Incorporating Vertical Permeability into Geological Modelling

Introduction

In dynamic reservoir modelling, we usually need to understand fluid flow on a kilometre scale to plan wells and estimate recovery. Petrophysicists and geologists often spend a lot of time deriving porosity-permeability relationships from cores and logs. Equations are applied to the cellular model before passing to the reservoir engineer, typically as horizontal permeability.

However, it is apparent from reviewing and re-building many reservoir models from across the World, that reservoir engineers often have to adjust the vertical permeability by an order of magnitude or more in the simulator to match historical production and pressure behaviour. Frequently this is because vertical baffles caused by silt and shale beds have not been captured realistically in the static model. Outlined here, are some practical methods that can be used to enhance our geological estimate of vertical and horizontal permeability on a simulation-scale.

Scale of Permeability

The first aspect to estimating permeability is direct measurement of core plugs. These are of course small-scale and are typically biased towards the better reservoir. The second aspect is the architecture of the permeability variations. For example, the lateral extent of the poor-quality facies, which may be 10s or 100s metres but may not be resolved on borehole logs. The architecture of a sediment is primarily controlled by the depositional environment, but may be modified by diagenesis or fracturing.

Core Measurements

An example well log and core is shown from a turbidite reservoir deposited in a deep sea fan lobe environment (Figure 1). This comprises two main lithofacies associations: good quality very fine to fine grained sandstone beds are periodically interbedded with laminated siltstone beds. The core plug permeabilities are clearly related to the LFA. For the sandstone LFA in bed 1, the simple average Kh is 735mD and the Kv is 623mD. Under typical flow conditions this is likely to represent the horizontal permeability. For the silt LFA in bed 2, the average Kh is 7mD and Kv is significantly less, at 0.47mD. The small-scale Kv can be used as a starting point to quantify vertical permeability on a larger scale. Note that not all the silty beds are sampled and this needs to be added in the geological model.

![Figure 1 Log and core of a turbidite reservoir with thin silt beds.](image)
Field Outcrop Example

Similar turbidite lobe complexes are well exposed in the Mount Messenger Formation in the Taranaki Basin, New Zealand. In the amalgamated parts of the fan, the silty beds and mudstone drapes form less than 5% of the volume of the section, but they are clearly going to reduce the vertical permeability on a large scale (Figure 2). The degree of reduction is controlled by the actual permeability of each lithology, the degree of amalgamation of the lobes and the presence of mudstone drapes.

![Field Outcrop](image)

*Figure 2 Outcrop of turbidite lobes, Mount Messenger Formation (after Masalimova et al., 2016).*

Geo-Modelling Techniques

Let’s assume that the simulation cells are 50m across by 2m thick. It is not necessary to directly model cm thick beds in the full-field model, nor is it desirable, as we cannot correlate from well to well on a cm scale.

The first method to account for the presence of laminations of poor-quality facies is to build mini-models on a bed-scale. This technique has been employed for lower shoreface heterolithics (Ringrose et al., 2015, Onyenam et al., 2019) and fluvio-esturine deposits (Hao et al., 2019). In a simplified form, a single simulation cell can be built for each LFA to estimate the vertical permeability and net porosity. The detailed lithologies and properties are modelled on a finer scale inside the single simulation cell, including the core estimates of vertical permeability. A number of algorithms are available to upscale the directional (I,J,K) permeabilities and it is generally recommended to use a flow-based solution with boundaries. In addition, several mini-models can be built for each LFA and potentially discern some relationships between the vertical permeability and the input parameters.

A second technique that can be used in the full-field model is to apply transmissibility modifiers according to the geological architecture, for example to account for baffles due to shale drapes or cemented surfaces. In the turbidite example, is necessary to identify specific cells at the base of lobes, including the possibility of sand-on-sand cells. A workflow has been designed (for industry standard software) to scan the cells in the model and assign a flag where lobe objects and a particular facies are adjacent. These techniques are illustrated using a simple reservoir model at simulation scale (Figure 3).
Figure 3 Illustrating the geo-modelling techniques. Scale in metres.
Four LFAs are defined, two in the channel lobes and two in the background (a). Average properties (b) have been derived for each LFA using mini-models. In this example additional baffles due to shale drapes have been added in the relevant cells (c). The resulting Kh and Kv (d and e) is modelled according to facies and relative position.

In this simple model, only using average properties for each LFA, there is a dramatic effect on the directional permeability and could not have been built using a constant Kv/Kh method. This shows the importance of quantifying vertical permeability and not put all the modelling effort into refining horizontal permeability.

This example provides a rapid first pass model of the geological architecture which is then refined by adding the petrophysical log analysis and sedimentological evaluation of the wells. The methodology can produce additional deterministic and/or stochastic models and needs be adapted according to the project objectives and the data available.

**Conclusions**

Estimating vertical permeability is a key part of the geological modelling process and should not be left to a selection of mathematical averaging options or an arbitrary range applied in the dynamic simulation. The geological modelling workflow should combine specific core observations and knowledge of depositional environment to make an intelligent estimate of vertical permeability. If this is done on a simulation-scale it eliminates the need for full-field upscaling and allows rapid iteration between dynamic and static models.

Bed-scale modelling can assist in determining directional permeability for a particular facies association. Identification of cells where baffles may be expected can be incorporated into the workflow to enable more realistic architecture and improve the inputs for the dynamic simulation.

There is more uncertainty in the vertical permeability, but it is worth spending time in the static modelling to provide a realistic range of vertical permeability for the dynamic simulation modelling.

**References**


