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New Approaches to Upscaling Fault Zones for Flow Simulation

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SUMMARY

Natural faults are complex three-dimensional volumes with abundant displacement partitioning between individual fault segments. This displacement partitioning results in different across-fault and up-fault flow paths to those present in conventional faulted simulation models in which faults are represented as single planar surfaces. Recent research has focused on defining methods for (a) modelling realistic sub-seismic fault zone structure, and (b) representing this in flow simulation models. This presentation focuses on the second of these topics, and described a new, flow-based upscaling method that is more accurate, more flexible and easier to apply, than the existing geometry-based geometrical upscaling algorithm.

Introduction

Geological faults are a general source of heterogeneity within petroleum reservoirs and may have a considerable influence on fluid flow due to both the formation of non-stratigraphic across-fault connections and to the presence of lower permeability fault rock (e.g. Childs et al. 2009; Braathen et al. 2009; Fredman et al. 2008; Manzocchi et al. 2010; Soleng et al. 2007). Though generally represented in reservoir models as planar surfaces, faults are actually complex 3D zones in which undeformed rocks are mixed and deformed to various extents at different positions within the zones. Details of across-fault flow depend on the precise geometrical arrangements of different fault zone components, which are generally below the resolution of seismic data and therefore cannot be modelled deterministically. Developing high-resolution models of fault zones are beyond the scope of this work, but associated to this is the need for methods for representing the possible sub-resolution fault zone structure in full-field flow simulation models (e.g. Soleng et al. 2007, Manzocchi et al. 2008).

In this work, we develop upon the geometrical upscaling method of Manzocchi et al. (2008), in which the flow effects of 3D fault structure are captured as non-neighbour transmissibilities at the resolution of the full-field flow simualtion model. We introducing a new flow-based method for calculating the transmssibilities. We compare the impact of fault zone geometry for the new and existing geometrical upscaling approaches and, by comparison to the behaviour of a fine-scale model, we show that the new method is both more accurate and more flexible.

Geometrical Upscaling

Geometrical upscaling (e.g. Manzocchi et al. 2008) is defined as the process of calculating the cell centre to cell centre connection transmissibilities associated with complex 3D fault zone structure (Figure 1a) and representing them at the resolution of the full-field flow model (Figure 1b). In this example, the coloured cells in the high resolution model represent transmissibility values associated with tortuous 3D flow paths through the fault zone between the cell that is coloured and the reference cells highlighted by thick lines on the footwall of the fault (Figure 1a). These transmissibilities can be represented as non-neighbour connections in a lower resultion model (Figure 1b), to give the same flow paths. The tricky part of the algorithm is calculating the transmissibilites of all possible cross-fault and up-fault flow paths associated with the fault zone, and in the existing geometry-based approach this is done geometrically. The present work develops a new flow-based approach to the upscaling.

Existing Geometry-Based Upscaling Algorithm

Transmissibility is defined as the flow potentiality and is calculated from the centre of one cell to the centre of another cell (Figure-2a) as a function of geometry, contact area, and properties of the cells (e.g. Schlumberger Geoquest 2005). The objective of geometry-based upscaling technique (e.g. Manzocchi et al. 2008) is to calculate all the possible flow paths (transmissibilities) that exist in the detailed fault zone model. Considering an extremely simple two-cell reservoir model (Figure 2b) containing the intervening sub-seismic fault zone structure illustrated in (Figure 2b), there are four possible flow paths between cell 1 and cell 2. Transmissibility from the centre of cell 1 to the centre of cell 2 is calculated by combining the transmissibilities of flow paths up the relay ramps and through the relay ramp bounding faults, and is given by;

$$T_{12} = \frac{1}{[T_A + T_B]^{-1} + [T_C + T_D]^{-1}} \qquad (1)$$

Where T_A, and T_B are the transmissibilities from cell 1 to the relay ramp, and T_C, and T_D are the transmissibilities from cell 2 to ramp, using four different flow paths indicated by arrow sign (Figure 2b). In a realistic 3D model, individual transmissibilties are calculated using a standard geometrical and fault rock property approach (e.g. Manzocchi et al. 1999), and are combined according to a specific rules developed for a limited sub-set of possible fault zone structure.

New Flow-Based Upscaling Algorithm

We have developed a new flow-based geometrical upscaling method to simplify the approach and to make it more flexible, In this method, all the cell centre to cell centre connection transmissibilities through the fault zones are calculated as a function of pressure differences, flow rate, and viscosity of the flowing fluid using single-phase steady state numerical flow simulation (Figure 2c). To perform the numerical flow simulation, we use a high-resolution reservoir model, which contains the 3D fault zone structures explicitly. For a reservoir model with N layers, one injection well and (2N-1) production wells placed at the centre of the grid cells, and are used to calculate all the possible connection transmissibilities, which are associated with the cell containing the injection well. The same procedure is applied to all other cells, requiring a total of 2N flow simulations. Mathematical expression of transmissibility for flow-based upscaling case is derived based on Darcy's law and is given by;

$$T_{12} = \frac{q_{12} * \mu}{\Delta P} \qquad (2)$$

Where ΔP is the pressure difference between the centres of the cells, q_{12} is the volumetric flow rate, and μ is the viscosity of the flowing fluid.

Test Models and Results

The test reservoir models used to test the accuracy of the upscaling (Figure 3) is comprised of a single pair of cell stacks and the dimension of each cell is 75m by 75m by 4m. The dimensions of the high-resolution flow simulation model is 50×25×4 (Figure 3a) and low-resolution upscaled flow simulation model is 2×1×4 (Figure 3b). The high-resolution model contains fault zone structures explicitly whilst in the low-resolution upscaled model versions , the fault rock and geometrical effects of the fault zone are included implicitly as a function of neighbour and non-neighbour cell-to-cell connection transmissibilities, and transmissibility multipliers calculated either using the existing geometry-based, or the new flow-based, geometrical upscaling method.

An Injection well located at the middle of top layer of footwall, and a producer well located at the middle of bottom layer of hanging wall, are both controlled by Bottom Hole Pressure, ensuring a fixed flow rate. The pressures in the six the remaining grid-blocks are monitored, and the accuracy with which the upscaled cell pressures match those observed in equivalent positions in this high resolution model are testament to the accuracy of the upscaling.

The flow responses of flow-based model and high-resolution model are almost identical (Figure 4), while there are significant differences in flow response (Figure 4) between geometry-based upscaled model and high-resolution model. A lower total misfit in cells pressure (Figure 5a) and misfit in production rate (Figure 5b) is observed in the flow-based models whatever the locations of the injector and producer wells, implying that the new, flow-based method is more accurate, than the existing geometry-based method.

Conclusion

Our results show that the sequential responses in terms of pressure behaviour for a high-resolution model and two upscaled versions reveal significant differences. The flow-based geometrical upscaling is more accurate and efficient method to represent the fault zones into low-resolution flow simulation models.

References

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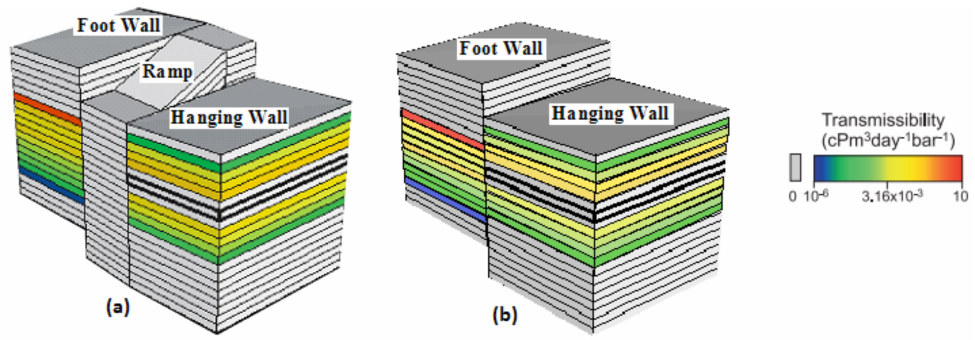

Figure 1 *Example figure of geometrical upscaling (Manzocchi et al 2008) method where the black coloured cell of hanging wall is connected to different coloured cells of foot wall and hanging wall through the ramp. (a) High-resolution model contains an unbreached relay ramp as 3D fault zone structure. (b) Upscaled model containing 3D fault zone structures as a function of non-neighbour, neighbour connection & transmissibility multiplier.*

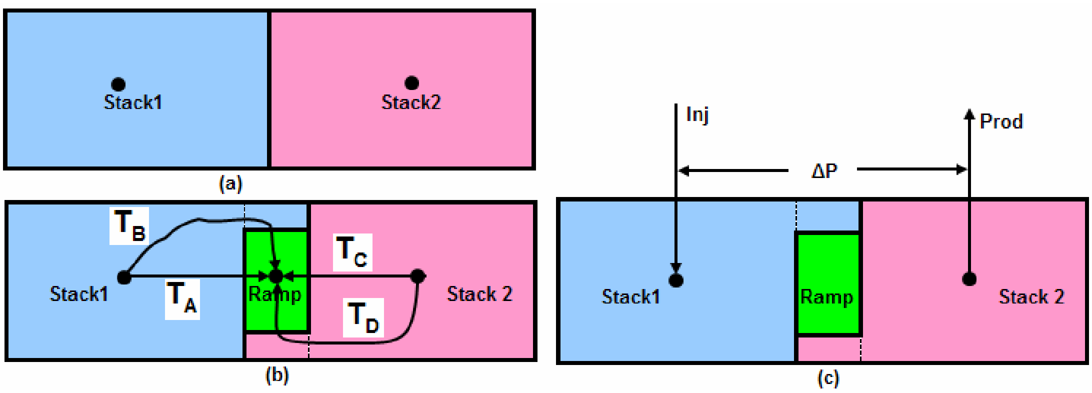

Figure 2 *Two dimensional geometric configuration of reservoir model comprises of a single pair of grid block. (a) Upscaled model contain fault zones implicitly. (b) High-resolution model contain detailed fault zones used for calculating the transmissibility of geometry-based upscaling. (c) As (b) used for calculating transmissibility of flow-based method.*

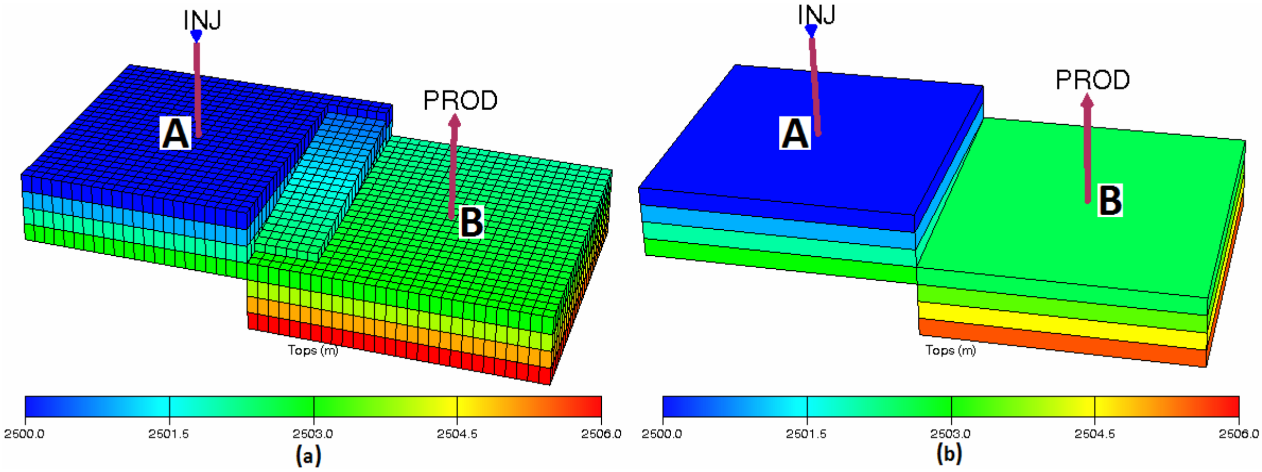

Figure 3 *Example of reservoir test models with four layers where foot wall (e.g. A) and hanging wall (e.g. B) are separated by faults. (a) High-resolution flow simulation models contain 3D fault zone structures explicitly. (b) Low-resolution upscaled models contain the same fault zone structures implicitly as a function of non-neighbour and neighbour connection.*

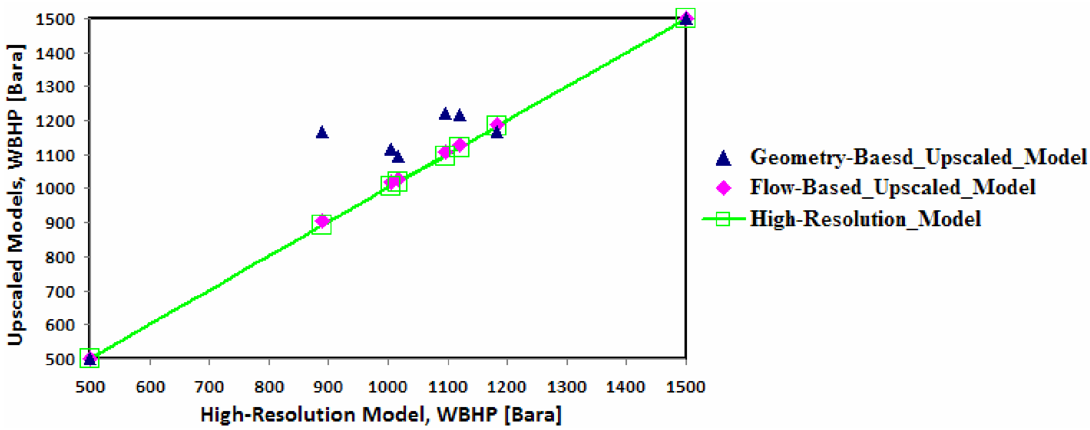

Figure 4 *Cross plot of the sequential flow responses of two upscaled versions (Black: geometry-based method, pink: flow-based method) in terms of Well Bottom Hole Pressure (WBHP) with high-resolution model (green) for a specific well placement (Inj[A1]-Prod[B4]).*

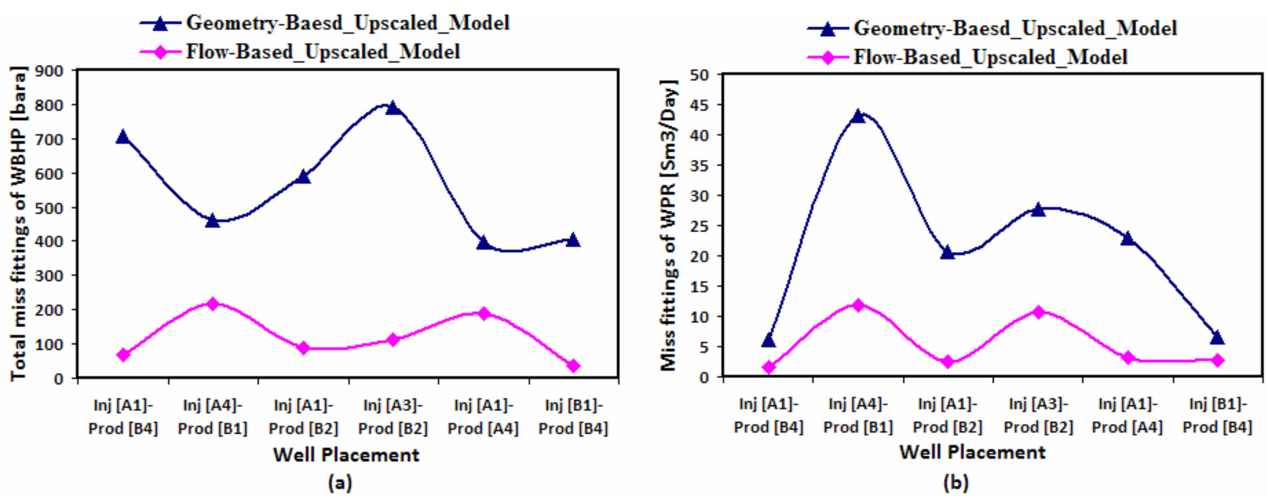

Figure 5 *Miss fittings of two upscaled models with respect to high-resolution model for different well placements. (a) Well Bottom Hole Pressure (WBHP). (c) Water Production Rate (WPR).*