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The Transmissibility of Partially Connected Cells

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SUMMARY

Flow simulators assume that the transmissibility between two cells is proportional to their connection area. We show that this assumption is incorrect for partially connected cells, and assess the significance of this previously ignored error.

Faulted reservoir flow simulation models built using corner-point geometry contain partially connected cells across faults. Partial connections are an inevitable consequence of miss-alignments of grid-cells resulting from the fault displacement, and it is not possible to eliminate them without compromising either the sedimentary layering or the across-fault juxtaposition geometry. Across-fault cell connections vary in shape from triangular to hexagonal, and have widely-varying fractional connection areas (the area of the connection expressed as a fraction of the area of the cell face).

Using high-resolution flow simulation models of the volume between the centres of partially juxtaposed grid-blocks, we examine systematically the magnitude of the transmissibility error. For two cells, the error is greater when the fractional connection areas are smaller, and the kv:kh and cell length:height ratios are larger. For a realistic cell aspect ratio of 60:1, kv:kh ratio of 0.1, and fractional connection area of 0.2, tortuous flow within the cells results in a transmissibility that is about five times greater than the simulator assumption. The errors decrease when fault rock is present between the cells, and when angular miss-alignments between the cells are larger.

Analysis demonstrates that the transmissibility between partially juxtaposed cells is influenced not only by the geometry and properties of the two cells in question, but also by the surrounding cells, and the error is larger in more heterogeneous sequences. Because of the complexity of the dependencies there is no analytical solution. A wider recognition of the problem, combined with our analysis of its magnitude, may aid a better appreciation of fault-related transmissibility uncertainties.

1. Introduction

Most faulted full-field simulation models built in the last 20 years have used corner-point geometry (CPG) to define the reservoir structure. CPG was introduced to allow a greater flexibility than existed in the older, rectangular Cartesian grids, for the representation of geological attributes such as faults, pinch outs, and cross stratified beds (Ponting 1989, Ding and Lemonnier 1995, Peaceman 1996, Sammon 2000, SchlumbergerGeoquest 2005, Fanchi 2006). CPG is based on co-ordinate lines that define the edge of each vertical stack of cells, and the eight corner point depths of each cell are defined explicitly (Figure 1a). A reservoir model with grid dimension N_X by N_Y by N_Z therefore requires $2N_X.2N_Y.2N_Z$ corner points and $(N_X+1).(N_Y+1)$ non horizontal co-ordinate lines. Cells from adjacent cells stacks in a CPG model share two co-ordinate lines, and because the depths of the corners of each cell can be defined individually, individual cells can have multiple connections in a particular direction, with irregular connection interfaces (Figure 1b). This flexibility allows faulted models to be build which include realistic lateral variations in fault displacement over the length of a fault (e.g. Figure 2), resulting in individual cell-to-cell connections with between three and six corners and mutual overlap areas significantly smaller than the size of the cell face (Figure 2c).

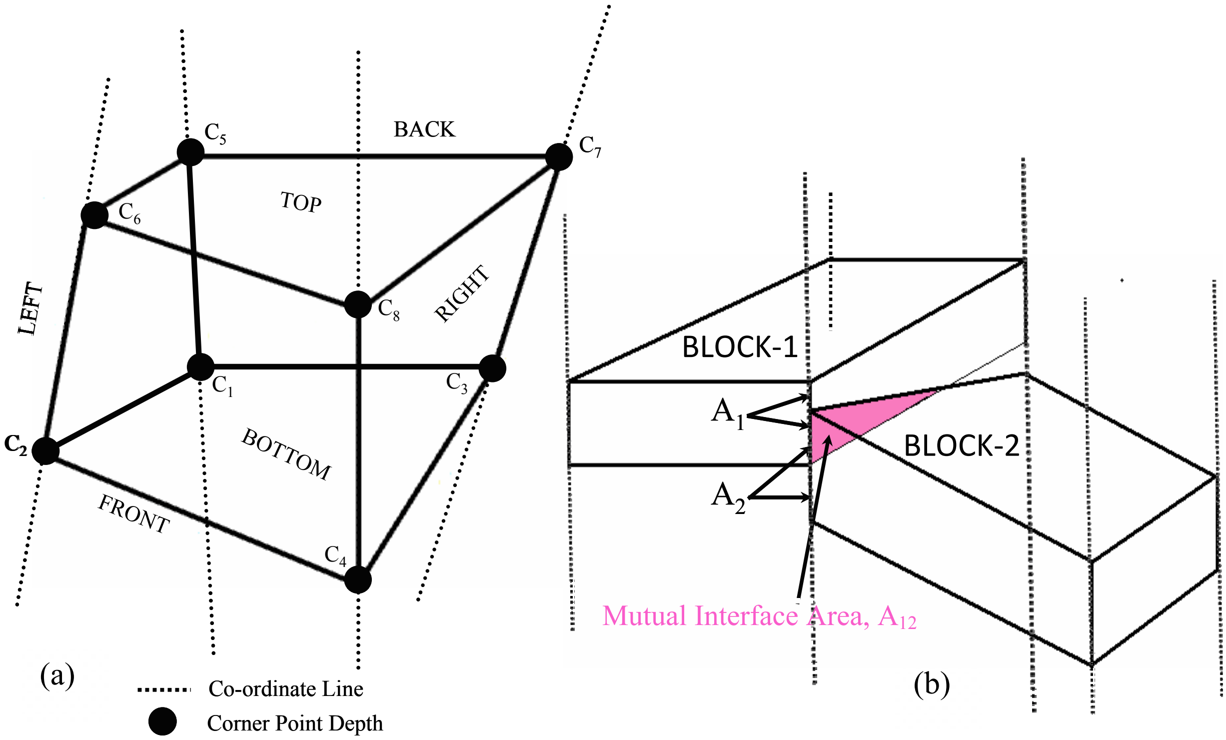


Figure 1 *Corner Point Geometry cell structure. (a) One grid cell of a reservoir model defined in CPG. After Sammon (2000). (b) Two grid cells with a partial connection area.*

Flows between cells in finite difference simulation models are calculated from a discretization of Darcy's Law originally devised for orthogonal Cartesian grids. Several researchers have investigated the inaccuracy in the expression caused by angular departures from orthogonality, and have shown it to be relatively small for the modest angular distortions present in well-built CPG models (Aziz and Settari 1983, Mattax and Dalton 1990, Cordazzo et al. 2002, Fanchi 2006). Our work focuses on a different, unrelated error associated with the transmissibilities of partial connections produced by across faults in CPG models. We show that the error, which to the best of our knowledge has not previously been discussed, is potentially significant, and becomes more so in more heterogeneous reservoirs with more permeable fault rocks.

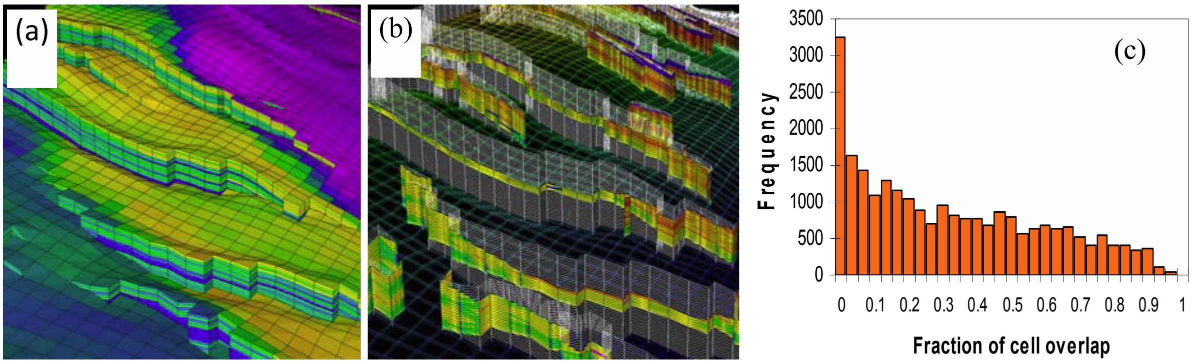
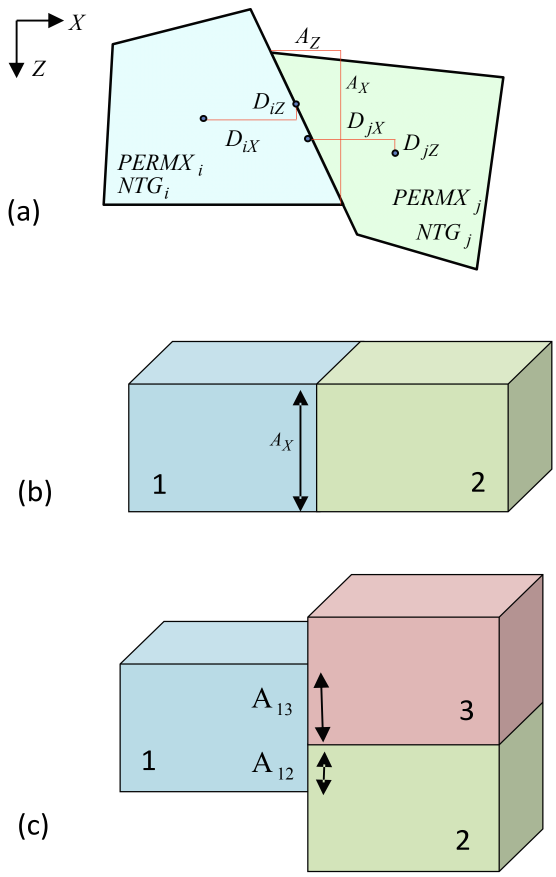


Figure 2 *A 3D full-field faulted reservoir model built with constant size cells (75m×75×4m) and faults with variable throws. (a) The cells. (b) Faulted cell-to-cell connections, coloured by transmissibility. (c) Histogram of the area of faulted connections, expressed as a fraction of the area of a cell face (i.e. 75m×4m). After Manzocchi et al. (2008).*

Transmissibility defines the flow potentiality from the center of one cell to the center of another cell. Commercial simulators generally use a vectorial two point flux approximation (TPFA) to estimate the inter-block transmissibility due to its simplicity and to reduce the computational effort (e.g. Figure 3a; Aziz and Settari 1983, Goldthorpe and Chow 1985, Hegre et al. 1986, White and Horne 1997, SchlumbergerGeoquest 2005). For orthogonal cells (e.g. Figure 3b,c), the expression implies that transmissibility between two cells is directly proportional to the area of juxtaposition between them.



$$TRANX = T_{Mult} CDARCY \left[\frac{1}{T_i} + \frac{1}{T_j} \right]^{-1}$$

$$T_i = PERMX_i NTG_i \frac{A_X D_{iX} + A_Y D_{iY} + A_Z D_{iZ}}{D_{iX}^2 + D_{iY}^2 + D_{iZ}^2}$$

$$T_j = PERMX_j NTG_j \frac{A_X D_{jX} + A_Y D_{jY} + A_Z D_{jZ}}{D_{jX}^2 + D_{jY}^2 + D_{jZ}^2}$$

$$\mathrm{TRANX} \propto \mathrm{A_X} \left[\frac{1}{k_1} + \frac{1}{k_2} \right]^{-1}$$

$$\mathrm{TRANX}_{12} \propto \mathrm{A}_{12} \left[\frac{1}{k_1} + \frac{1}{k_2} \right]^{-1}$$

$$\mathrm{TRANX}_{13} \propto \mathrm{A}_{13} \left[\frac{1}{k_1} + \frac{1}{k_3} \right]^{-1}$$

Figure 3 *(a) Vectorial approach to the transmissibility between two cells. After Schlumberger Geoquest (2005). Simplified expression for the transmissibiltiy of (b) two and (c) three orthogonal cells.*

While this proportionality, which follows directly from Darcy's law, is clearly to be expected in the case of cells with 100% mutual juxtaposition (Figure 3b), it is unlikely to be accurate in the case multiple connections to cells with differing permeabilities (Figure 3c), since tortuous flow paths associated with preferential flow into the higher permeability cell will be underestimated by this expression. The purpose of this paper therefore is to document and quantify this error and to understand the sensitivities upon it. We do this by constructing high resolution flow models of two (or sometimes three) grid-blocks, and comparing the cell to cell transmissibilities back-calculated from these models, with the simplified TPFA transmissibility expression.

2. The transmissibility of partially juxtaposed cells in two dimensions

2.1 Modelling procedures

The initial scenario we investigate is a simple 2D case, similar to the case investigated by Walsh et al. (1998), of two cells with identical properties and variable amounts of juxtaposition between them. A schematic cartoon of the simulation model used, which represents the area between the centers of the two cells, is shown in Figure 4a. These two cells are characteristic of the sizes used in conventional flow simulation models, with a length (*L*) of 75m and a height (*H*) of 1.25m; implying a horizontal to vertical aspect ratio of 60:1. The cell properties are identical and isotropic, with a $k_1 = k_2 = 100$mD, and $k_V/k_H = 1.0$.

A flow simulation model of the region between the two cell centers has been built using 250×1×125 cells (for simplicity in Figure 4a and elsewhere in this paper, the model is shown with only 20×1×5 cells, but the actual model used is much more refined). The juxtaposition area (A_C) between the grid-blocks varies systematically between 0.8% and 100% of the cell height, ensuring in each case that the small cells in the high resolution flow model have 100% juxtapositions across the fault (as they do in the simplified Figure 4a). Vertical injection and production wells located at the edges of the model are controlled by constant bottom hole pressure (BHP), and are perforated in each high resolution cell. All the single-phase flow simulation models are run until steady-state flow is achieved. The actual transmissibility of the coarse cell-center to cell-center region is then back-calculating from the observed flow rates in the high resolution model (Figure 4b), and in this case is much higher than would be expected from the simple proportionality between transmissibility and connection area that is generally assumed by flow simulators when the cells are partially juxtaposed (i.e. when $0\% < A_C < 100\%$).

The reason for the discrepancy between the actual transmissibility and the simulator approximation is that the approximation does not include the possibility of tortuous flow within the grid-blocks, and this flow imparts a significant overall increase in transmissibility. For example, Figure 5a shows schematically flow streamlines between two cells that are completely juxtaposed ($A_C = 100\%$). In this case the streamlines are parallel to each other, perpendicular to the interface between the two cells, and equally spaced throughout the grid-block height. This is reasonable in this case as there are no asymmetries in the geometry of the model to perturb these streamlines. The cells in Figure 5b are the same length but half the height of those in Figure 5a. The juxtaposition area between the two cells is half as much, and it is sensible also to expect the transmissibility between these cells to be half the value of the transmissibility of those in Figure 5a, since two such pairs of cells on top of each other would be exactly equivalent to the situation shown in Figure 5a, but at a different resolution. The problem comes with the case of partial juxtaposition shown in Figure 5c. In this case the juxtaposition area between the two cells is the same as in Figure 5b, and the simulator assigns the same transmissibility to the connection. In terms of flow streamlines, however, this has the same effect as saying that no flow whatsoever is possible a forbidden area shaded in Figure 5c, as flow is restricted to the area perpendicular to the connection. The actual streamlines (Figure 5d) in the high resolution model exploit this forbidden area and, though restricted by the partial juxtaposition, nonetheless have much higher flow rates than would be expected from the simulator assumption (Figure 4b).

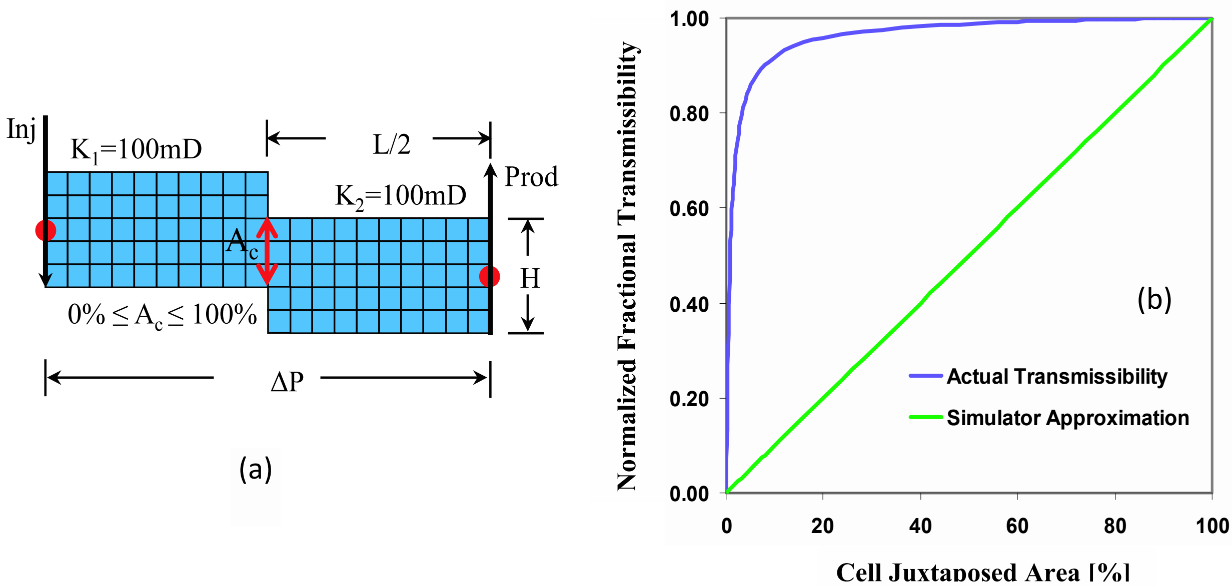


Figure 4 *(a) Cartoon of the 2D high resolution flow model used in this study. Note that the actual model is much more refined. (b) Actual transmissibility back-calculated from flow simulation results, compared to the simulator approximation to transmissibility, as a function of the cell juxtaposition area (A_C).*

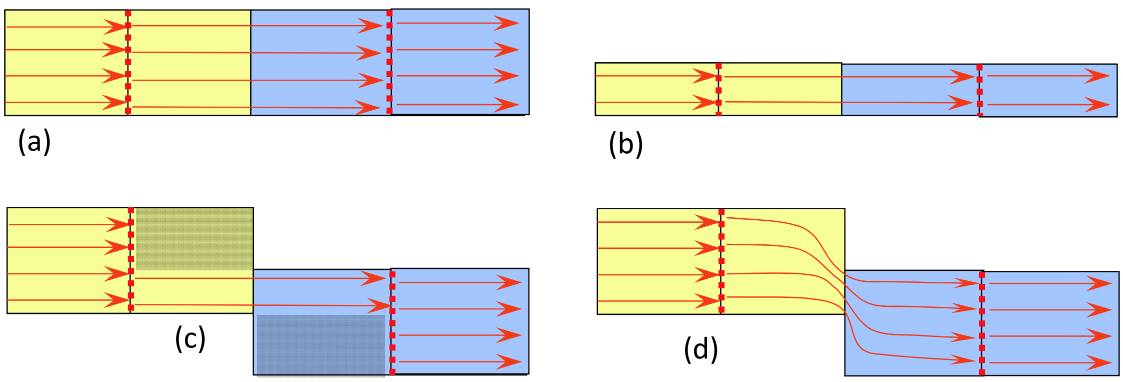


Figure 5 *Two cells (one yellow, one blue) and conceptual streamlines (red array) between cell centers (dashed red lines). Cases (a) to (d) are discussed in the text.*

2.2 Effects of cell aspect ratio and permeability anisotropy

The considerations above have rationalized the results in terms of the utilization of the asymmetrical model volume by streamlines. We take these considerations further to consider what the effect of partial juxtapositions would be, for models with different cell aspect ratios (Length: Height) and permeability anisotropy (k_V:k_H), assuming that Figure 6a shows the streamlines in a reference model. The shape of the streamlines is a reflection of the model geometry and content, and the greater the divergence of the streamlines from the simulator approximation (Figure 5c), the greater the under-estimation of transmissibility. In the case of a lower k_V:k_H ratio (Figure 6b), we expect the streamlines to exploit less of the forbidden area because the lower vertical permeability implies that the vertical deflection of the streamlines must occur over a wider distance from the connection. Therefore we expect models with lower k_V:k_H to have lower transmissibilities for the same partial connection area. The end-member is to consider a case with k_V = 0.0. In this case no vertical flow is possible and all streamlines must be entirely horizontal. In this case the simulator approximation (Figure 5c) must be correct, as the forbidden area in this case is truly forbidden and cannot be utilized.

In Figure 6c, the k_V:k_H and juxtaposition area are assumed to be the same as Figure 6a, and therefore the streamlines are the same shape. However, the aspect ratio of the cells in Figure 6c is greater. This increase in cell length for the same cell height has the effect of increasing the proportion of the forbidden area which contains streamlines, and therefore we expect this model to have a larger error in transmissibility relative to the simulator approximation.

The expectations for these considerations are that the error in transmissibility is likely to be greater in models with a greater k_V:k_H ratio and a greater cell aspect ratio (L:H), and are borne out by the high resolution flow modelling (Figure 7a, b). If the true transmissibility obtained from the high resolution flow modelling is normalized by the simulator approximation that ignores tortuous flow, we obtain a ratio we term the Transmissibility Correction Factor (Figure 7c,d). This is the factor by which the simulator transmissibility must be corrected to account for the error, and can be considerable for realistic aspect ratios used in full-field flow models (L:H is typically in the range 20-100), given the preponderance of lower fractional juxtaposition areas present across faults in realistic faulted simulation models (Figure 2b). It is worth noting that the curves for the different aspect ratio cases (lavender to red lines) and k_V:k_H ratio cases (light yellow to black lines) have the same shape (Figure 7c, d), indicating that the simple considerations and asymmetry and anisotropy used in Figure 6 are appropriate.

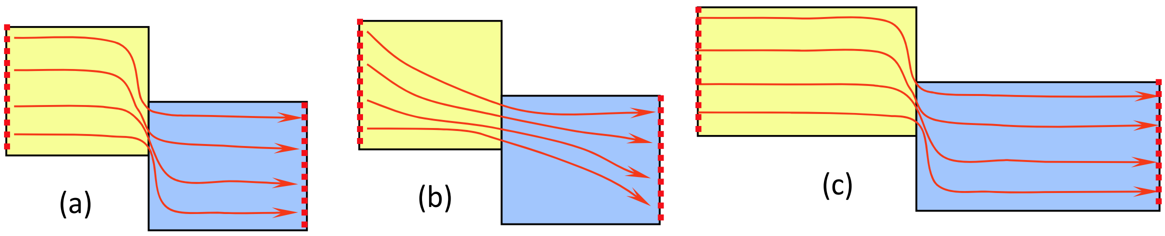


Figure 6 *(a) A datum set of streamlines between the centers of two cells, and the modifications to these as a function of (b) decreasing the vertical permeability, and (c) increasing the cell length.*

2.3 Effects of permeability heterogeneity

The discussion above shows that a consideration of idealized streamlines can explain the effects that the cell aspect ratio (L:H) and permeability anisotropy ratio (k_V:k_H) have on the transmissibility of partially juxtaposed cells. In this section we extend these considerations to examine effects of differences in absolute permeability of the two cells, and the presence of low permeability fault rock between them. Throughout the discussion in this section we use models with a particular k_V:k_H ratio (0.1) and cell aspect ratio (L:H = 60).

In a first set of models, the permeability of Cell 1 is kept constant (100mD) and the permeability of the Cell 2 is varied systematically in the range 1mD to 100mD (Figure 8a). The cell-to-cell transmissibility depends on the harmonic average permeability of the two cells (Figure 3), and this change in k_2 changes both the simulator approximation, as well as the observed transmissibility, between the cells. However, when we calculate the normalized fractional transmissibility (T_N: the transmissibility observed in the partially juxtaposed high resolution flow model normalized by the transmissibility that would be present between the same two cells in the case of 100% juxtaposition), we find that all cases have exactly the same curves of T_N vs. A_C (which is shown for the $k_1 = k_2 =$ 100mD case by the red curves in Figure 7a which is identical to the red curve labelled $T_{mult} = 1.0$ in Figure 8a). In other words, the difference in permeability between the two cells does not change the transmissibility error in the simulator approximation compared to the high resolution flow model. We interpret this result to be because absolute permeability does not change the shapes of the pressure distributions within the grid-cells, but merely the relative magnitude of pressure drop within each. Therefore both cells, irrespective of their differences in permeability, have the same fractional transmissibility error which is a function of the geometry and anisotropy of permeability field but not the actual permeability magnitude. Hence when the cells are combined, the T_N value is identical irrespective of the precise values of k_1 and k_2, so long as the geometry (L:H and A_C) and anisotropy (k_V:k_H) of cells are the same.

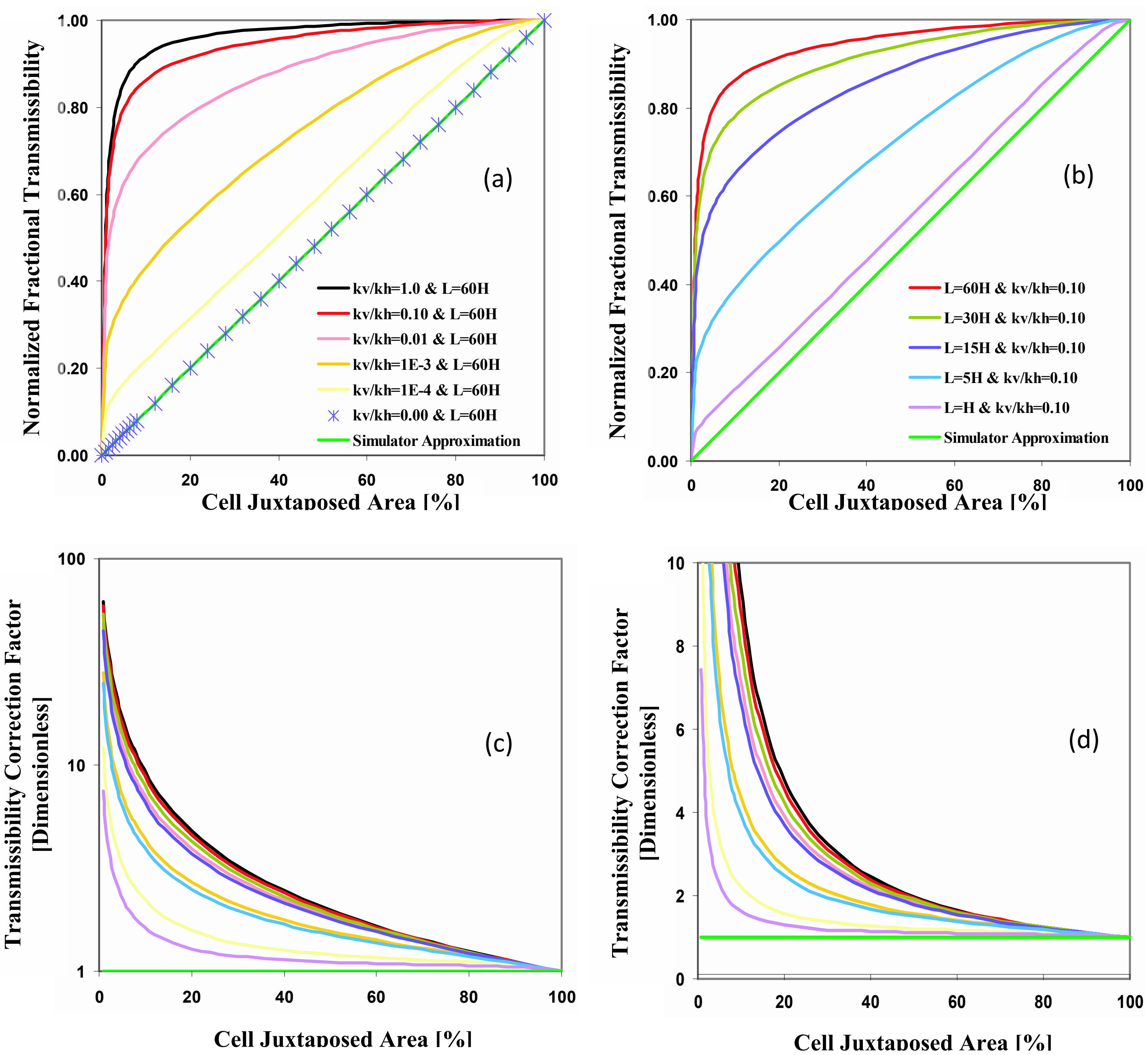


Figure 7 *Transmissibility as a function of cell juxtaposition area for cases with (a) different* k_V:k_H *ratio and (b) different cell aspect ratio. (c, d) Transmissibility correction factor (i.e. the transmissibility derived from the numerical results normalized by the simulator approximation) for the* k_V:k_H *cases (light yellow to black) and the cell aspect ratio cases (lavender to red).*

In a second set of models we examine the influence of a specific thickness of low permeability fault rock between the two partially juxtaposed cells. Fault rock can be included in these models in two ways: firstly be explicitly defining the properties of cells between the grid-blocks (Figure 8b), and secondly by assigning transmissibility multipliers to the across-fault connections in the high resolution models (Figure 8a). The appropriate value of the multiplier can be determined from the following expression (Manzocchi et al. 1999):

$$T_{mult} = \left[1 + t_f \frac{2/k_f - 1/k_A - 1/k_B}{(L_A/k_A + L_B/k_B)} \right]^{-1}, \qquad (1)$$

Where t_f and k_f are the fault rock thickness and permeability, and lengths L_A and L_B refer, in this case, to the size of the fine-scale model cells. We have applied both methods in this study and have obtained identical results with both.

We find that irrespective of k_1 and k_2, models with the same transmissibility multiplier at the scale of the large grid-blocks (i.e. with the same value of T_{mult} calculated in Equation 1 using the $L_A = L_B = L$) have the same curve of T_N vs. A_C (Figure 8c). The curve with the greatest divergence from the simulator approximation of T_N occurs when $T_{mult} = 1$, and the error is less than a factor of 2 even for very low A_C, provided $T_{mult} < 0.5$ (Figure 8d). We conclude that because of the model geometry, the streamlines through the fault rock are perpendicular to the cell face even when A_C is low, and therefore the simulator assumption is correct for the portion of flow through the fault rock. In a model with a more restrictive fault (i.e. a model with a lower T_{mult} value), relatively more of the pressure drop occurs within the fault rock, and relatively less within the grid-cells, and therefore the error in the simulator approximation of transmissibility is lower.

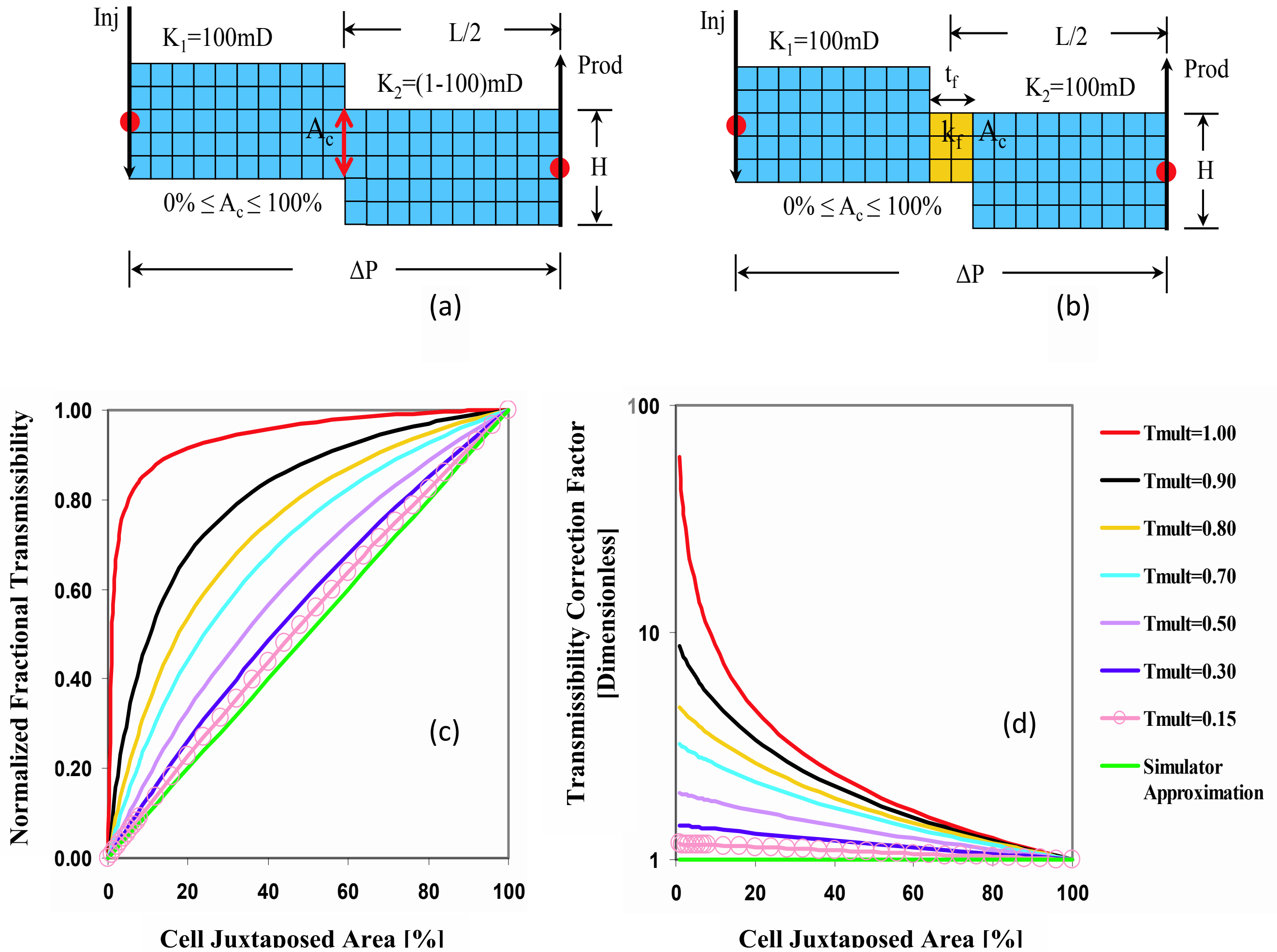


Figure 8 *Fault rock properties can be attached to the models either as transmissibility multipliers on the fine model grid (a) or discretely as low permeability cells (b). (c) Transmissibility as a function of cell juxtaposition area for cases with different permeabilities in the two cells as well as different fault rock properties. In each case, models with different large-scale transmissibility multipliers have identical curves. (d) Ditto, but shown the transmissibility correction factor.*

3. Three-dimensional effects

In Figures 7 and 8 we have examined the transmissibility of two partially connected grid-cells as a function of cell aspect ratio (L:H), anisotropy (k_V:k_H) and heterogeneity (k_1, k_2, k_f), in two dimensional models. An aspect of full-field faulted models is that fault displacement gradients can cause angular misalignments between grid cells, as shown in Figure 2. Hence the effects of partial juxtapositions should ideally be considered in a 3D, rather than 2D context. Figure 9a,b shows how a constant 10% partial juxtaposition area can differ spatially as a function of cell misalignment in 3D. Displacement gradients on normal faults at the scale of flow simulation models are generally less than about 10°.

It is difficult to build high resolution 3D models with entirely overlapping fine-scale cells for the geometries shown in Figure 9a, therefore the flow models built to examine this effect have a constant cell geometry with 100% cell overlap (Figure 9c), and the effect of the irregular juxtaposition area is included by allowing flow through only the selection of connections shown in red in the 4 cases in Figure 9d. The reason for this modelling scheme is partly because it is much simpler to build, and partly because it ensures that there are no partial connections in the high resolution model. In the absence of gravitational effects, the scheme preserves the asymmetry of flow in the two cells, and therefore the results should be reasonably accurate.

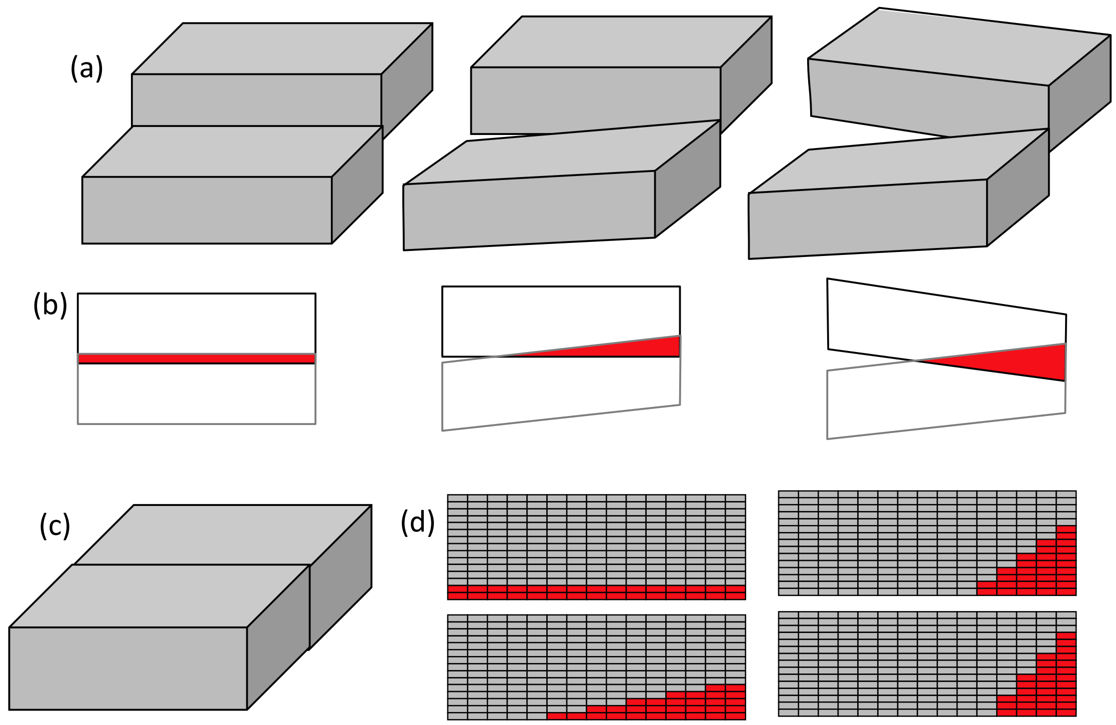


Figure 9 *3D considerations. (a) Two cells separated by a fault with different angular misalignments between the cells. (b) Juxtaposition plots for the three cases in (a) with the partial connections shown in red. (c) Outline of a 3D high resolution grid used to assess the significant of angular misalignments. (d) Cartoon of the contact area of the two cells shown in (c), with active connection in red and inactive ones in grey, representing cases with different angular misalignment.*

We have calculated the transmissibility of 3D models at different angular misalignments and different k_V:k_H ratios for a system with constant cell aspect ratio (L:H = 60) a partial juxtaposition area (A_C = 2%) and no fault rock (T_{mult} = 1.0) In the 2D case with these properties the transmissibility correction factors required to transform the simulator approximate transmissibility to the observed value are high – for example a factor of 43 is required when k_V:k_H = 1.0 and 26 when k_V:k_H = 0.01. The 3D results are quite complex (Figure 10), as they balance two competing trends. The end-member trends are illustrated by the curves at k_V:k_H = 0.0 and 1.0. In the case of k_V:k_H =0.0, no flow perpendicular to the top or base of the cell is possible, and, as we discussed above, the simulator approximation is accurate in the 2D case (Figure 7a). Angular misalignments in the grid cells, however, mean that areas of cell-to-cell juxtaposition become available for lateral flow, hence horizontal deflections to the streamlines allow increases in transmissibility relative to the simulator approximation. Therefore the transmissibility correction factor increases from 1.0 as the dip angle increases (Figure 10). In the case where k_V:k_H =1.0, it is just as easy to flow vertically as horizontally and therefore this effect is irrelevant. Instead, the transmissibility decreases as the dip angle increases, because the area of cell-to-cell juxtaposition become progressively more clustered in the corner of the cell face, and therefore an average streamline need to be longer to achieve the same flow. Intermediate k_V:k_H cases show elements of both these trends (for example a transmissibility minimum is evident at about 5° dip angle when k_V:k_H = 0.001, Figure 10), but in general it is evident that the extreme transmissibility correction factors present at high k_V:k_H ratio in the 2D case (Figure 7) are reduced significantly by even a few degrees of angular misalignment between the cells.

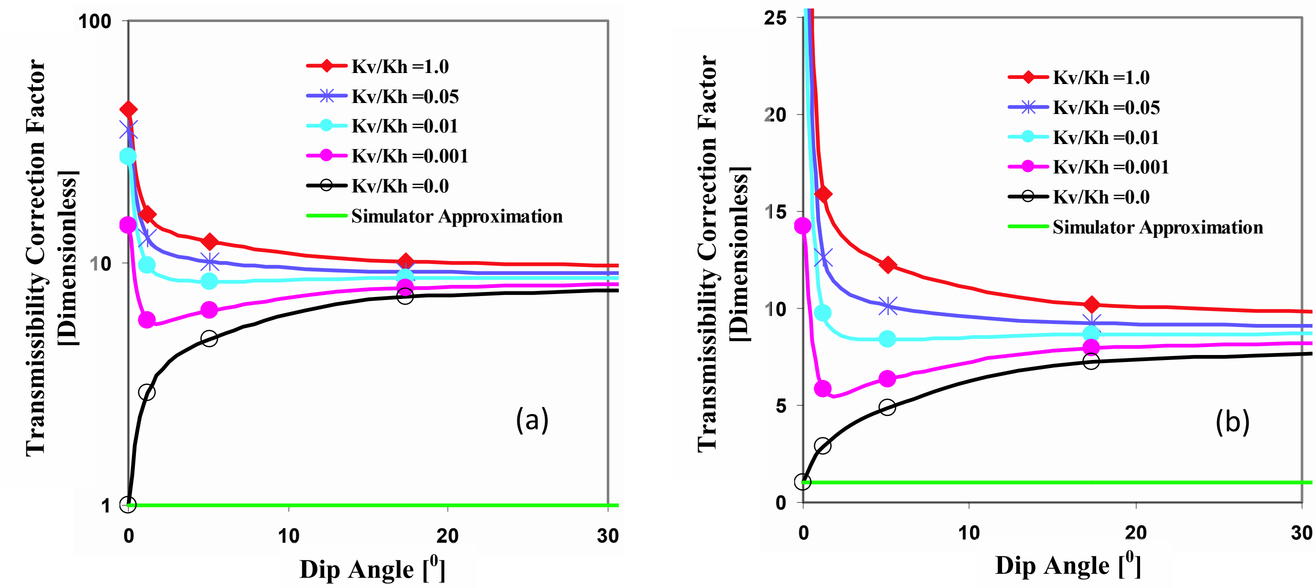


Figure 10 *Transmissibility correction factor for cases with different angular misalignment and k_V:k_H ratio for cells with a constant aspect ratio (L:H = 60) and juxtaposition area (A_C = 2%).*

4. Discussion

In his initial formulation of corner-point grids, Ponting (1989) discussed transmissibilities associated with partial connections, and drew a Figure similar to Figure 11 to consider what the transmissibility of partial connections should be. Ponting (1989) reasoned logically that the total transmissibility between the two sets of cell-stacks shown in Figure 11 should be identical even though one has partial juxtapositions and one does not, and that this must be achieved using a transmissibility formulation in which the cell to cell transmissibility is proportional to the juxtaposition area. This reasoning is correct, yet our flow simulation models, which include a single pair of cells from the stack shown in Figure 11b, indicates that the assumption that transmissibility is proportional to contact area is incorrect and too restrictive to flow.

These contrasting views can be reconciled be considering vertical heterogeneity of cell properties. In Ponting's (1989) considerations, the two stacks of cells (Figure 11a, b) can only be equivalent if the properties of the cells in each stack are identical, i.e. if there is no vertical heterogeneity. If the cells labelled 2 and 3 in Figure 11b, for example, have different properties to each other, then there can no longer be any equivalence between Figure 11a and 11b, as the spatial arrangements of the permeability fields must be different. Therefore there is no longer any reason to expect the total transmissibility between the two stacks to be the same. Hence our models, which take an extreme case of vertical heterogeneity in which only cells 1 and 2 (Figure 11b) are active, is fundamentally different to Ponting's (1989), and therefore there is no contradiction in his conclusions and our model results.

To illustrate this point, we have built a high resolution 2D flow model of a portion of Figure 11b. The model (Figure 12a) consists of cell 1 and a portion of cells 2 and 3, and has constant permeability (100mD) in cells 1 and 2, with a range of permeabilities between 0 to 100mD in cell 3. Transmissibilities from cell 1 to cell 2 and cell 1 to cell 3 back-calculated from a high resolution models (which includes a vertical no-flow restraint between cells 2 and 3) are compared to the simulator approximation in Figure 12b and c, while Figure 12d shows the correction factor for total transmissibility across the model. In the case where $k_3/k_2 = 1.0$, there is no vertical heterogeneity in the model and the simulator and high resolution transmissibilities are identical. This is equivalent to the case discussed by Ponting (1989). In the case where $k_3/k_2 = 0.0$, cell 3 is inactive, and the geometry of the model is similar to the case we have been discussing in this paper. We find that the simulator approximation underestimates the transmissibility into the higher permeability cell (Figure 12b), but overestimates it into the lower permeability one (Figure 12c). Overall, however the total transmissibility is underestimated (Figure 12d). Significantly, we observe that the transmissibility between cells 1 and 2 varies as a function of the properties of cell 3 even though the geometry and properties of cells 1 and 2 are identical in all cases. This result demonstrates, therefore, that an accurate two-point flux approximation solution to the transmissibility between two partially juxtaposed cells is impossible, as the transmissibility depends on the properties of the surrounding ones. The issue of accurately determining the transmissibility between partially juxtaposed cells, therefore, requires a solution based on multi point flux approximation (MPFA). Many researchers have discussed transmissibility solutions associated with non-orthogonality and unstructured grids based on MPFA (Aavatsmark et al. 2001, Aavatsmark 2002, Chen et al. 2007, Potsepaev et al. 2009), but the issue of partial connections in orthogonal corner-point grids has, to our knowledge, not previously been highlighted.

In addition to highlighting the error, our aim has been to gain some appreciation of the magnitude of the error in transmissibility of partially connected cells when it is assumed to be proportional to their contact area. We have seen that the error is larger across smaller connections (low A_C), between cells with higher aspect ratios (L:H), and higher cell anisotropy (k_V:k_H). Our initial 2D models (Figure 7) suggested that the effect could be severe, with frequent underestimates of transmissibility by a factor of 10 or more, in realistic faulted reservoir models. Subsequent models, however, have shown that the effect is reduced with fault rock properties are included (Figure 8), when connections are considered in 3D rather than 2D (Figure 10) and in less vertically heterogeneous sequences (Figure 12).

The contribution of fault rock properties at attenuating the error is particularly significant. In many cases fault rocks between good quality grid-block can result in very low multipliers (Manzocchi et al. 1999), and in this case the error is virtually non-existent (Figure 8d). Our results suggest than even relatively permissive fault rocks, which can result in a transmissibility multiplier as high as 0.5, can reduce the error by several orders of magnitude, with a maximum error (at the particular L:H and k_V:k_H ratios we have considered) of a factor of 2. Hence we conclude that the error is not particularly significant for across-fault connections if they are modelled with realistic fault rocks, but may be significant if partial connections are built into model as a means of representing geometrical complexities in the sedimentological architecture of a reservoir, as such connections would not be associated with a low permeability membrane.

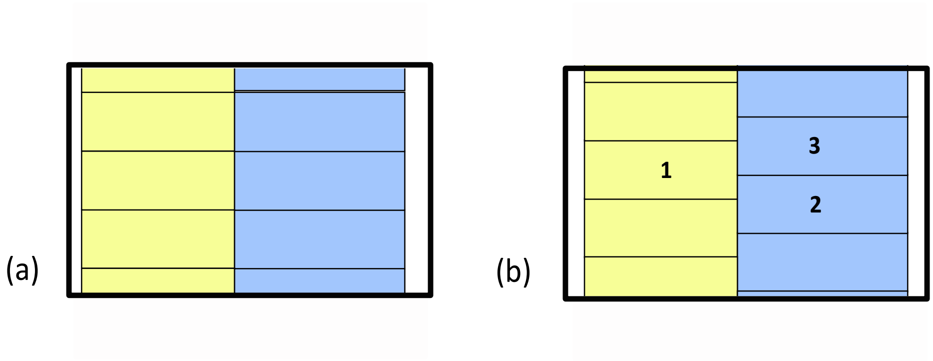


Figure 11 *Two stacks of cells with complete (a) and partial (b) connections. Cells 1, 2 and 3 are referred to in the text.*

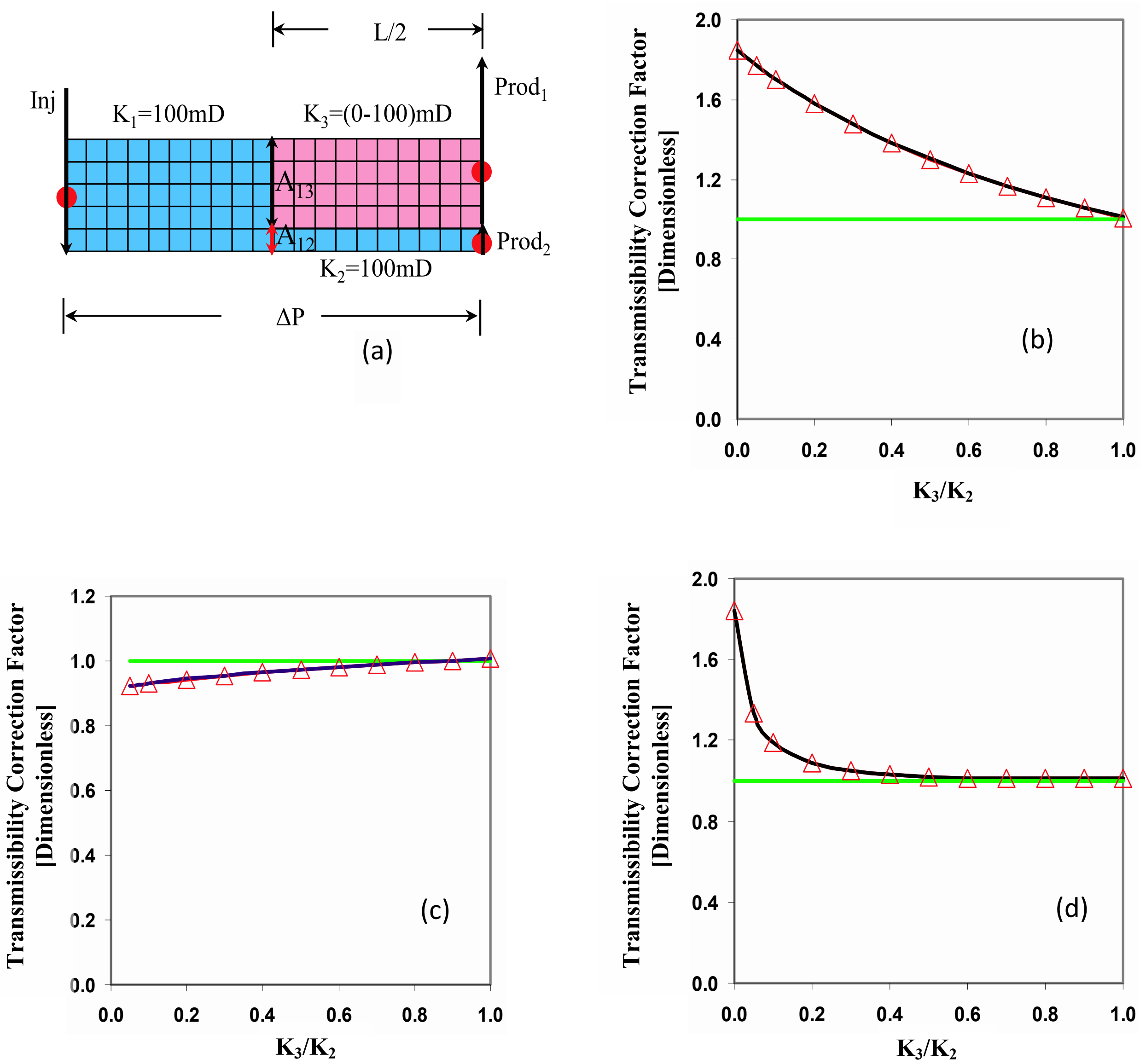


Figure 12 *(a) Cartoon of a 2D model of portions of cells 1, 2 and 3 (Figure 11). Transmissibility correction factors as a function of the ratio between the permeability of cells 3 and 2, for (b) the connection between cells 1 and 2, (c) the connection between cells 1 and 3, and (d) total transmissibility. The green line is the simulator approximation and the patterned line is the actual value as determined from the high-resolution flow simulation model.*

5. Conclusions

High resolution flow simulation modelling has shown that the transmissibility expression generally used for partially connected cells is incorrect. The error is largest for:

- Smaller juxtaposition areas.
- Connections between cells with higher k_V:k_H ratios.
- Connections between cells with higher aspect ratios.
- More heterogeneous sequences.
- Connections containing more permissive fault rocks.
- Connections between cells with lower angular misalignments.

Overall, we do not think that the error is particularly significant for faulted reservoir models built using corner-point grids, as it is very effectively reduced (but not entirely eliminated) by realistic fault transmissibility multipliers. Nonetheless, a wider appreciation of this error, which has no analytical solution, would be useful when addressing fault-related transmissibility uncertainties.

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