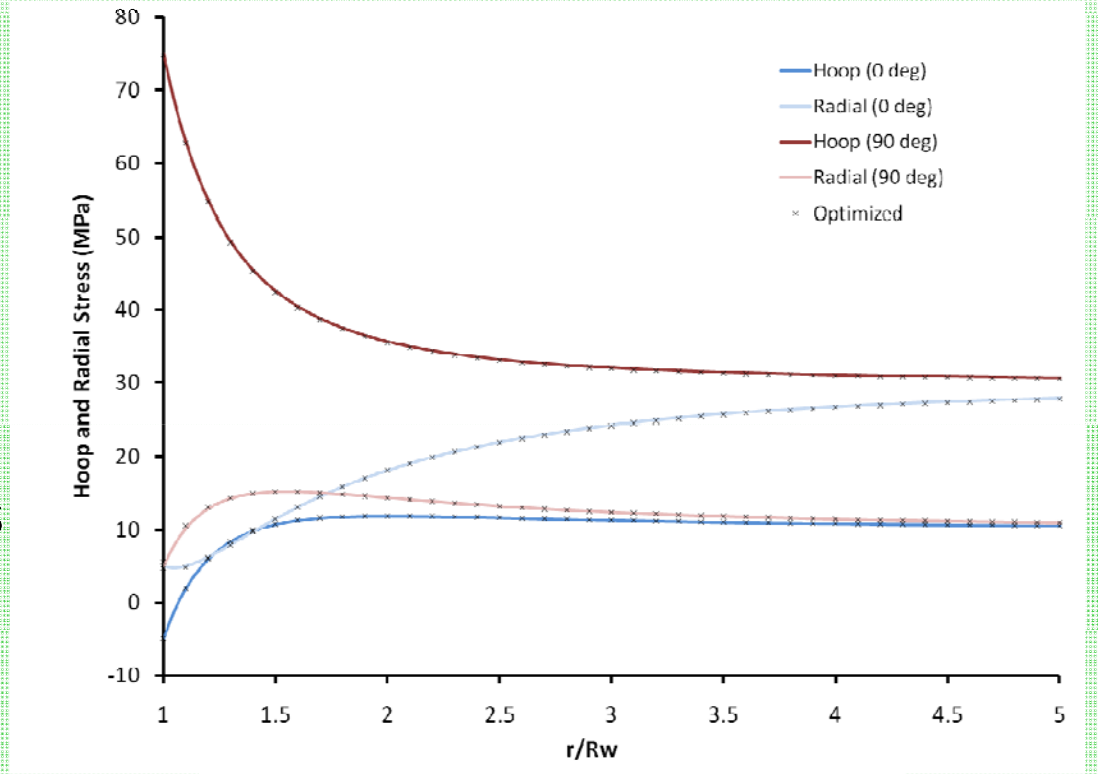
	Error at borehole wall (MPa)
Hoop (0 deg)	4.62
Radial (0 deg)	2.58
Hoop (90 deg)	-8.23
Radial (90 deg)	0.10

Mesh optimization necessary!

Discretization guideline for optimized model

Guideline:

- Displacement boundary conditions
- Model size: >15R
  (R: borehole radius)
- 2nd order quad elements
- Radial mesh density: >30 elements per 5R distance to borehole center



	Error at the borehole wall (MPa)	
	Base	Optimized
Hoop (0 deg)	4.62	0.09
Radial (0 deg)	2.58	-0.29
Hoop (90 deg)	-8.23	-0.25
Radial (90 deg)	0.10	0.50

Wellbore stability implications

		Errors of the modeled stress (MPa)		
		NF	SS	RF
Base Model	$\sigma_{\theta\theta}$ at 0°	-1.17	0.43	-5.65
	σ_{rr} at 0°	3.38	5.07	6.14
	$\sigma_{\theta\theta}$ at 90°	-6.42	-10.93	-10.78
	σ_{rr} at 90°	2.36	2.87	4.77
Optimized Model	$\sigma_{\theta\theta}$ at 0°	-0.13	-0.12	-0.25
	σ_{rr} at 0°	0.06	-0.05	0.20
	$\sigma_{\theta\theta}$ at 90°	-0.25	-0.38	-0.45
	σ_{rr} at 90°	0.38	0.65	0.63

	Safe Mud Weight Window (PPG)		
	NF	SS	RF
Analytical Solution	10.5 – 12.91	14.66 – 15.24	16.58 – 34.90
Base Model	9.08 – 12.41	12.66 – 15.41	13.99 – 33.03
Optimal Model	10.33 – 12.83	14.41 – 15.16	16.33 – 34.82

- Underestimation of minimum mud weight: Breakouts and borehole collapse.
- Possible leakage pathways!

Project Milestones

Project Parts	Tasks	Milestones to be achieved	Planned completion	Actual completion
I & II	1	Final negotiated project management plan	Y1Q1	Y1Q1
I & II	2.1	CO_2 sequestration lecture	Y1Q3	Y1Q3
I & II	2.2	Literature research summary for both project parts	Y1Q3	Y1Q3
I	3.1	Set of generic 2D models for initial stress states	Y2Q1	Y2Q1
I	3.2	Set of generic 2D models for pore pressure loading; Fracure analysis	Y2Q2	ongoing
I	3.3	Set of generic 2D models for fracture re-modeling; Fluid migration analysis	Y2Q3	
II	4	Initial 3D wellbore model: comparison to analytical solution	Y2Q2	Y2Q2
I	5.1	Set of generic "pre-stressed" 3D models	Y3Q1	
I	5.2	Set of generic 3D models after CO_2 injection; Fracture analysis	Y4Q1	
II	6.1	Integrated wellbore model with results from task 5; well placement analysis	Y3Q1	
II	6.2	Integrated wellbore model with results from task 5; well integrity analysis	Y4Q1	
I & II	7	Final report to DOE	Y4Q1	

Anticipated Efforts for the Coming Year

- **<u>Task 5.0:</u>** 3D FE Study of Reservoir Settings
- ***<u>Subtask 5.1:</u>*** Pre-stressed 3D Model (PI, MP)
  - Initialize the 3-D models with a stress state in equilibrium to applied loads to generate geologically realistic results.
- **<u>Task 6.0:</u>** 3D Wellbore Placement & Integrity Analysis (Co-Pi, ML)
- ***<u>Subtask 6.1:</u>*** Optimal Drilling Locations & Orientations
  - Integrate part I results as boundary conditions for wellbore scale models. Optimal drilling locations and optimal orientations of the wellbore trajectories shall be developed for each geological setting of the CO_2 injection site.

PI Contact Information

- If you have any questions or would be interested in collaboration please contact:

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