Benefits of Automation in Hydrostratigraphic Framework Modeling – 2 Translating Geologic Framework Assignments from Solids Modeling to Flow Modeling Software

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ABSTRACT

Computer simulations of complex geologic environments are often performed with dedicated solids modeling software as opposed to conceptual modeling packages bundled with groundwater modeling programs. This approach results in more sophisticated framework models and better visualizations, however, translating the resulting framework into flow modeling software can be challenging. This has been the experience at the Nevada National Security Site (NNSS) where hydrostratigraphic framework models (HFM) have been developed in EarthVision™ (EV) while the groundwater flow models have been developed in FEHM. As part of a sub-domain modeling exercise conducted in 2012, the NNSS EV modeling team developed a process that greatly reduces the time and complexity associated with the translation effort. The process leverages EV tools combined with UNIX-shell scripts and a step-wise procedure to render nodal assignments onto a pre-defined finite-element mesh. Assignments included: layer elevations; material properties characteristic of country-rock, damaged zones around faults, and fault core zones; and boundary conditions extracted from the full-domain model. The new process requires hours as opposed to days or even weeks that have been characteristic of similar previous translation efforts. The sub-domain modeling exercise used FEFLOW but the process is adaptable to any nodal-based code such as FEHM or MODFLOW.

INTRODUCTION

Groundwater rarely flows through a homogeneous and isotropic material such as uniform sand. Even though this type of flow system is easy to conceptualize and expedient to simulate, models built to these simplistic specifications yield useless results. Flow paths and travel times are usually dictated by the complexities of a hydrologic system such as the presence of discontinuous, variably thick, low permeability lenses in unconsolidated materials, networks of fractures in impervious rock, or solution conduits in carbonate aquifers. However, even when there is sufficient data to define these complexities, constructing a model that incorporates them is tedious and time consuming. Most current groundwater modeling software come with packages enabling the user to link outside data streams into the model construction process. However, this process usually still requires layer by layer delineation of input parameters through the creation of layer specific polygons, point files and line arcs. At the other end of the spectrum, there are data based visualization tools such as EarthVision™ (Dynamic Graphics, Inc.) which compile and analyze data in a truly three-dimensional way resulting in high resolution three dimension datasets representing complex flow systems in a Hydrostratigraphic Framework Model (HFM).

Previous efforts to translate the HFM into a useable format for groundwater flow modeling entailed considerable effort. Even after development of automated routines to export surfaces and faults from the EarthVision™ model, substantial user intervention was required to manage individual surfaces and active fault planes. In one instance in an area adjacent to the model domain presented in this study, the EarthVision™ HFM was translated into a FEHM model using the Los Alamos LaGriT mesh optimizer. Although a very capable set of tools were available for each step of the process, there were numerous hands-on steps such as articulation of the “tiploop” polygons which define the active fault surface area, culling out anomalies at complex zone intersections and handling problems in the vicinity of very steeply dipping surfaces. The resulting FEHM model provided an accurate representation of the EarthVision™ HFM, but the time required to prepare intermediate products discourages model updates and exploration of alternative scenarios.

This paper presents an example of how we are able to link these three-dimensional datasets directly to the construction of complex groundwater flow models.

MODEL CONSTRUCTION

As part of a modeling software comparison project for the NNSS, we were tasked with creating a model that more accurately represented the flow system of a sub-domain of their existing model. The sub-domain consisted of a 5,000 meter wide by 9,500 meter long by 1,740 meter thick block of a carbonate aquifer containing 27 faults which were complex non-linear planar features, Figure 1. Each fault had continuously morphing strike and dip. Most of the faults fully penetrated the model domain, however some faults terminated within the domain by either intersection with another fault or by simply dying out. The faults were conceptualized as inhibiting groundwater flow along the actual trace of the displacement (core zone) but as enhancing groundwater flow along the strike direction through a fracture zone (damage zone) surrounding the displacement. The unfaulted country rock was conceptualized to be isotropic and homogeneous and the sub-domain was assumed to be fully saturated and confined. The finite-element software FEFLOW was chosen to simulated flow in the sub-domain because the adaptable mesh could most accurately represent the fault complexity.

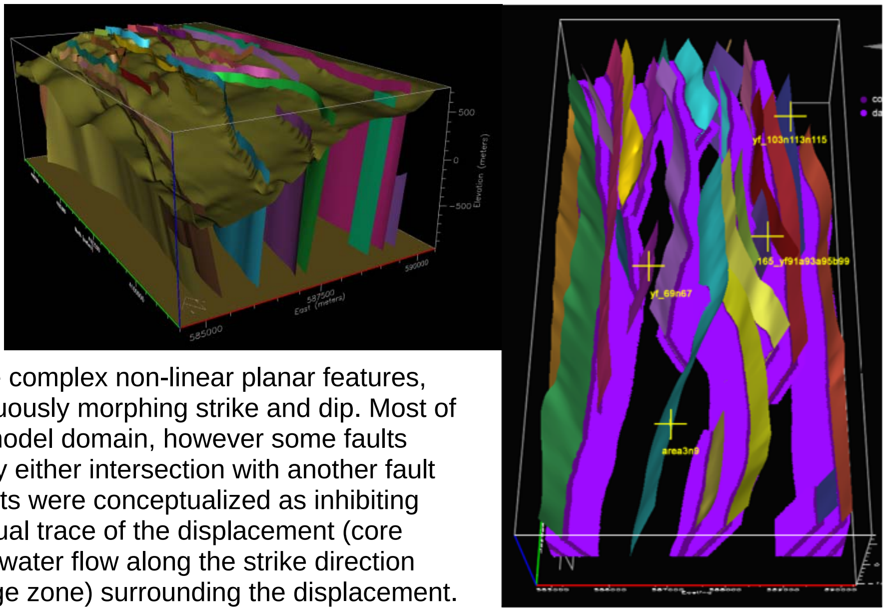

Figure 1. Three-dimensional views of the project sub-domain showing the sub-domain surfaces and faults.

Mesh Construction

The FEFLOW mesh was to be designed such that the core zone of the faults is represented by a 60-meter buffer around the fault trace and the damage zone is represented by an additional 60-meter buffer outside of the core zone. A flattened view of the fault surfaces bounded by the top and bottom sub-domain model surfaces and the bounding coordinates of the sub-domain model was exported from the HFM. A faulted zone was defined as all parts of the domain that contained faulting at any depth. The faulted zone was increased by an external 120-meter buffer in order to incorporate the full extent of the core and damage zones. A mesh of triangular elements with variable node spacing was then defined across the x-y space such that the fault intersects with the LCA surface were defined by a series of continuously connected element sides. The maximum node spacing within the faulted zone was set at 30-meters and was allowed to coarsen outside of the faulted zone to

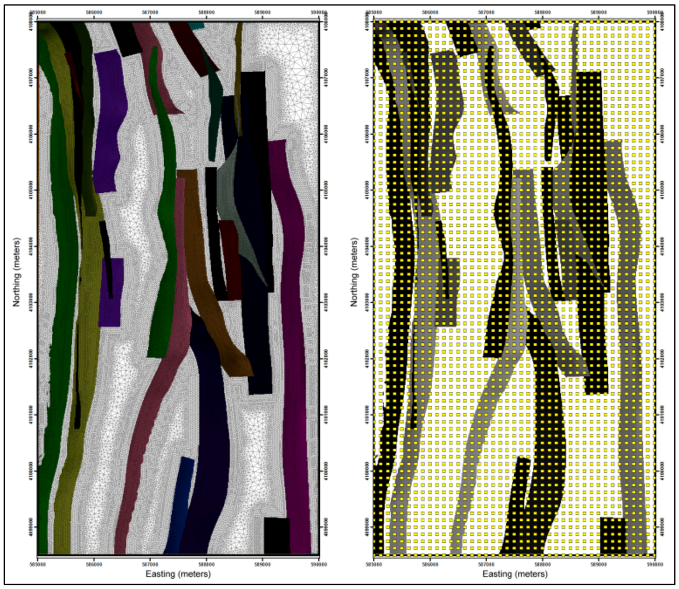

Figure 2. Flattened fault surfaces exported from the HFM relative to the FEFLOW mesh and the FEHM mesh nodes.

minimize the number of nodes and elements. The 30-meter maximum spacing within the faulted zone was chosen to ensure that at least two unique element would exist on each side of the fault trace representing the core or damage zones and ensuring that each zone would be continuous along the fault trace. The resulting mesh contained 64,660 nodes and 127,856 elements, Figure 2.

Layer Construction

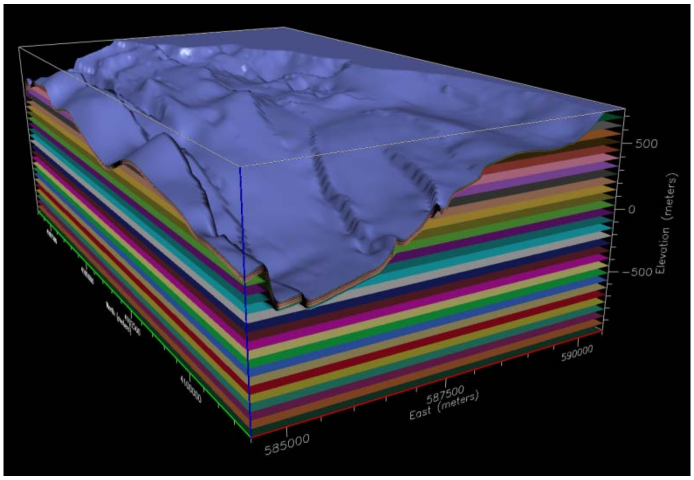

Figure 3. Geometry of the model layer stack.

Just as in the horizontal direction, the core and damage zones had to be continuous in the vertical direction. This meant that the model layers had to be designed such that a fault's inner core element (the core zone element closest to the fault trace) in an over lying layer had to directly overly the fault's outer core zone element in the lower layer and the same for damage zone elements. Using EarthVision^{TM}, the minimum fault dip (defined by the HFM) in the domain was calculated and a sequence of flat slices was created filling the vertical component of the domain with a target separation value of 60-meters ensuring core and damage zone overlap on even the most shallow fault dip. Where the resulting slice at a 60-meter spacing would intersect the LCA surface, the spacing was reduced to 4-meters below the overlying slice. A total of 30 slices were required to cover the domain at the target spacing (Figure 3) resulting in a total of 1,939,800 nodes and 3,707,824 elements in the 3D mesh.

Parameter Assignment

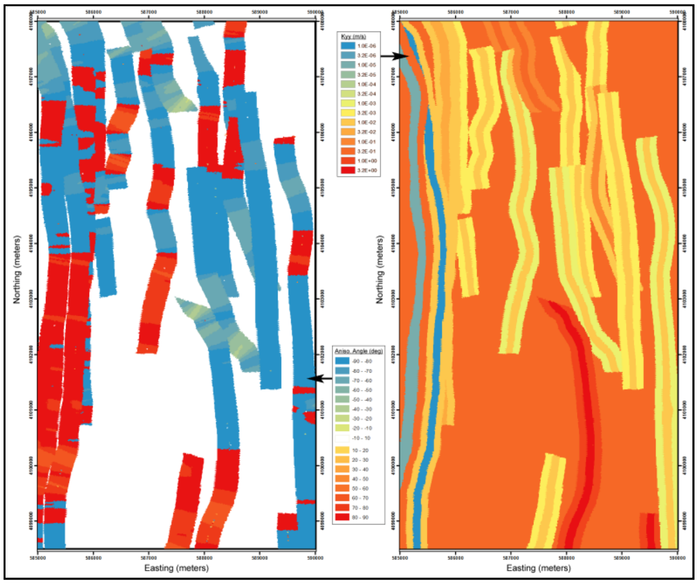

Figure 4. Elemental hydraulic conductivity and anisotropy assignments in layer one of the flow model.

Each fault within the domain had a unique core and damage zone hydraulic conductivity value. A multi-step process was developed to quickly assign this complexity to the 3,707,824 model elements. The first step was to assign each fault a unique identifier. Then, the center-points for all of the mesh elements were compiled into a single ASCII file. EarthVision^{TM} was used to identify the nearest fault surface to each center-point and the distance from each center-point to that surface. The ID and distance values were then assigned to each center-point. If the distance was less than or equal to 60 meters, the point was assigned the fault ID and labeled core. If the distance was between 60 and 120 meters, the center-point was assigned the fault ID and labeled damage. If the distance was greater than 120 meters the fault ID was dropped and the center-point was labeled country rock. Hydraulic conductivity values based on the labeling process were then assigned to each center-point and the modified ACSII file was used to directly import the elemental hydraulic conductivity values into the model, Figure 4.

While the core zone and country rock are conceptualized and isotropic, the damage zones are anisotropic with enhanced flow along the fault strike. In a finite difference model, the faults would be represented as orthogonal north-south oriented vertical planes and core and damage zones would be represented as orthogonal north-south oriented sets of nodes that fall within the specified distance from the faults. Anisotropy would be assigned with respect to primary Kxx and Kyy directions. However, in the FEFLOW model the fault surfaces were represented according to the orientation and dip defined by the HFM. In order to accurately reflect the fault-strike anisotropies, each fault damage zone element had to be assigned an anisotropy angle according to the strike of the corresponding fault at the point on the surface closest to the element center-point. This was done using the ASCII file created for the mesh element center points and a series of EarthVision$^{\text{TM}}$ model queries and calculations. This modified file was then used to directly import the elemental anisotropy angle values into the model, Figure 4.

SUMMARY

This paper demonstrates our ability to directly link the output from sophisticated, high-resolution solids models, such as EarthVision$^{\text{TM}}$, to groundwater flow model construction files. This ability allows for the articulation of complex flow systems resulting in groundwater flow simulations which accurately honor the conceptualization of the system. In addition, this process allows for the construction of these models in a fraction of the time previously required when using layer by layer parameter assignment methods.