Impact of Heterogeneous Geomechanical Properties on Coupled Geomechanical-Flow Simulation of SAGD

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In the modern oil industry, geostatistical property models are built for different purposes such as resource estimation and flow simulation. Processing of multiple realizations, obtained from geostatistical simulation techniques, helps assess uncertainty analysis which is important for development planning and decision-making processes. Each geological model is a combination of structural, facies, and attributes models. In the case of conventional flow simulation (i.e. without considering geomechanical simulation), the petrophysical properties porosity, permeability and saturation, are the only attributes necessary to model. These parameters are included in the fluid flow governing equations. But in the case of dealing with coupled geomechanical-flow simulation, rock mechanical properties are also required. In the case of conventional simulation process, geostatistical property models have been used widely, but in the case of coupled geomechanical-flow simulation processes, geostatistical modeling for geomechanical attributes has yet to be incorporated. Therefore, uncertainty assessment could be underestimated according to the spatial distribution of these parameters. In this work, the effect of heterogeneous geomechanical properties on coupled geomechanical-flow simulation process was investigated for a steam assisted gravity drainage (SAGD) process for a heavy oil reservoir in Alberta-Canada. Cumulative oil Production (COP), Steam Oil Ratio (SOR) and Vertical Deformation Profile (VDP) of the top of reservoir is considered as three simulation output variables. Consideration of heterogeneous models for both flow and geomechanical properties in coupled geomechanical flow simulation of the SAGD process resulted in a range of uncertainties for these three variables. The importance of considering geomechanical properties as heterogeneous models is illustrated by comparing these ranges with the ranges obtained from coupled simulations in which geomechanical properties are considered as homogeneous models. Representative synthetic data of a sand/shale spatial distribution of McMurray formation in Alberta-Canada is considered for the case study.

Introduction

Canada has large heavy oil (oil sand) resources, which are mostly deposited in northern Alberta and Saskatchewan. Surface mining technology is used to extract and produce oil reserves which are close to the surface (<65m), however about 80% of the oil sands are below economical open pit mining depth. This oil must be recovered by in situ recovery techniques including Steam Assisted Gravity Drainage (SAGD), Cyclic Steam Stimulation (CSS) and Vapor Extraction (VAPEX). With the exception of Imperial Oil's Cold Lake CCS operations, SAGD has been proven to be the most effective. In the SAGD process, two parallel horizontal wells are drilled in the formation, the first about 5m above the base of the reservoir and the second about 4 to 6 meters above the first well. The upper well injects steam and the lower one collects the heated crude oil or bitumen that flows out of the formation, along with any water from the condensation of injected steam.

The role of geomechanics has been proven to be an important issue in SAGD process (Chalaturnyk (1997)). Because of continuous steam injection, temperatures and pore pressures change in reservoir, which results in change in effective stress and therefore deformation of formation. Geomechanical response of reservoir has an effect on hydraulic parameters of formation (i.e. porosity, permeability and rock compressibility).

Oldakowski (1994), Scott et al. (1994) and Touhidi-Baghini (1998) conducted series of lab test experiments to characterize relationship between permeability change and geomechanical processes. Chalaturnyk (1996) summarized test results on oil sands and provided a relationship between oilsand compressibility and effective confining stresses.

Geomechanical analysis of the SAGD process is important not only for correct prediction of reservoir performance but also for other aspects of reservoir studies in which geomechanics plays significant role such as cap rock integrity analysis. However, in this work our focus is just on the effect of geomechanics on production performance of reservoir during the SAGD process.

In conventional reservoir simulation techniques coupled mechanism between fluid flow and reservoir deformation is not considered. For a more accurate prediction of SAGD performance there is a need to couple geomechanical effect with thermodynamic and hydraulic effects of SAGD process. Fully coupling (Du et al. (2005) and Yin et al. (2009)), iterative coupling (Settari et al. (1998) and Tran et al. (2005a)), explicit coupled (Minkoff et al. (1999) and Tran et al. (2005b)) and pseudo coupling (Tran et al. (2005b) and Espinoza (1983)) approaches are four main types of coupling which are discussed and applied variously. Tran et.al (2009) compares these approaches according to accuracy, adaptability and running time speed aspects. Because of its complexity, fully coupling approach has less been applied in comparison to other types.

Almost all natural soils are highly variable and rarely homogeneous. Lithological and inherent spatial variability of soils, are two categories of soil heterogeneity. To improve the accuracy of SAGD performance predictions, detailed high-resolution geological models are built geostatistically, which are applied in numerical simulation process. In this way, instead of deterministic analysis, probabilistic analysis is performed and uncertainty analysis on range of output variables results in making further decisions with lower level of risk. Work has been done to see the effect of heterogeneity related to petrophysical parameters on SAGD performance (Dharmeshkumar (2010)). Although the effect of rock mechanical heterogeneities has been investigated on macro behavior of soil for some aspects of geotechnical engineering problems, for coupled geomechanical-flow simulation, heterogeneity consideration related to rock mechanical parameters has yet to be incorporated.

The objective of this work is to investigate the importance of considering heterogeneous models for geomechanical properties during coupled geomechanical flow simulation of SAGD process. Considering heterogeneous models for both petrophysical and rock mechanical properties results in range of uncertainty for each output variable and it is expected that this range decreases if homogenous property models are considered instead of heterogeneous models. In the following work, by comparing ranges of uncertainty obtained from the simulation models with heterogeneous petrophysical and rock mechanical properties with the range obtained from heterogeneous petrophysical but homogenous rock mechanical properties, the effect of heterogeneity consideration for rock mechanical properties on coupled geomechanical flow simulation of SAGD process is investigated.

Cumulative oil Production (COP), Steam Oil Ratio (SOR) and Vertical Displacement Profile (VDP) of top of reservoir are considered as three output variables. COP and SOR are two of main parameters of interest for petroleum engineers to investigate performance of SAGD process. VDP is one of the main geomechanical responses of reservoir which should be investigated for different aspects of reservoir in which geomechanics is an issue.

Synthetic data, which is representative of sand/shale spatial distribution of McMurray formation in Alberta-Canada, is considered for case study.

In this study, STARS (from CMG group) and FLAC (from Itasca) are used for flow and geomechanical simulation process respectively.

Geomechanical behavior of oilsand

Several geomechanical lab tests have been performed to determine the stress strain behavior of oil sand under different operating condition. According to the results obtained by Wan (1991), it could be concluded that oil sand behaves as strain softening and accompanying dilation after yielding at lower confining stress, whereas it becomes stiffer (hardening) and compressible at higher confining stress. The degrees of softening/dilation, hardening/compression rise with increasing temperature.

Critical state theory and associated critical state model, such as the Cam-Clay model would be appropriate for describing this kind of mechanical behavior. But for simplicity, in this study an elastic-perfectly plastic Mohr-Coulomb failure criteria has been used. Before failure oil sand behavior is controlled by elastic theory and using bulk and shear modulus elastic parameters. After yielding, the material is assumed to behave perfectly plastic.

Dilation and associated volumetric strain are calculated based on the associated and non-associated flow rule. In non- associated flow rule (used here), the potential function is not the same as yield function. The potential function in non-associated flow rule is described by dynamic dilation angle to address change of dilation and associated volumetric strain.

Permeability increase of oilsand

In this work, the results of experimental work by Touhidi-Baghini (1998) was used for updating permeability. Based on that work, when oil sand specimens experienced contraction in the beginning of shearing, there was almost no change in absolute permeability. However, permeability increase was observed when shear induced dilation occurred and this permeability increase could be formulated as a function of its volumetric strain as follow.

$$\ln\frac{k}{k_0} = C\varepsilon_v \tag{1}$$

Based on data analysis obtained from Touhidi-Baghini (1998) experimental work, for vertical cores in formula (1) the value of C was 17.48 and for horizontal core it was 9.07.

Model description

To decrease boundary effects and to make more precise analysis, the dimensions of model considered for geomechanical analyses is usually 3 to 4 times larger than dimensions of model considered for flow analysis. In addition to the common reservoir section between two simulators, additional depth above and below of the reservoir (over burden and under burden) and some side burden will be considered in the geomechanical model (Figure 1). Since the reservoir section is the only part which is considered for coupled geomechanical-flow analysis process, a coarser gird was considered for other parts in comparison to fine grid system considered for the reservoir.

Fixed horizontal displacement in all sides and fixed vertical displacement at the bottom of the model are applied the boundary condition considered for this study. In situ stress configurations (i.e. magnitudes and directions) have significant effect on any geomechanical study. In reservoir geomechanics, consideration of this fact has significant effect on parameters such as optimization of injection pressure to prevent cap-rock instability, maximum dilatancy of reservoir, and selection of direction for drilling to maximize SAGD performance.

The magnitudes selected for minimum and maximum horizontal stresses, pore pressure and vertical stress considered for this study are based on study of Collins (2002) and summarized in Table 1.

Table 1: Initial stress, pore pressure and temperature for the case under study [After Collins (2002)]

Parameter	Value
Reservoir Depth	150 meter
σ_h / σ_v	1
σ_H / σ_v	1.5
Initial reservoir pressure	650 KPa
Initial reservoir temperature	12 °C

According to previous studies of Azad (2011) and Li (2006), higher injection pressures result in larger geomechanical effects. By considering initial stress values (mentioned in Table 1), 3000 KPa has been selected in this study for steam injection pressure, which is suspected to be below cap-rock fracture gradient.

Petrophysical and rock mechanical properties of oilsand

The focus of this study was to investigate heterogeneous geomechanical property effects on results obtained from flow and geomechanical simulation. Porosity, permeability and saturation are petrophysical inputs and elastic (bulk and shear modulus) and plastic (friction angle, dilation angle and cohesion) inputs are rock mechanical properties which could be modeled stochastically.

The reservoir section is the only part which is in common between two simulators. Therefore, other parts of model shown in Figure 1 were modeled as constant. The over, under and side burden zones are modeled linear elastically (Table 2).

In addition to the mechanical rock properties for the geomechanical simulation, other rock mechanical properties will be considered in flow simulator as well. In Table 3 these properties which are just related to reservoir section have been summarized. Parameters in Table 2 and Table 3 have been selected from previous researches done by Chalaturnyk (1996) and Li (2006).

Table 2: Grid Density information for the model under study

Zone	Parameter	Value
Overburden	Bulk Density (Kg/m^3)	2200
	Bulk Modulus (MPa)	208
	Shear Modulus (MPa)	96.2
	Linear Thermal Expansion coefficient (°K^{-1})	2×10^{-5}
Side Burdens	Bulk Density (Kg/m^3)	2200
	Bulk Modulus (MPa)	620
	Shear Modulus (MPa)	286
	Linear Thermal Expansion coefficient (°K^{-1})	2×10^{-5}
Under Burden	Bulk Density (Kg/m^3)	2200
	Bulk Modulus (MPa)	4167
	Shear Modulus (MPa)	1923
	Linear Thermal Expansion coefficient (°K^{-1})	2×10^{-5}

Table 3: Rock parameters used in flow simulator

Parameter	Value
Rock Compressibility (1/KPa)	5×10^{-6}
Rock Expansion Coefficient (°C^{-1})	3.84×10^{-5}
Rock Heat Capacity (KJ/Kg°K)	1865
Rock Thermal Conductivity (W/m°K)	1.736

No project specific data was selected for this research, therefore synthetic geostatistical models have been built for petrophysical and rock mechanical properties of reservoir section. For that purpose, an unconditional sequential gaussian simulation algorithm with specific mean and standard deviation values for each property has been used for to prepare several realizations for that property. The "sgsim" program from "GSLIB" package (Deutsch (1998)) was used for that purpose.

In Table 4 mean, standard deviation, minimum and maximum cut-offs which was used for synthetic data generation and for sgsim process has been summarized.

Table 4: Mean, SD, minimum and maximum cut-offs of attributes considered for Oil sand

Property	Mean	Standard Deviation (SD)	Minimum Cut-Off	Maximum Cut-Off
Bulk Modulus (MPa)	700	80	500	900
Shear Modulus (MPa)	320	30	250	400
Friction angle (°)	60	7	40	75
Dilation angle (°)	20	3	15	25
Horizontal Permeability (mD)	4000	450	2500	5000
Porosity (%)	0.32	0.04	0.25	0.4
Oil Saturation (%)	0.85	0.05	0.75	1

Results

Elastic Parameters Sensitivity Analysis. Three different models with minimum, mean and maximum values for elastic parameters were considered for the sensitivity analysis. By considering the same property models for flow simulation and by comparing responses obtained from geomechanical simulator, it could be concluded that if there is a need to consider elastic properties as heterogeneous or homogenous. Figure 2 shows vertical displacement profile response at the top of reservoir, obtained from explicit coupled simulation of these three different cases. As it could be concluded from Figure 2, considerable changes in VDP can be seen. Therefore, geomechanical responses are sensitive to elastic properties and conventional approaches of considering mean value for elastic properties may results in biased results.

Plastic Parameters Sensitivity Analysis. In the Mohr-Coulomb failure criteria, cohesion and friction angle are the values which should be specified for the material under analysis. Dilation angle is another plastic property which should be determined in the case of considering non-associated flow rule. Cohesion is considered as a constant value (zero) and sensitivity analysis is performed on friction and dilation angle only. Figure 3 shows the sensitivity of displacement profile respect to dilation angle (a) and friction angle (b). As could be concluded from these graphs, geomechanical responses are more sensitive to friction angle in comparison to dilation angle. To investigate this further, the same scenario but with different injection pressure (P_{inj}=3000 kPa) was completed. As shown in Figure 4, the same trend of change in displacement profiles was seen for the new injection pressure as well.

Uncertainty Analysis. As mentioned earlier, to investigate how heterogeneity considerations for geomechanical parameters affect a range of output results, two different cases for property models are considered:

a) Heterogeneous petrophysical and rock mechanical properties
b) Heterogeneous petrophysical and homogeneous rock mechanical properties

The difference between the range of uncertainty of output variables (COP, SOR and VDP) in these two cases is related to the effect of heterogeneous considerations for rock mechanical properties. Considering "homogeneous petrophysical and heterogeneous rock mechanical properties" is unusual, but to have a comparison between the effect of heterogeneity for petrophysical and rock mechanical properties on overall range of uncertainty, this case is considered as well. This case is named as case (c) in the following sections.

Figure 5, shows the results of different cases for one realization. The red curve is related to the model with homogeneous petrophysical and rock mechanical properties.

By investigating the results obtained from this single realization it could be concluded that COP and SOR curves for case (a) and case (b) are close to each other but there is considerable change in displacement profile. By comparing the results obtained from case (b) and case (c) it could be concluded that COP and SOR are more sensitive to petrophysical properties and heterogeneity of these properties has more effect on these variables in comparison to rock mechanical properties while displacement profile is more sensitive to rock mechanical properties respect to petrophysical properties.

To make more accurate conclusions it is necessary to analyze the results obtained from several realizations. In Figures 6, 7 and 8 maximum and minimum COP, SOR and displacement profiles obtained from 25 realizations are shown. Like Figure 5, the red solid line is the curve obtained from homogeneous petrophysical and rock mechanical property model.

P10, P50 and P90 are the most important values which petroleum engineers and management use to inform their decisions. In Figures 9, 10 and 11, a box plot format is used to illustrate the minimum, P10, P50, P90 and maximum values for COP, SOR and VDP.

As could be seen from above graphs, COP and SOR range of uncertainty is bigger for case (c) in comparison to case (b).

It could be concluded that, although heterogeneous models for rock mechanical properties results in considerable differences in range of uncertainty in flow output variables (specially in COP results), their effects are lower than the effects of heterogeneity for petrophysical properties. However, by comparing range of uncertainty for displacement profile for case (c) and case (b) it could be concluded that, heterogeneity in rock mechanical properties has more effect on geomechanical response of reservoir in comparison to heterogeneity consideration for petrophysical properties. Since both flow and geomechanical responses should be considered simultaneously to predict and optimize SAGD production performance, it could be concluded that ignoring heterogeneity considerations for rock mechanical properties may result in biased analyses.

Case Study

Oil sands resources of Canada are deposited in the McMurray formation, which is a complex sequence of sand/shale deposit. The McMurray formation's geological structure is fairly well known and uncertainty in facies and petrophysical that contribute the most to uncertainty in production performance has been studied very well. However, uncertainty in production performance and geomechanical response of the reservoir as a result of uncertainty in rock mechanical properties has not been investigated very well. Based on the results obtained in previous section it could be concluded that ignoring considering heterogeneity models for rock mechanical properties may results in underestimation of range of uncertainty in the case of coupled geomechanical-flow simulation process.

In this case study and by considering synthetic facies models which are representative of sand/shale sequences in McMurray formation, the effect of heterogeneity consideration for rock mechanical properties is investigated. Information described in previous sections for sand properties, operating condition and model dimensions are used below.

Geomechanical behavior of Inter Bedded Shale (IBS)

IBS behaves as a strain softening material similar to oil sand and dilation could be observed in low confining stresses but will decrease significantly at higher confining stresses. An elastic-perfectly plastic constitutive model with non-associated flow rule for controlling dilation and associated volumetric strain has been considered for IBS materials.

Permeability increase of IBS

In this work and for updating permeability change, the following simple formulation has been applied.

$$Shale\ Permeability = \begin{cases} Constant & Before\ Failure \\ 100\ mD & After\ Failure \end{cases} \quad \textbf{(2)}$$

Petrophysical and rock mechanical properties of IBS

Table 5 shows information about shale petrophysical and rock mechanical properties used for IBS.

Table 5: Mean, SD, minimum and maximum cut-offs of attributes considered for IBS

Property	Mean	Standard Deviation (SD)	Minimum Cut-Off	Maximum Cut-Off
Bulk Modulus (MPa)	300	50	150	450
Shear Modulus (MPa)	140	20	80	180
Friction angle (˚)	30	7	10	50
Dilation angle (˚)	7	2	4	10
Cohesion (kPa)	550	50	400	700
Horizontal Permeability (mD)	0.0001	0.0001	0.00005	0.0002
Porosity (%)	0.01	0.005	0.005	0.02
Oil Saturation (%)	0.01	0.005	0.005	0.02

Sequential indicator simulation (sisim) from GSLIB package (Deutsch (1998)) was used to build several sand/shale sequences and then by using the sgsim approach and considering data from Table 4 and Table 5, property models were built. It should be mentioned that the percentile of shale considered for this study is 20%. Figure 12 shows one of facies realization and property models based on this facies model.

Results

Elastic Parameters Sensitivity Analysis. Figure 13 shows the result of sensitivity analysis on elastic parameters. Left Figure shows three different deformation models by considering 3 different homogeneous elastic properties. Right Figure shows 3 different displacement profiles by considering mean value, maximum value and minimum values for both shale and sand properties.

Plastic Parameters Sensitivity Analysis. Figure 14 shows sensitivity of vertical displacement profile with respect to plastic parameters. It could be concluded that both facies and inherent rock mechanical properties have effect on geomechanical response of reservoir.

Uncertainty Analysis. Cases (a), (b) and (c) defined in the previous section is considered here as well as well as a case considering homogeneous models for both petrophysical and rock mechanical properties. Figure 15, shows the results of different cases for one realization. The red curve is related to the model with homogeneous petrophysical and rock mechanical properties. Differences in COP, SOR and displacement profiles can be seen.

To make more accurate analysis several realizations are considered. According to facies heterogeneity, even by considering homogeneous property models, range of uncertainty in output variables should be expected. So in addition to three previous defined cases, cases (a), (b) and (c), another case which is homogenous models for both petrophysical and rock mechanical properties is considered here as well. In Figures 16, 17 and 18 maximum and minimum of COP, SOR and displacement profile obtained from 25 realizations of 4 different cases are shown respectively. The red solid line in each graph is representative of mean of 25 realizations for the case in which homogeneous models is considered for petrophysical and rock mechanical properties. Figures 19, 20 and 21 summarized the results of uncertainty analysis and P10, 50, and P90 calculations for different cases mentioned above. The same conclusion as previous could be made for this case study. Heterogeneity considerations for rock mechanical properties has an effect on COP and SOR range of uncertainties, but their effect is not as significant as petrophysical heterogeneity consideration. However, rock mechanical heterogeneity is more important and has more effect on the displacement profile in comparison to petrophysical properties.

Discussion and Conclusions

Investigations on the impact of considering heterogeneous rock mechanical properties in coupled geomechanical flow simulation of SAGD process was the objective of this study. To reach to that purpose, a range of uncertainties of COP, SOR and displacement profiles by considering heterogeneous models for both petrophysical and rock mechanical properties was compared with the range of uncertainties of these output variables by considering heterogeneous petrophysical but homogeneous rock mechanical properties. The difference between these two ranges was interpreted as the effect of rock mechanical heterogeneity. The main conclusion obtained from the base case analysis and case study analysis in this study is as follow:

- Although the effect of rock mechanical heterogeneity on COP and SOR should not be ignored, the effect of heterogeneity for petrophysical properties is more important in comparison to rock mechanical properties.
- The displacement profile which was selected as geomechanical response of reservoir for this study is more sensitive to rock mechanical properties than to petrophysical properties.
- In the case of investigating coupled geomechanical flow simulation of SAGD process both flow and geomechanical responses was analyzed. It could be concluded that heterogeneity for both of these groups of parameters should be considered. This consideration results more accurate analysis and more precise decisions which should be made based on simulation analysis.

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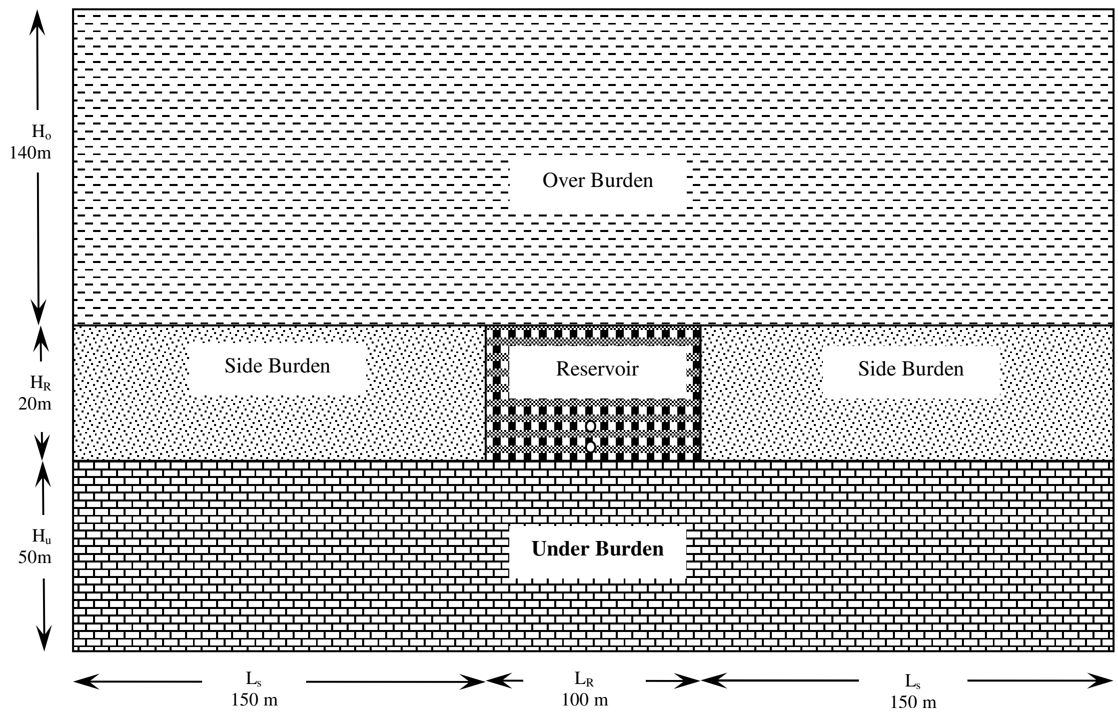


Figure 1: Model description and dimensions used for this study

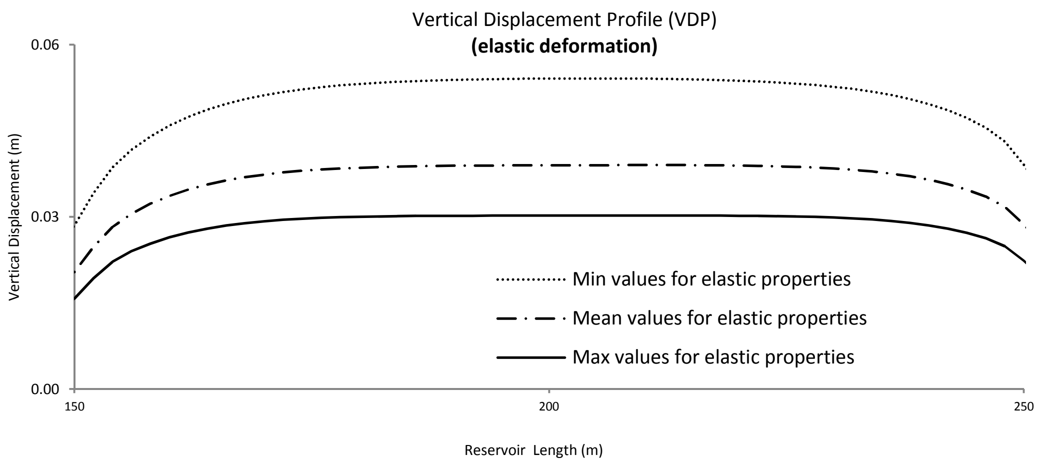
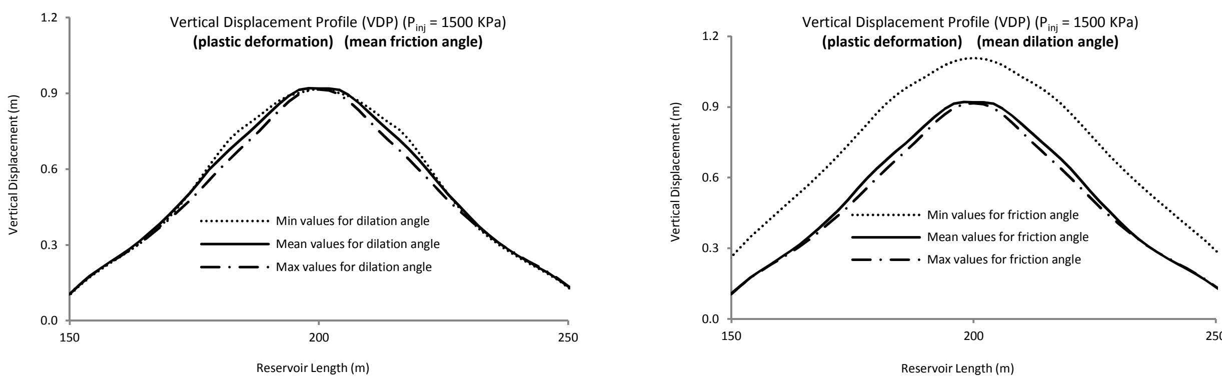
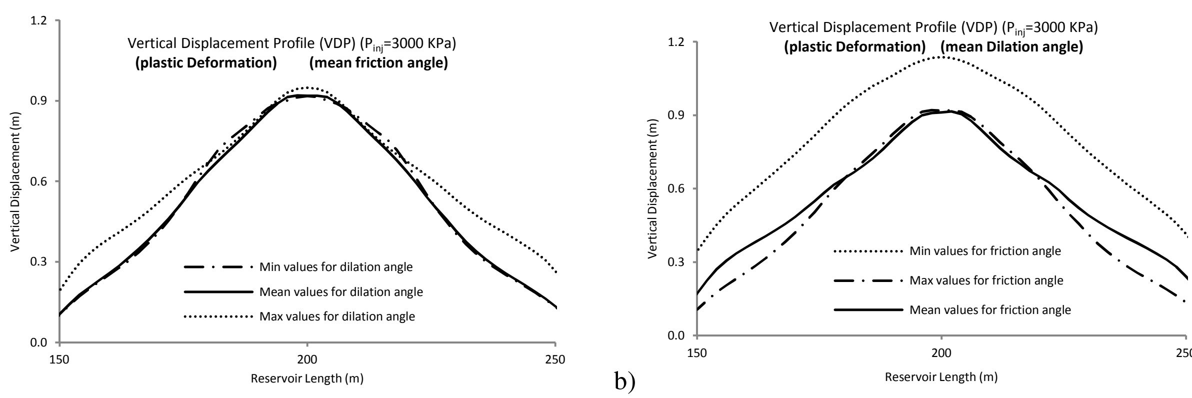


Figure 2: VDP of top of reservoir – Sensitivity to elastic parameters



a) b)

Figure 3: VDP of top of reservoir, a) Sensitivity to dilation angle and b) Sensitivity to friction angle [P_{inj}=1500 kPa]



a) b)

Figure 4: VDP of top of reservoir, a) Sensitivity to dilation angle and b) Sensitivity to friction angle [P_{inj}=3000 kPa]

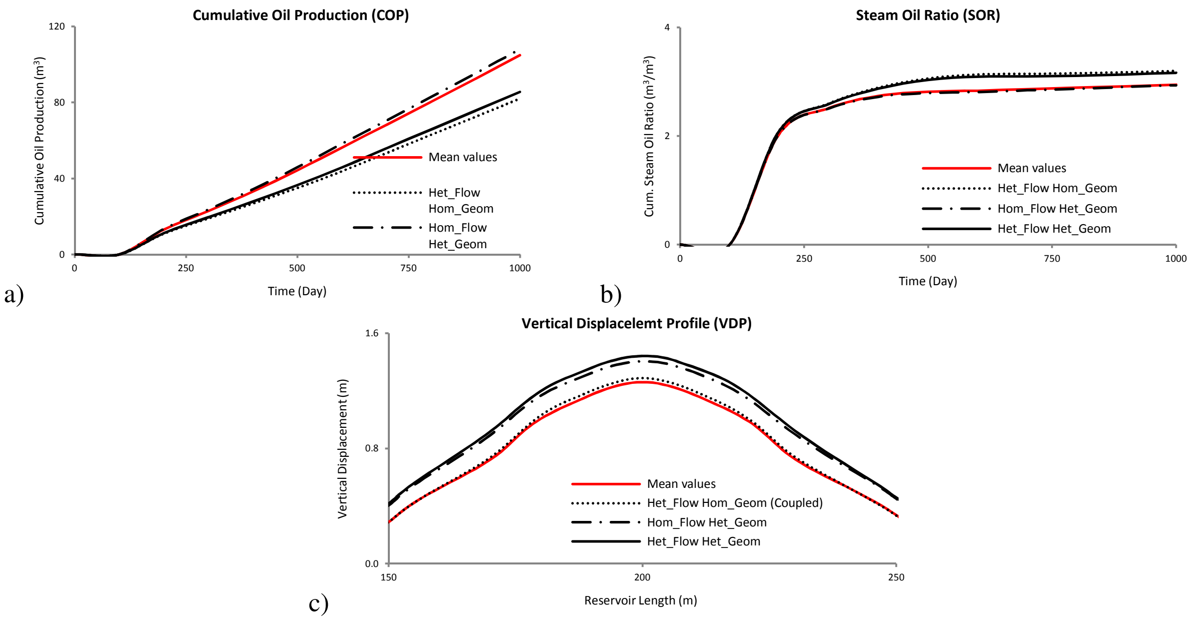


Figure 5: Flow and Geomechanical simulation output results for different cases of 1 realization, a) COP, b) SOR and c) VDP

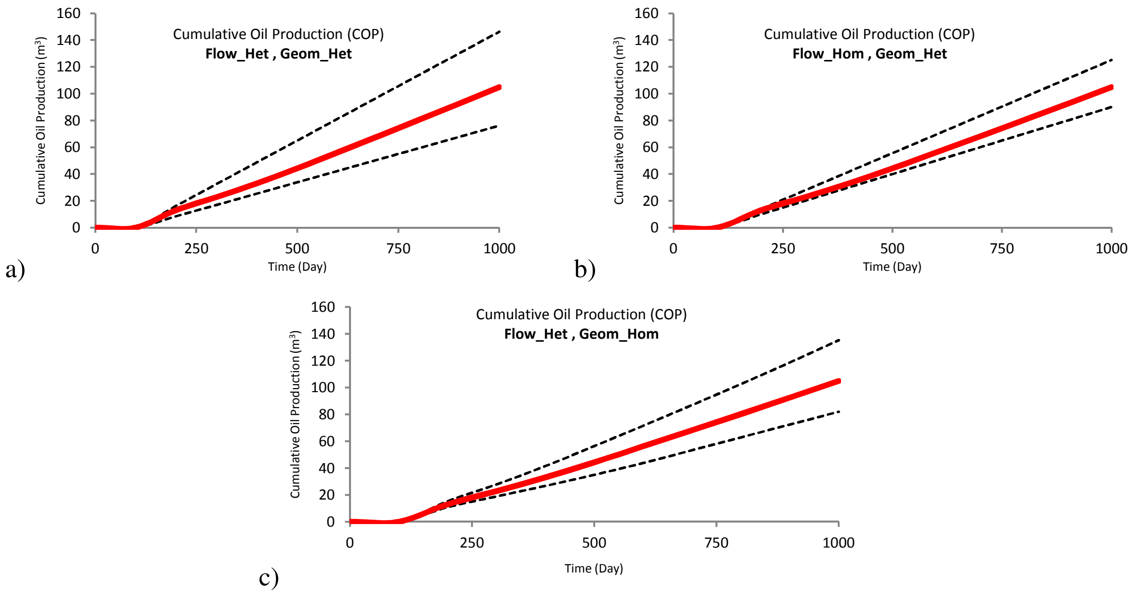


Figure 6: COP results for different cases of All Realization, a) Flow_Het , Geom_Het, b) Flow_Hom , Geom_Het and c) Flow_Het , Geom_Hom

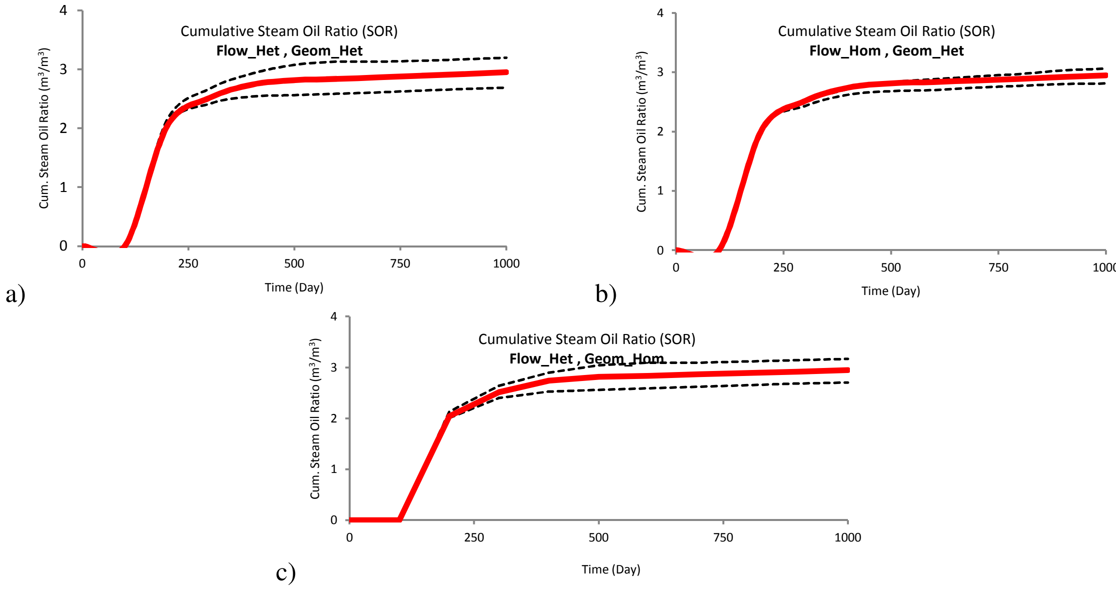


Figure 7: SOR results for different cases of All Realization, a) Flow_Het , Geom_Het, b) Flow_Hom , Geom_Het and c) Flow_Het , Geom_Hom

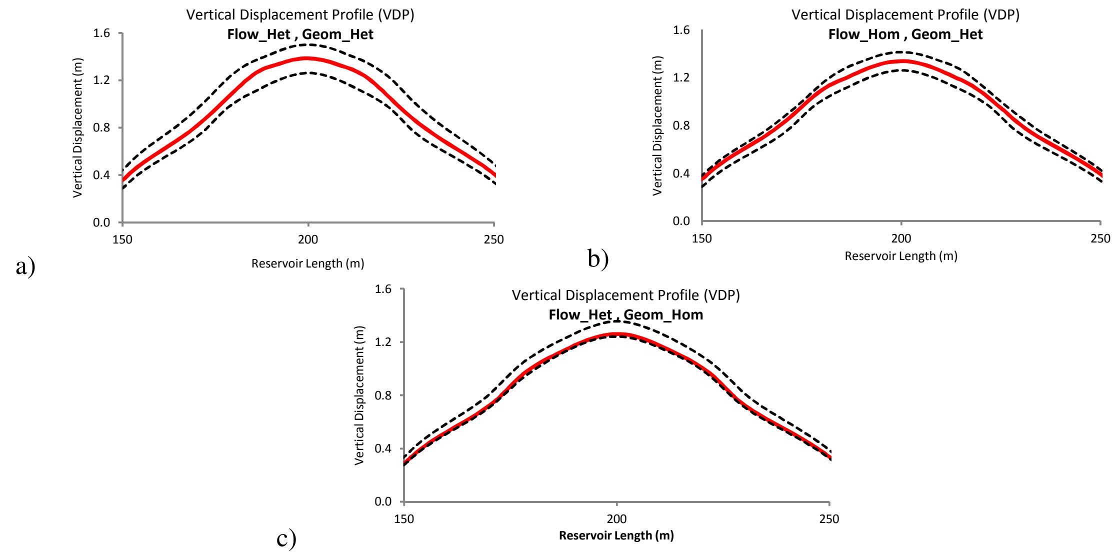


Figure 8: VDP results for different cases of All Realization, a) Flow_Het , Geom_Het, b) Flow_Hom , Geom_Het and c) Flow_Het , Geom_Hom

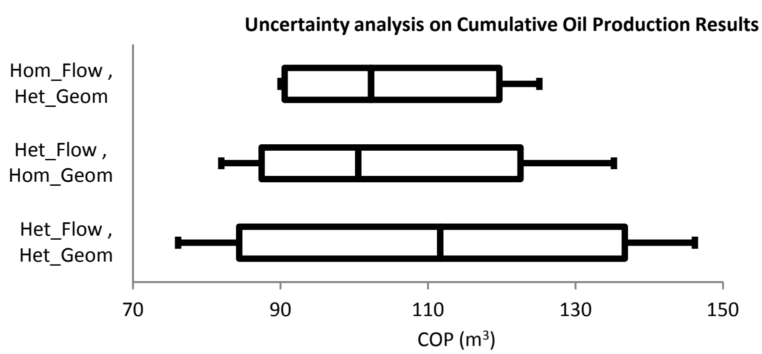


Figure 9: Box Plots of COP for all considered cases

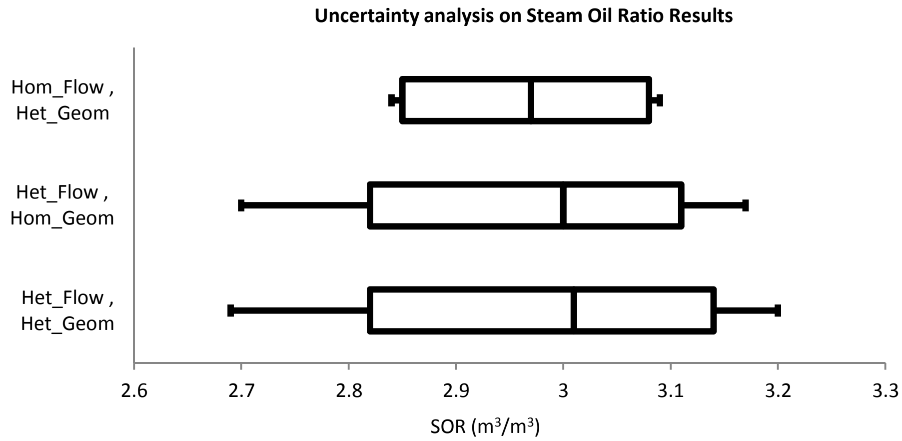


Figure 10: Box Plots of SOR for all considered cases

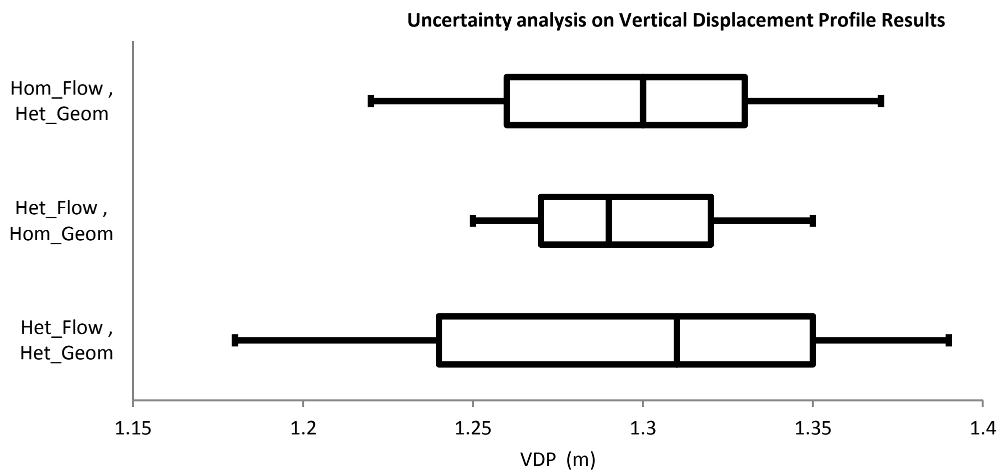


Figure 11: Box Plots of VDP for all considered cases

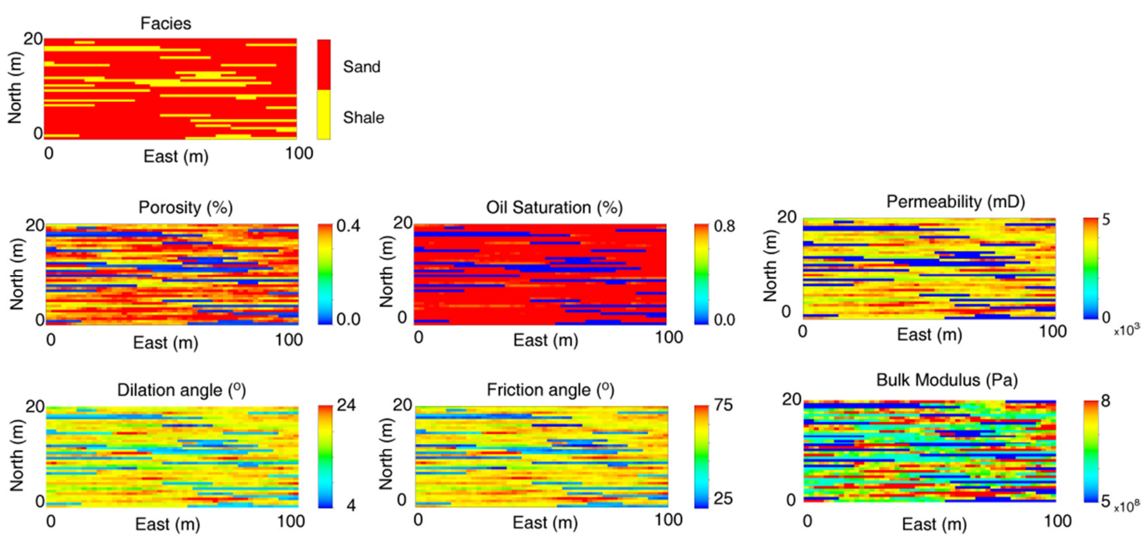


Figure 12: One facies realization and the associated property models for that realization

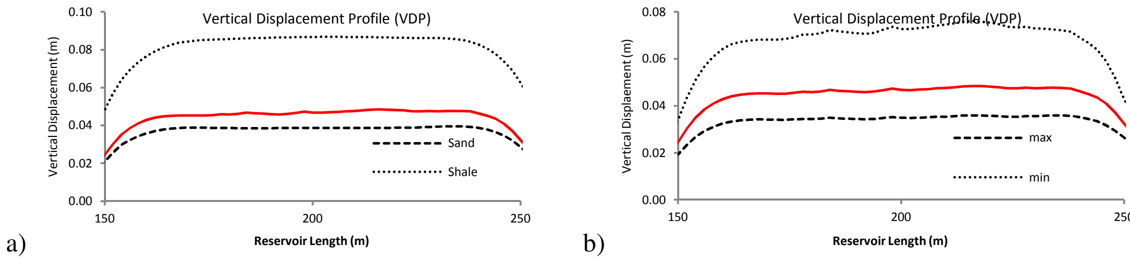


Figure 13: VDP of top of reservoir , a) Sensitivity to facies and b) Sensitivity to magnitude of elastic properties

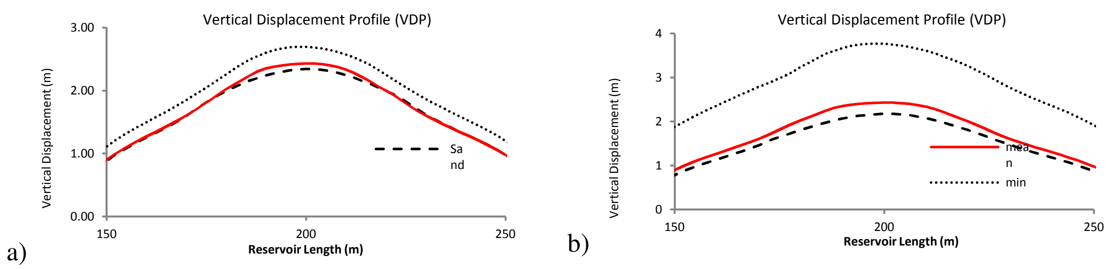


Figure 14: VDP of top of reservoir , a) Sensitivity to facies and b) Sensitivity to magnitude of plastic properties

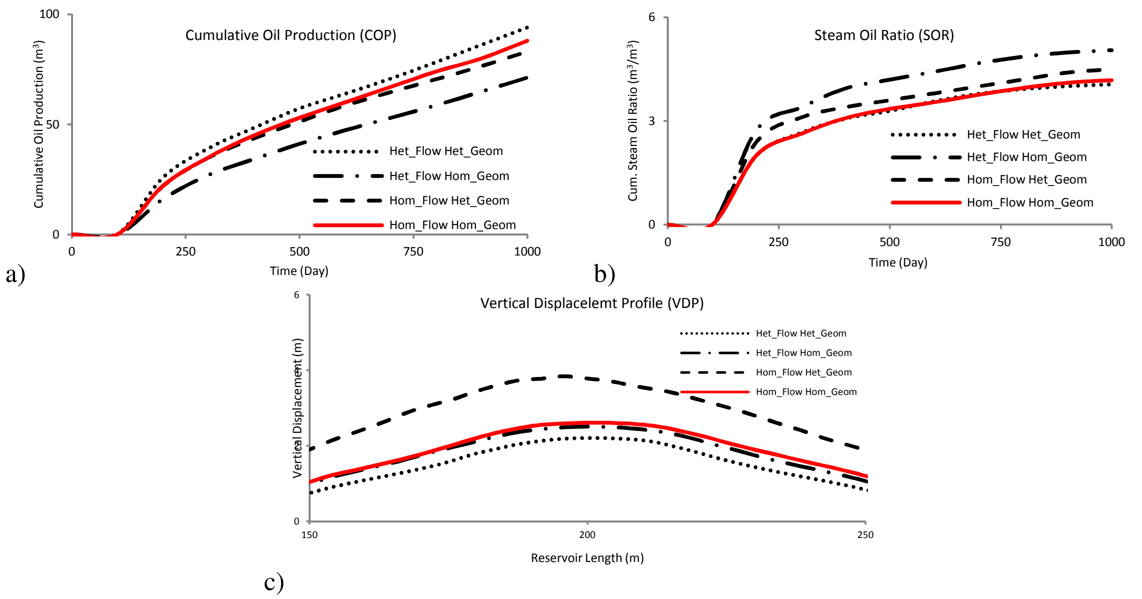


Figure 15: Flow and Geomechanical simulation output results for different cases of 1 Realization, a) COP, b) SOR and c) VDP

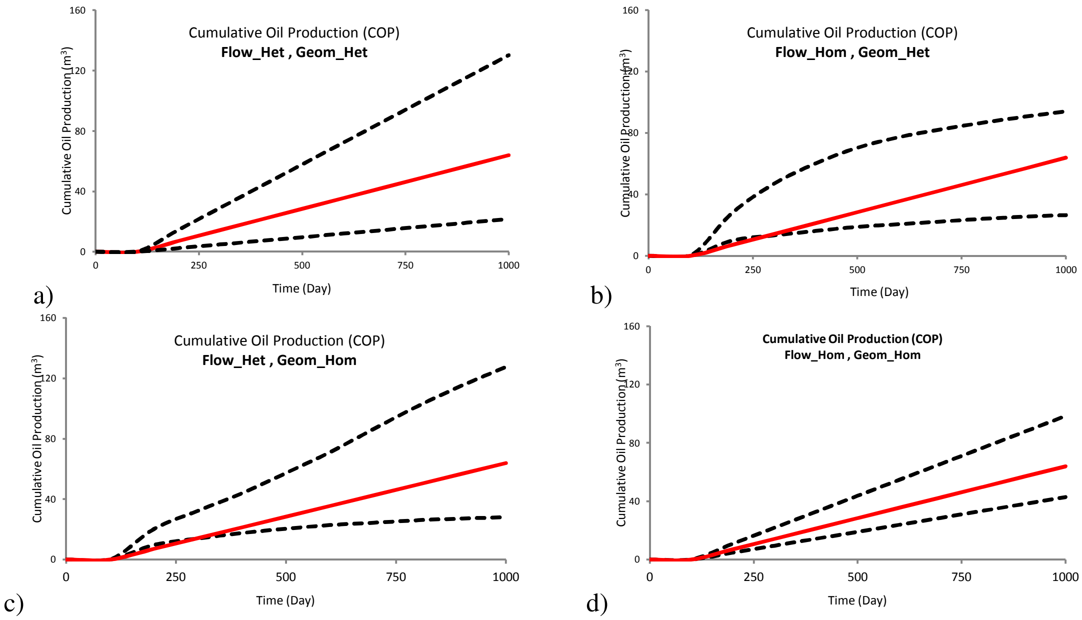


Figure 16: COP results for different cases of All Realization, a) Flow_Het , Geom_Het, b) Flow_Hom , Geom_Het, c) Flow_Het , Geom_Hom and d) Flow_Hom , Geom_Hom

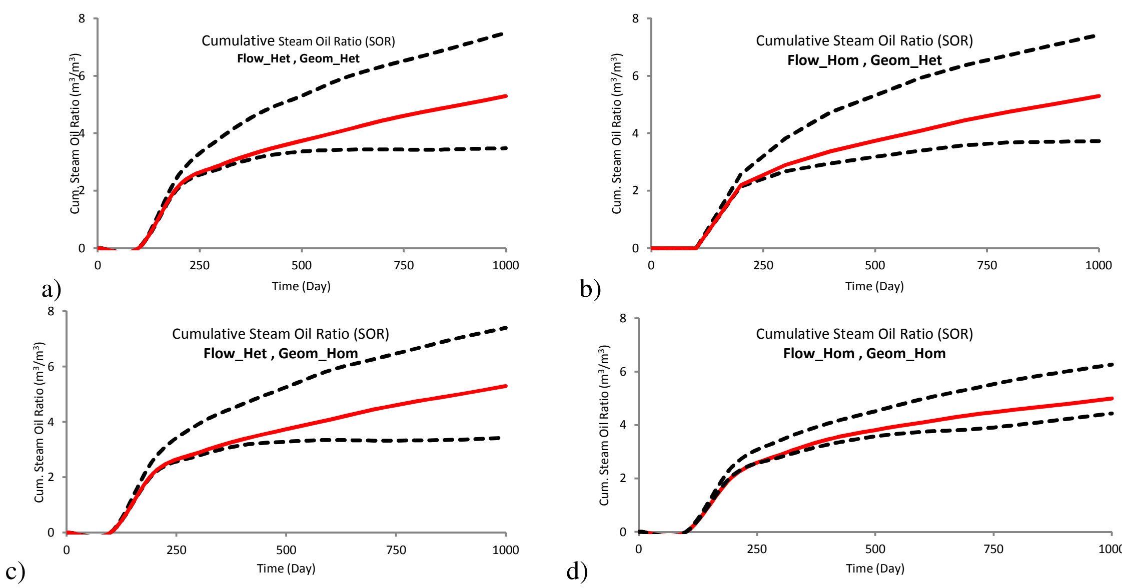


Figure 17: SOR results for different cases of All Realization, a) Flow_Het , Geom_Het, b) Flow_Hom , Geom_Het, c) Flow_Het , Geom_Hom and d) Flow_Hom , Geom_Hom

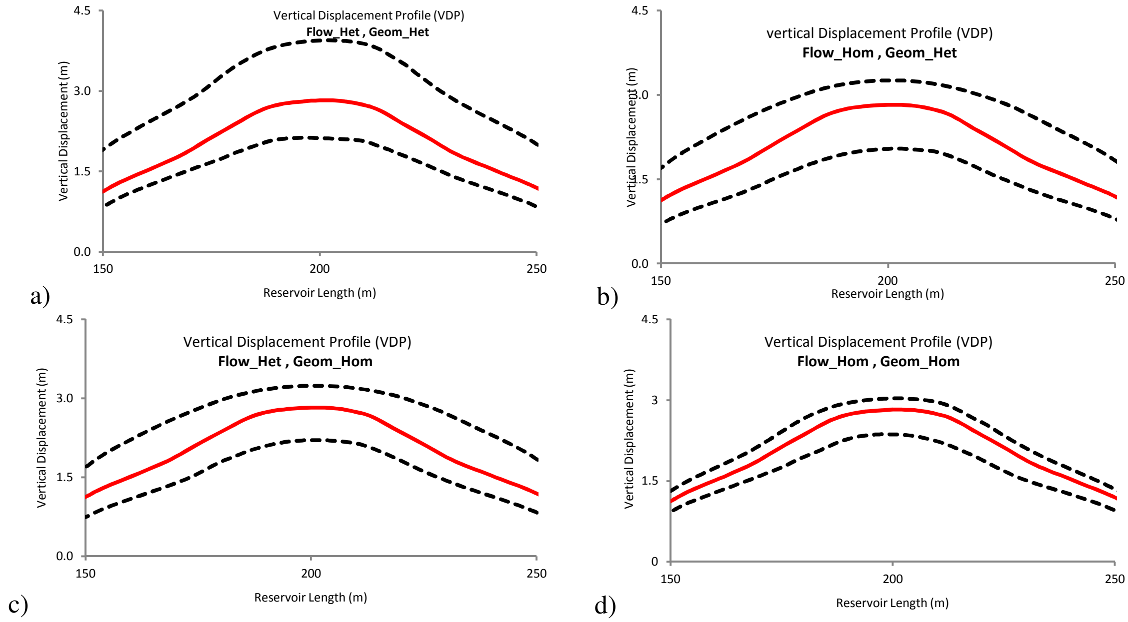


Figure 18: VDP results for different cases of All Realization, a) Flow_Het , Geom_Het, b) Flow_Hom , Geom_Het, c) Flow_Het , Geom_Hom and d) Flow_Hom , Geom_Hom

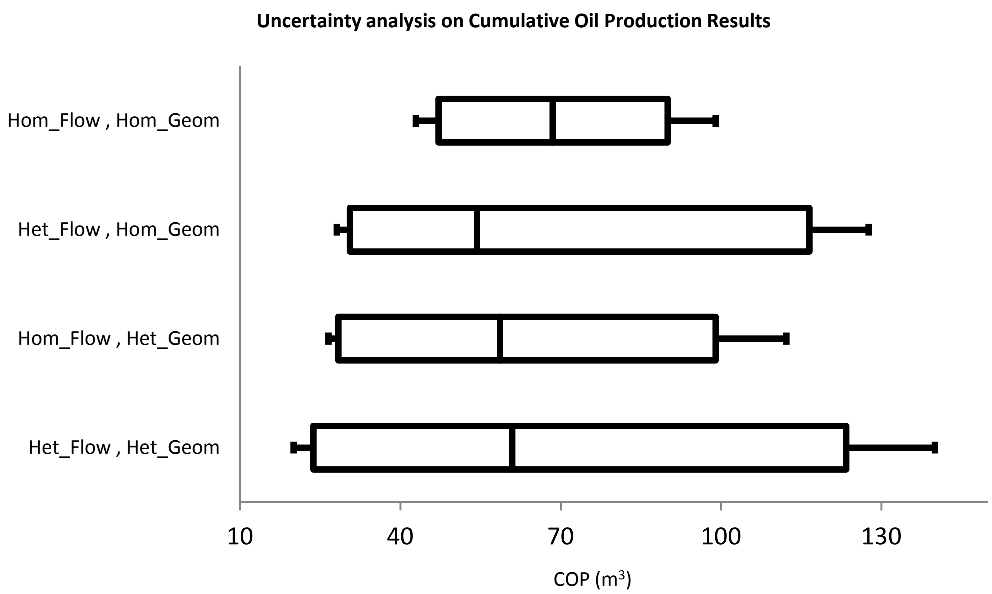


Figure 19: Box plot of COP for all considered cases

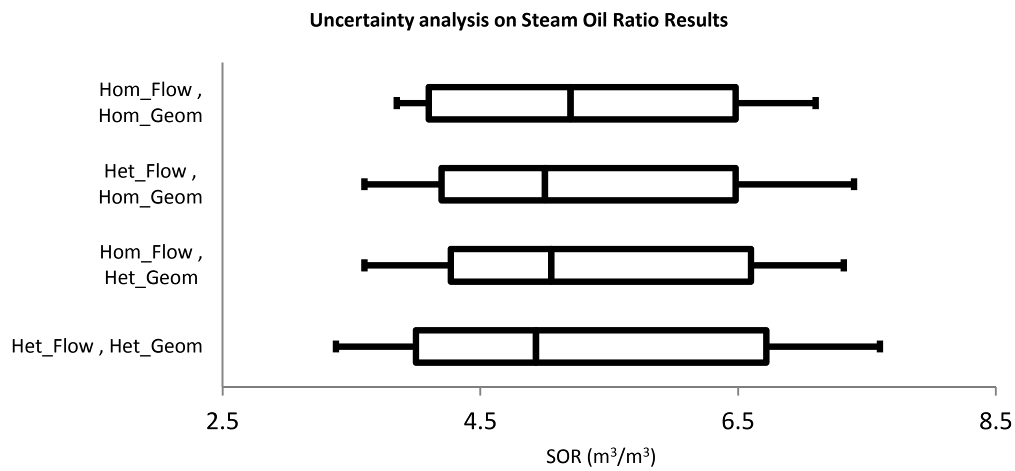


Figure 20: Box plot of SOR for all considered cases

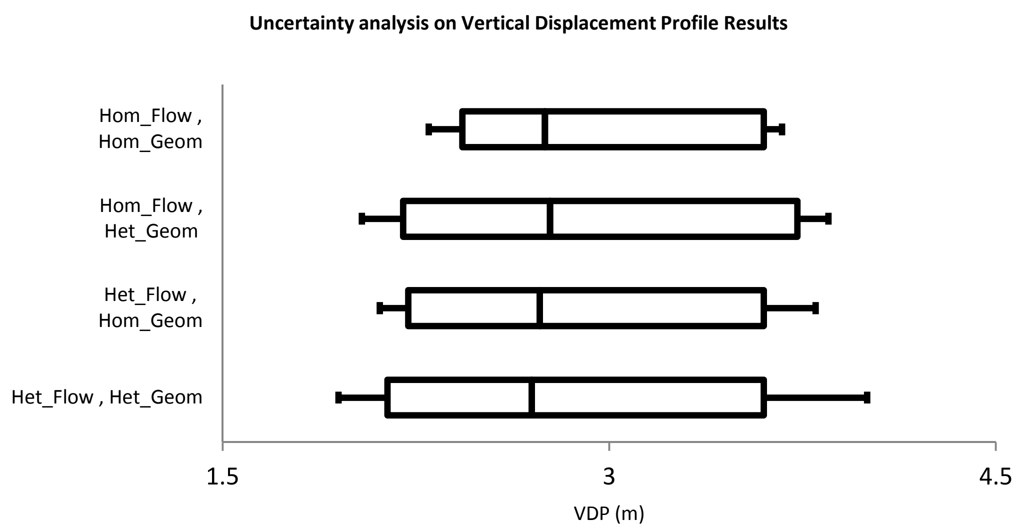


Figure 21: Box plot of VDP for all considered cases