Effects of Directional Permeability Anisotropy on Sweep Efficiency of Water Injection under Fracturing Conditions Process.

E. O. MUÑOZ MAZO
UNICAMP/CEPETRO/DEP/UNISM

J. M. MONTOYA MORENO
UNICAMP/DEP/UNISIM

D. J. SCHIOZER
UNICAMP/CEPETRO/FEM/DEP/UNISIM

Abstract

Water injection under fracturing conditions is an important method to overcome the production decline caused by the injectivity loss in reservoirs with strong formation damage. Also, the modeling of injectivity loss and fracturing processes is subject of several studies, and the effects of the reservoir properties over the model performance become significant. Quantification of these effects, by means of technical and economical performance indicators is important for the injection project dimensioning and to determine the efficacy and viability of the injection process to be implemented.

The objective of this work is to quantify the effects of directional permeability anisotropy, using Sweep Efficiency and Net Present Value (NPV) as study parameters, on the production performance during a waterflooding under fracturing conditions, in which the injectivity loss is represented by an analytical decline equation, and a virtual horizontal well is used to represent the fracture growth.

The results show the applicability of water injection under fracturing conditions. Also, it can be established the importance of reservoir properties into the injectivity loss and fracture propagation models, and the significance of the Recovery Factor (RF) and NPV in the determination of these effects. Finally, is showed the relation between the permeability anisotropy degree and production parameter, and its importance in the waterflooding behavior.

Introduction

Water injection under fracturing conditions allows overcoming the effects of the injectivity loss due to formation damage in reservoirs. Besides, it is the most common method for additional oil recovery used worldwide and its use...
represents about 80% of all recovery methods. Singh (1982) states that water injection involves different variables that influence the flood performance, the facilities dimensioning, and the economic performance of a waterflooding project.

The injectivity loss phenomenon, mainly due to the formation damage caused by the solid particles deposition, implicates continuously rise the bottom-hole pressure to maintain a constant water rate. Typically, the operational limit for injection bottom-hole pressure is the fracture pressure. Nowadays, an option to combat loss injectivity is to increase the injection pressure above the formation fracturing pressure creating high conductivity channels (fractures). One possible problem related to this procedure is the possibility of the fractures to intercept producing wells yielding high water production and low recovery factors.

Due to complexity and number of variables involved in water injection above formation fracturing pressure, the use of simulation tools is important to allow monitoring the growth of the fractures and their effect in the performance of the reservoir during the process of water injection. Besides, recent studies are focused in different aspects as fracture mechanisms, modeling and fracture effects in the reservoir performance (Van den Hoek, 2004, Gadde et al., 2001).

To model those effects, the fracture behavior must be reproduced in the flow simulator and its effects in the behavior of the production during the process of injection of water. It is also necessary to model the injectivity loss. In this way, it can couple the process injection with loss of injectivity and fracturing in a more complete and coherent way for refined and coarse simulation grids. In commercial simulators, it is common practice to consider the presence of fractures by means of mathematical models, refinement of the simulation mesh, or the use of transmissibility modifiers. Another alternative, proposed in this study, is the use of virtual horizontal wells to represent the fracture propagation in the porous medium.

The main objective of this work is to study the effects of permeability anisotropies on the production behavior (sweep efficiency) during a waterflooding under fracturing conditions. In addition, this work aims to show the modeling of the injectivity loss and how it can be coupled with fracture propagation models for commercial flow simulators.

**Injectivity loss and fracture propagation modeling for commercial simulators**

In order to model the well impairment, the injectivity index is varied as a result to consider permeability as a time function. The permeability variation around the injector well, which is related with factor damage, is modeled by an analytical expression (Montoya Moreno et al., 2006):

\[
\frac{k_i}{k_0} = \left( \frac{c_0 + c_1 t}{c_0} \right)
\]

As commercial simulators do not present options to model induced fractures by water injection, it is necessary the introduction of some modifications, such as transmissibility modifiers, local refinements and equivalent well radius, to represent the fracture propagation.

In an attempt to overcome this difficulty, Souza et al. (2005) altered the block transmissibility to model the fracture induced by water injection. Although geomechanical simulators are a good option to model the fracturing phenomenon more accurately, these simulators are in development phase or present some inconveniences as high time consumption for field scale simulation.

For the purpose of this work, the fracture propagation is modeled using a virtual horizontal well (or virtual multilateral wells for multi-layered grids) as shown in the Figure 1. In this approach, the perforations are open according to the fracture propagation profile. Fracture characteristics are obtained from in-house program for simulation of hydraulic fracturing process, which based on the rock and fluid injection properties and water injection parameters (Devloo et. al., 2001) calculates formation fracturing pressure, vertical penetration, pressure propagation and fracture width and length.

**Effect of directional permeability anisotropy on sweep efficiency of waterflooding under fracturing conditions**

**Methodological proposal**

The simulation process is carried out in three stages: First, a base model is simulated without considering both injectivity loss and fracturing presence (this is the “original model”, named as NLNF for No Loss – No Fracture).

Second, the injectivity loss is introduced into the simulation model by modifying the simulation WI for the time steps, reproducing in this way the effect of the formation damage, and maintaining the pressure of the reservoir below the value of fracture pressure (WLNF, for With Loss – No Fracture). The purpose of this stage is to establish the effect of the formation damage on the original model.

Finally, the fracture propagation is introduced when the well bottom-hole pressure reaches the fracturing pressure. Fracture propagation is represented using a horizontal virtual well, whose perforations are open following the fracture propagation profile determined from the geomechanical simulation (WLWF, for With Loss – With Fracture).

The simulation models that were used to obtain the results reported in this work consist in a Cartesian grid, with 51x51x10 active cells. Each cell has 30 x 30 x 4 m. The production strategy implemented for the simulations represents a five spot arrangement, with a central vertical injector well, and four vertical producer wells, as it is shown in Figure 2.

Other properties of the simulation model are:
- Porosity (\(\phi\)): 25\%.
- Vertical permeability (kz): 200 mD (except for the case with \(k_x = k_y = 100\) mD, where \(k_z = 40\) mD).
- Matrix compressibility (\(c_f\)): \(4.5\times10^{-7}\) (kg/cm²)⁻¹.

\[
WI = \frac{2\pi\theta k_w p_{sat}}{\ln\left(\frac{r_f}{r_i}\right)} + \frac{r_f}{r_i}
\]
The tests aim to analyze the behavior of the production under anisotropic horizontal permeability conditions. To accomplish this scope, some sets of horizontal permeability with different anisotropies were defined. As it was stated, it is important to consider that the model only presents anisotropy in the horizontal permeability not considering the condition of heterogeneous to define the model. In Table 1 the sets of directional permeability used in the tests are shown.

In Table 1 two groups can be distinguished: one isotropic formed by the sets 1, 2 and 5; and other anisotropic formed by the sets 2, 3 and 4, where the permeability value in the x direction is always minor or equal to the y direction value. The idea is to make that for anisotropic cases y-axis, which is the fracture propagation direction, has a greater permeability value (according to Ji et al, 2004) than x-axis.

The quantification of the anisotropy degree is necessary for the analysis of the results obtained from numerical simulation and for allow establish the degree of decline or recovery of the productivity of the reservoir. The parameters used for the results of the simulation stage are listed in Table 2.

In Table 2, kmean corresponds to the geometric mean of the permeabilities in the directions x and y and is given by Equation 3.

\[ k_{\text{mean}} = \sqrt{k_x k_y} \]

The Directional Anisotropy Coefficient (DAC) aims to establish the anisotropy degree of the simulation models. Equation 4 gives the definition of DAC:

\[ \text{DAC} = \frac{k_x - k_{\text{mean}}}{k_y} \]

DAC is formulated as an adaptation of the Dykstra-Parsons Coefficient of Heterogeneity. The Dykstra-Parsons formulation is based on the accumulated probability that a heterogeneous system has that its equivalent permeability, has a determined value between the minimum permeability and the maximum permeability of the system (Maschio et al., 2003). Because the cases tested did not present heterogeneities and, in any direction the probability of the permeability to have a certain value is 1 the coefficient of Dykstra-Parsons was not used. Hence DAC is introduced to determine the reservoir anisotropy degree (Muñoz Mazo et al., 2007).

DAC values oscillate between 0 and 1, with zero indicating a total isotropy in the directional permeability, and the value of one indicating an elevated degree of this condition.

The Decline Index (DECLI) is the ratio between the values obtained from the simulation of the cases involving injectivity loss due to the formation damage (WLNF) and the cases with the original model (NLNF). In this way, if DECLI values are smaller than 1, indicates that there is a decrease in the control parameters decreases as a function of the increase in permeability. The analysis using the mean permeability can be much more useful for the results obtained from isotropic cases (DAC = 0) reported in the Table 5; the effect on DECLI for the control parameters is illustrated in Figure 4.

From Figure 3, it can be noticed that DECLI does not follow a specific trend for the control parameters with relation to the variation of mean permeability. Also it can be observed that for the model with kmean = 2000 mD, FR and NPV increase showing improvement of the system behavior. This shows that injection rates shall be observed with attention for high permeability systems, aiming to establish an efficient injection rate for the model within established limits by the geomechanical simulation.

From Figure 4, it can be observed that DECLI for the control parameters decreases as a function of the increase in DAC. This is evidence that when the anisotropy increases, the effect of the injectivity loss also increases, affecting the productive behavior of the reservoir.

The Recovery Index (RECOVI) is the ratio of the obtained values from the simulation of the cases that involve the fracture presence (WLWF) and the values of the other two cases: (1) the original case (NLNF) and (2) the case that considers the injectivity loss (WLNF). For the Recovery Index, values smaller than 1 indicate that the presence of the fracture do not improve the behavior of the system. Otherwise, values equals to 1 show that the case with the fracture is equal to the original. Values greater than 1 show improvement of behavior of the reservoir.

Other performance indicators such as the Recovery Factor (RF), the Net Present Value (NPV), the Cumulative Water Production (Wp) and the Cumulative Water Injection (Wi) are used as control parameters. The economic scenario used for the calculation of NPV is shown in Table 3.

Results and Discussion

Quantification of the directional anisotropy degree

In Table 4, the values of the indexes for the anisotropy degree quantification, for the directional permeability sets tested are shown.

Effect of injectivity loss and anisotropy in directional permeability on production performance

The results of the comparison of the original model (NLNF) and the case with injectivity loss (WLNF) are analyzed. The Decline Index (DECLI) is used, and the impact of the indicators of directional anisotropy (kmean and DAC) on the reservoir performance is examined.

In Table 5, the results of the comparison of the cases for the control parameters are shown. The effect of the mean permeability on the Decline Index (DECLI) of the control parameters is shown in Figure 3.

From Figure 3, it can be noticed that DECLI does not follow a specific trend for the control parameters with relation to the variation of mean permeability. Also it can be observed that for the model with kmean = 2000 mD, FR and NPV increase showing improvement of the system behavior. This shows that injection rates shall be observed with attention for high permeability systems, aiming to establish an efficient injection rate for the model within established limits by the geomechanical simulation.

The analysis using the mean permeability can be much more useful for the results obtained from isotropic cases (DAC = 0) reported in the Table 5; the effect on DECLI for the control parameters is illustrated in Figure 4.

In Table 4, the values of the indexes for the anisotropy degree quantification, for the directional permeability sets tested are shown.

Effect of injectivity loss and anisotropy in directional permeability on production performance

The results of the comparison of the original model (NLNF) and the case with injectivity loss (WLNF) are analyzed. The Decline Index (DECLI) is used, and the impact of the indicators of directional anisotropy (kmean and DAC) on the reservoir performance is examined.

In Table 5, the results of the comparison of the cases for the control parameters are shown. The effect of the mean permeability on the Decline Index (DECLI) of the control parameters is shown in Figure 4.

From Figure 3, it can be noticed that DECLI does not follow a specific trend for the control parameters with relation to the variation of mean permeability. Also it can be observed that for the model with kmean = 2000 mD, FR and NPV increase showing improvement of the system behavior. This shows that injection rates shall be observed with attention for high permeability systems, aiming to establish an efficient injection rate for the model within established limits by the geomechanical simulation.

The analysis using the mean permeability can be much more useful for the results obtained from isotropic cases (DAC = 0) reported in the Table 5; the effect on DECLI for the control parameters is illustrated in Figure 4.

In Figure 4, it is shown the effect of the permeability for isotropic cases where it is observed a decrease tendency in the indicators as the permeability decreases. It is also possible to notice that the decline, caused by the injectivity loss, is higher for lower permeabilities.

The analysis of anisotropic cases is carried out using DAC; and the results are shown in Figure 5.

From Figure 5, it can be observed that DECLI for the control parameters decreases as a function of the increase in DAC. This is evidence that when the anisotropy increases, the effect of the injectivity loss also increases, affecting the productive behavior of the reservoir.

Effect of the directional permeability anisotropy and fracture presence on the sweep efficiency of reservoirs with injectivity loss problems

In this section, the results of the comparison of the model with injectivity loss (WLNF) and the case with injectivity loss...
and with fracture (WLWF) are analyzed using the Index of Recovery (RECOVI).

RECOVI, kmean and DAC for the tested cases are shown in Table 6. It can be observed that for permeability of 2000 mD there are not registered values of RECOVI in Table 6, this is because the process of injectivity loss, although it has leaded to an increase in the injector bottom-hole pressure, it does not increase to the fracture pressure value. That condition confirms the discussed in the previous section regarding the injection rates for reservoirs with high permeabilities.

In Table 6, it is possible to observe that the values of the control parameters increase while mean permeability decreases. With $k_{\text{mean}} = 100$ mD, RECOVI for Wp has an infinite value due to the production of water, which is zero in the case with injectivity loss. Water production is a consequence of the presence of the fracture and it is observed that for all the control parameters the effect of the fracture was favorable. Figures 6 and 7 show the behavior of RECOVI for both isotropic and anisotropic models.

For the models with anisotropy in directional permeability, Figure 7 shows that RECOVI grows as the anisotropy increases, being much more expressive for high anisotropy coefficient. It can be observed that the Wp is the control parameter that presents the highest increment due to water canalization caused by the combination of the anisotropy presence and the induced fracture in the producing wells located parallel to the axis of fracture propagation. This fact is more evident for higher coefficients of anisotropy.

Also, it is observed that for all the cases, although the water production experienced an increase as consequence of the fracturing process, this is not negative for NPV behavior, which is higher for the cases with fracture presence if compared with cases only with injectivity loss, independent of the degree of anisotropy of the models. In general, a favorable result of the fracture presence is observed, which gets to improve the productive behavior of the reservoir, overcoming the current effects of the injectivity loss.

Comparison between the cases with fracture propagation and the cases without injectivity loss nor fracture

The results of the comparison of models without injectivity loss and without fracture (NLNF) and the case with injectivity loss and fracture (WLWF) are analyzed in this section. The Recovery Index (RECOVI) is used to study the effects of the indicators of directional anisotropy (kmean and DAC) on the behavior of the tested models. This comparison of cases aims to illustrate how the fracture presence can increase the value of the control parameters in relation to the models without injectivity loss. In Table 7, the results of the comparison of the cases WLWF and NLNF in terms of RECOVI are shown.

The results reported in Table 7 show that although the fracture presence improves the behavior of systems under the effect of the injectivity loss, it does not get to improve the conditions of the model to the conditions of the original model (without injectivity loss and without fracture). Figure 8 shows the behavior of RECOVI between the cases WLWF and NLNF for the isotropic models tested in function of the mean permeability. It can be seen that RECOVI, which in the previous section it was ascending, now decreases with the diminishing of the mean permeability, and for lower permeabilities the difficulty that the fracturing process has for returning to the original system conditions is larger. That same difficulty that the fracture has is also evident in the models with anisotropy, as it is shown in the Figure 9.

It can be observed that the fracture presence, even improving the indicators of systems with injectivity loss, it does not yield an elevation of those indicators at the level of the original case (NLNF). It is noticed that it is difficult to return to the level of the original case, this is more evident for models with larger degree of anisotropy showing that the influence of the damage is larger and it needs a more careful treatment for models with high anisotropy degree.

Conclusions

In order to evaluate the effect of anisotropies, it is necessary the introduction of some performance indexes that aim to consider the effect of these anisotropies in a waterflooding under fracturing conditions process.

It can be inferred, from the observed results, that the mean permeability doesn’t get to reflect a specific tendency of the results for cases with anisotropy, making necessary the calculation and use of new performance indexes as the Index of Decline (DECL) and the Index of Recovery (RECOVI) for the quantification of these effects in the used control parameters and to describe the behavior of anisotropic systems. To establish the anisotropy level, it was necessary to analyze the behavior of the tested models, and for that the Directional Anisotropy Coefficient (DAC) was developed.

With those indexes it was possible to establish (1) the relationship between the decrease of the sweep efficiency and the increase of the anisotropy level, (2) the capacity that the generation and propagation of the fracture has to remedy the problem of the injectivity loss in anisotropic models, and (3) the capacity of the fracture to improve the productive conditions of the models with respect of cases where there are no injectivity loss nor fracture propagation.

The fracture propagation improves the behavior and the sweep efficiency in reservoirs with injectivity loss problems, and this capacity of improvement is significant in systems that present high degrees of anisotropy. In a similar way, the fracturing process, however improves the performance indicators, in the most of the cases does not get to elevate the production conditions at the level of the cases that do not have injectivity loss nor fracture propagation, and the difficulty in recuperating the performance levels increases as function of the index of anisotropy of the tested models.

Acknowledgements

The authors wish to thank to the Petroleum Engineering Department of the State University of Campinas – UNICAMP, PETROBRAS, FINEP and CNPq for their technical and financial support.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>cf</td>
<td>Rock compressibility</td>
</tr>
<tr>
<td>c</td>
<td>Equations constant</td>
</tr>
<tr>
<td>DAC</td>
<td>Directional Anisotropy Coefficient</td>
</tr>
<tr>
<td>h</td>
<td>Reservoir thickness</td>
</tr>
<tr>
<td>$k_{ij}$</td>
<td>Absolute permeability</td>
</tr>
<tr>
<td>$k_{\text{mean}}$</td>
<td>Mean permeability</td>
</tr>
<tr>
<td>$k_{s}$</td>
<td>Damaged region permeability</td>
</tr>
<tr>
<td>$r_{c}$</td>
<td>Reservoir equivalent radius</td>
</tr>
<tr>
<td>$r_{t}$</td>
<td>Damaged region radius</td>
</tr>
<tr>
<td>s</td>
<td>Skin factor</td>
</tr>
<tr>
<td>t</td>
<td>time</td>
</tr>
<tr>
<td>$w_{\text{frac}}$</td>
<td>Reservoir simulator factor</td>
</tr>
</tbody>
</table>
**REFERENCES**


---

**Table 1. Directional permeability sets.**

<table>
<thead>
<tr>
<th>Set number</th>
<th>kx (mD)</th>
<th>ky (mD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2000</td>
<td>2000</td>
</tr>
<tr>
<td>2</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>3</td>
<td>100</td>
<td>500</td>
</tr>
<tr>
<td>4</td>
<td>50</td>
<td>500</td>
</tr>
<tr>
<td>5</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

---

**Figure 1. Fracture propagation using virtual wells**

**Figure 2. Well arrangement in the simulation grid.**

**WI = Well Index**

**φ = porosity**
Table 2. Parameters used in the directional permeability anisotropy effects analysis.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>kmean</td>
<td>Mean Permeability</td>
</tr>
<tr>
<td>DAC</td>
<td>Directional Anisotropy Coefficient</td>
</tr>
<tr>
<td>DECLI</td>
<td>Decline Index (Reservoir performance)</td>
</tr>
<tr>
<td>RECOVI</td>
<td>Recovery Index (Reservoir Performance)</td>
</tr>
</tbody>
</table>

Table 3. Economic data for the simulations.

<table>
<thead>
<tr>
<th>Taxes</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Discount rate (%)</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Royalties (%)</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td>0.3665</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Price</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil price (US$/bbl)</td>
<td>35</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oil price (US$/m³)</td>
<td>220.15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gas price (US$/m³)</td>
<td>0.09</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Investments</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Platform (US$)</td>
<td>1000000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Producer well (US$)</td>
<td>2000000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Injector well (US$)</td>
<td>2000000</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Costs</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil production (US$/m³)</td>
<td>37.74</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water production (US$/m³)</td>
<td>4.03</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gas production (US$/m³)</td>
<td>0.002</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water injection (US$/m³)</td>
<td>4.03</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gas injection (US$/m³)</td>
<td>0.002</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4. Quantification of the degree of directional anisotropy.

<table>
<thead>
<tr>
<th>Set</th>
<th>kx</th>
<th>ky</th>
<th>kmean</th>
<th>DAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2000</td>
<td>2000</td>
<td>2000.0</td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
<td>500</td>
<td>500</td>
<td>500.0</td>
<td>0.00</td>
</tr>
<tr>
<td>3</td>
<td>100</td>
<td>500</td>
<td>223.6</td>
<td>0.55</td>
</tr>
<tr>
<td>4</td>
<td>50</td>
<td>500</td>
<td>158.1</td>
<td>0.68</td>
</tr>
<tr>
<td>5</td>
<td>100</td>
<td>100</td>
<td>100.0</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Table 5. Decline indexes for the used control parameters.

<table>
<thead>
<tr>
<th>Set</th>
<th>kx</th>
<th>ky</th>
<th>kmean</th>
<th>DAC</th>
<th>DECLI</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2000</td>
<td>2000</td>
<td>2000</td>
<td>0.00</td>
<td>FR</td>
</tr>
<tr>
<td>1</td>
<td>2000</td>
<td>2000</td>
<td>2000</td>
<td>0.00</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>500</td>
<td>500</td>
<td>0.00</td>
<td>0.87</td>
</tr>
<tr>
<td>2</td>
<td>500</td>
<td>500</td>
<td>500</td>
<td>0.00</td>
<td>0.82</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>500</td>
<td>223.6</td>
<td>0.55</td>
<td>0.91</td>
</tr>
<tr>
<td>3</td>
<td>100</td>
<td>500</td>
<td>158.1</td>
<td>0.68</td>
<td>0.54</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>0.00</td>
<td>0.01</td>
</tr>
<tr>
<td>4</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>0.00</td>
<td>0.36</td>
</tr>
</tbody>
</table>

Figure 3. Effect of kmean on DECLI.

Figure 4. Effect of kmean on DECLI for the isotropic models.
Table 6. Recovery Index (RECOVI) for the used control parameters.

<table>
<thead>
<tr>
<th>kx</th>
<th>ky</th>
<th>kmean</th>
<th>DAC</th>
<th>RECOVI</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>2000</td>
<td>2000.0</td>
<td>0.00</td>
<td>1.13</td>
</tr>
<tr>
<td>500</td>
<td>500</td>
<td>500.0</td>
<td>0.00</td>
<td>1.69</td>
</tr>
<tr>
<td>100</td>
<td>500</td>
<td>223.6</td>
<td>0.55</td>
<td>108.24</td>
</tr>
<tr>
<td>50</td>
<td>500</td>
<td>158.1</td>
<td>0.68</td>
<td>187.96</td>
</tr>
<tr>
<td>100</td>
<td>100</td>
<td>100.0</td>
<td>0.00</td>
<td>2.04</td>
</tr>
</tbody>
</table>

Table 7. Recovery indexes (RECOVI) for the used control parameters.

<table>
<thead>
<tr>
<th>kx</th>
<th>ky</th>
<th>kmean</th>
<th>CAD</th>
<th>RECOVI</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>2000</td>
<td>2000.0</td>
<td>0.00</td>
<td>1.03</td>
</tr>
<tr>
<td>500</td>
<td>500</td>
<td>500.0</td>
<td>0.00</td>
<td>0.92</td>
</tr>
<tr>
<td>100</td>
<td>500</td>
<td>223.6</td>
<td>0.55</td>
<td>1.00</td>
</tr>
<tr>
<td>50</td>
<td>500</td>
<td>158.1</td>
<td>0.68</td>
<td>0.85</td>
</tr>
<tr>
<td>100</td>
<td>100</td>
<td>100.0</td>
<td>0.00</td>
<td>0.81</td>
</tr>
</tbody>
</table>

Figure 5. DECLI vs. DAC for anisotropic models.

Figure 6. Effect of kmean on the Recovery Index of the isotropic cases.

Figure 7. RECOVI vs. DAC for anisotropic models

Figure 8. Effect of kmean on the Recovery Index of the isotropic cases.
Figure 9. RECOVI vs. DAC for anisotropic models