Applied Numerical Modeling in Geomechanics – 2020 – Billaux, Hazzard, Nelson & Schöpfer (eds.) Paper: 06-02
©2020 Itasca International, Inc., Minneapolis, ISBN 978-0-9767577-5-7

Iterative coupling of single-phase reservoir flow and geomechanics

Y.N. Saraiva, H.A.V. Haro & L.G. Rodrigues
Federal University of Ceará, Fortaleza, CE, Brazil

1 INTRODUCTION

Analysis by simulation in oil reservoirs is necessary due to the great importance of predicting and anticipating the consequences of behavior that occurs during depletion, as well as the geomechanical properties that change over time.

Our aim in comparing the fully coupled solution reported by Dean et al. (2006) with our external coupling using *IMEX* 2018 (CMG 2018) and *FLAC3D* 6.0 (Itasca 2017), is to point out the changes in permeability, porosity and compressibility, due to changes in volumetric strain caused by reduced pore pressures in a depletion scenario.

A simulation was performed of the flow-geomechanical coupling of problem 1, proposed by Dean et al. (2006) that involved subsidence and compaction drive in a single-phase water reservoir. To solve this problem, *FLAC3D* 6.0, *IMEX 2*018 and *MATLAB* 2018 software were coupled. The simulation was achieved by explicit iterative coupling, where the porous-flow and displacement calculations are performed sequentially. This technique gives a stable approach if there is convergence through established criteria.

By applying boundary conditions and entering pore pressures at each grid point, volumetric strain is calculated and reported using *FISH* commands. The equilibrium condition is adjusted by observing the mechanical ratio average, velocity and displacement graphs. The results show how well the iterative external coupling technique compares to the fully coupled solution reported by Dean's article.

The originality is related to the incorporation of the well into *FLAC3D* with different Young's Modulus, and the use of reaction force to aid in establishing model equilibrium. This methodology was also developed to solve complex situations that evolve from petroleum production and injection, especially at high levels of pressure depletion, and near faults or boundaries. The novelty of this procedure is that it has been detailed in a practical way to help model and understand uncertainties during petroleum production.

2 DESIGN AND ANALYSIS

According to observations made by researchers in the field of geomechanics, coupling is necessary because of the influences that occur in the reservoir. Zoback (2007) notes that reductions in reservoir pore pressure with production can cause significant deformation in a reservoir, including compaction and permeability loss, and, perhaps counter-intuitively, induce faulting in some reservoirs under normal faulting regimes or in the surrounding region.

Connell (2009) developed a coupling study for coal seams under gas production using coupling with SIMED II and *FLAC3D*, causing effects on permeability and porosity, due to changes in the effective stress.

Chalaturnyk (2010) proposed new porosity and permeability models for reservoir and geomechanical coupling, discussing the relationship between permeability and pore pressure.

Tran et al. (2004) developed a new formula for porosity as a function of pressure, temperature and mean total stress, which is used to improve the convergence speed of the iterative coupling used in *CMG* software. Only porothermoelastic materials are considered in the study. Mikelic et al. (2014) discuss the iterative coupling of fixed stress for a compositional flow model and include the corresponding parallel computational result in the structured grid. The flow model used is single-phase flow with finite element method.

Applications in the petroleum industry require both an understanding of the porous flow of reservoir fluids and an understanding of reservoir stresses and displacements. Some processes, such as high depletion in a soft rock or water injection in fractured reservoirs, involve a stronger coupling between porous flow and geomechanics (Dean et al. 2006). Hosseini & Chalaturnyk (2017) also showed that if the volumetric strain increases, the reservoir rock dilates and, porosity increases as a result of rock expansion.

So, our design for coupling flow and geomechanics is justified and it is applied in Dean´s problem 1 (Dean et al. 2006) described briefly here. Problem 1 is a single-phase water depletion that illustrates the role that stress, and displacement boundary conditions play in porous-flow calculations.

This problem imposes zero displacement boundary conditions on the vertical faces of the grid and at the bottom. The grid is 11×11×10 cells with dimensions of 70 m in the horizontal direction and 6 m in the vertical direction. Therefore, the overall dimensions are 770 × 770 × 60 (m) and totaling 35,574,000 m^3 in volume. The top of the grid is at a depth of 1829 m. The Young's modulus is 68.94 MPa, Poisson's ratio is 0.3, and the initial horizontal stresses are 27.58 MPa across the depth of the reservoir, while the initial vertical stress is 41.37 MPa at top of the grid.

Problem 1 assumes a uniaxial strain behavior. The problem has a vertical well with a wellbore radius of 0.08 m and is completed in the center of the pattern in all 10 grid layers, this well is produced at a rate of 15,000 bbl/day.

Our methodology allows both *FLAC3D* and *IMEX* to safely perform internal force calculations, achieving proper numerical control and material balance and is described in the following.

When a simulation is completed in any time-step of *IMEX*, the pore pressure data are extracted, and with these values, a program in *MATLAB* is developed to interpolate these pore pressures in the center of the zone to the grid points of each zone in *FLAC3D*.

Next, a workflow was designed in *FLAC3D* to be structured as follows: 1) creation of the model by brick size, 2) apply constitutive model and initial stress conditions, 3) fix all grid points, 4) apply reaction forces, 5) free the grid points, and 6) apply the constraint conditions of the problem with zero initial displacement before any change in pore pressure. To calculate the correct effective stress, reservoir pore pressures at time zero are applied to each grid point. Then, at selected time steps, the difference of pore pressure related to the previous step is applied by the calculated time in each grid point in an incremental way. Finally, we create *FISH* to export the volumetric strain data of each zone to *IMEX*.

With these values of volumetric strain, another program was designed in *MATLAB* that will use volumetric strain to update the values of permeability, compressibility and porosity of the reservoir in *IMEX* simulator. After, *IMEX* simulator is executed for a new time step, thus ending the cycle of coupled simulation, with mass conservation and convergence via restart option in *IMEX*.

The boundary conditions are similar for both *IMEX* and *FLAC3D,* restriction of displacement on the sides and bottom of the model, while the top is free (without restriction of displacement), thus providing uniaxial compression behavior, which guarantees vertical displacement. And thus, it is possible to observe the subsidence effect and other properties.

3 RESULTS AND DISCUSSION

The results obtained at the end of the *FLAC3D* simulation proved that the equilibrium conditions were guaranteed, as shown in Figure 1. This simulation was performed in the elastic stress regime, providing only the Poisson ratio and Young's modulus parameters.

Figure 1 shows the mechanical ratio average balancing calculation process developed by *FLAC3D*. The peak region of the graph is characterized by the entry of initial pore pressures and soon after applying the difference of pore pressures from 0 to 250 days until equilibrium is reached again.

The values of volumetric strain, in studied time interval, were obtained, as shown in Figure 2. It is observed that the strain in the center is higher in relation to the boundary, indicating a tendency of traction in the extremities and contraction in the center, confirming the arc effect.

Figure 2 also shows the distribution, over space in a specific time, of the incremental volumetric strain of the entire cells-zones of the reservoir. It is observed that the difference in pore pressures provides a smooth and precise distribution of the deformations that occur in the reservoir.

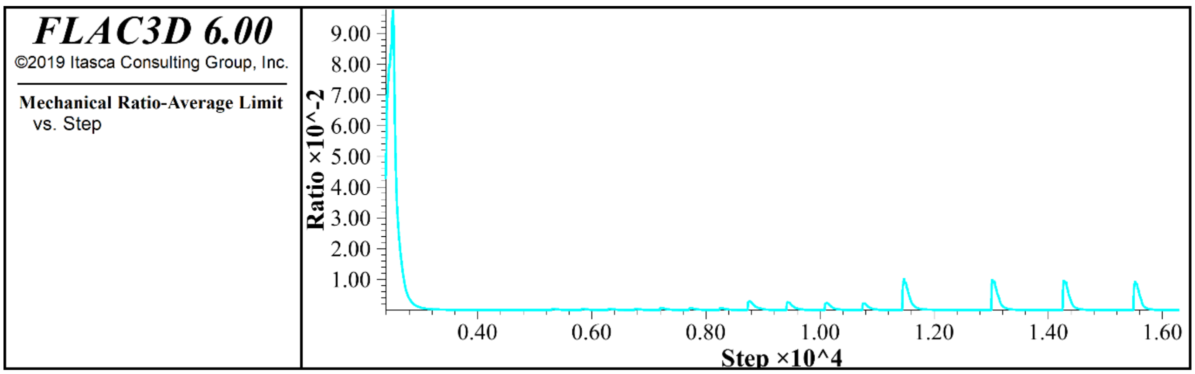

Figure 1. Mechanical ratio-average limit until 250 days.

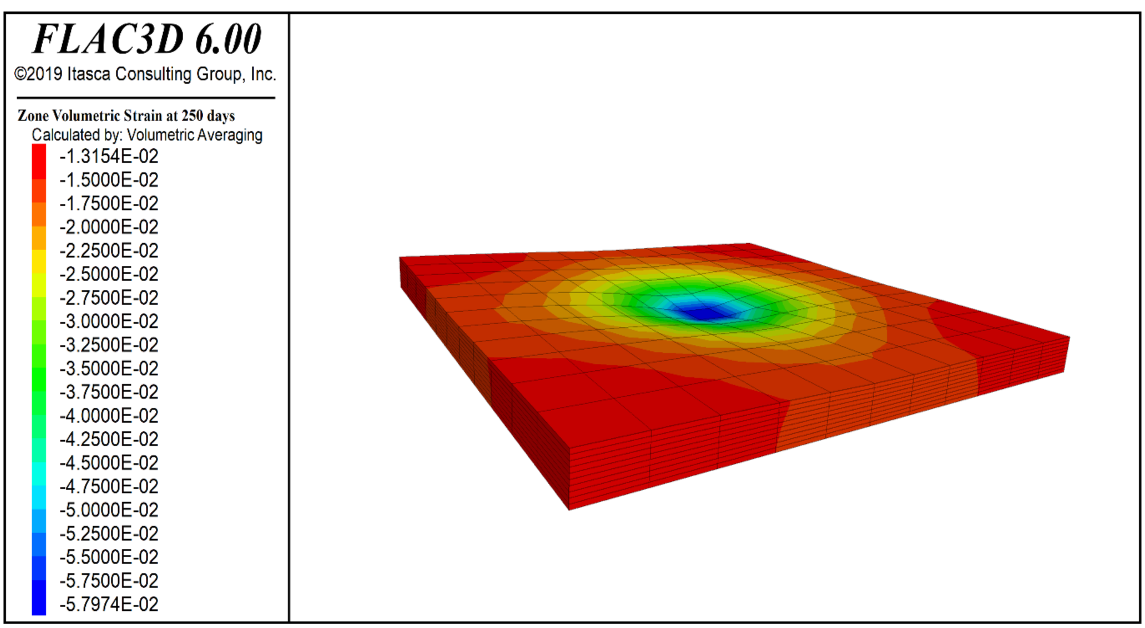

Figure 2. 3D visualization of volumetric strains at 250 days.

The development of reservoir subsidence, at high levels (>30 cm), may compromise reservoir and well integrity or even cause accidents such as reservoir collapse. In addition, reducing pressure inside the reservoir may provide a decrease in the well production ratio due to decreased permeability.

4 CONCLUSIONS

Values of volumetric strains and stresses due to the reduction of pore pressures because of depletion is a significant relationship as shown in this work.

This work also shows how the reservoir behaves and how it deforms during exploitation, ensuring a safe monitoring of the reservoir, updating key reservoir parameters as porosity, permeability and compressibility.

The new external iterative coupling proposed in this work obtained the same result as the full coupling proposed in Dean's article. However, the coupling developed in this work ensures better control of the properties and behavior of the simulation, due to the adjustment and analysis of geomechanical parameters.

REFERENCES

Chalaturnyk, R. 2010. Permeability and Porosity Models Considering Anisotropy and Discontinuity of Coalbeds and Application in Coupled Simulation. *Journal of Petroleum Science and Engineering* 74: 113-131. New York, USA: Elsevier Scientific Publishing Company.

CMG, Computer Modelling Group, Ltd. 2018. *IMEX – Black Oil & Unconventional Simulator, User's Guide*. Calgary, CAN: CMG.

Connell, L.D. 2009. Coupled Flow and Geomechanical Processes During Gas Production from Coal Seams. Elsevier Scientific Publishing Company, *International Journal of Coal Geology* 79: 18-28. New York, USA.

Dean, R.H., Gai X., Stone C. M. & Minkoff S. E. 2006. A Comparison of Techniques for Coupling Porous Flow and Geomechanics. Society of Petroleum Engineers, *SPE Journal* 79709: 132-140.

Hosseini, B.K. & Chalaturnyk, R. 2017. A Domain Splitting-Based Analytical Approach for Assessing Hydro-Thermo-Geomechanical Responses of Heavy-Oil Reservoirs. Society of Petroleum Engineers, *SPE Journal* 170193: 300-315.

Itasca Consulting Group, Inc. 2017. *FLAC3D – Fast Lagrangian Analysis of Continua in 3 Dimensions, Ver. 6.0 User's Manual*. Minneapolis: Itasca.

MATLAB & Simulink for Building Simulation – State of the Art, MathWorks, Inc., 2018. MA, USA.

Mikelic, A., Wang B. & Wheeler M.F. 2014. Numerical Convergence Study of Iterative Coupling for Coupled Flow and Geomechanics. Springer Science + Business Media Dordrecht, *Comput Geosci* 18: 325-341 2014. Berlin, GER.

Stevenson, M. & Pinczewski, V. 1995. *SIMED II – Multi-Component Coalbed Gas Simulator. User's Manual Version 1.21*. Centre for Petroleum Engineering, University of New South Wales. Sydney, AUS.

Tran, D., Settari A. & Nghiem L. 2004. New Iterative Coupling Between a Reservoir Simulator and a Geomechanics Module. Society of Petroleum Engineers, *SPE Journal* 88989: 362-369.

Zoback, M.D. 2007. *Reservoir Geomechanics*. Cambridge University Press. New York, USA.