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Griddle generation of *FLAC3D* models for the Baihetan Dam project

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1 INTRODUCTION

The Baihetan dam and hydropower plant project currently under development is located on the Jinsha River, in the southwest of China. It is the second largest hydropower project in China, after the Three Gorges Dam Project, in terms of power generation capacity (Meng & Jiang 2010). The project (see Fig. 1) includes the design and construction of 300-500 m slopes, a 289 m double curvature concrete dam, two underground powerhouses (up to 34 m in span and 88.7 m in height) with a total capacity of 16,000 MW, and 8 chambers (43–48 m in diameter and over 100 m in height).

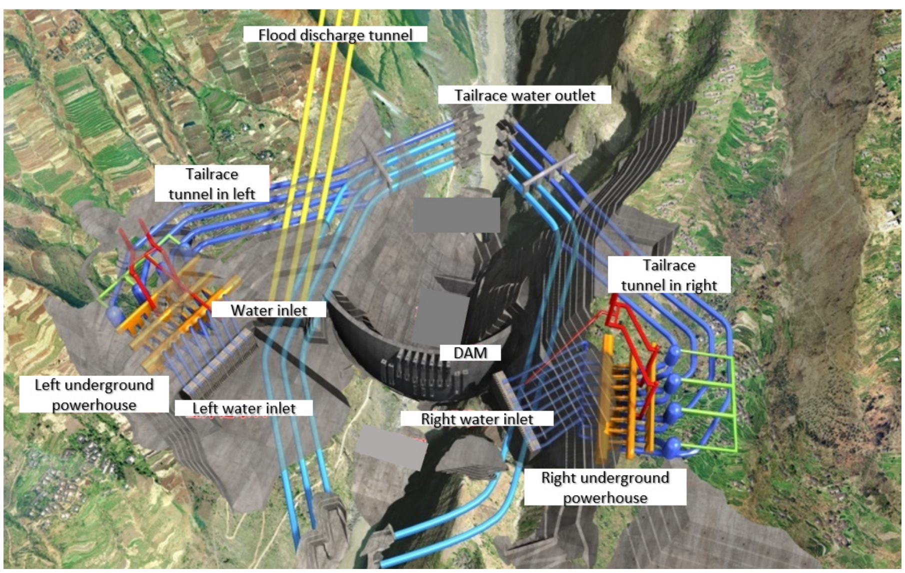

Figure 1. Three-dimensional computer model showing the layout of the Baihetan dam project.

The large scale of the Baihetan dam project, and the complex geological conditions attract potential rock mechanics problems (Meng et al., 2016), such as spalling of brittle basalt induced by high stress conditions, discontinuous deformation generated by discontinuities in the rock mass, and anisotropic unloading relaxation of columnar jointed basalt during construction (Detournay et al. 2016).

FLAC3D (Itasca 2017) and *3DEC* (Itasca 2016) numerical simulations play an important role in the Baihetan dam project; they are used for rock mechanics analysis, optimization design, reinforcement design and feedback analysis for the slopes, dam, and caverns. However, to build a *FLAC3D* mesh with many explicit features is often a major technical challenge for large-scale projects in complex geological conditions.

2 MESHING METHOD

For large-scale projects, it is often difficult to represent many relevant geologic and engineering structures in the mesh, even if various methods are available, including *Griddle* (Itasca 2016), *Kubrix* (Itasca 2015), *BlockRanger* (Itasca 2016) and *FISH* scripts for cutting. For complex models, the *FISH* and *BlockRanger* methods are time-consuming; they require intensive human interaction and expertise. On the other hand, it is usually difficult to automatically generate a full hexahedral mesh with the *Kubrix* method. By contrast, the *Griddle* method with its automatic hex-dominant meshing capabilities offers the right balance of modeling efficiency and quality.

Griddle is a fully interactive, general-purpose mesh generation plug-in for the Rhinoceros 3D CAD software. A *Griddle* meshing workflow is shown in Figure 2. *Griddle* can be used to remesh Rhino surface meshes to comply with precise size specifications and type (triangle or quad-dominant). Surface meshes can then be used as boundaries for *Griddle*'s volume mesher, which produces high-quality tetrahedral or hex-dominant meshes (Abbasi et al. 2013). The volume meshes are ready for import into most engineering analysis packages, including *FLAC3D* and *3DEC*.

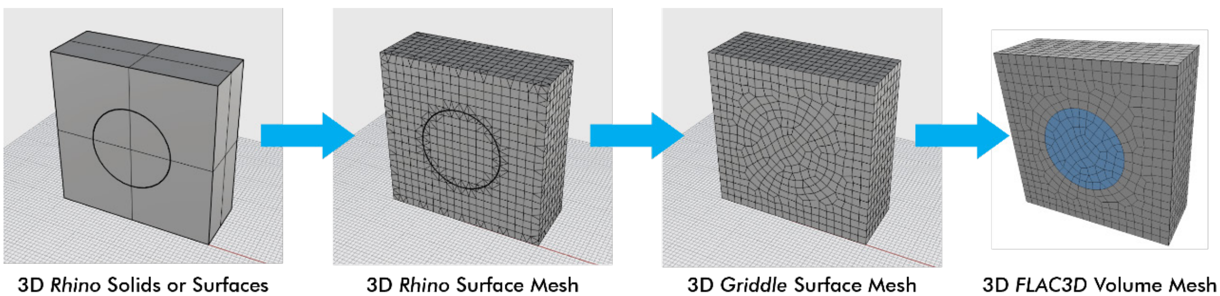

Figure 2. *Griddle* meshing workflow (Itasca 2017).

In view of the outstanding capability to easily build unstructured meshes for very complex 3D geometries, *Griddle* has become the first choice for complex geomechanical applications, and it has been widely used in the Baihetan dam project.

3 SLOPE MODEL

3.1 *Geometric model*

A photograph of the 500 m natural slope and the main structures of the left bank at the Baihetan site is shown in Figure 3a. The bedding planes C2, C3, C3-1, and LS337, are sloping toward the valley, and the faults F14, f114, and J110, are of steep inclination. The displacement and stability of the slope are dominated by the presence of discontinuities, including bedding plane and faults. In the study of a structure-controlled slope such as this, it is particularly important to simulate accurately the topography and the discontinuities.

Griddle was used to generate the grid for the natural slope. A three- step procedure was adopted. Step 1 consists of starting Rhino and reading a DXF file containing topography contours and faults, building a surface mesh from contours representing the topography, building a surface extending over the topography based on the mesh, trimming the topography and adding vertical walls, and building a closed volume. Step 2 includes building several surfaces representing the bedding and fault planes and assembling the solid and the surfaces into a single non-manifold polysurface, as shown in Figure 3b. Step 3 involves meshing the polysurface and using *Griddle* surface remesher and volume mesher to output a hex-dominant *FLAC3D* mesh.

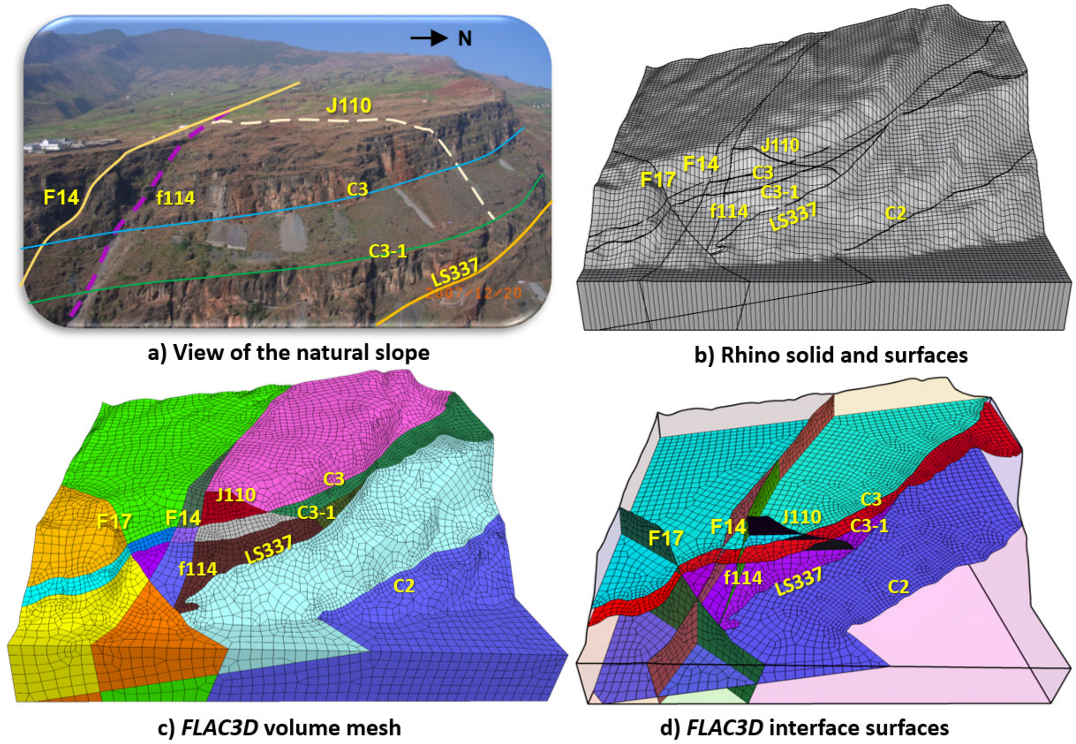

Figure 3. *FLAC3D* model with 8 intersecting discontinuities of the natural slope meshed using *Griddle*.

3.2 *FLAC3D model*

The *FLAC3D* mesh generated by Griddle for the natural slope is shown in Figure 3c; it contains 101,226 zones and 22 groups. The ratio of tetrahedra, pyramids, prisms and hexahedra in the mesh by volume is 2.7%, 9.7%, 2.5% and 85.1% respectively.

In addition, the *FLAC3D* grid has 8 face group names, shown in Figure 3d, that were assigned to mesh faces extracted from Rhino. Interfaces are created on those faces to represent the bedding planes and faults behavior. It is convenient to use the strength reduction method to reveal the preferential block displacements and to study possible sliding along the slope discontinuities.

4 DAM MODEL

4.1 *Geometric model*

The Baihetan dam project is in a section of the Jingsha River with typical "V"-gorge- profile. This project includes a 289m-high double-arched concrete dam embedded in the river bank slopes. The dam with complex structure is under construction, see Figure 4a. The stress distribution in the dam is controlled by both geological and dam structures. Therefore, a detailed meshing of the dam body should be included in the model of the valley slope excavation to perform the dam stress analysis.

Griddle was used to generate the grid of the dam. The three-step meshing procedure is similar to that used in the above natural slope. It consists of first building a closed volume containing topography, faults and excavation surface. Then, of importing the dam structure from a DXF file, and assembling the valley solid and the dam body into a single more complex non-manifold polysurface, as shown in Figure 4b. Finally, of meshing the polysurface, and using *Griddle* surface remesher and volume mesher to output a hex-dominant *FLAC3D* mesh.

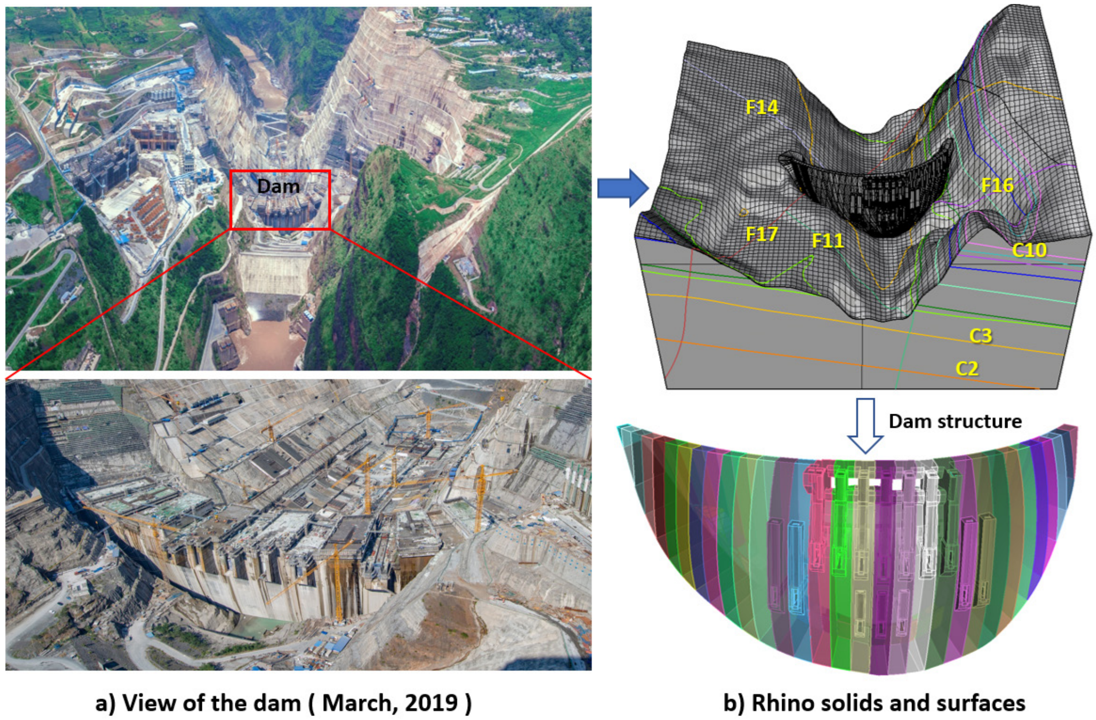

Figure 4. Rhino solids and surfaces of the Baihetan dam.

4.2 *FLAC3D model*

The *FLAC3D* mesh generated by *Griddle* for the valley and dam is shown in Figure 5a; it contains 430,269 zones and 98 groups. The ratio of tetrahedra, pyramids, prisms and hexahedra in the mesh by volume is 3.5%, 12.4%, 3.3%, and 80.8% respectively. The total amount of zones in the grid is controllable, and a fine simulation of diversion holes, elevator shafts, corridors, transverse joints, etc., is guaranteed.

As shown in Figure 5b, the *FLAC3D* grid has 17 face group names, assigned to mesh faces extracted from Rhino. Interfaces are created on those faces to represent the bedding plane and faults behavior. In addition, different zone groups and material properties are assigned to the weathering layers via the GEOMETRY command, using the DXF files imported in *FLAC3D*.

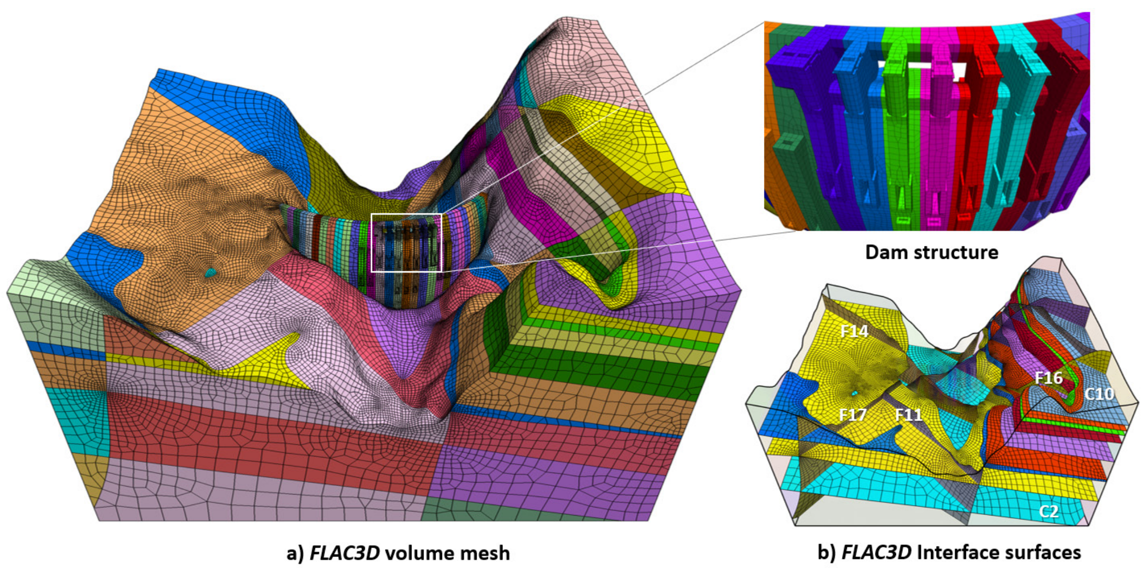

Figure 5. *FLAC3D* model with 17 intersecting discontinuities of Baihetan dam meshed using *Griddle*.

The *FLAC3D* model in Figure 5 is appropriate for mechanical analysis of the dam body and dam foundation. However, it cannot be used as-is for coupled fluid-mechanical analysis, because seepage along interfaces is not considered in the current version of the code. Moreover, the model contains tetrahedral zones, which do reduce the flow calculation accuracy and efficiency. For coupled stress-seepage analysis, an alternative full hexahedral mesh with imposed limit on smallest zone size was generated for the Baihetan project. The discontinuities are modelled with zones. The meshing technique uses a combination of *Griddle* for the base layer of the model, and an extrusion scheme assisted by *FISH* scripts for the overlaying rock mass, including bedding layers and faults (Detournay et al. 2019).

5 CAVERNS MODEL

5.1 *Geometric model*

The Baihetan dam project include the world's largest underground powerhouse caverns, the total excavation volume is about 25 million m^3. As shown in Figure 6a, the caverns are crisscrossing each other, with scales ranging from 2×3m to 34×88.7m, making the mesh generation work very complicated.

For the back-analysis work, it is often necessary to rebuild the numerical model according to actual geological data, including bedding, faults, and joints in the carven area that were mapped during excavation, see Figure 6b.

The meshing work is again divided into three steps. Step 1 consists of projecting the geological structure network onto the excavation surface. Step 2 includes building several surfaces representing the major geological structures based on the mapping points and lines and assembling the caverns solid and the surfaces into a single non-manifold polysurface. Step 3 involves meshing the polysurface and using *Griddle* surface remesher and volume mesher to output a hex-dominant *FLAC3D* mesh.

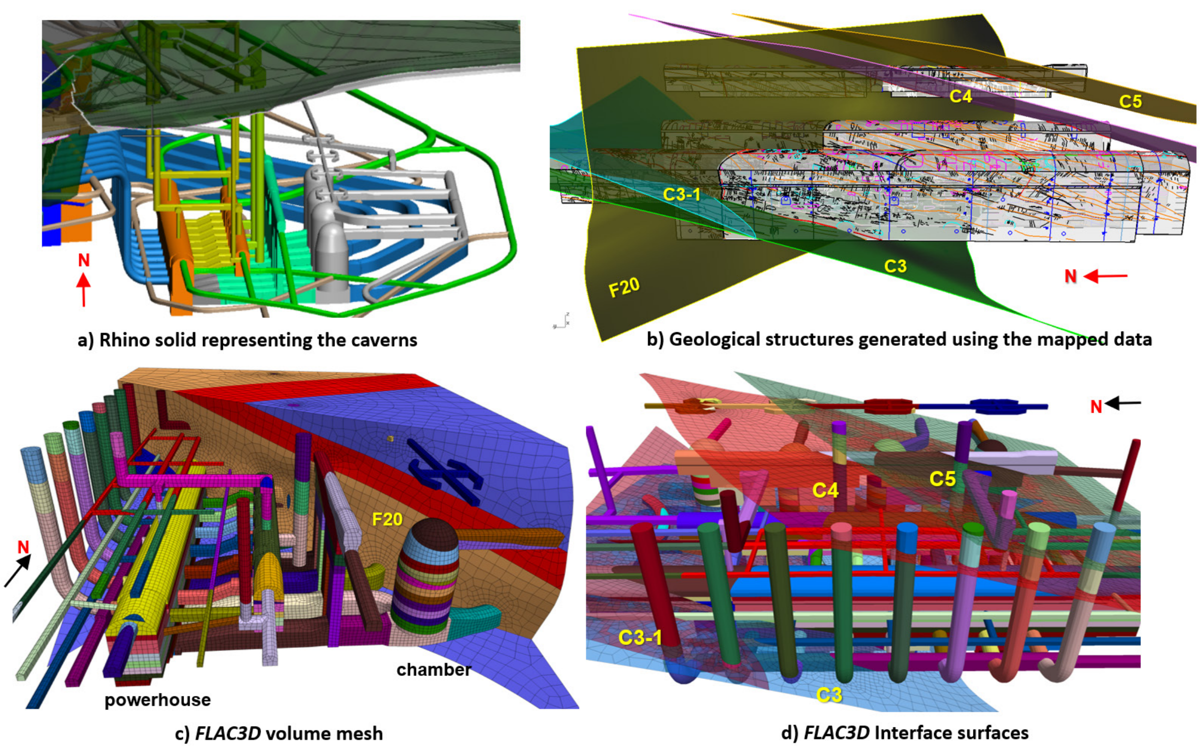

Figure 6. *FLAC3D* model with 5 intersecting discontinuities of Baihetan caverns meshed using *Griddle*.

5.2 *FLAC3D model*

The *FLAC3D* mesh generated by *Griddle* for the caverns is shown in Figure 6c; it contains 1,039,301 zones and 315 groups. The ratio of tetrahedra, pyramids, prisms and hexahedra in the mesh by volume is 8%, 23%, 5%, and 64%, respectively.

In addition, the *FLAC3D* grid has 5 face group names shown in Figure 6d, assigned to mesh faces extracted from Rhino. Interfaces are created on those faces to represent the bedding planes and faults behavior. In general, the representation of major geological structures via interfaces instead of by a thin layer of zones allows for better control of mesh size transition, total number and quality of elements, and it improves computational efficiency.

6 CONCLUSIONS

This paper introduces a *Griddle* meshing workflow, and applies it to the mesh generation of slopes, dam and caverns for the Baihetan dam project. The main conclusions are as follows:

1. *Griddle* has a simple work flow and is easy-to-use. It usually takes only a few hours to build a geometrically complex mesh based on CAD model.
2. *Griddle* is powerful, it can handle the most complex geometries with multiple volumes and surfaces, including floating surfaces. It allows for rapid rebuilt models based on mapping data obtained during the excavation and construction periods.
3. *Griddle* can generate high-quality hexahedral-dominant unstructured meshes. The percentage of hexahedra in the meshes by volume considered in the paper reaches 64~85%. This percentage is suitable for stress analysis but may not be high enough for coupled fluid-mechanical analysis.

The *Griddle* mesh generation is a good compromise between efficiency and accuracy; it can significantly improve the performance of *FLAC3D* numerical simulations in large-scale engineering practice.

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