Implications of Cell Dimensions on Dipping Bed Continuity in Flat-Layered Geomodels*

Gregory Benson[1]

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[1]ExxonMobil Upstream Research Company, Houston, TX, USA (gregory.s.benson@exxonmobil.com)

Abstract

There is a mathematical relationship linking the degree of continuity that a horizontally-layered model framework can preserve with cell width/length/height, bed thickness, and bed dip angle. With very small cells, the continuity of beds at any dip angle can be approximately represented in a geologic model. However, as cell sizes get larger, dipping bed continuity cannot be accurately represented by horizontal model layers. At certain critical dip angles and bed thickness, cells of a given size will fail to maintain any bed continuity. Two types of bed continuity are important to preserve in geologic models destined to be used in flow simulation: flow barriers and flow conduits.

Introduction

For flow barriers, edge-to-edge continuity must be maintained to prevent flow-through in simulations. If the bed dip exceeds the threshold for a given cell size and bed thickness, gaps will form between the barrier cells, allowing flow-through. A simple trigonometric relationship exists between the bed thickness, dip angle, and the maximum allowed cell width to maintain edge-to-edge continuity of barrier beds:

1) MaxWidth = BedThickness/TAN(BedDip)

For flow conduits, face-to-face continuity must be maintained to allow flow within the bed in simulation. However, the degree of face-to-face contact between adjacent cells is necessarily degraded as bed dips increase in a flat-layered framework. Beds with zero dip have 100% face to face contact, but as dip angles increase, the amount of elevation offset at cell edges causes fewer and fewer layers to communicate, until at a critical angle, only non-flowing corner-to-corner continuity exists. Beyond that critical angle, conduit beds do not touch and therefore will not flow in simulation. The algorithm for approximating the fraction of face-to-face contact of conduit beds is:

2) VertOffset = (CellWidth*TAN(BedDip))

3) MinLayers = ROUNDDOWN(BedThickness/LayerThickness, 0)

4) Fraction = MAX(0, IF(OR(BedThickness/2 < LayerThickness, (VertOffset >= BedThickness)), 0, 1-ROUNDUP((VertOffset/LayerThickness), 0)/MinLayers))

These algorithms can be used to optimize cell sizes to a combination of bed thickness and bed dip. However, to avoid the continuity problem entirely, geologic models should be built with model layers inclined parallel to the beds. With bed-parallel layering, the occurrence of stair-step bed boundaries will be kept to a minimum.

Statement of Problem

When selecting cell dimensions for dividing a volume into horizontally layered geomodel cells, it is important to consider both:

1) the thickness of the critical high perm and low perm beds, and
2) the dip of those beds.

If cells are extremely small, like the pixels on a computer screen, the bed will appear nearly 100% connected in the dip direction. As cell sizes are made larger, either in thickness or in width, the beds will be increasingly represented as stair-stepped bodies. When cell angles go above a critical threshold, face-to-face connectivity (represented with yellow arrows in Figure 1) will be lost and a high perm bed will no longer act as a flow conduit in simulation. Similarly, when angles go above a somewhat higher threshold, edge-to-edge continuity will be lost and low perm beds will no longer act as barriers in simulation (green arrows in Figure 1 show where flow would occur through gaps in the barriers).

This issue was encountered during an outcrop-based modeling exercise on a Miocene carbonate shelf in southeastern Spain (Benson et al, 2014). The model was used to investigate the impact on flow of 0.5-meter thick low-perm barriers (gray, blue, and purple beds in Figure 2A). We defined a geomodel framework with layers inclined 20 degrees to capture the clinoform bedding of the outcrop. This framework resulted in a large number of inactive cells (~90%) and many pinched cells. We feared these inactive and pinched cells would create simulation issues, so we investigated what cell size was required to capture the continuity of beds in a horizontally-layered “brick model” or “sugar cube” framework (Figure 2B) with no pinched cells or inactive cells.

By trial and observation, the “sugar cube” model cell dimensions were progressively reduced. At the fourth iteration, the model (Figure 2B) appeared to maintain the continuity of 0.5-meter low-perm beds. The resulting cell dimension was 1/5 of the original cell width and 2/5 of the original cell height, resulting in 5 x 5 x 2.5 = 62 fine sugar-cube cells for each single inclined cell. We decided it was preferable to deal with 90% inactive cells than to attempt to simulate 62 times as many active cells. We could have avoided much iterative work if we had a tool to calculate the maximum cell size in advance of creating a framework.

The Barrier Continuity Solution

The “EdgeToEdge” visualizer spreadsheet (Figure 3) was designed to calculate the critical cell size required to maintain no-flow cell contact continuity of an inclined bed in a horizontally layered geologic model by implementing Equation 1.

The Conduit Continuity Solution

In a horizontally layered model, there is no cell size that will produce 100% face-to-face connection of inclined beds because, by definition, the beds must stair-step across layers in order to change elevation (Figure 4). Further, the degree of face-to-face contact can only be a fraction determined by the number of layers needed to portray the bed's thickness. For example, Figure 4B shows a bed 2 meters thick and model layers are 1 meter thick, face-to-face contact area can only occur as 100%, 50%, and 0% (when bed dip is steeper than the critical angle).

The "FaceToFace" connection visualizer spreadsheet (Figure 5) was designed to calculate the conservative minimum fraction of bed area that is preserved as flowing face-to-face cell continuity in the model. It takes as input the thickness and the dip of the thinnest high-perm beds that need to maintain flowing continuity.

The calculated values are the "bottleneck" face-to-face fraction of bed area anywhere along the modeled bed (e.g. if most of the bed face-to-face contacts are 75% fractions of bed cross section, but a few of the cells are only 50% fractions of bed cross section, the algorithm returns 50%). The calculations are "conservative", predicting face connectivities that may be one cell-height thinner than the reality. This is due to the geometric difficulty of determining whether the pillar-to-pillar position at which beds will be offset by the maximum number of layers will spatially coincide with the pillar-to-pillar position at which the minimum number of layers represents the bed.

The minimum number of layers required to represent a bed is calculated by this Excel expression:

MinLayers = ROUNDDOWN(BedThickness/LayerThickness, 0)

The vertical offset per cell width is calculated by this Excel expression:

VertOffset = (CellWidth*TAN(BedDip))

The Excel expression to estimate the fraction of bed area remaining at the points of maximum offset and minimum number of bed layers is:

Fraction = MAX(0, IF(OR(BedThickness/2 < LayerThickness, (VertOffset >= BedThickness)), 0, 1-ROUNDUP((VertOffset/LayerThickness), 0)/MinLayers))

The fundamental assumptions are:

1) If the layer is more than half the thickness of the bed, then the bed will never be two layers thick, and thus it is impossible to maintain face-to-face contact with even one layer offset.
2) If the slope of the dipping bed produces offset greater than the thickness of the bed across one cell width, it is impossible to maintain face-to-face contact.

3) Bed continuity is the complement of the portion of the bed thickness, in whole multiples of layers, represented by the quotient of maximum number of offset layers divided by the minimum number of bed layers.

This algorithm assumes that the occurrence of the minimum number of bed layers will coincide spatially with the occurrence of the maximum number of offset layers somewhere in the model volume. This is certainly true when the bed thickness is a whole multiple of the cell thickness, since the number of bed layers never changes regardless of position, but this is not true when bed thickness is not a whole multiple of the layer thickness. For this reason, the results of the algorithm should be considered to be conservative minimum connectivities.

Conclusions

In a horizontally layered model, there is no cell size that will produce 100% face-to-face connection of inclined beds because, by definition, the beds must stair-step across layers in order to change elevation. Stair stepping can occur only in increments of cell thickness, which will create partial or complete discontinuities at certain positions along the modeled bed. Even edge-to-edge continuity is broken at certain critical combinations of cell width, cell height, bed dip angle, and bed thickness. A spreadsheet has been created that estimates the maximum cell size required to maintain different fractions of bed continuity in horizontally layered frameworks that attempt to capture inclined bedding.

The “EdgeToEdge” connection calculation spreadsheet is used to determine the maximum cell width that will maintain barrier bed cell contact in the geologic model. It takes as input the dip of the thinnest low-perm beds that form an impermeable barrier. The algorithm considers a bed to be broken when there is not at least an edge-to-edge cell contact. Brick model spot testing confirms that the results of the calculations are precisely correct.

The “FaceToFace” connection calculation spreadsheet is used to determine the conservative minimum fraction of bed area that is preserved as flowing face-to-face cell continuity in the model. It takes as input the thickness and the dip of the thinnest high-perm beds that need to maintain flowing continuity. The calculated values are the “bottleneck” face-to-face fraction of bed area anywhere along the modeled bed. Brick model spot testing reveals that the calculations are “conservative”, predicting face connectivities that may be one cell height thinner than the reality unless certain geometric alignment criteria are met.

The algorithms operate on the assumption that the cell orientations are parallel to the dip azimuth. If this is not the case, then the apparent dip of the bed relative to cell orientation needs to be used in the spreadsheet. For both beds and cell heights, all calculations assume true vertical thickness, not true stratigraphic thickness.

Geologic modelers need to discuss the implications of offset at cell boundaries on edge-to-edge and face-to-face continuity with their simulation engineer counterparts when deciding upon cell dimensions. Imprudent choices for cell geometries can result in a model that neither represents the continuity of flow barriers nor represents the connectivity of flow conduits. The safest layering choice for geomodel frameworks is layers that are oriented parallel to bedding. Any other arrangement will create partial or complete bed offsets that disrupt barrier continuity and conduit connectedness.

Reference Cited

Benson, G.S., E.K. Franseen, R.H. Goldstein, and Z. Li, 2014, Workflows for incorporating stratigraphic and diagenetic relationships into a reservoir-analogue model from outcrops of Miocene carbonates in SE Spain: Petroleum Geoscience, v. 20/1, p. 55-78, doi: 10.1144/petgeo2013-008.

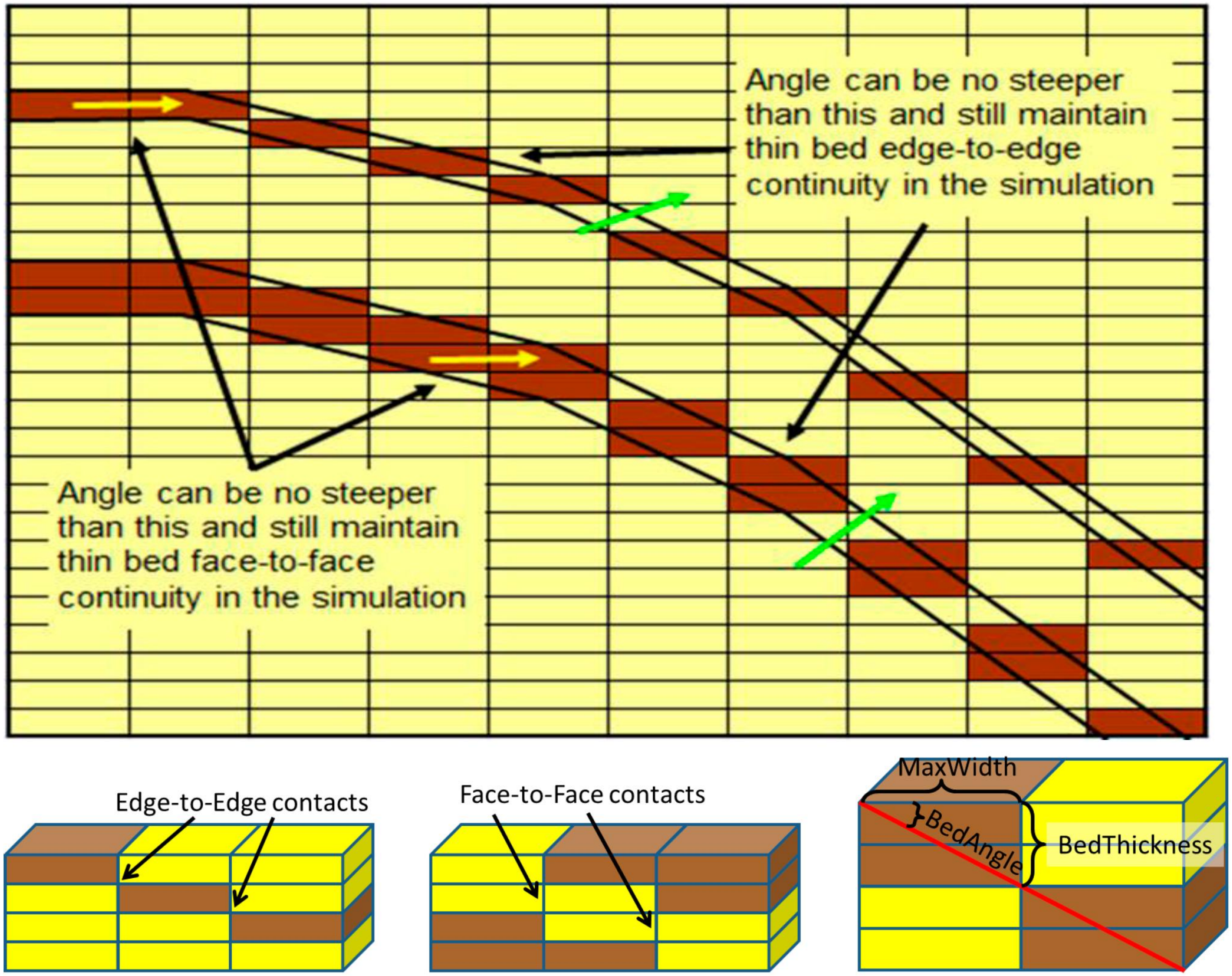

Figure 1. The brown beds in the upper image can either represent flow conduits or flow barriers. At certain critical angles and bed thickness, cells of a given size will fail to maintain continuity. For flow conduits, face-to-face continuity must be maintained (yellow arrows) to allow flow within the bed in simulation. For flow barriers, edge-to-edge continuity must be maintained to prevent flow-through (green arrows) in simulations. There is a mathematical formula (Equation 1) that relates the maximum cell width that will maintain edge-to-edge continuity in a geologic model representation of a bed with a given thickness and a given dip angle.

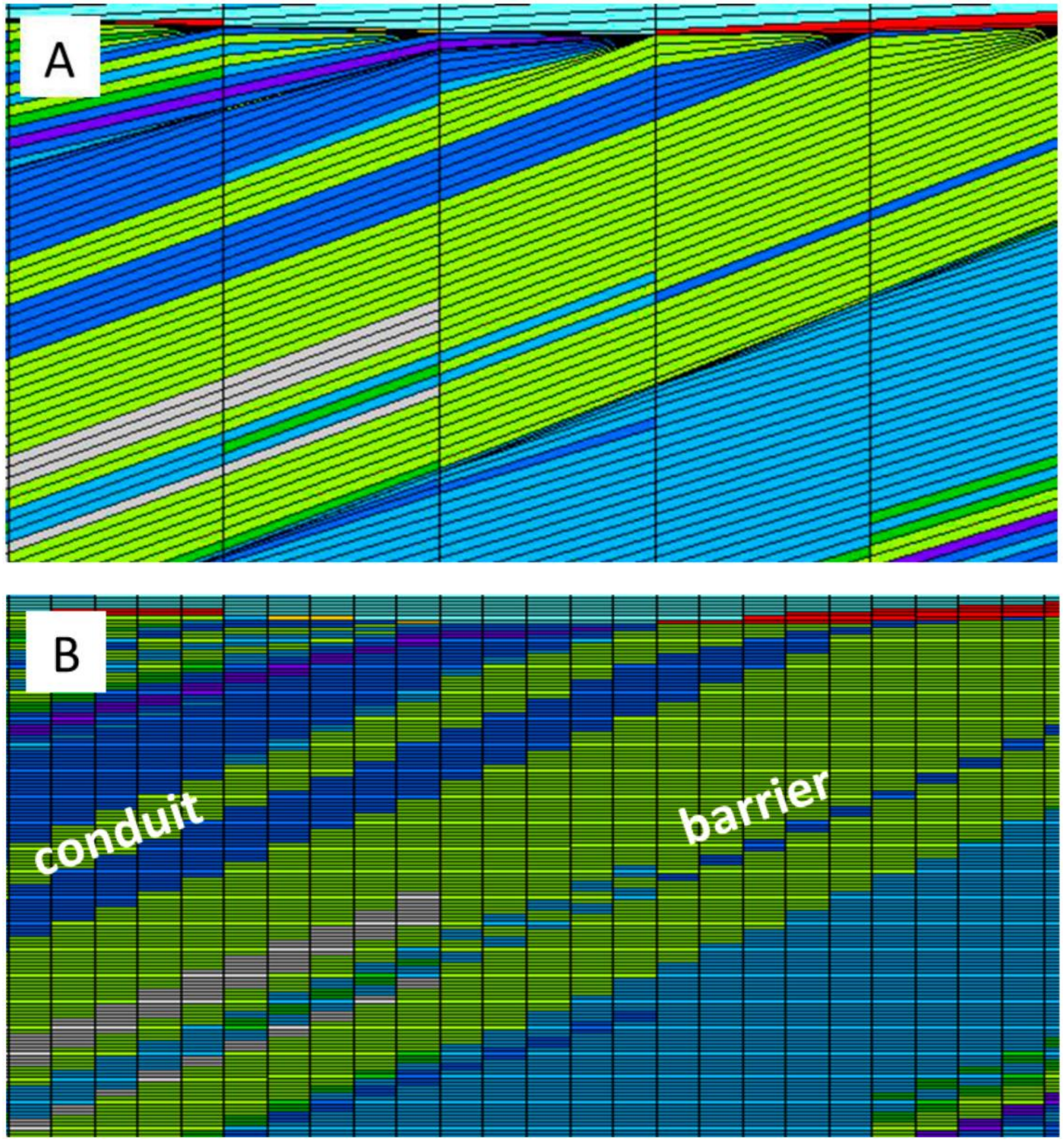

Figure 2. Image A illustrates an inclined-layer model that accurately captures the clinoform bedding on a carbonate shelf outcrop in southeastern Spain. Image B shows a horizontally layered model that approximately retains the continuity of the thin flow barriers (gray, blue, and purple). To attain this degree of continuity, the cell sizes of the horizontally layered model had to be reduced to 1/62 the original cell size of the inclined-layered model.

Degrees of inclination		Edge-to-Edge Continuity if Dip Direction Aligned with Rows or Columns																												
6	Cell width =>	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.5	2.0	2.5	3.0	3.5	4.0	5.0	6.0	7.0	8.0	9.0	10	12	14	16	18	20	25	30
Bed Thickness	0.1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0.2	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0.3	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
KEY	0.4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Continuous	0.5	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Broken	0.6	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
	0.7	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0
	0.8	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0
	0.9	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0
	1.0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0
	1.5	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0
	2.0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0
	2.5	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0

Figure 3: The "EdgeToEdge" visualizer worksheet implements Equation 1:

MaxWidth = BedThickness/TAN(BedDip)

The user enters the bed dip in the upper left hand corner. On the left side of the table, the user finds the thickness of the no-flow barrier that needs to be maintained, then looks across that row to the last green "continuous" cell, then reads the maximum allowable cell width from the top row. Example: For a 2-meter thick bed dipping 6 degrees, the largest allowable cell size is between 18 and 20 meters (black oval). The precise maximum cell width is **2 meters/TAN(6) = 19.03 meters**.

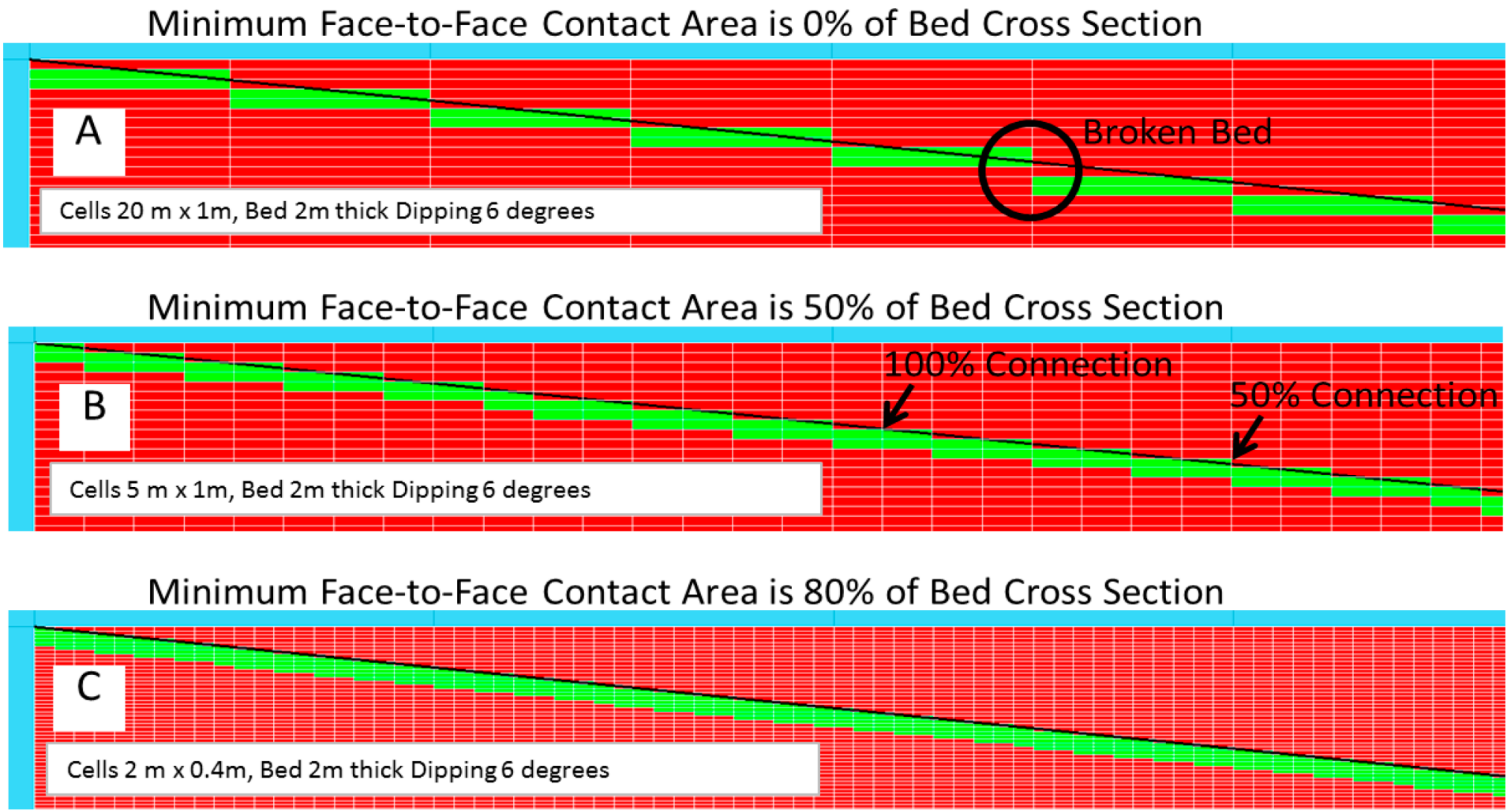

Figure 4. These three example sections through flat-layered geomodels are shown at the same scale. Because beds cannot be represented as fractions of cells, there are discontinuities in the functions that describe face-to-face continuity. **Image A**: The cell widths have been selected to be just slightly larger than the discontinuity threshold at which continuous edge-to-edge connections become broken somewhere along the bed. This is the case shown by the circled cells in Figure 3. **Image B:** The cell size has been chosen to make the bottleneck degree of bed cross section connection equal 50%. If this model was built any coarser, either in cell width or cell height, it would create no-flow edge-to-edge connections somewhere along the bed. Notice that while some cells maintain 100% connection, every second connection is only 50%. This is the flow "bottleneck". Notice also that every 20th cell skips the 100% connection. These discontinuities in behavior result from a geometric effect in which the bed slope is not an even multiple of the cell diagonal slope. **Image C:** The cells are fine enough that 80% of the bed cross section is maintained as partial face-to-face connections.

Minimum thickness bed to be resolved	Degrees of inclination
2.0	6.0

Degree of Face-to-Face Continuity if Dip Direction Aligned with Rows or Columns

	Offset per Cell Width -->	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.11	0.16	0.21	0.26	0.32	0.37	0.42	0.53	0.63	0.74	0.84	0.95	1.05	1.26	1.47	1.68	1.89	2.1	2.63	3.15	3.68
Min # Cells	Cell width -->	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.5	2.0	2.5	3.0	3.5	4	5	6	7	8	9	10	12	14	16	18	20	25	30	35
20	Layer Thickness --> 0.10	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.90	0.90	0.85	0.85	0.80	0.80	0.75	0.70	0.65	0.60	0.55	0.50	0.45	0.35	0.25	0.15	0.05	0.00	0.00	0.00	0.00
10	0.20	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.80	0.80	0.80	0.80	0.70	0.70	0.60	0.60	0.50	0.50	0.40	0.30	0.20	0.10	0.00	0.00	0.00	0.00	0.00
6	0.30	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.67	0.67	0.67	0.67	0.50	0.50	0.50	0.33	0.33	0.17	0.17	0.00	0.00	0.00	0.00	0.00	0.00
5	0.40	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.60	0.60	0.60	0.60	0.40	0.40	0.40	0.20	0.20	0.00	0.00	0.00	0.00	0.00	0.00
4	0.50	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.50	0.50	0.50	0.50	0.50	0.25	0.25	0.25	0.00	0.00	0.00	0.00	0.00	0.00
3	0.60	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.33	0.33	0.33	0.33	0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.70	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.80	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.90	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	1.00	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1	1.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Minimum Continuity Fraction

KEY: 1.00, 0.95, 0.90, 0.85, 0.80, 0.75, 0.70, 0.65, 0.60, 0.55, 0.50, 0.45, 0.40, 0.35, 0.30, 0.25, 0.20, 0.15, 0.10, 0.05, 0.00

Figure 5. In the “FaceToFace” visualizer worksheet, the user enters the minimum thickness of the bed to be resolved and the bed dip in the upper left hand corner. The cells in the visualizer are colored to represent the conservative minimum "bottleneck" fraction of bed thickness that is preserved with various combinations of bed thickness and cell widths. The black circle highlights the scenario of Figure 3 and Figure 4A, in which there is no face-to face cell continuity expected for a 2-meter thick bed with 6 degrees of dip modeled with cells 20 meters on a side and layers 1 meter thick. The green circle highlights the scenario for Figure 4B, in which cells five meters on a side and layers one meter thick preserve only 50% of the face-to-face continuity of bed cross section area. The red circle highlights the scenario of Figure 4C in which cells two meters on a side and layers 0.4 meters in height preserve 80% of the face-to-face continuity of beds.