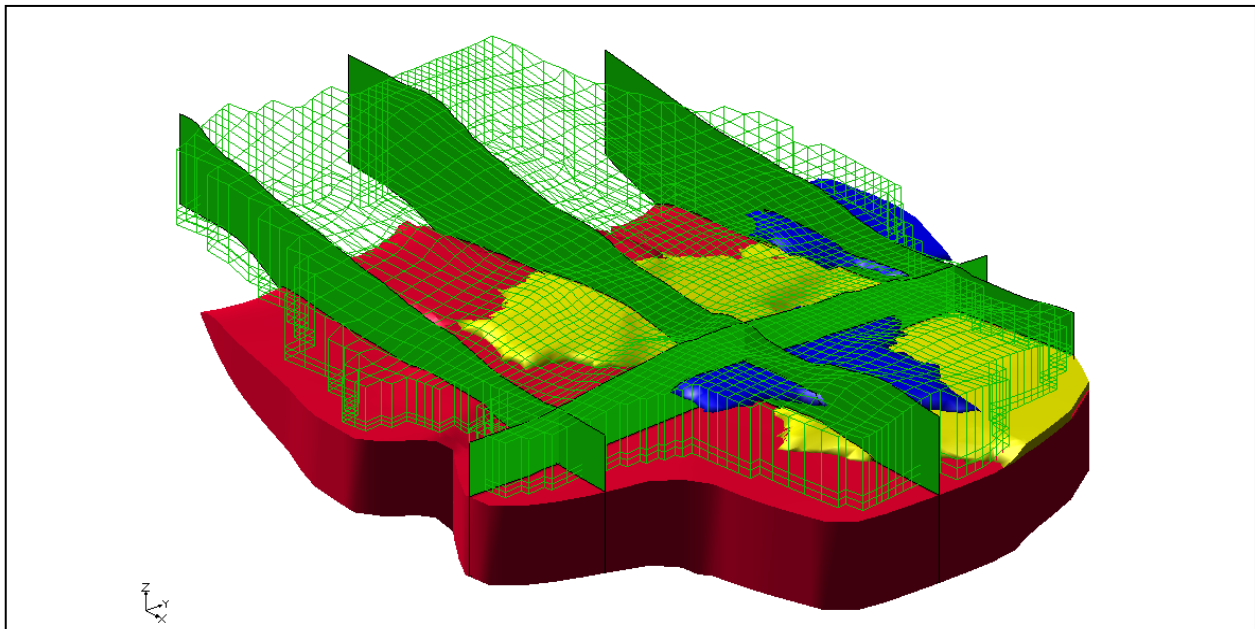


GMS 9.2 Tutorial

MODFLOW – Generating Data from Solids

Using solid models to represent complex stratigraphy with MODFLOW



Objectives

Learn the steps necessary to convert solid models to MODFLOW data on a 3D grid. The elevations associated with the grid are adjusted to match the elevations defined by the solid models. Also, the material assigned to each grid cell is inherited from the solid that encompasses the cell.

Prerequisite Tutorials

- None

Required Components

- Sub-surface Characterization
- Grid
- Map

Time

- 30-60 minutes



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2 Introduction

Complex stratigraphy can be difficult to simulate in MODFLOW models. MODFLOW uses a structured grid that requires that each grid layer be continuous throughout the model domain. This makes it difficult to explicitly represent common features such as pinchouts and embedded seams in a MODFLOW model.

Solid models can be used to represent arbitrarily complex stratigraphy. Figure 1 shows a cross section through a solid model where different stratigraphic units pinchout. Designing a MODFLOW compatible grid for this type of stratigraphy is very difficult.



Figure 1. Cross-section through a solid model.

In this tutorial we will cover the steps necessary to convert solid models, like the one in Figure 1, to MODFLOW data. The elevations associated with the finite-difference grid will be adjusted to match the elevations defined by the solid models. Also, the material assigned to each grid cell will be inherited from the solid that encompasses the cell. Figure 2 shows a MODFLOW compatible grid of the cross section shown in Figure 1.

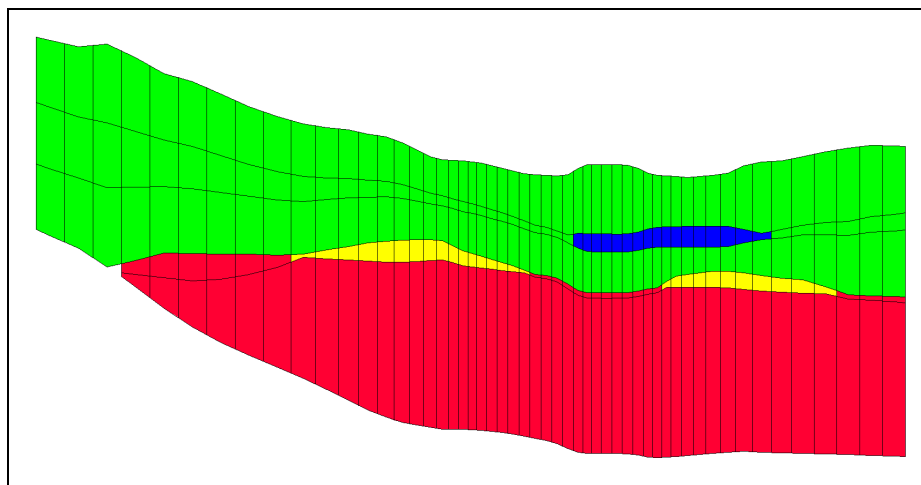


Figure 2. Finite difference grid with elevations and materials inherited from the solid model.

One of the main benefits of using solid models to define stratigraphy for MODFLOW models is that it provides a grid-independent definition of the layer elevations that can be used to immediately re-create the MODFLOW grid geometry after any change to the grid resolution.

Solid models of stratigraphy can easily be created in GMS using the “horizons approach.” The tutorial entitled *Stratigraphy Modeling – Horizons and Solids* explains how to create solid models using GMS.

2.1 Outline

This is what you will do:

1. Open a file containing solids data.
2. Use the *Solids* → *MODFLOW* command using the Grid Overlay option.
3. Assign grid layers to the solids
4. Use the *Solids* → *MODFLOW* command using the Boundary Matching option.
5. Fix problems associated with thin cells.
6. Convert the conceptual model to MODFLOW and run MODFLOW.
7. Convert the solids to HUF data.
8. Convert the conceptual model again and run MODFLOW.


3 Getting Started

Let's get started.

1. If necessary, launch GMS. If GMS is already running, select the *File* | *New* command to ensure that the program settings are restored to their default state.

4 Reading in the Solids

First, we will read in a file containing a set of solids for the site we are modeling.

1. Select the *Open* button .
2. Locate and open the directory entitled **Tutorials\MODFLOW\sol2mf**.
3. Open the file named **start.gpr**.

You should see cross-sections in the main GMS window that show the stratigraphy for this site.

There are five different solids in this project file. There are two main units labeled *upper_aquifer* (green) and *lower_aquifer* (red). Inside of *upper_aquifer* there are two silty-clay (blue) units, and between *upper_aquifer* and *lower_aquifer* there is a clay (yellow) unit.

5 Boundary Matching Versus Grid Overlay

There are three options when doing Solids \rightarrow MODFLOW, the Boundary Matching option, the Grid Overlay option and the Grid Overlay with K . These options are illustrated in the following figure.

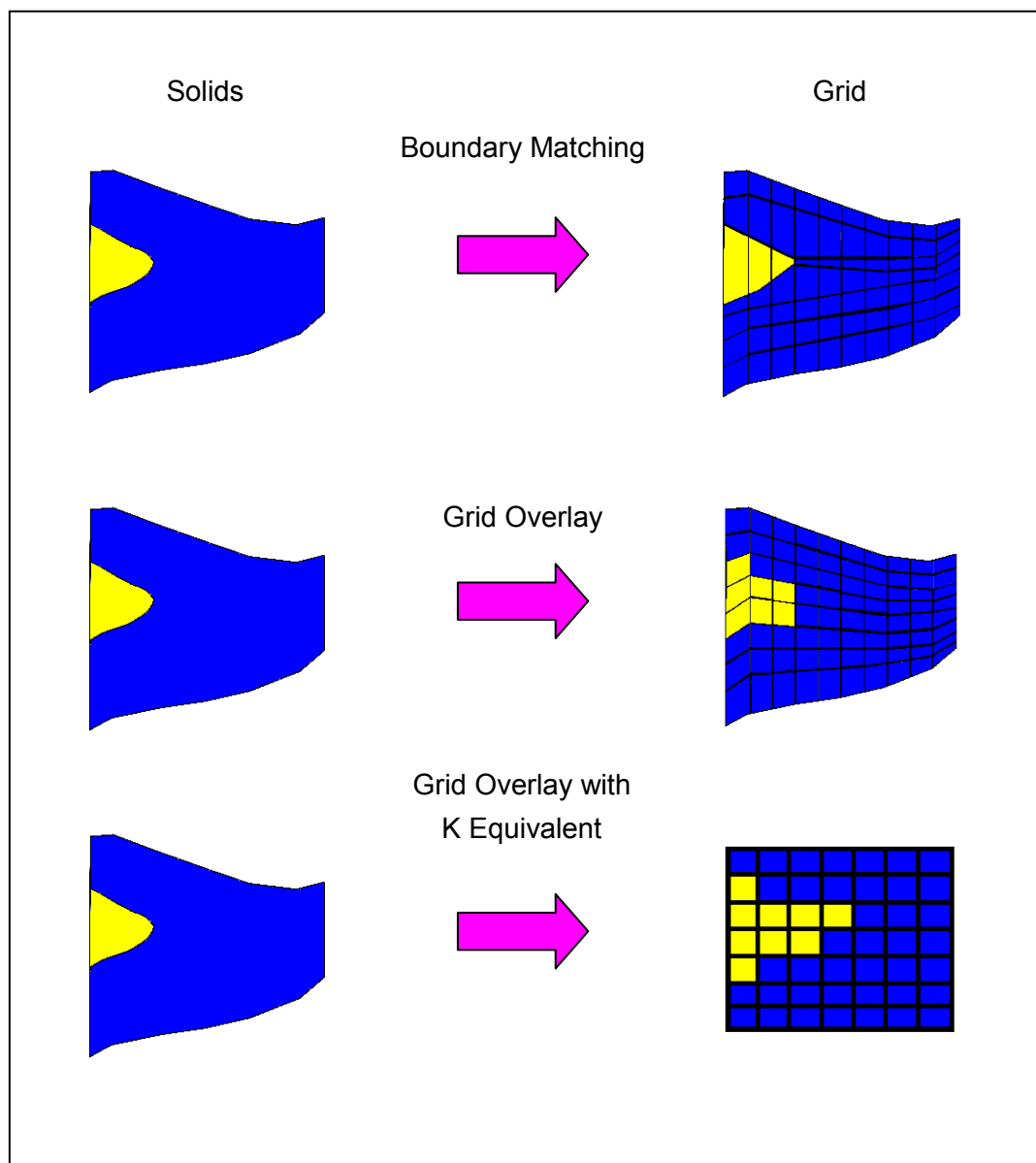


Figure 3. Solids \rightarrow MODFLOW options illustrated. Side view shown.

5.1 Boundary Matching

With the Boundary Matching option, the top and bottom of the grid are deformed to match the tops and bottoms of the solids. The interior grid layers are also deformed to

match the boundaries of the solids. The grid cell materials are set to match the material of the solid that the grid cell center is located in.

This option results in a close fit between the grid and the solids, but it can result in thin cells which can cause stability problems or dry cell issues when running MODFLOW. This option requires that you determine which grid layers should be associated with which solids.

5.2 Grid Overlay

With the Grid Overlay option, the top and bottom of the grid are deformed to match the tops and bottoms of the solids. The interior grid layer boundaries are deformed to be evenly spaced between the top and bottom of the grid using a simple linear interpolation. The interior grid layers are not changed to match the solid boundaries. As with the boundary matching option, the grid cell materials are set to match the material of the solid that the grid cell center is located in.

This option does not result in as close a fit between the grid and the solids as the boundary matching option, but may avoid the thin cell problems associated with the Boundary Matching option. This option does not require you to assign grid layer ranges to each solid.

5.3 Grid Overlay with K Equivalent


This option is very similar to the Grid Overlay option. One of the problems with the Grid Overlay option is that if there is a relatively thin layer in the solids and the layer does not happen to encompass any cell centers or it encompasses few cell centers, the layer will be under-represented in the MODFLOW grid. This becomes particularly important if the layer is meant to represent a low permeability layer. For such cases, the Grid Overlay with Keq option may give superior results. The Grid Overlay with Keq method is identical to the Grid Overlay method in terms of how the elevations of the grid cells are defined. The two methods differ in how the material properties are assigned. Rather than simply assigning materials based on which solid encompasses the cell centers, the Keq method attempts to compute a custom K_h and K_v value for each cell. When assigning the material properties to a cell, GMS computes the length of each solid in the cell (from a vertical line at the cell center that intersects the solids) and computes an equivalent K_h , K_v , and storage coefficient for the cell that takes each of the solids in the cell into account. Thus, the effect of a thin seam in a cell would be included in the K_h and K_v values for the cell.

6 Solids → MODFLOW Using Grid Overlay

We will first examine the Grid Overlay option. With this option, all that is needed are a set of solids and a grid in the same location.

6.1 Displaying the 3D Grid



The grid was read in as part of the project, but the display of the grid cells was turned off. Let's turn on the display of the grid.

1. In the *Project Explorer* turn on the *3D Grid Data* folder .

You should now see the 3D grid.

6.2 Initializing MODFLOW


We must initialize MODFLOW before we can execute the *Solids* → *MODFLOW* menu command.

1. If necessary expand the *3D Grid Data* folder  the *Project Explorer* by clicking on the plus symbol next to the item.
2. Right-click on the *grid* item  underneath the *3D Grid Data* folder and select the *New MODFLOW* command.


Normally we would set the Starting heads here but since it is set to be equal to the grid top elevation by default we can leave it alone. It will be set to 300 by default in this model.

6.3 Activating Cells

We need to inactivate the cells outside our model domain.

1. In the *Project Explorer* select the *Map Data* folder .
2. Select the *Feature Objects* | *Activate Cells in Coverage(s)* menu command.



6.4 Solids→MODFLOW

1. In the *Project Explorer* select the *Solid Data* folder .
2. Select the *Solids* | *Solids* → *MODFLOW* menu command.
3. Make sure that the *Grid Overlay* option is selected and select *OK* to execute the *Solids* → *MODFLOW* menu command.

The *Solids* → *MODFLOW* command may take a few seconds to a few minutes to complete depending on the speed of your computer. When done, the 3D grid should appear to be deformed to match the top and bottom of the solids.

6.5 Viewing the Grid

Let's examine the grid.

1. Select the *Display Options* button .
2. Select the  *3D Grid Data* item on the left.
3. Turn on *Cell faces*.
4. Click *OK*.

Notice the solid cross sections are now mostly obscured from view by the grid, but you can still see them poking out in places. If you look closely you can see that the top of the grid matches the top of the solid cross sections quite well. The grid and cross sections should appear as shown in Figure 4.

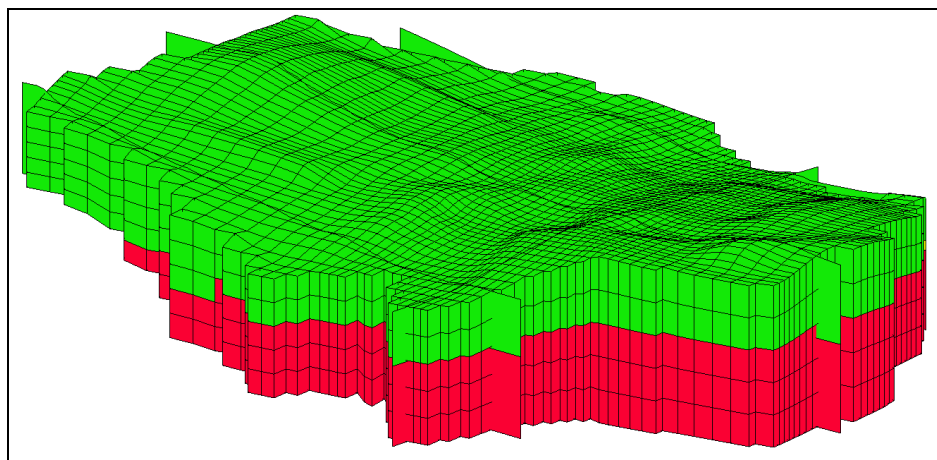








Figure 4. Grid and solid cross-sections after Solids → MODFLOW using grid overlay.

Let's look at the grid from the side.

5. Select the *Ortho Mode* button .
6. In the *Project Explorer*, click on the *3D Grid Data* folder .
7. Select the *Select Cells* tool .
8. Select a cell somewhere near the middle of the grid.
9. Select the *Front View* button .

The solid cross sections are in front of the grid row we are viewing.

10. In the *Project Explorer*, turn **off** the *Solid Data* folder .
11. In the *Mini Grid* toolbar, use the arrow buttons  to view the grid along different rows.

The grid at row 14 should appear as shown in Figure 5 below.

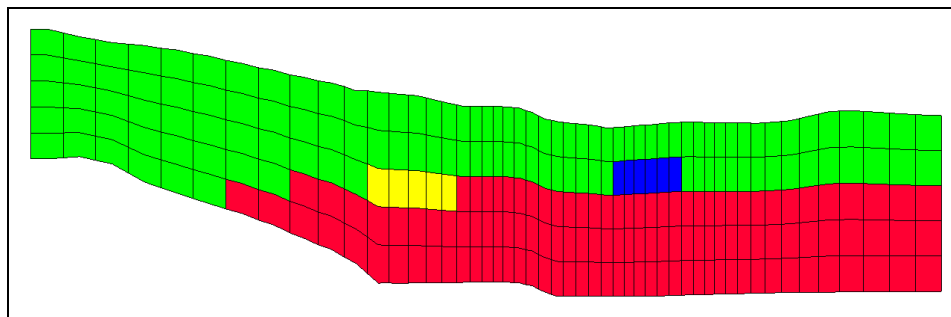


Figure 5. Grid row after Solids → MODFLOW using grid overlay.

At this point we could continue to develop the MODFLOW model, but before doing that we'll take a look at the Solids → MODFLOW Boundary Matching option.

7 Solids → MODFLOW Using Boundary Matching

The boundary matching option results in a close fit between the solid boundaries and the grid layer, but it requires a bit more work on your part.

7.1 Layer Ranges

Before we can convert the solids to MODFLOW data using the Boundary Matching option we must assign a layer range to each of the solids. The layer range represents the consecutive sequence of layer numbers in the MODFLOW grid that are to coincide with the solid model. A sample set of layer range assignments is shown in Figure 6(a). The example in Figure 6 is a case where each solid is continuous through the model domain and there are no pinchouts. Each of the solids is given a layer range defined by a beginning and ending grid layer number. The resulting MODFLOW grid is shown in Figure 6(b).

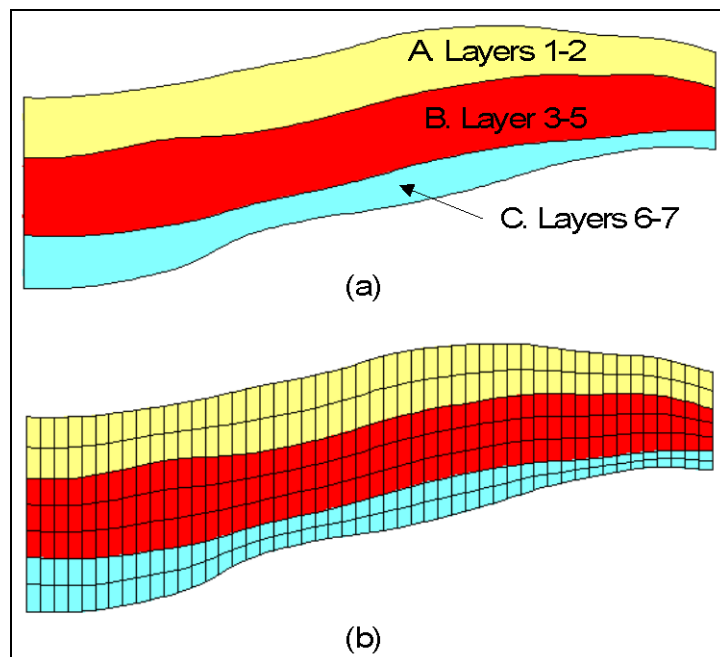


Figure 6. (a) A set of simple solids with grid layer assignments.
 (b) The MODFLOW grid resulting from the layer assignments.

A more complex case with pinchouts is illustrated in Figure 7(a). Solid A is given the layer range 1-4, and the enclosed pinchout (solid B) is given the layer range 2-2. The set of grid layers within the defined range that are actually overlapped by the solid may change from location to location. The layer range represents the set of grid layers potentially overlapped by the solid anywhere in the model domain. For example, on the left side of the problem shown in Figure 7(a), solid A covers grid layers 1, 2, 3 and 4. On the right side of the model, solid A is associated with grid layers 1, 3 and 4 since the enclosed solid (solid B) is associated with layer 2. Likewise, Solid C is associated with grid layers 5 and 6 on the left side of the model but only with layer 6 on the right side of the model where solid D is associated with layer 5. The resulting MODFLOW grid is shown in Figure 7(b).

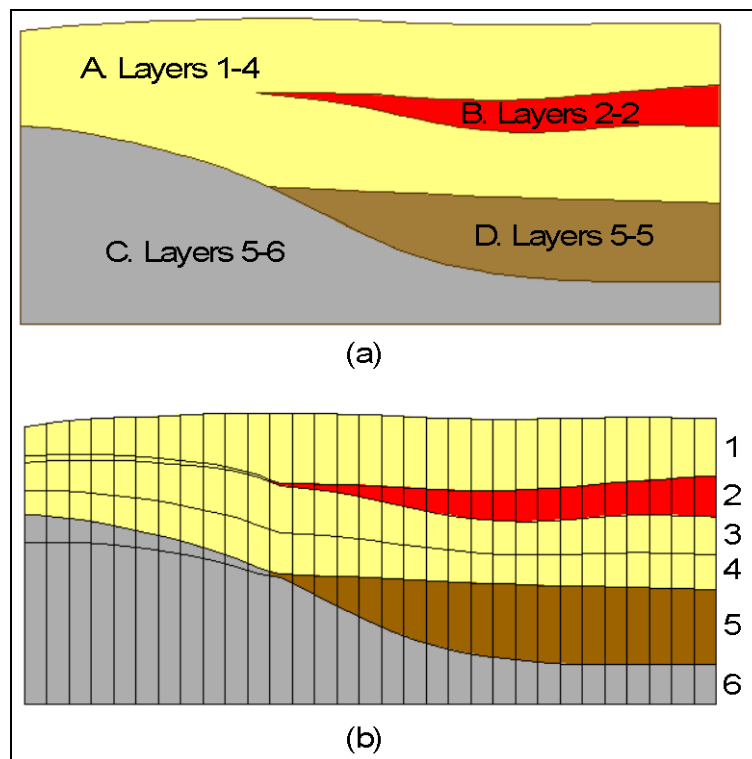


Figure 7. (a) Grid layer assignments for a set of solids with pinchouts.
 (b) The MODFLOW grid resulting from the layer assignments.

When assigning layer ranges to solids, care must be taken to define associations that are topologically sound. For example, since solid B in Figure 7(a) is enclosed by solid A, solid B could not be assigned a layer range that is outside the layer range of solid A.



7.2 Assigning Layers to Solids

Now we are ready to assign the grid layers to the solids.

The figure below is a cross section through our site. Notice that we must have a minimum of five grid layers in order to represent all of the layers present in this cross-section. In this case the upper_aquifer (green) will be assigned to layers 1-3. The silty-clay (blue) will be assigned to layer 2. The clay (yellow) will be assigned to layer 4, and the lower_aquifer (red) will be assigned layers 4-5.



Figure 8. Cross-section through the model domain.

1. In the *Project Explorer* expand the *Solid Data* folder  if necessary.
2. Double click on **upper_aquifer 1** solid  in the *Project Explorer*. For the *Begin layer*, enter **1** and for the *End layer*, enter **3**. Click *OK*.
3. Repeat this process on the remaining solids, entering the values shown in the following table.

	upper_aquifer 1	lower_aquifer 2	clay 3	silty-clay 4	silty-clay 5
<i>Begin layer</i>	1	4	4	2	2
<i>End layer</i>	3	5	4	2	2

7.3 Solids→MODFLOW

1. Select the *Solids | Solids → MODFLOW* menu command.
2. Select the *Boundary Matching* option and select *OK*.

The *Solids → MODFLOW* command may take a few seconds to a few minutes to complete depending on the speed of your computer.

8 Viewing the Grid

See how our grid has changed. Your view should look something like that shown in Figure 9.

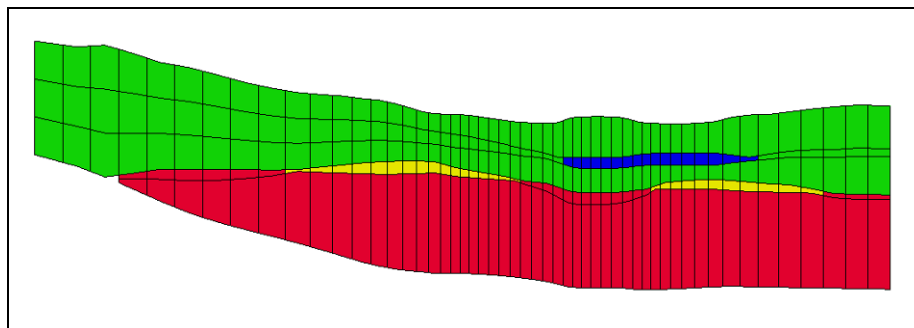





Figure 9. Row 30 of grid after Solids → MODFLOW using boundary matching.


1. Notice that the second layer has both silty-clay (blue) and upper_aquifer (green) materials assigned to it.
2. Use the arrow buttons  to view the grid along different rows.
3. Select the *Side View* button .
4. Use the arrow buttons  in the *Mini-Grid Display* to view the grid along different columns.

9 Thin Cells

The purpose of the *Boundary Matching* option for the *Solids → MODFLOW* command is to ensure that each upper and lower boundary defined by the solid model is precisely matched by a layer boundary in the MODFLOW grid. As a result of this approach thin cells often occur where solids pinchout. Notice the thin cells that you get on the edges of the clay (yellow) and silty-clay (blue) solids in Figure 9. If you want to limit the effect of the thin cells in your model grid you can set a target minimum thickness for each of the solids.

9.1 Assigning Minimum Thickness


Now we will use the *Target minimum thickness* to limit the thin cells in our model.

1. Double click on the **upper aquifer 1** solid  in the *Project Explorer*.
2. Change the *Target min. cell thickness* to **20** and select *OK* to exit the dialog.
3. Repeat these steps for all of the remaining solids.

9.2 Top Cell Bias

Another problem that may be encountered using the *Boundary Matching* option is that the cells in the top layer of the grid may also be too thin and subject to wetting and

drying. To ensure that the top layer of your grid is sufficiently thick you can use the *Top cell bias* option.

1. Double-click on the **upper_aquifer 1** solid  in the *Project Explorer*.
2. Change the option next to *Use top cell bias* to **Yes** and select *OK* to exit the dialog.
3. Select the *Solids | Solids* → *MODFLOW* menu command.
4. Select *OK* to execute the *Solids* → *MODFLOW* menu command.

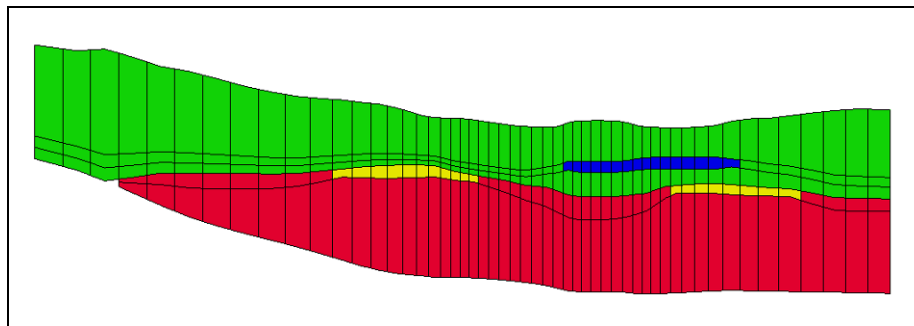




Figure 10. Row 30 of the model grid using target minimum thickness and top cell bias.

Your grid should now look similar to Figure 10. Notice the top row is thicker, and the thin cells in the yellow and blue areas are now thicker.

10 Converting the Conceptual Model

We can now finish developing the MODFLOW model. In the interest of time, the conceptual model has already been built and was read in when we read in the project file. For more information on conceptual models, refer to the *MODFLOW – Conceptual Model Approach* tutorial.

1. In the *Project Explorer* select the *Map Data* folder .
2. Select the *Plan View* button .
3. Select the *Feature Objects | Map* → *MODFLOW* menu command.
4. Ensure the *All applicable coverages* option is selected and select *OK*.

10.1 Using Materials to Define Hydraulic conductivity

Now we need to set the option for MODFLOW to use the material assigned to the grid cell to define the hydraulic conductivity for the cell.

1. Select the *MODFLOW | LPF - Layer Property Flow* menu command.



2. Select the *Use Material IDs* option in the *Layer property entry method* section of the dialog.
3. Select the *Material Properties* button in the *Layer data* section of the dialog.
4. Select each material in the list and enter the values for the properties shown in the table below.

	<i>Horizontal k</i>	<i>Vert. anisotropy (Kh / Kv)</i>
upper_aquifer	15.0	3.0
lower_aquifer	30.0	3.0
clay	0.5	3.0
silty-clay	1.0	3.0

5. Select *OK* twice to exit both dialogs.

11 Running MODFLOW

We are now ready to run MODFLOW. First, we must save our MODFLOW simulation.

1. Select the *File | Save As* menu command.
2. Save the project with the name **run1_lpf.gpr**.
3. Select the *MODFLOW | Run MODFLOW* menu command.
4. When MODFLOW has finished running, select the *Close* button. The MODFLOW solution will automatically be read in.
5. Select the *Display Options* button .
6. Select the  *3D Grid Data* item on the left.
7. Turn off the *Cell faces* option and select *OK* to exit the dialog.

You should now see the head contours on the grid. Cycle through the layers to see how the head contours change within the different layers. You can also switch into side view to see the contours on the rows or columns.

12 Solids → HUF

Now we will use the HUF package in MODFLOW instead of the LPF package to define the hydraulic properties of the grid cells. This package is designed to represent complex stratigraphic relationships in a grid independent fashion.

The hydro-stratigraphy is represented using a set of hydrogeologic units. Each unit is defined by two arrays, one for the top elevation and one for the thickness. The thickness

values can be set to zero in regions of the model where the unit is not present. When MODFLOW is executed, each cell is compared to the corresponding unit elevation arrays and equivalent hydraulic properties are assigned to the cell. The figure below shows an example of HUF units on a MODFLOW grid.

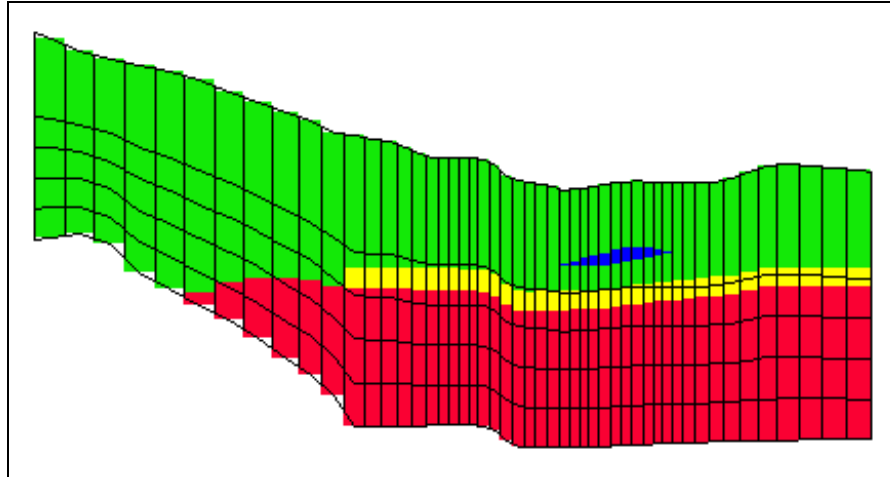


Figure 11. HUF data.



12.1 Selecting the HUF Package

First, we need to select the HUF package as our flow package.

1. Select the *MODFLOW* | *Global Options* menu command.
2. Select the *Packages* button.
3. In the *Flow Package* section of the MODFLOW Packages dialog change the flow package to **Hydrogeologic Unit Flow (HUF)**.
4. Select *OK* twice to exit both dialogs.

12.2 Converting the Solids to HUF Data

We are now ready to convert the solids to HUF data. However, when we ran the *Solids* → *MODFLOW* command some of the cells were inactivated in layers 4 and 5. We want those cells to be active for this new model.

1. In the *Project Explorer* select the *Map Data* folder .
2. Select the *Feature Objects* | *Activate Cells in Coverage(s)* menu command.
3. In the *Project Explorer* select the *Solid Data* folder .
4. Select the *Solids* | *Solids* → *HUF* menu command.







5. Turn on the *Adjust grid cell elevations* toggle.

The MODFLOW top elevation array of the top layer and the bottom elevation array of the bottom layer are adjusted to match the tops and bottoms of all the solids. The interior top and bottom elevation arrays are assigned based on the proportions entered in the *Elevation bias* spreadsheet. The entire grid depth for each grid column is distributed according to the entries in the spreadsheet for each layer.

6. In the *Elevation bias* spreadsheet, change the value for layer 1 to **0.4**.
7. Select *OK* to execute the *Solids* → *HUF* menu command.




12.3 Viewing the HUF Data

To view the HUF data:

1. In the *Project Explorer* select the *3D Grid Data* folder .
2. Select the *Display Options* button .
3. Change the *Color* option under *Cell edges* to **Specified**.
4. Switch to the *MODFLOW* tab.
5. Turn **on** the *Display hydrogeologic units* toggle.
6. Select *OK* to exit the dialog.
7. Select the *Select Cells* tool .
8. Select a cell somewhere near the middle of the grid.
9. Select the *Front View* button .
10. Use the arrow buttons   to view the grid along different rows.

12.4 Converting the Conceptual Model

We need to convert the conceptual model again to ensure that any cells that were inactive will have the correct boundary conditions.

1. In the *Project Explorer* select the *Map Data* folder .
2. Switch to plan view by selecting the *Plan View* button .
3. In the *Project Explorer* right-click on the *MODFLOW* conceptual model  and select *Properties* from the menu.

4. Change the flow package to HUF and select *OK* to exit the dialog.
5. Select the *Feature Objects | Map → MODFLOW* menu command.
6. Ensure the *All applicable coverages* option is selected and select *OK*.

12.5 Running MODFLOW

We're now ready to save the project and run MODFLOW.

1. Select the *File | Save As* menu command.
2. Save the project with the name **run1_huf**.
3. Select the *MODFLOW | Run MODFLOW* menu command.
4. When MODFLOW has finished running, select the *Close* button. The MODFLOW solution will automatically be read in.

You should now see the head contours on the grid. You may see some red triangles on certain grid cells. These cells have gone dry (the water table is below the bottom of the cell) in this simulation. Cycle through the layers to see how the head contours change within the different layers. You can also switch into side view to see the contours on the rows or columns.

13 Conclusion

This concludes the tutorial. Here are some of the key concepts in this tutorial:

- Solids can be used to define the MODFLOW layer elevations. They can also be used to create MODFLOW HUF data.
- You must assign layer ranges to the solids before using them to create a layered grid if using the Solids → MODFLOW Boundary Matching option.
- You can use a minimum thickness to avoid thin cells. You can also specify a top cell bias to make the top grid layer thicker.
- If you are using solids to define your MODFLOW layer data, you probably want to use the Material IDs approach to define the hydraulic properties of grid cells based on their material.