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The Influence of Permeability Anisotropy on Reservoir Simulation Model Behaviour in Oil Fields

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Abstract

With a geological and dynamic model of the hydrocarbon field, adapted to historical exploitation data, petroleum engineers can gain invaluable insights into the current situation and evaluate proposed solutions with great effectiveness. This resource is highly beneficial, providing invaluable insights that can result in favourable results. Therefore, in order to obtain reliable results, it is very important to build a reservoir model, taking into account their geological features. One of these features can be considered anisotropy of permeability. This is very important when it comes to low porosity and permeability reservoirs, which oil and gas companies are actively developing. The goal of this study was to assess how permeability anisotropy impacts the performance of a hydrodynamic model for a productive reservoir in an oil field.

This study involves creating a field model and performing hydrodynamic calculations. This includes using field data to determine a close-to-real value for permeability anisotropy, optimizing an existing development system, and analyzing development maps. As a result of the study, it was found that the omission of permeability anisotropy leads to an overestimation of the accumulated field development indicators. It was found that an increase in the value of anisotropy does not always lead to an increase in cumulative oil production, which undoubtedly emphasizes the peculiarity of the geological structure of the reservoir. In the final stage, a hydrodynamic calculation of the development was performed for 15 years, allowing conclusions to be reached about the correctness of applying operations to enhance oil recovery (EOR).

Keywords: Permeability anisotropy; Reservoir simulation; Geological structure; Petrophysical heterogeneity; EOR

Introduction

It is common knowledge that permeability is a vector quantity and its alteration happens in three planes that are mutually orthogonal [1-4]. As a consequence, permeability can be represented as a third-order tensor and viewed as a cuboid:

$$\bar{K} = \begin{bmatrix} K_{xx} & K_{xy} & K_{xz} \\ K_{yx} & K_{yy} & K_{yz} \\ K_{zx} & K_{zy} & K_{zz} \end{bmatrix} \quad (1)$$

The elements of the main diagonal of the matrix, kxx, kyy, and kzz, are orthogonal to the planes of the parallelepiped. However, with this representation, the description of the phenomenon of permeability anisotropy becomes much more complicated and still has no solution.Therefore, in the general case, a simplified representation is adopted, the essence of which is to assume the permeability vector as a second-order tensor:

$$\bar{K} = \begin{bmatrix} K_{ii} & K_{ij} \\ K_{ji} & K_{jj} \end{bmatrix} \quad (2)$$

Where i, j are indices characterizing a certain direction of the vector (x, y, z). The assumption here is that the tangent components kij=kji=1 (Figure 1). The introduction of the described assumption is a forced measure, but nevertheless, it already allows one to conduct a study of the phenomenon, which is supported by a fairly good mathematical basis.

Some authors associate the phenomenon of permeability anisotropy with the lithological and petrophysical heterogeneity of reservoir rocks [5-7]. Coordinated changes in the structure and texture of rock with a specific spatial orientation are typically recognized as occurrences of interest. It is now well known that the creation of such coordinated changes occurs for two reasons: the interaction of several depositional environments during reservoir formation and the influence of subsequent post-sedimentation processes [8-10].

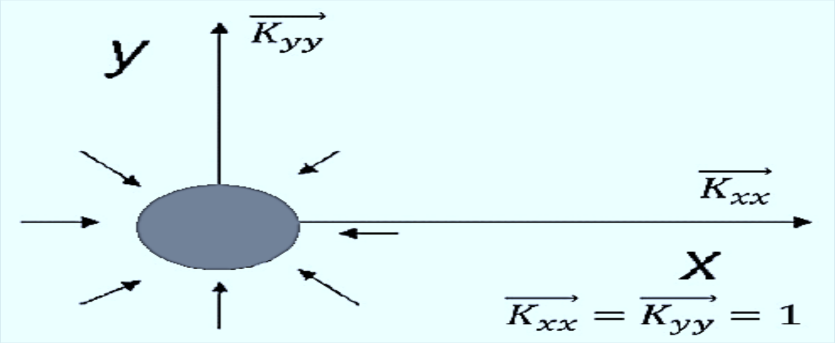

Figure1: Anisotropy of permeability, simplified [2].

It is crucial to understand that the depositional settings play a vital role in shaping the structure and texture of the rocks that make up a reservoir. This is due to the sediment material of the grains, as well as their size and sorting. The latter are directly dependent on the energy at which they move from the place of their formation to the place of deposition. It is widely recognized that water is the primary carrier of the sediments [11-13].

This refers to the main flow direction that grinds, crushes, sorts, and pulls grains in a specific direction. This leads to the fact that the direction of the sediment, which corresponds to the direction of elongation of the grains, ultimately has improved filtration (flow) properties than in the orthogonal one. Serious changes in lithological and petrophysical states occur when the sedimentation environment changes. However, such processes are not instantaneous and take a long time. After the formation of the reservoir, its further subsidence may be accompanied by a significant manifestation of secondary processes. Such processes can be tectonic movements leading to rock deformation, metasomatic processes, cementation, carbonatization, etc. All considered phenomena form the final heterogeneous flow characteristics of rocks, which is manifested in the phenomenon of permeability anisotropy [14-18].

Thus, the anisotropy of permeability can be characterised based on its direction and the level of manifestation. It is another important geological characteristic of the reservoir, which must be taken into account when building a geological model in order to obtain more correct results of hydrodynamic calculations in the future. This is exactly what this study aims to accomplish.

Methodology

The object of study is one of the oil fields of the Tomsk region, consisting of terrigenous deposits. The field is situated within a complex system of local uplifts of different orders. This is a notable characteristic of the area. The Jurassic deposits are the main contributor to productivity. These deposits were formed by various sedimentation processes, including regression and transgression, resulting in a diverse distribution of reservoir properties [19-22].

Construction of Geological and Hydrodynamic Models

In this work, all hydrodynamic calculations were performed using the Petrel Schlumberger software [23-25]. The following input data were used to build the reservoir model:

- Locations and altitudes of twenty-one wells;
- Well inclinometry;
- Structural map of the base of the studied formation obtained from seismic data;
- Tops of formation Z3 identified for each well;
- Interpreted log data.

The process of geological modelling consists of four stages:

1. Structural modelling and construction of a cellular model.
2. Facies modelling.
3. Petrophysical modelling.
4. Modelling of fluid saturation.

Results and Discussions

Structural Modelling

The first step in structural modelling was the loading of each well at given coordinates and inclinometry. Afterwards, a structural map of the surface was created, which was projected along the tops of the Z3 formation. An interpolation method was used to generate the structural map, which was cropped to fit the area under evaluation [26-29].

In the second step, a cellular model was built. The horizontal cell size was chosen as 50x50 m due to the small size of the area under consideration. The vertical cell size was 0.5 m. This value made it possible not to miss small interlayers in the facies modelling of well-logging data and not to spend a lot of time on calculations on a smaller grid. The size itself was chosen by analysing the range of values from 0.2 to 0.7 m.In conclusion, it can be noted that the size of the created cellular model was 5x5 km horizontally and 21.8 m vertically. The number of cells was 1040000.

Facies Modelling

Based on the preliminary information, the analysed log data was classified into facies based on hydrodynamic flow units [30-33]. The Truncated Gaussian simulation method was used to build the facies model, which is a method that can be used to characterize heterogeneous reservoirs and environments whose petrophysical properties alternate unevenly, as is the case with coastal bar sandstones [34-37].

According to the general rules, the facies cube was created by determining the parameters of the variograms, which include the results of saturation and petrophysical modelling. The parameters themselves are shown in Table 1 and were taken as recommended [38-39].

Layer	Variogram Type	Correlation Length, m
Z3	Major	18000
	Minor	17800
	Vertical	33,36

Table 1: The parameters of a variogram for the facies modelling.

The variogram parameters for modelling the facies themselves were selected in accordance with their percentage, presented over the entire reservoir thickness (Table 2). Facies eight is a non-reservoir facies (Figure 2).

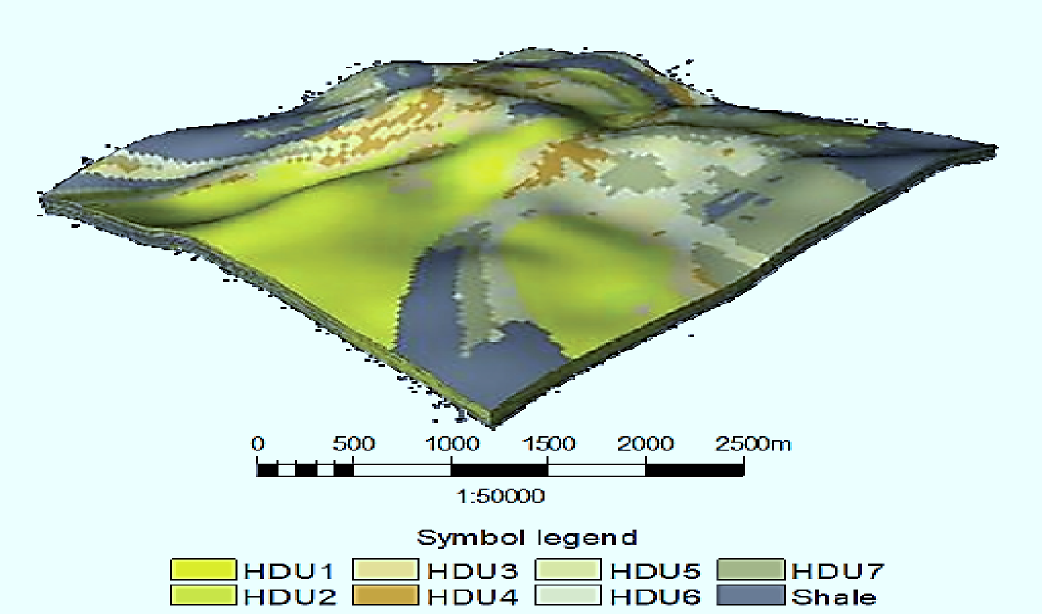

Figure 2: Reservoir Z3 facies model.

Facies	Thickness Percentage, %	Thickness, m	Range, m	Nugget, m
1	2,34	0,498	0,998	0,0001
2	1,7	0,362	0,714	0,0001
3	4,84	1,029	1,265	0,0001
4	6,26	1,332	1,363	0,0001
5	12,51	2,661	3,302	0,2586
6	6,96	1,480	2,081	0,2279
7	23,68	5,036	6,432	0,3239
8	41,71	8,872	12,388	–

Table 2: Parameters of each facies in the variogram.

The next step in the calculations was considering the influence of the lateral anisotropy of permeability on the behaviour of the intrusion model. This was accomplished by multiplying the permeability cube of the model by 1.48 in the X direction, whereas a factor of 0.67 was applied in the Y direction according to anisotropy calculations [40-43]. This case's model calculation results can be seen in Table 3 and in Figures 3 & 4. Where in the Table 3, a_z – vertical anisotropy value, Q_o – cumulative oil production, Q_w – cumulative water production, Q_{inj} – cumulative water injection, RF – oil recovery factor.

	Scenario, MM m^3		
	Pessimistic	**Most Likely**	**Optimistic**
a_z	0,1	0,5	0,86
Qo	1,785	2,031	1,975
Qw	1,017	1,321	0,935
Qinj	2,634	3,246	2,763
RF	0,134	0,153	0,148

Table 3: The outcomes stem from the alteration of vertical and lateral anisotropies.

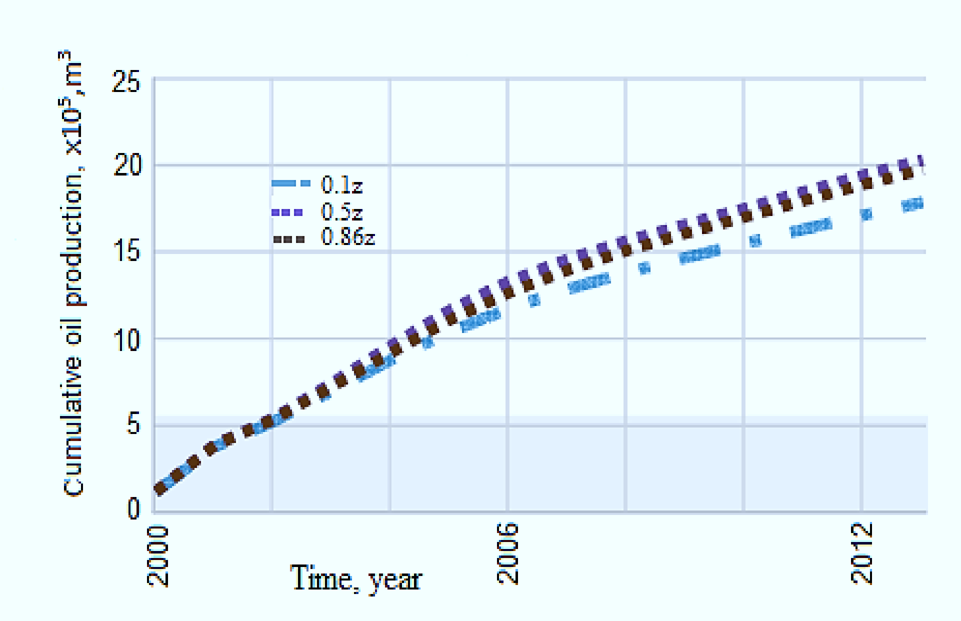

Figure 3: A comparison of three variants of the anisotropic model for cumulative oil production.

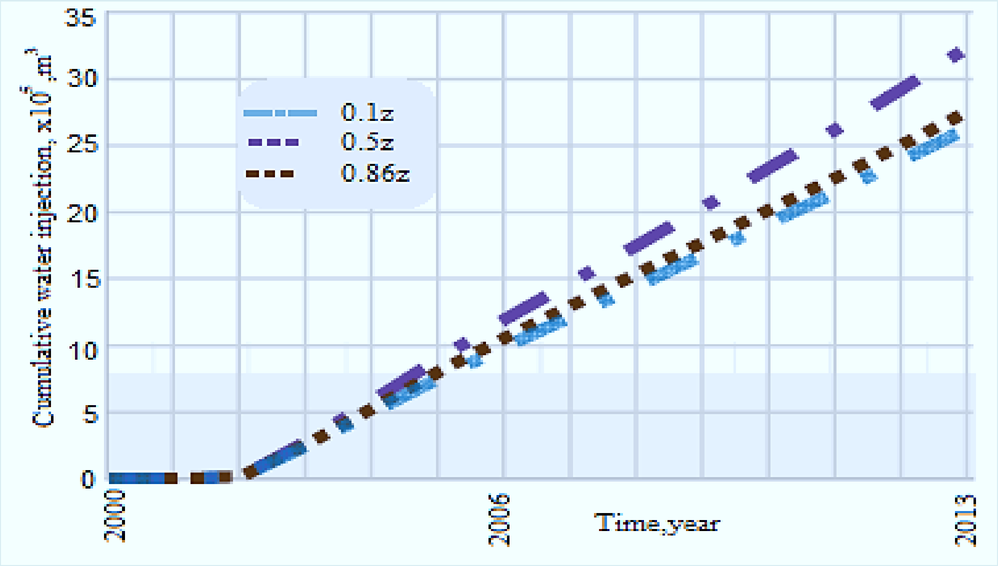

Figure 4: A comparison of three variants of the anisotropic model for cumulative water injection.

Although the calculation results show similar trends when the value of vertical anisotropy changes, introducing lateral anisotropy into the model calculation generally increases the values of development parameters like Q_o, Q_w, and Q_{inj}. It is clear, therefore, from hydrodynamic calculations that taking permeability anisotropy into account is crucial for obtaining a more realistic reservoir structure. Further, this makes it easier to adapt the model to historical data and increases the degree of confidence in its forecasts.

Development System Optimization

To assess the effect of permeability anisotropy, a comparison was made of the behaviour of the reservoir in isotropic and anisotropic cases. The calculation results are presented in Table 4 and Figures 5-7.

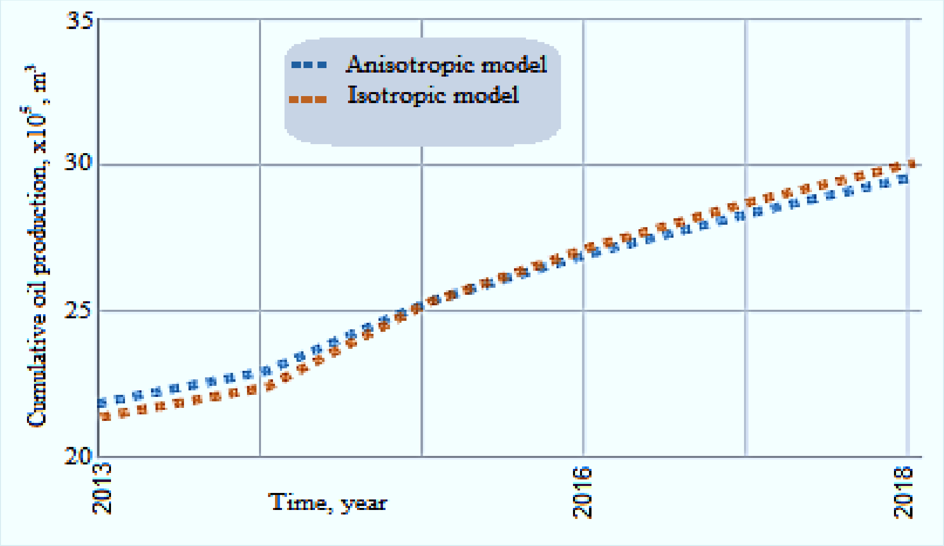

Figure 5: Anisotropic and isotropic models of oil cumulative production.

Figure 5 shows that the cumulative oil production for the isotropic model turned out to be higher than the cumulative oil production for the anisotropic model. It is apparent from this result that omitting anisotropy from the model building can result in an overestimation of development parameters, thereby leading to an overestimation of expected production and incorrect economic analysis. This fact again confirms the significant influence of permeability anisotropy on the field development modelling process. To conclude, a calculation was carried out on an anisotropic model, taking into account decisions on hydraulic fracturing in candidate wells and infill drilling of production and injection wells for a period of 15 years (from 2013 to 2028). The results of these calculations are given in Table 4 and Figures 6 and 7. Where STOIIP is the remaining geological oil reserves, (in million m^3), OWC External is the outer contour of the oil-water contact, OWC Internal is the inner contour of the OWC, Boundary are the site boundaries.

	Development parameters, MM m^3	
	5 years	**15 years**
Qo	3,046	3,700
Qw	5,237	11,998
Qinj	8,745	16,607
RF	0,231	0,278

Table 4: Improved development system calculation results.

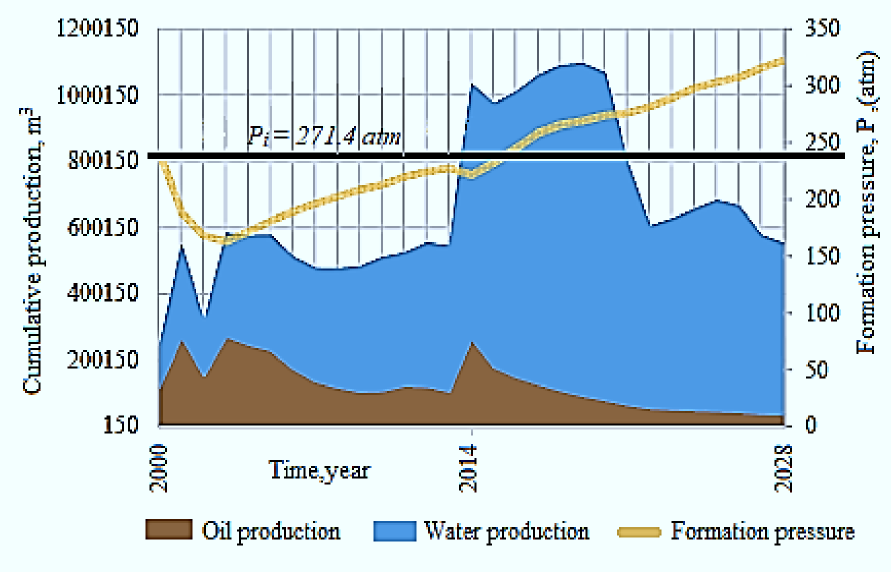

Figure 6: Oil and liquid cumulative production and reservoir pressure dynamics until 2028 for the selected development option.

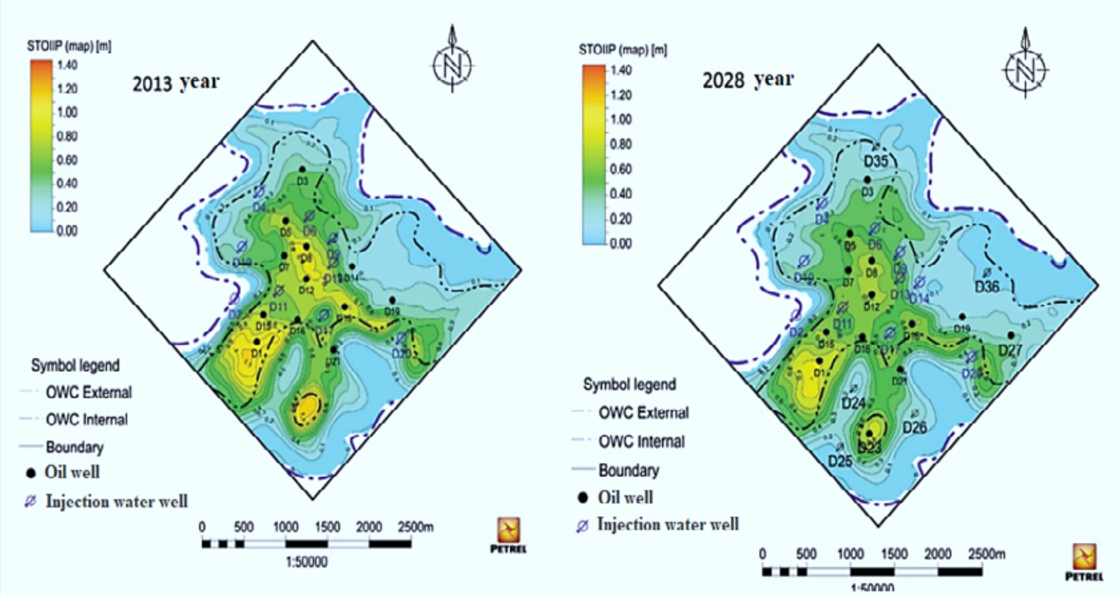

Figure 7: Residual oil reserves maps.

Based on the findings, it is possible to predict the most likely movement of fluids and fractures during hydraulic fracturing by considering anisotropy of permeability, as confirmed by model calculations [44-47]. According to Figure 6, since 2013, hydraulic fracturing operations have been performed and fluid production has sharply increased in production wells situated parallel to injection wells. Infill drilling of production wells with horizontal wells along the axis of improved properties made it possible to significantly increase oil production to levels close to the initial period of development of the area [48-50]. This was also facilitated by sidetracking of production wells in areas with degraded properties, which led to an increase in the production of residual reserves in such areas. Infill drilling was also performed for injection wells. As a result, fluid production with a large amount of water has increased sharply, and since 2018, reservoir pressure has been overcompensated by the reservoir pressure maintenance system (RPM). However, despite this consequence, it also contributed to the efficiency of reservoir development and allowed profitable hydrocarbon production in conditions of increased water cuts [51-55]. Starting in 2023, some injection wells will be phased out.

Conclusion

In this sense, the vertical and lateral anisotropy of permeability introduced into the geological and hydrodynamic model significantly impacts reservoir behaviour. When the vertical anisotropy value is changed, the calculation results show similar trends, but introducing lateral anisotropy generally increases the values of development parameters like Q_o, Q_w, and $Q_{inj.}$

Field development indicators are overestimated when permeability anisotropy is omitted. This highlights the peculiarity of the geological structure of the reservoir since an increase in anisotropy does not always result in an increase in cumulative oil production.

By constructing an anisotropic model, it is possible to omit from the accumulated indicator for oil production up to 1% of the same value according to the isotropic model, according to the results of calculations. Therefore, further modelling of the proposed operations to enhance oil recovery will cause this deviation to continue to increase, resulting in distorted development information.

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