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## CASE STUDY – 3-D FLOW MODELING OF THE SNC LAVALIN EARTH DAM

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### ABSTRACT

The Sainte Marguerite-3 (SM-3) Complex is among the largest hydroelectric projects in eastern Canada. The Complex is located some 90 km from the mouth of the Sainte-Marguerite River, a 280 km long river that empties into the St. Lawrence River near Sept-Îles, Quebec. Two small privately owned power stations are located near the river mouth: Sainte-Marguerite-1 (8.5 megawatt (MW)), which belongs to Hydrowatt, and Sainte-Marguerite-2 (18 MW), operated by Gulf Power. To meet Quebec's energy needs, Hydro-Québec started building an 882 MW hydroelectric generating station on the Sainte-Marguerite River in 1994. The works include a 171 m high earth and rockfill dam, a three-gate spillway, an 8 km headrace tunnel, and a two-unit underground power-house. Construction of the dam required the excavation of a 900 m long diversion tunnel and the construction of an upstream cofferdam. The project develops a total hydraulic head of 330 m, of which ~180 m are in the 13 km of rapids from the dam toe to the powerhouse tailrace. Filling the reservoir started in the spring of 1998 (i.e., before the dam construction was finished) and was completed in the autumn of 2002. A 140 km long reservoir was created with a depth of 120 m near the dam toe. The reservoir follows a jagged course and its width varies from a few hundred metres to 10 km over its length. The project was completed in 2002 and power generation started in 2003.

This paper discusses the issues surrounding the creation and solution of a 3-D finite element numerical model based on a compilation of field data from various sources. The creation of a successful finite element mesh utilizing actual field data is presented. Results are discussed in relation to numerical modeling in 2-D carried out in the traditional manner. Recommendations for future flow numerical modeling of these types of 3-D structures are discussed.

### RÉSUMÉ

Le complexe Sainte Marguerite-3 (SM-3) est l'un des plus importants projets hydroélectriques de l'est du Canada. Le complexe est situé à environ 90 km de l'embouchure de la rivière Sainte-Marguerite, une rivière de 280 km qui se jette dans le fleuve Saint-Laurent près de Sept-Îles, au Québec. Deux petites centrales privées sont situées près de l'embouchure de la rivière: Sainte-Marguerite-1 (8,5 mégawatts), qui appartient à Hydrowatt et Sainte-Marguerite-2 (18 MW), exploitée par Gulf Power. Pour répondre aux besoins énergétiques du Québec, Hydro-Québec a commencé à construire une centrale hydroélectrique de 882 MW sur la rivière Sainte-Marguerite en 1994. Les travaux comprennent un barrage de terre de 171 m de haut, un déversoir à trois voies, un tunnel de 8 km, Et une centrale électrique souterraine à deux unités. La construction du barrage a nécessité l'excavation d'un tunnel de dérivation de 900 m de long et la construction d'un batardeau en amont. Le projet développe une tête hydraulique totale de 330 m, dont ~ 180 m sont dans les 13 km de rapides du barrage toe à la queue de la centrale. Le remplissage du réservoir a commencé au printemps 1998 (c'est-à-dire avant la fin de la construction du barrage) et a été achevé à l'automne 2002. Un réservoir de 140 km de long a été créé à une profondeur de 120 m près du barrage. Le réservoir suit un cours dentelé et sa largeur varie de quelques centaines de mètres à 10 km sur sa longueur. Le projet a été achevé en 2002 et la production d'électricité a commencé en 2003.

Cet article traite des questions entourant la création et la solution d'un modèle numérique à éléments finis en 3 dimensions basé sur une compilation de données de terrain provenant de diverses sources. La création d'un maillage

d'éléments finis efficace utilisant des données de terrain réelles est présentée. Les résultats sont discutés en relation avec la modélisation numérique en 2-D réalisée de manière traditionnelle. Les recommandations pour la modélisation numérique des flux de ces types de structures 3D sont discutées.

## 1 INTRODUCTION

Numerical analysis of earth dam structures has become common in the past few decades. Such numerical analysis is typically performed related to issues of i) seepage through the earth structure, ii) slope stability analysis, or iii) response to seismic events. The analysis may be in terms of finite element, finite difference or limit equilibrium analysis. The common industry practice has been to analyze a 2-D section at the midpoint of a dam in a valley. This practice has been found to ignore a number of numerical effects such as the following:

- What about lateral seepage around the abutments?
- What about accounting for 3-D slope stability of the earth dam?
- Has the 3-D stability of the abutments been properly analyzed?
- Are there 3-D seismic effects that need to be considered?

Therefore there has been a recent focus on the consideration of 3-D effects on the analysis of earth dam structures in numerical models. A common limitation of such analysis is that the constructed profile of a typical earth dam may be somewhat complex. It also becomes complex to ensure that the earth dam layers properly splice into the existing valley walls. These types of pinch-outs must be determined exactly in a 3-D numerical model or there are subsequent meshing errors.

3-D finite element numerical models make use of grids to define 3-D surfaces. The difficulties of this approach are as follows:

**Bent quad issue:** Any quadrilateral unit in a grid can be “bent” by definition. The four corner points may not define a perfectly flat plane. Therefore when designing where two grids pinch out there may be inherent ambiguity. This can lead to meshing issues.

**Near-vertical surfaces:** Grids do not handle the definition of near vertical surfaces well and this can cause issues for the definition of certain zones in a typical earth dam.

Experience from previous numerical models at SoilVision Systems Ltd. has determined that often the creation of proper 3-D geometry can be the bulk of the time in creating a 3-D numerical model. A more optimal approach is through the use of triangulated surfaces which are subsequently converted to 3-D volume meshes. This allows creation of a well-defined 3-D volume which can be subsequently utilized in either a flow, seismic, or slope stability numerical model. This paper demonstrates the use of the SVDESIGNER conceptual model builder tool to speed design of an earth dam in a valley numerical model. In this case the Sainte Marguerite dam is utilized as an example in which to test the creation of a volume mesh for subsequent use in a 3-D numerical modeling tool.

## 2 CASE STUDY – SNC LAVALIN EARTH DAM

The Sainte Marguerite-3 (SM-3) Complex is among the largest hydroelectric projects in eastern Canada. The Complex is located some 90 km from the mouth of the Sainte-Marguerite River, a 280 km long river that empties into the St. Lawrence River near Sept-Îles, Quebec. Two small privately owned power stations are located near the river mouth: Sainte-Marguerite-1 (8.5 megawatt (MW)), which belongs to Hydrowatt, and Sainte-Marguerite-2 (18 MW), operated by Gulf Power. To meet Quebec’s energy needs,

Hydro-Québec started building an 882 MW hydroelectric generating station on the Sainte-Marguerite River in 1994. The works include a 171 m high earth and rockfill dam, a three-gate spillway, an 8 km headrace tunnel, and a two-unit underground power-house. Construction of the dam required the excavation of a 900 m long diversion tunnel and the construction of an upstream cofferdam. The project develops a total hydraulic head of 330 m, of which ~180 m are in the 13 km of rapids from the dam toe to the powerhouse tailrace. Filling the reservoir started in the spring of 1998 (i.e., before the dam construction was finished) and was completed in the autumn of 2002. A 140 km long reservoir was created with a depth of 120 m near the dam toe. The reservoir follows a jagged course and its width varies from a few hundred metres to 10 km over its length. The project was completed in 2002 and power generation started in 2003.

In this paper, a process is demonstrated to develop a high quality, three-dimensional tetrahedral mesh of the SM-3 Complex. Subsequent papers would examine the use of this model to model flow or stress/deformation situations.

### **3 CONCEPTUAL MODEL BUILDING PROCESS**

Models are built using stacked layers. Each layer contains a single material type. Boundaries between layers are called surfaces. The surface is a well-formed unbroken triangular mesh (often called a TIN). Surfaces may touch but must not overlap each other. Layers can be sliced vertically into distinct sections by defining one or more 2-D polygons in plan view, which are then used to create vertical side walls that act as pinch-out boundaries.

Pinch-outs are the intersections between two or more layers that typically contain different materials. They can also be used to eliminate meshing problems by aligning tetrahedral elements. It will typically lead to a faster analysis by reducing the number of mesh nodes required in the final model. Region boundaries must align with these pinch-out boundaries.

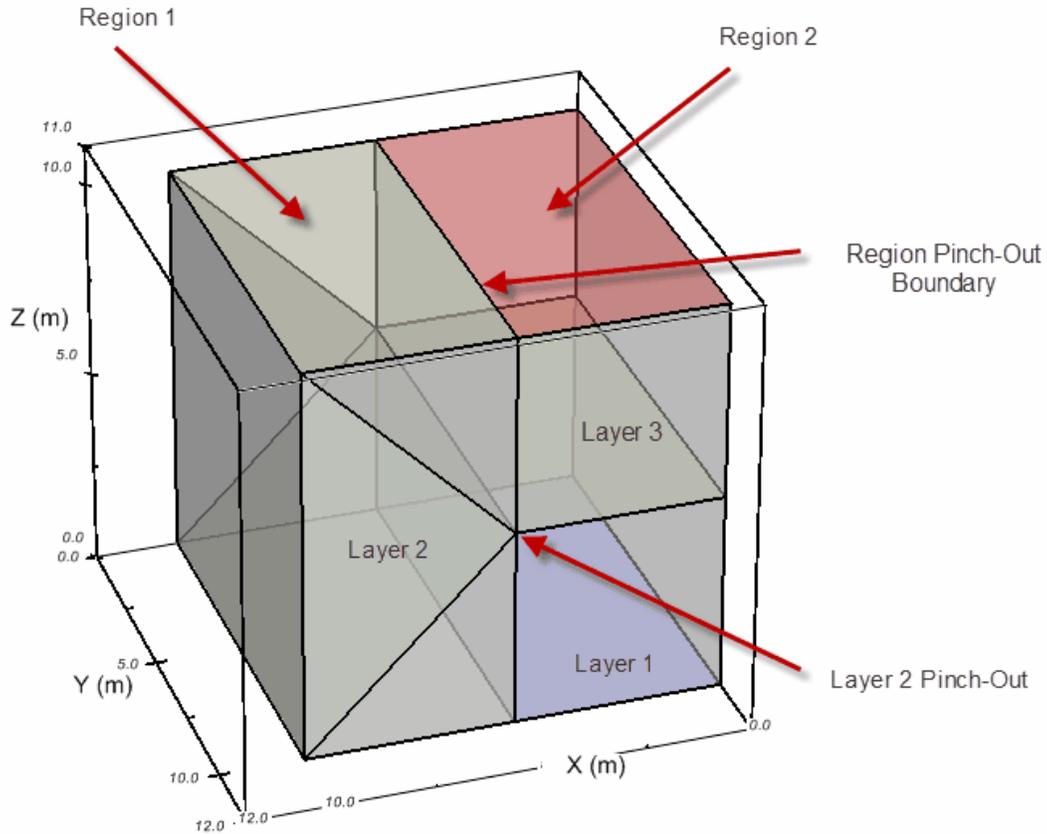


Figure 1. Illustration of layer/region concept in software

#### 4 WHY USE A TRIANGULAR MESH (TIN)?

A key improvement in this modeling process is the use of a TIN instead of a regular or irregular grid. By using a TIN, the accuracy of the surfaces being modeled is improved due to the removal of the requirement to align elevation values along grid lines. However, it is still important to balance the level of detail desired with the requirement to generate the tetrahedral mesh (discussed later), and eventually solve the model, in finite time.

#### 5 MODEL CREATION STEPS

Each layer is defined as a boundary is created as a TIN to create the model. Intersection calculations are used to calculate a TIN that precisely joins together the pieces that comprise it. The boundaries are then ordered by height, and bounding polygons are added to create the final layers. The resulting model is then meshed to create the final tetrahedral mesh.

##### 5.1 Step 1: Import the Ground Surface

The ground surface is imported as a set of contour polylines, stored in a DXF file. A TIN is then created from the contour lines, by group selecting the contour lines to merge together into a single surface mesh. A process known as Delunay Triangulation is used to join these contour lines together, with the contour

line segments used as boundaries to ensure accuracy of the mesh. This extra step is a significant improvement over the data loss incurred by using Kriging and relying on point values to determine the overall shape of the surface.

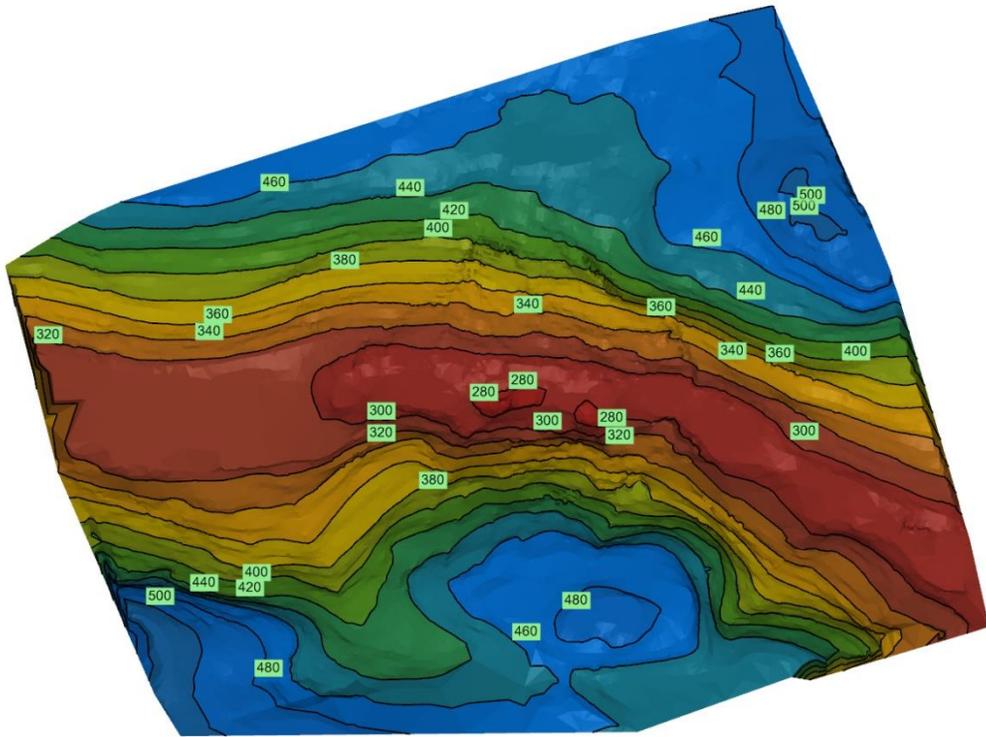


Figure 2. Imported ground surface prior to the placement of the engineered dam structure

### 5.2 Step 2: Create the Earth Dam Cross-Section

The DXF file used in the previous step also contains an earth dam 2-D cross-section. This cross-section data is also imported into the new model. A cross-section template is then created from the imported polylines and a specified projection plane. The width of the dam is defined as a single line segment of constant elevation. This information is then used to generate the surface “fragments” that comprise the dam. Each fragment then defines the desired surfaces.

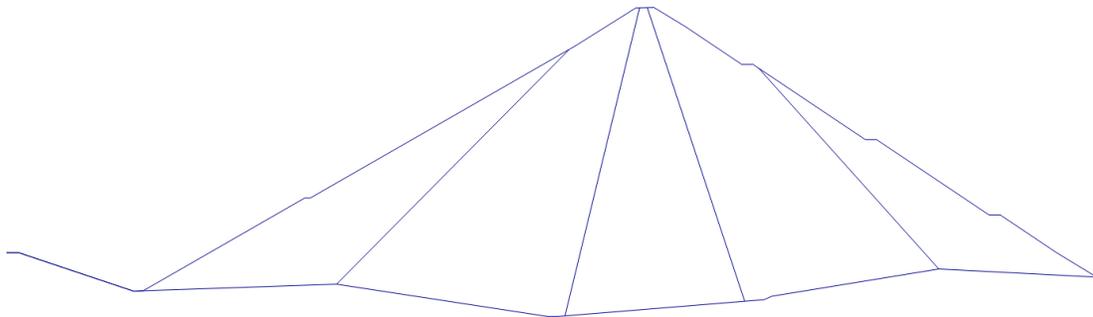


Figure 3. Cross-section of the designed earth dam

### 5.3 *Step 3: Defining Intersections Between Surfaces*

Each surface is built by adding the area of one part of the earth dam on top of the area below it. This is accomplished by using the intersection tool, which creates a new TIN by merging together the information from the two original TINs. This almost always requires new triangles to be added to account for the intersection lines formed where the two surfaces intersect one another, and for elevation data to be calculated at these new intersection points.

The earth dam contains four surfaces; therefore, the above process will be repeated to create four TINs. These four TINs, plus the original ground surface and a flat bottom surface, are used as the basis of the earth dam layers.

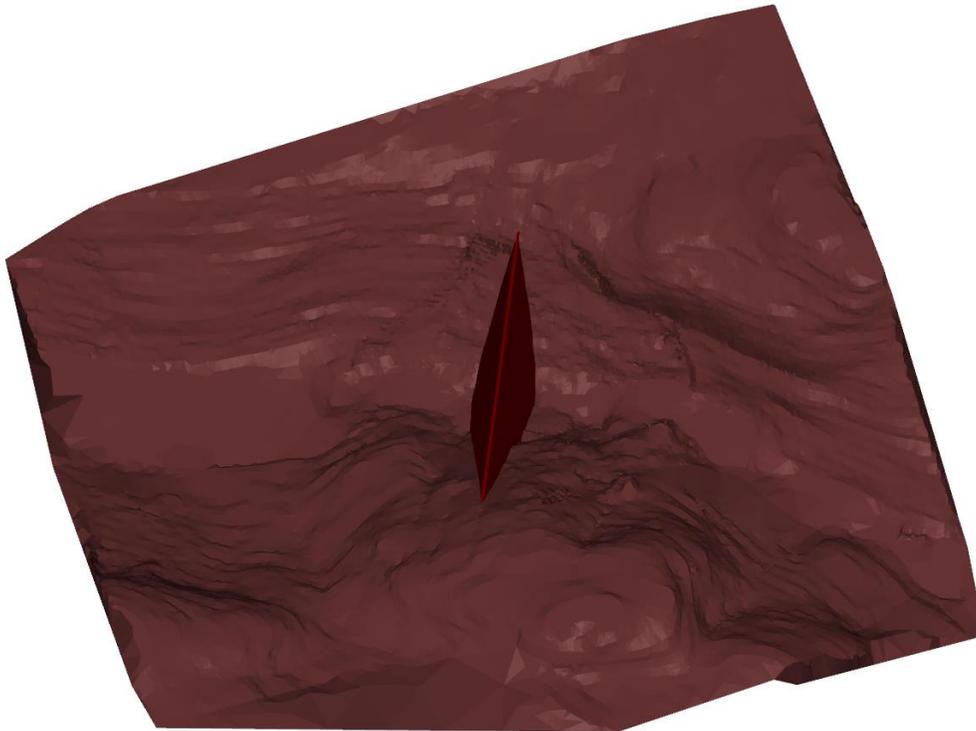


Figure 4. Earth dam inner core extruded and intersected with the valley surface

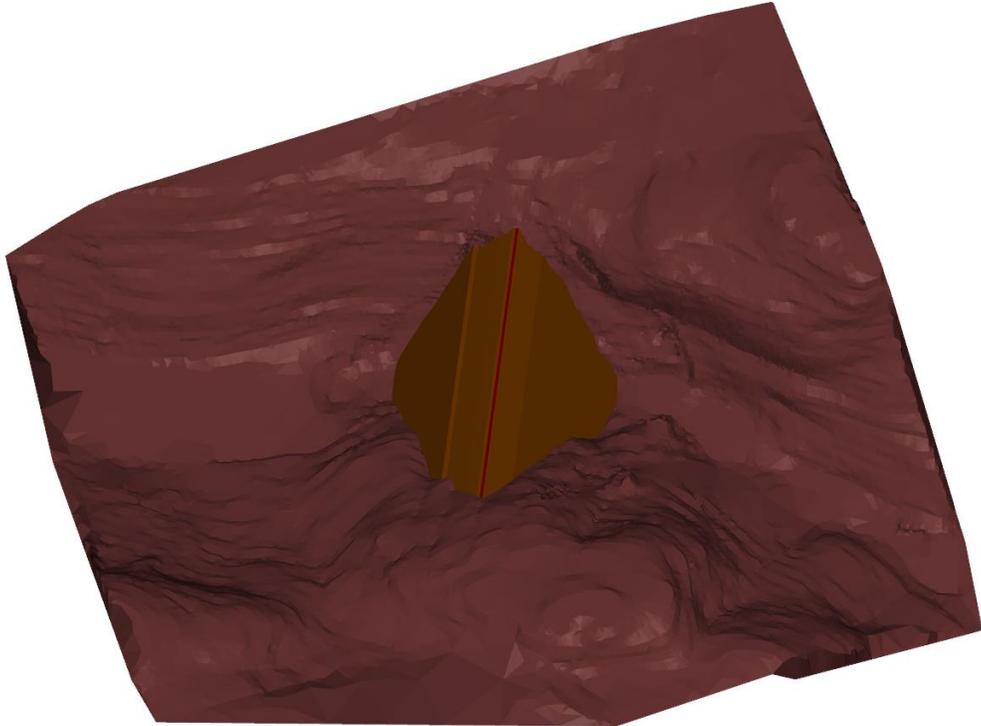


Figure 5. Earth dam outer core extruded and intersected with the valley surface

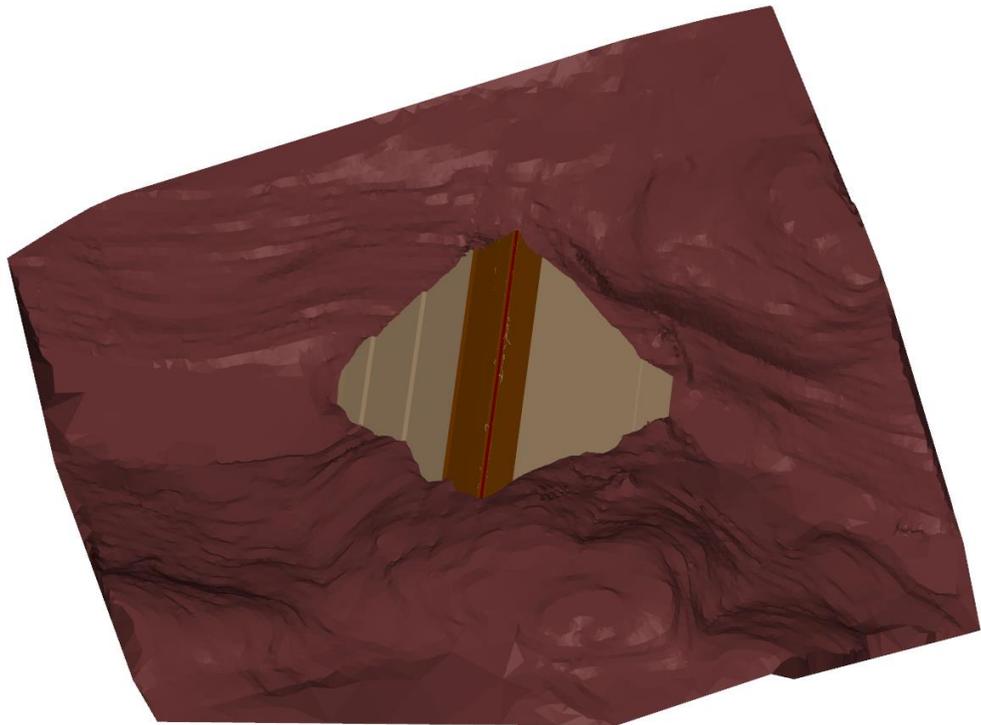


Figure 6. Exterior of the finalized earth dam in the valley

#### 5.4 Step 4: Define Layer Bounding Regions

Two bounding polygons are defined to ensure that a separate material can be applied to the earth dam separately from the surrounding ground. The outer polygon is created directly from the imported ground surface. The inner polygon is created directly from the earth dam surface, as stored before its use to create the surface intersections above. Once created, these polygons are converted to regions, which cut through every surface to form each layer.

### 6 FINAL CONCEPTUAL MODEL

It is now possible to create the final conceptual model. The six surfaces are selected and placed in the correct order, and the two regions are selected, with the outer region listed first. The final result is then created and can be reviewed for accuracy.

It can be seen from the sliced view (Figure 9) that the zones of the earth dam are properly preserved in the numerical model. It can also be noted that the correct location of the pinch-out zones where the earth dam meets the valley walls have been mathematically determined exactly.

The conceptual model at this point then can be exported to either a finite element or a limit equilibrium 3-D software program for subsequent analysis. The geometry is well-defined and the manipulation of geometry has happened with a streamlined and efficient process.

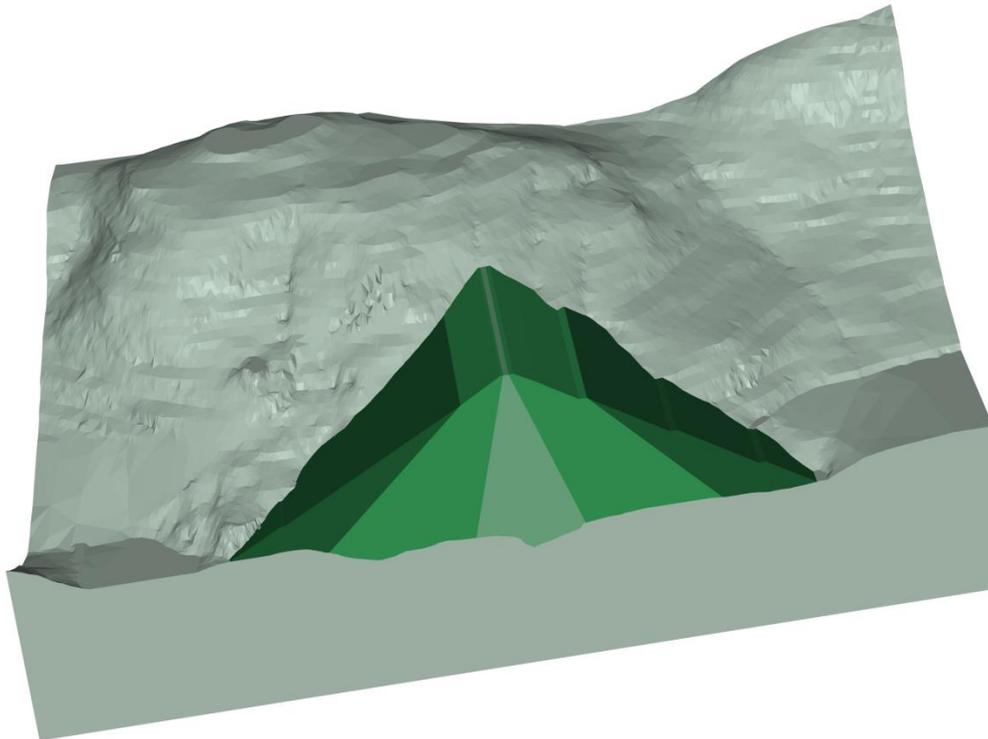


Figure 7. Sliced view of final conceptual model

## **7 CONCLUSION**

The process presented in this paper summarizes a process of building 3-D numerical models which has the potential to reduce the amount of time required in conceptual model design. The new conceptual model design method is also applicable to all types of subsequent numerical modeling including both finite element and finite difference numerical modeling. The level of complexity which can be modeled in 3-D is also greatly increased.

## **8 REFERENCES**

SoilVision Systems Ltd. (2016). SVDESIGNER User Manual. Included with SVOFFICE 5, pp 7-14.