Geothermal Capacity Building Program Indonesia - Netherlands

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Geomechanics and Reservoir Modelling

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ABSTRACT

Progress activities WP 2.02 is as part of Ichwan A. Elfajrie master's thesis in Geothermal Master Program, ITB. The objective of the research was tailored to one of WP 2.02 objectives -- to improve the understanding of geothermal reservoir behaviour by coupling the geomechanics effect and reservoir fluid and heat flow simulation.

To estimate the geothermal reservoir, complex behaviour is a challenge in geothermal reservoir development strategy. Production and injection activities influence the reservoir properties, such as pressures and temperatures in geothermal system. The decreasing of pore pressure affects the effective stress of rocks, and it leads to changes of rock's permeability and porosity, also the compaction or subsidence. In order to clearly see such behaviour, the coupled geomechanics and heat flow model becomes inevitable. The geomechanics effect involved in reservoir modelling was conducted through coupling the heat flow simulator of TOUGH2® and geomechanics module of ABAQUS®. An iterative coupling scheme was used by linking input and output from both tools iteratively at each time step. They are both coupled through a developed python scripts with xlwings library. The output from TOUGH2® is processed in Microsoft Excel® before it becomes the input for ABAQUS®, and vice versa. The geothermal synthetic model was adopted from Wairakei geothermal field, New Zealand which is designed to represent geothermal reservoir water dominated system. It has 10 production wells with total production of 600 kg/s and no injection well. It is simulated for ten years with one year of simulation time step. The simulation results showed a decrease in permeability and porosity values in some producing layers, including the occurrence of subsidence. The sensitivity of total mass production is conducted by comparing the changes of porosity, permeability, and the subsidence rate. The total mass variation is between 600 kg/s and 1000 kg/s. The results are as expected, that the 1000 kg/s of mass production would change the permeability, porosity and subsidence rate more than the lower mass production. Based on the results, the coupling program is considered able to perform iterative coupling between TOUGH2® and ABAQUS®. The important parameters which influence the fluid flow simulation are the porosity and permeability, as well as changes in the shape or volume of elements. (Elfajrie, Geomechanics Effect on Geothermal Reservoir Modeling, 2016)

1 INTRODUCTION

1.1 BACKGROUND

Geothermal reservoir simulation is conducted to estimate reservoir behaviour or performances of geothermal field for a certain period of time. Geothermal reservoir modelling is expected to be able to predict changes in pressure and temperature as a result of the production and injection process. The effect of pressure and temperature changes across the reservoir causes rock deformation and failure. Furthermore, the rock deformation influences hydraulic rock properties (porosity and permeability) to a certain degree. Permeability is one of the most crucial hydrologic parameters and often determines the feasibility of projects involving geological processes. The changes in pressure and temperature observed through reservoir modelling resulting stress change and ultimately, its changes will lead to changes in porosity, permeability, and the new pressure distribution (Bataee & Irawan , 2014).

Analysis of reservoir geomechanics becomes part of reservoir management. Excessive production can cause a decrease in pressure and temperature. Geothermal Wairakei field-New Zealand is one field examples that has experienced subsidence due to its excessive production. The cause of the subsidence in Wairakei is considered to be compaction of a high porosity, low-permeability lacustrine mudstone at 100±200 m depth (Allis, 2000). Reservoir management is also conducted to optimize the development of the power plant.

The coupled models use a finite-difference method for the reservoir simulator and a finite-element method for the geomechanics simulator. There are four main types of coupled models; one way, two way, interactive, and fully coupling. In one way coupling scheme the geomechanical model is solved separately, the reservoir properties are updated from time to time and information is transformed only from geomechanical model to reservoir simulation. Two way coupling is an extension of this concept and the data from the flow portion of the model is also used to update the geomechanical implementation. Convergence and numerical stability are issues that these coupling schemes must deal with.

Geomechanics modelling has been used on the fully coupled flow-geomechanics to analyse the fluid production and injection of cold water (Enhanced Geothermal Systems) as the cause of the earthquake in the geothermal field. Simulation of changes in stress and strain on the simulator is used to analyse the performance of shear slip (Fakcharoenphol, Hu, & Wi, Fully-Implicit Flow and Geomechanics Model:

Application for Enhanced Geothermal Reservoir Simulations, 2012) (Fakcharoenphol & Wu, A Fully-Coupled Flow-Geomechanics Model for Fluid and Heat Flow in Geothermal Reservoirs, 2011). Utilization of geomechanics and fluid flow coupling has also been developed to analyse the interaction between propagating and existing fractures during hydraulic fracturing performed (Fu, et al., 2011). The results of the study was the development of a simulator that combines the FEM (Finite Element Method) and DEM (Discrete Element Method) analysis codes. In other words, the study of coupled geomechanics-fluid flow coupled still focuses on the optimization of fracture propagation as the basis of geothermal field development.

The research on coupled geomechanics-fluid flow consists of two parts. The first part is the data assimilation, which analyses important parameters that affect the behaviour of the reservoir. The second part is a simulation of geothermal fields by geomechanics-fluid flow coupling. Geomechanics simulator used is ABAQUS®, while the fluid flow simulations performed using TOUGH2®.

Simulations to be performed intended to predict reservoir behaviour changes during geothermal field operations. Indonesia geothermal field data will be used as input in the simulation. The final product of this research is a simulator that can be used in the geothermal industry. Coupled geomechanics-fluid flow method can provide significant results towards the development of geothermal field in the world, especially in Indonesia.

1.2 Objectives

The objectives of this research are:

1. Coupled modelling between geomechanics model and fluid and heat flow model
2. Data assimilation which analyses reservoir behaviour by varying input parameters

1.3 Problem Statements

The problem statements of this proposed research are:

1 Production of hot fluid and injection of cold water affect pore pressure changes then result in rock consolidation. This event modify the rock properties, especially stress and strain. These changes could influence partial or entire fractures within the geothermal reservoir.

2 Based on other studies, geomechanics knowledge plays an important role in conducting hydraulic fracturing. Initiating new fractures certainly resulted in changes of stress and strain of rock. Therefore, it is important to determine the effect of fractures propagation against existing fractures.

1.4 IMPORTANCE OF THE RESEARCH

1. To show the importance of coupled heat flow simulation & geomechanics to reservoir performance
2. Show the importance of monitoring reservoir due to geomechanical changes

2 METHODOLOGY OF RESEARCH

Research on coupled geomechanics – fluid flow consist of two things; analyse important parameters and development of the coupling method. Iterative coupling input-output (IO) method is implemented between geomechanics simulator and fluid flow simulator. ABAQUS® is used to simulate the geomechanics effects. Meanwhile fluid flow and heat flow in porous media is simulated by TOUGH2®. Distribution of stress, strain, nodal displacement and void ratio from geomechanics simulation can be used to update the input values in fluid flow simulation. The output of fluid flow simulation is used to update the input values in geomechanics simulation. Post processing data from fluid flow simulation to geomechanics simulation and vice versa is performed by Microsoft Excel®. While for reading and writing data from text file to Microsoft Excel® use WinPython®.

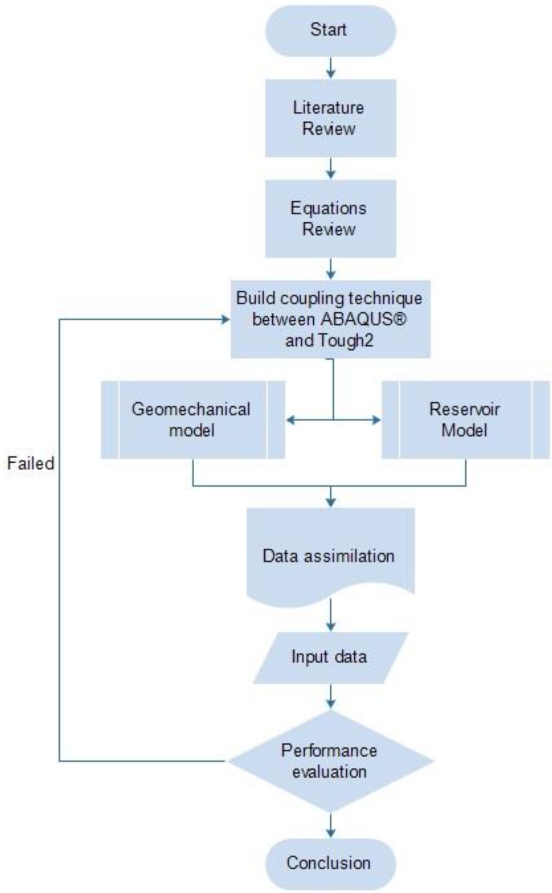


Figure 2.1 Research methodology.

A 3D model is created in both geomechanics and fluid flow simulator with specified parameter input. In TOUGH2® model, for the same element number have different position in ABAQUS®. Because of this, the coupling technique begins by replacing the element number on TOUGH2® by adjusting the number element in ABAQUS®. At this pre simulation phase, a fluid flow simulation is also performed to reach the natural state condition.

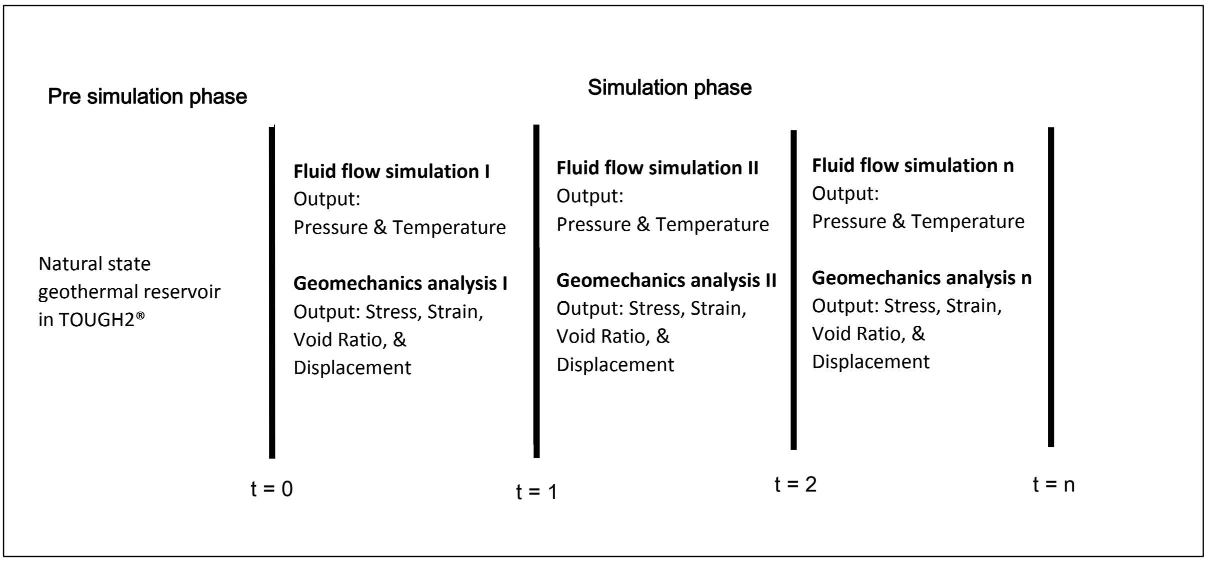


Figure 2.2 General simulation workflow.

Pre simulation phase is divided into three steps; synchronize the element identification number (element ID) between TOUGH® and ABAQUS® model, run reservoir model, and create the TOUGH2® input by extracting the results of ABAQUS®. The simulation phase is the iterative simulation with parsing data input and output from two simulators. This phase is repeated which depends on the number of required time steps. The simulation phase consist of; create input and run TOUGH2®; and create input and run ABAQUS®. Some of input data from each simulation will be updated while one loop of simulation has completed. The updated input data for TOUGH2® in one loop consist of:

a. Porosity of rocks
b. Permeability in three axis (-x,-y, and –z) of rocks
c. Volume of element
d. Centroid position of each element
e. Connectivity (distance from centroid to contact surface, and contact area plane)
f. Operation parameter (temperature and pressure)

The output data from fluid flow simulation (pressure and temperature distribution for each element) is used to update several input data in ABAQUS®. The data input for ABAQUS® which will be always updated are:

a. Nodal position
b. Operation parameters (void ratio, hydraulic conductivity, logarithmic bulk modulus and temperature)

The ABAQUS® output data which is used to create new data input for TOUGH2® are nodal displacement, void ratio, stress, and strain.

3 GEOMECHANICS & HEAT-FLUID FLOW MODELLING

3.1 SIMPLE SYNTHETIC MODEL

A simple model is created to facilitate the designed workflow. This model consists of eighteen elements with their own material. The illustration of simple synthetic model shown in Figure 3.1.

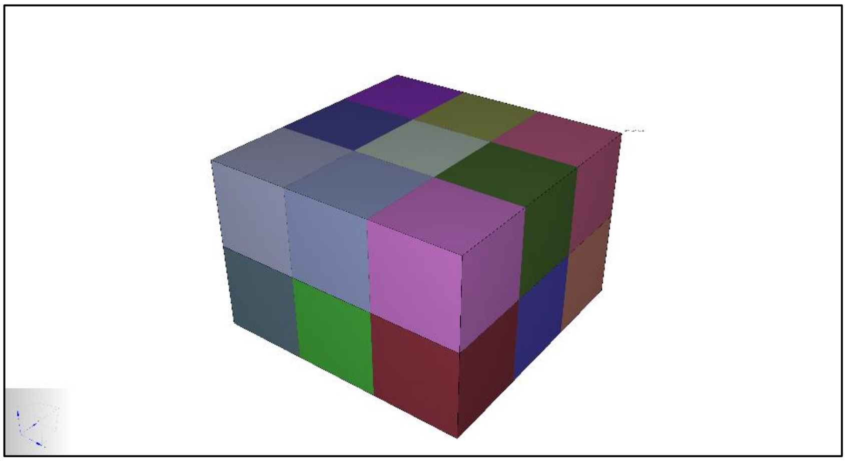


Figure 3.1 Simple synthetic model.

Table 3.1 Fluid flow properties of simple synthetic model.

Material	Rock Density (kgm^{-3})	Porosity	Horizontal Permeability k_x, k_y (mD)	Vertical Permeability k_z(mD)	Conductivity ($Wm^{-1}C^{-1}$)	Spesific Heat ($Jkg^{-1}C^{-1}$)
TOP	2600	0.01	4.00E-13	4.00E-13	2	1100
UOF	2600	0.01	1.00E-20	1.00E-20	2	900
HEAT	2700	0.01	1.00E-17	1.00E-17	3	1100
LOF	2700	0.01	1.00E-20	1.00E-20	2	900

Table 3.2 Geomechanics properties of simple synthetic model.

Material	Log Bulk Modulus	Poisson Ratio	Tensile Limit (Pa)	Modulus Young (Pa)	Drained Bulk Modulus (Pa)
TOP	2.5.E-04	0.4	1.50E+07	4.00E+10	6.7.E+10
UOF	2.5.E-04	0.4	1.50E+07	4.00E+10	6.7.E+10
HEAT	8.7.E-04	0.2	2.00E+07	5.00E+10	2.8.E+10
LOF	8.7.E-04	0.2	2.00E+07	5.00E+10	2.8.E+10

The fluid flow and geomechanics properties are shown in Table 3.1 and Table 3.2. Fluid flow model simulated until it reaches a natural state. Then, it is simulated by geomechanics-fluid flow simulator for ten years with one year time step.

3.2 GEOTHERMAL SYNTHETIC MODEL

The geothermal synthetic model was adopted from Wairakei geothermal field, New Zealand. It is designed to represent geothermal reservoir water dominated system. This model has 968 elements where each element has a different material as illustrated in Figure 3.2 and the summary of the material are shown in Table 3.3. This model covers 8.5 x 5 km area consist of 11 horizontal layers with depth 2.5 km. The surface and cap rock has thickness respectively 0.1 km 0.3 km thick. The reservoir is divided into 5 layers with total thickness is 2 km. Heat source is located at the bottom of layering system with 0.1 km of thickness.

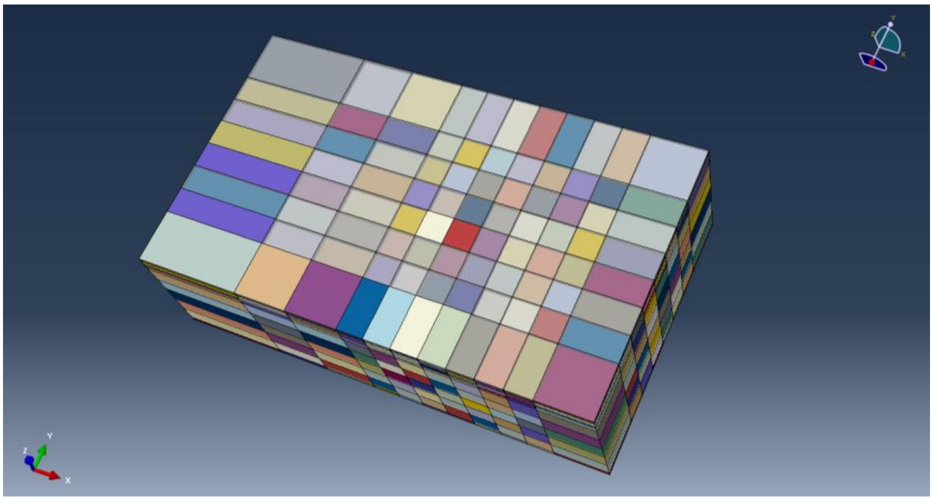


Figure 3.2 Geothermal synthetic model on ABAQUS®.

Table 3.3 Material properties of geothermal synthetic model.

Material	Rock Density (kgm^{-3})	Porosity	Horizontal Permeability k_x, k_y (mD)	Vertical Permeability k_z (mD)	Conductivity ($Wm^{-1}C^{-1}$)	Spesific Heat ($Jkg^{-1}C^{-1}$)	Hidraulic Conductivity (ms^{-1}) Min	Hidraulic Conductivity (ms^{-1}) Max	Log Bulk Modulus Min	Log Bulk Modulus Max	Poisson Ratio	Tensile Limit (Pa)	Modulus Young (Pa)
Ground Water	2150	25%	200.0	10.0	5	939	9.93E-05	1.08E-04	2.6.E-01	3.2.E-01	0.25	5.10E+06	4.17E+07
Cap Rock	2260	10%	0.6	0.001	5	875.7	1.03E-07	1.23E-07	1.6.E-01	2.6.E+00	0.25	5.70E+06	4.17E+06
Fault	2270	30%	1000.0	100.0	5	847.5	1.42E-05	2.74E-03	2.9.E-03	6.8.E-03	0.25	5.40E+06	8.33E+09
Boundary 1	2270	20%	0.5	10.0	5	847.5	2.07E-04	2.74E-04	4.3.E-03	5.9.E-03	0.25	5.40E+06	8.33E+09
Boundary 2	2270	20%	0.01	0.01	5	847.5	1.42E-07		2.6.E-03		0.25	5.40E+06	8.33E+09
Boundary 3	2270	20%	1	1	5	847.5	1.74E-05	2.74E-05	3.40E-03	5.9.E-03	0.25	5.40E+06	8.33E+09
Reservoir 1	2270	25%	500.0	5.0	5	847.5	5.78E-05	1.67E-03	1.9.E-03	2.1.E-03	0.25	5.40E+06	8.33E+09
Reservoir 2	2270	25%	400.0	10.0	5	847.5	5.90E-04		2.7.E-03		0.25	5.40E+06	8.33E+09
Reservoir 3	2270	25%	50.0	10.0	5	847.5	5.72E-04	5.83E-04	3.6.E-03	5.5.E-03	0.25	5.40E+06	8.33E+09
Basement	2540	15%	5.0	3.0	9	900.0	1.73E-04	5.67E-04	3.2.E-03	6.1.E-03	0.25	5.40E+06	8.33E+09

The basement as a host of heat produces a constant value of 4.0 x 10^{-5} $kgs^{-1}m^{-2}$ and constant enthalpy at 1.15 x 10^{6} Jkg^{-1}. The boundary condition set up for 1 x 10^{50} of volume factor. The pressure gradient follows hydrostatic equation, while temperature gradient applies the geothermal gradient, 3°C per km, with 20°C of surface temperature.

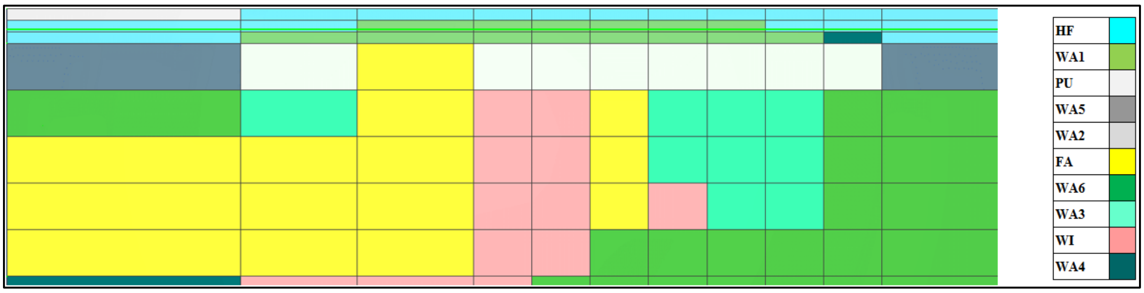


Figure 3.3 Cross section at center of geothermal synthetic model.

The fluid flow model is simulated until it reaches the natural state condition. After the natural state condition is achieved, ten production wells are implemented to the model and no injection well. Each production well has 60 kg/s for the mass flow rate. The entire depth of the well reaches 2 km with similar PI, 7.0 x10^{-13} m^3, and well head pressure 1.0 x 10^6 Pa.

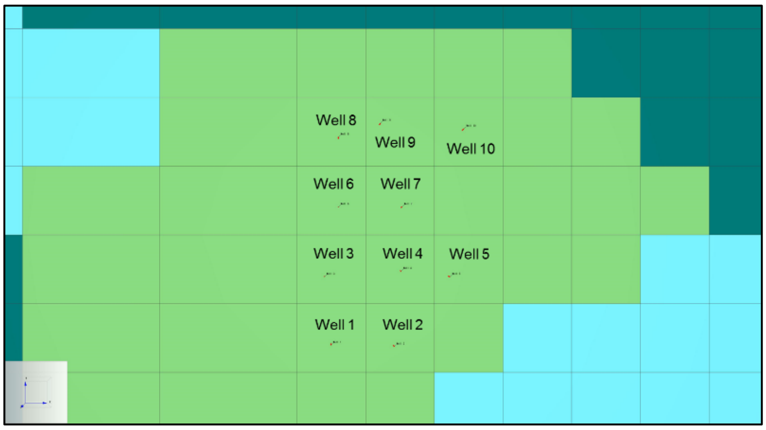


Figure 3.4 Well location in geothermal synthetic model.

4 SIMULATION RESULTS

4.1 SIMPLE SYNTHETIC MODEL

Simple synthetic model is simulated until it has a natural state condition. Figure 4.1 and 4.2 show the pressure and temperature distribution of natural state condition.

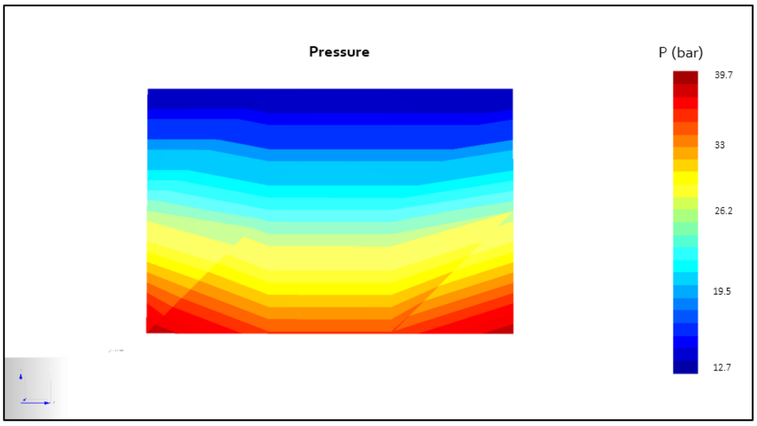


Figure 4.1 Pressure distribution natural state condition of simple synthetic model.

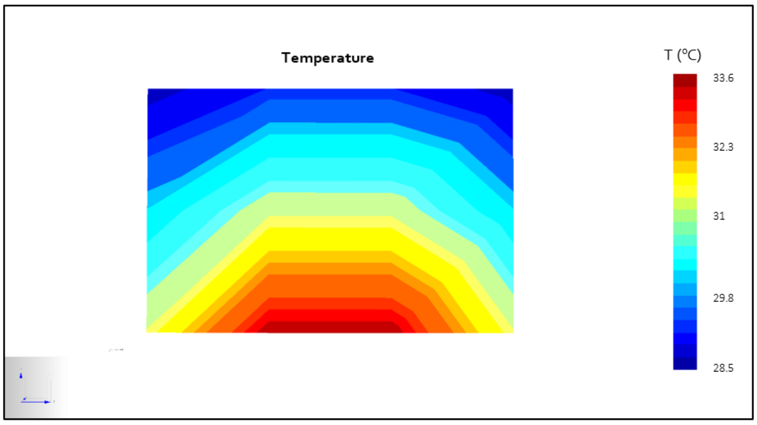
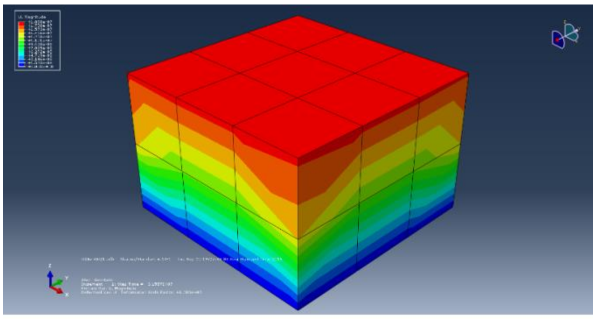
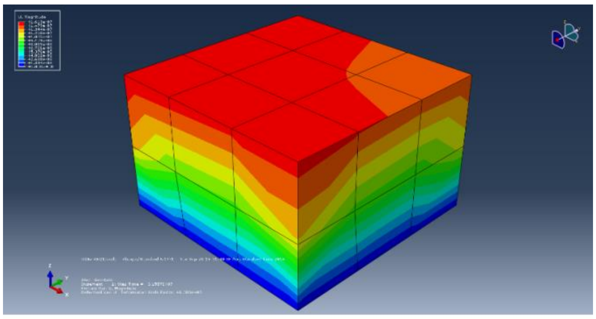


Figure 4.2 Temperature distribution natural state condition of simple synthetic model.

After this model reaches a natural state condition, iterative simulation is conducted. It is simulated for ten years with one year time step. The simulation results show that the permeability and porosity changes. The nodal position is changed due to stress and strain distribution. The nodal position changes at first year and tenth year can be seen in Figure 4.3.



(a)



(b)

Figure 4.3 Nodal displacement at first year (a) and tenth year (b) simulation.

The pore pressure changes may change the distribution of effective stress. Log bulk modulus value influence the changes in nodal position. The increase log bulk modulus value, the more resistant a material change in volume or shape.

Based on simulation results of simple synthetic model, the iterative simulator or the script can run properly. However, the process of making a script encountered many difficulties such as, the technical issues related to understanding the software input and output (IO) format. The effect of simulation to the IO format is not clearly explained in the manual books which requires a careful observation during run the script. The limitation of material number in TOUGH2® became an obstacle so it has been recompiled several times. While in coupled geomechanics-fluid flow simulation, each element must have a specific material to facilitate changes in porosity and permeability.

4.2 Geothermal Synthetic Model

The fluid flow model in geothermal synthetic model is simulated until it achieves the natural state condition. The natural state condition is achieved after 1,115,693,176.05 years and it is considered good enough to represent the natural condition before production activities. The pressure and temperature distribution are shown in Figure 4.4 and 4.5 with the vectors define as heat flow per surface area (m^2).

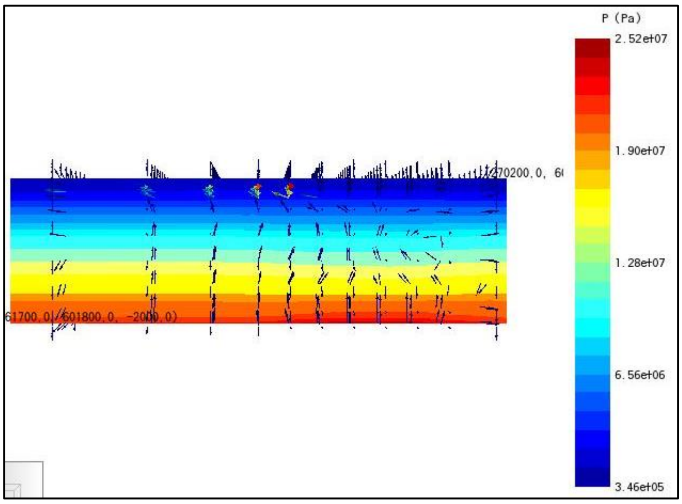


Figure 4.4 Pressure distribution natural state condition of geothermal synthetic model.

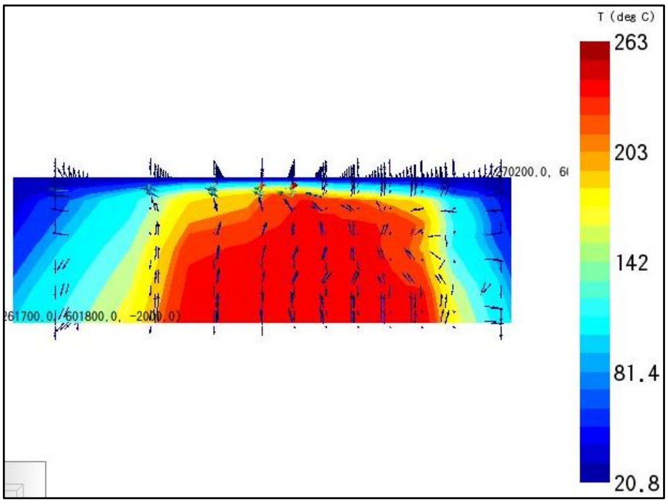
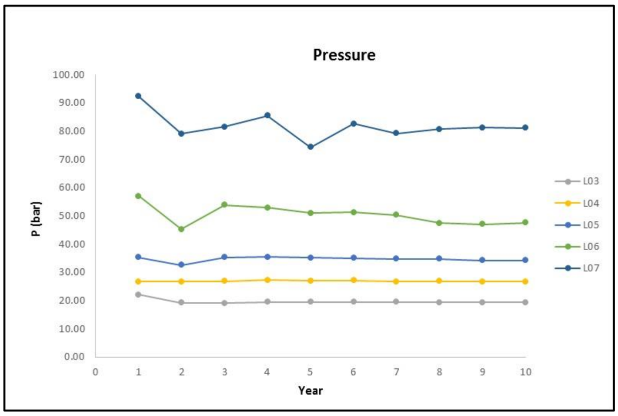
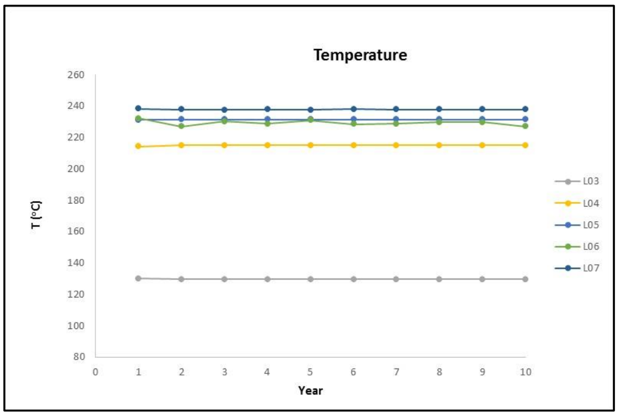


Figure 4.5 Temperature distribution natural state condition of geothermal synthetic model.

4.2.1 Pressure, Temperature, Porosity, and Permeability

After natural state condition has been achieved, the ten production wells are implemented and iterative simulation begins. Simulation is conducted for ten years with one year time step. The coupled geomechanics-fluid flow simulation results showed the changes in the value of the porosity, permeability, element volume, pressure, and temperature. The average value of pressure and temperature for each layer are shown in Figure 4.6.





(a) (b)

Figure 4.6 Pressure (a) and temperature (b) changes of each layer.

The pore pressure decrease lead to void ratio (porosity) change. There are porosity changes in each layer after ten years production (Figure 4.7).

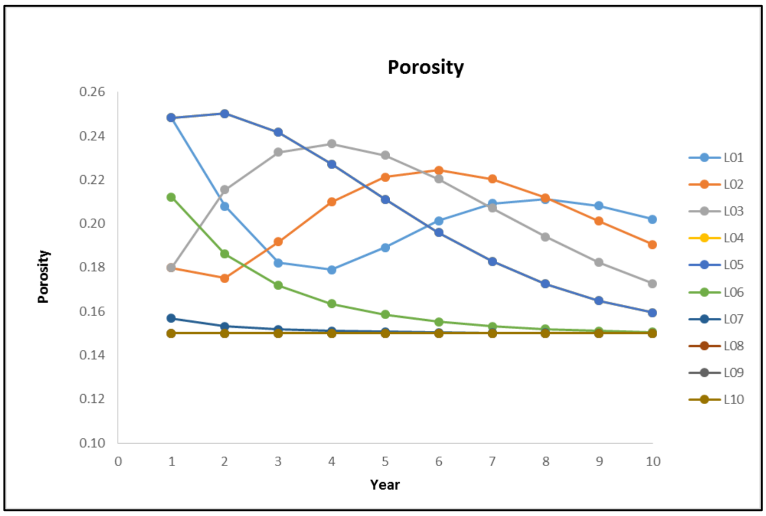
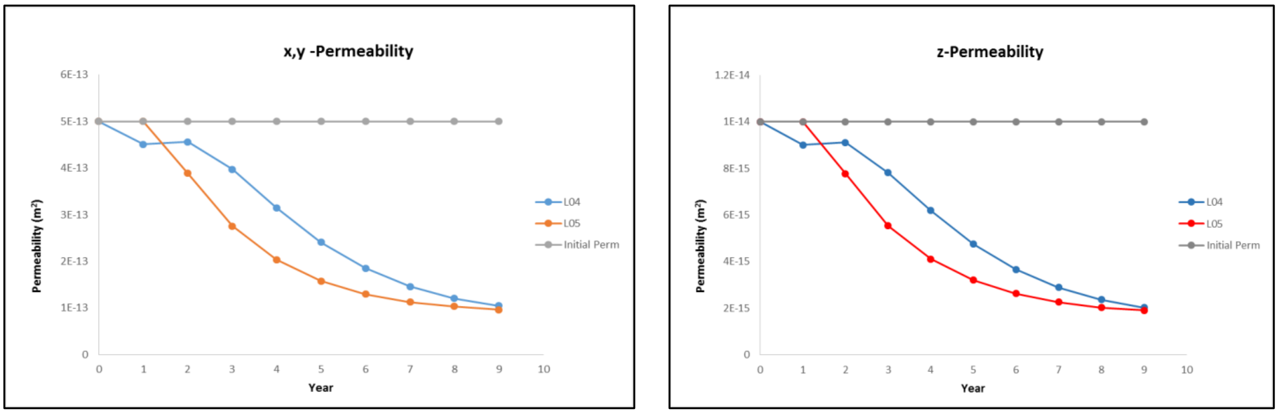


Figure 4.7 Porosity changes of each production layer.

Surface layer in TOUGH2® is assumed that no pressure change so volume of each element in L01 is assumed 0.0. Due to that assumption, the effect of fluid flow only reached L02. Meanwhile, volume of each element in the surface of geomechanics model still be calculated based on nodal position. The reservoir is located ranging from L03.

Porosity changes in all layers are divided into two types. First type is inconsistent changes as shown in L02 and L03 where the porosity enlarges until 5th and 6th year of production and then shrinks back. Pressure in L02 and L03 are too low so the value of porosity drops drastically. Then porosity slowly increases as pressure increases too after the second year. Porosity declines again since the pore pressure is stable after 5th year but the stress distribution remains unchanged. The second type is consistent changes. This type occurs in L04, L05, L06, and L07. Porosity in L04 until L07 slowly decrease which resulted a decrease in permeability. There are no permeability change in L08 to L10 because there are no porosity changes there.



(a) (b)

Figure 4.8 Permeability changes in x-y axis (a) and z axis (b).

4.2.2 Surface Displacement

The effective stress distribution of element will increase because of the change of an element volume that can occur when the pore pressure decreases. The nodal displacement changes occurred in x-y-z axis. Total displacement is calculated on all layers. Figure 4.9 shows the total displacement in production area is -36.7 mm with the depletion rate is about 3.6 mm per year.

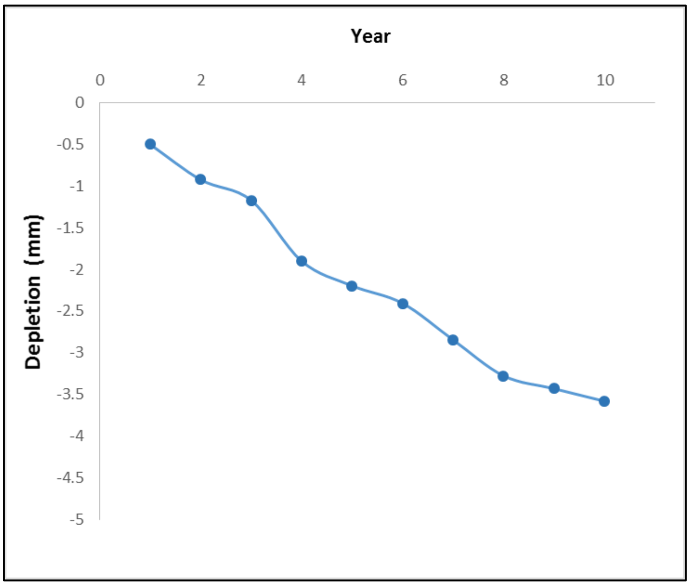


Figure 4.9 Total depletion in production area.

4.2.3 Mass Production Sensitivity Analysis

Mass production sensitivity analysis is conducted to observe the response of porosity and permeability value due to difference in production rates. The higher production rate, more decline of porosity and permeability. Sensitivity analysis has been done to this geothermal synthetic model to compare 600 kg/s production rate to 1000 kg/s. The response of porosity and permeability in reservoir layers are shown in Figure 4.10 and 4.11.

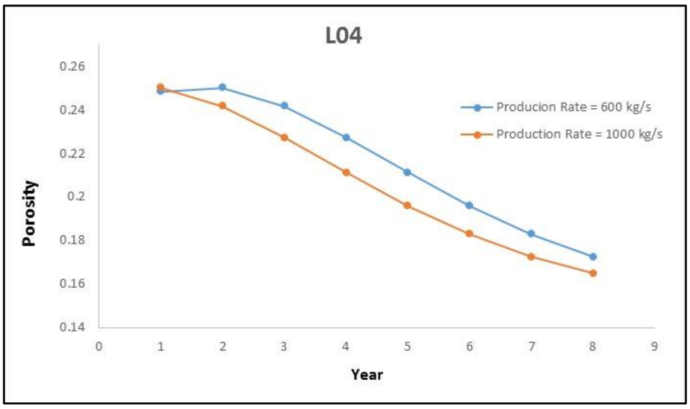
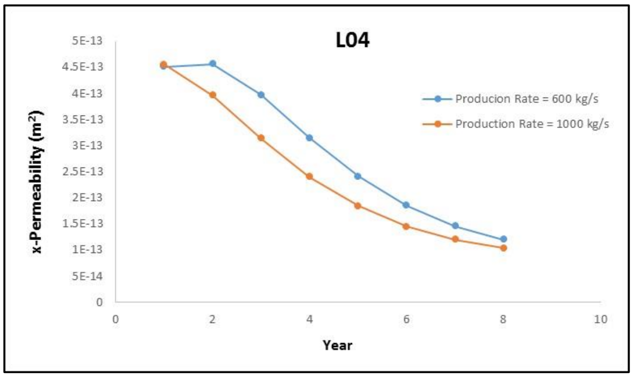
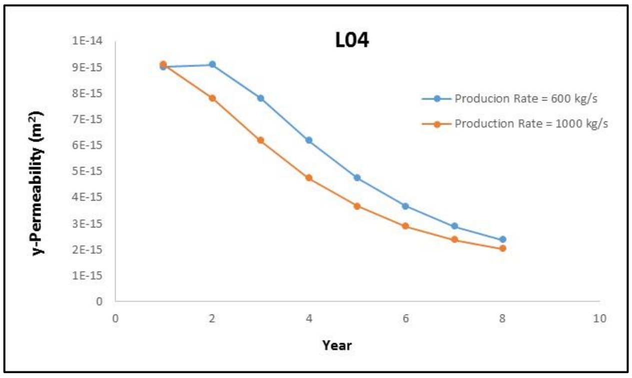


Figure 4.10 Porosity response in reservoir layer.



(a)



(b)

Figure 4.11 Permeability response of reservoir layer in x-axis (a) and y-axis (b).

5 SUMMARY OF CURRENT STATUS & FUTURE WORKS

The geomechanics-fluid flow simulation is as part of Ichwan A. Elfajrie master's thesis in Geothermal Master Program, ITB. The geomechanics-fluid flow simulation is able to run properly for synthetic models. The porosity and permeability can be updated in each time step. The geometry of the geothermal synthetic model may change as a result of the geomechanics effects. The void ratio changes affect the fluid flow at the next time step that would affect the pressure profile.

It was also found that this coupling method is frequently unstable due to the difficulties to satisfy the convergence criteria of the goemechanics module.

The plan for 2017 activities are:

a. Learn more about another geomechanics software,
b. Improve the coupling technique,
c. Use a simpler model for testing the simulation,
d. Apply on real field data,
e. Implement the assimilation technology for monitoring purpose,
f. Evaluate the result of simulation

REFERENCES

Dassault Systèmes Simulia Corp. (2014). *Abaqus 6.14 | Getting Started with Abaqus: Interactive Edition.* Dassault Systèmes Simulia Corp.

Allis, R. G. (2000). Review of subsidence at Wairakei field, New Zealand. *19*.

Altmann, J. B. (2010). *Poroelastic Effects in Reservoir Modelling.* Karlsruhe: Institut Teknologi Karlsruhe.

Anderson, E. M. (1951). *The Dynamics of Faulting and Dyke Formation with Application to Britain.* Edinburgh: Oliver and Boyd.

Bataee, M., & Irawan , S. (2014). Review of Geomechanical Application in Reservoir Modelling. *14*(10).

Biot, M. A. (1941). General Theory of Three Dimensional Consolidation. *12*.

Dassault Systèmes' Centers. (2005). *Abaqus 6.12 Analysis User's Manual* (Vol. Volume III: Materials). Dassault Systèmes' Centers.

Detournay, E., & Chang, A. (1993). Fundamentals of Poroelasticity. In J. Hudson, *Comprehensive Rock Engineering: Principles, Practice & Projects* (Vol. Vol 2 : Analysis and Design Methods). Oxford: Pergamon Press.

Elfajrie, I. A. (2016). *Geomechanics Effect on Geothermal Reservoir Modeling.* Bandung: Geothermal Master Program, Institut Teknologi Bandung .

Fakcharoenphol, P., & Wu, Y.-S. (2011). A Fully-Coupled Flow-Geomechanics Model for Fluid and Heat Flow in Geothermal Reservoirs. *35*.

Fakcharoenphol, P., Hu, L., & Wi, Y.-S. (2012). Fully-Implicit Flow and Geomechanics Model: Application for Enhanced Geothermal Reservoir Simulations. *Thirty-Seventh Workshop on Geothermal Reservoir Engineering.* Stanford: Stanford Geothermal Workshop.

Fu, P., Johnson, S. M., Hao, Y., & Carrigan, C. R. (2011). Fully Coupled Geomechanics and Discrete FLow Network Modelling of Hydraulic Fracturing for Geothermal Applications. *Thirty-Sixth Workshop on Geothermal Reservoir Engineering.* Stanford: Stanford Geothermal Workshop.

Logan, D. L. (2007). *A First Course in the Finite Element Method* (Vol. Fourth Edition). Chris Carson.

Terzaghi, K. (1943). *Theoretical Soil Mechanics.* New York: John Wiley & Sons, Inc.

Zoback, M. D. (2007). *Reservoir Geomechanics.* Stanford : University Press, Cambridge.