Use of gINT Databases to Analyze 3D Spatial Slope Stability

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ABSTRACT

The use of database applications such as gINT to manage site borehole data in geotechnical consulting practice has become common. Such databases reduce the potential cost of future site investigations and allow valuable borehole information to be managed on a broader scale between multiple offices. Such data provides a valuable source for building lithology for 3D site models. When combined with topology, geotechnical shear strength laboratory data (such as shear box or triaxial data), and geotechnical design data an improved 3D conceptual model can be constructed. Such a constructed 3D site model forms a digital twin of the proposed geotechnical design for the real site and can be subjected to analytical simulations to determine if the proposed design meets specifications. Analysis such as slope stability, seepage, and stress/deformation can be performed on the conceptual model based on 2D profile slices or on the full 3D conceptual model.

The movement to performing 3D stability analysis instead of the traditional 2D profile analysis has also heightened the need for fully formed 3D conceptual models of proposed geotechnical designs at sites. 3D slope stability analysis provides the benefit of improved rigor in the calculation of the factor of safety. Calculated 3D factors of safety are higher than 2D factors of safety and allow potential for cost savings on engineering designs that may be over-conservative. These new methodologies are providing advantages in the design of large engineered structures. The additional use of spatial sweeping slope stability analysis such as the multi-plane analysis (MPA) provide maps of factors of safety which further strengthen professional design.

This paper presents an integrated approach to building lithology based on a gINT database and performing 3D spatial slope stability analysis. The new approach leverages the strength of existing borehole databases and provides more rigorous analysis to aid in the design of transportation structures such as embankments, retaining walls, and slopes adjacent to roadways.

1.0 INTRODUCTION – 3D MODELING

The history of geotechnical analysis has been heavily influenced by the analysis of 2D profiles of designed earth structures. The centerline of an earth dam, a typical cross-section of a levee, or a typical road embankment may be analyzed. In the process the 3D aspects of the engineered design are often ignored. The last decade has noted the dramatic increase in the ability of geotechnical engineers to collect data in the context of a 3D world. Detailed LiDAR data can provide 3D topology information with less effort than surveying and without the need to traverse a site. Engineering designs are becoming much more 3D in nature as engineering structures become larger. This is particularly true in the mining world. There is also movement to a digital BIM model (Zhang, 2016). Simple management of borehole information in databases has facilitated the easier management of subsurface borehole information. Simplified and standardized collection of CPT and SPT information in the field has resulted in greater amounts of subsurface information to manage. Collection of data from the field such as piezometer readings or slope movement readings from inclinometers has become automated and can be managed in the cloud. Laboratory data can also be managed in database applications. The typical geotechnical workflow can be seen in Figure 1.

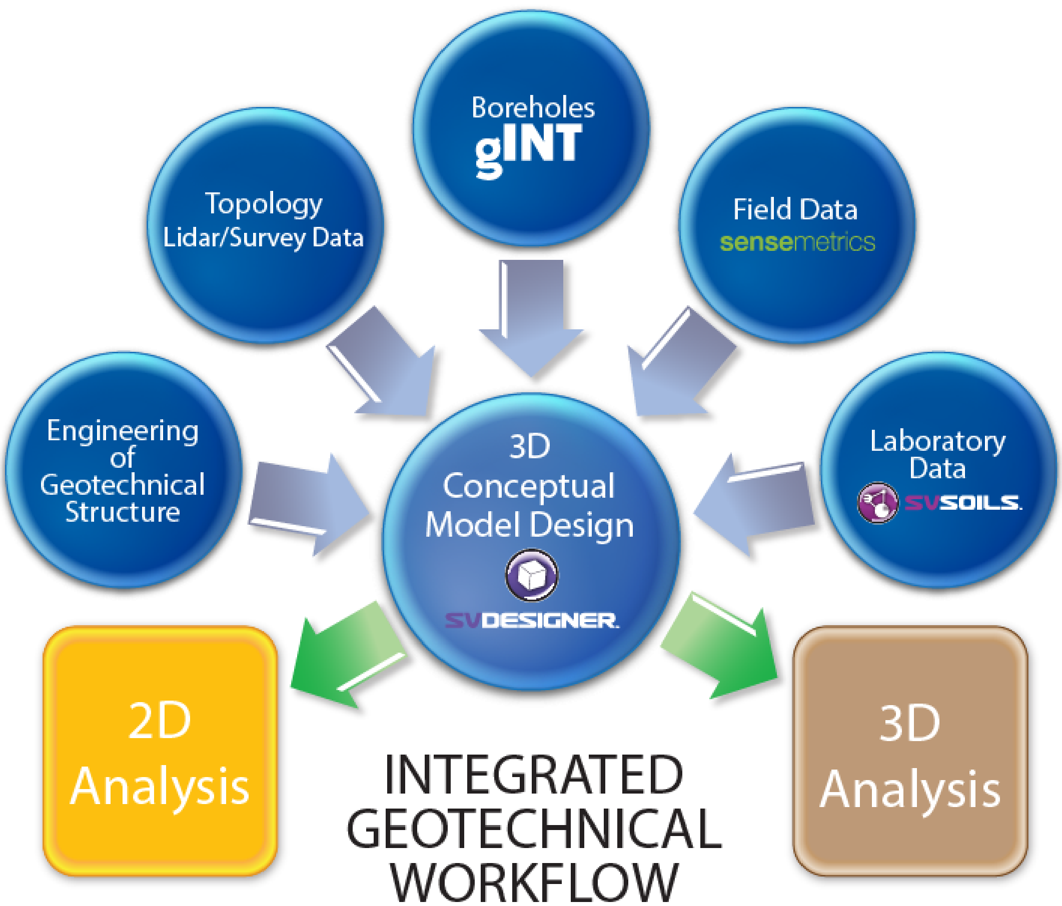

Figure 1 Integrated geotechnical workflow

Operationally there are significant challenges in managing the typical workflow data related to a geotechnical analysis. Data from the multiple sources must be combined into a common and centralized 3D conceptual site model and visualized (Azaronak, 2015). Data may need to be plotted over time. Coordinate systems must be managed in a standard Geographic Information System (GIS) coordinate system. The process may ultimately be described as creating a digital twin of a site. Such a process is a powerful exercise for geotechnical designers and forms the basis for a forward design/analysis which is based on the most comprehensive site data available.

The convenient collection of data in a 4D world (3D + time) has resulted in a dramatic increase in the potential for 3D numerical modeling in the geotechnical field. Slope stability, seepage, and stress/deformation analysis are all possible to greater extents than previously possible. Furthermore, it has been noted that 3D analysis results more closely match noted real-world results (Fredlund, 2018).

It is worth noting that a high portion of geotechnical design projects remain 2D in current engineering practice. The reason for this hinderance for adoption of 3D analysis became apparent after working alongside geotechnical consultants over the past number of years in the industry. A host of 3D geotechnical numerical modeling projects were reviewed a decade ago and found that approximately 80% of the time required to model/analyze a project in 3D was spent in collecting all data, visualizing it on a common source, and resolving impossible geometry issues. It was found that this 80% of the time in managing 3D spatial representation of geotechnical sites required additional strategies which software tools needed to provide.

This paper focuses on current methodologies of managing the 3D geometry of geotechnical site. There is not one historical workflow for developing 3D geometry which has become dominant in engineering practice. Therefore a hybrid number of methodologies of managing data must be considered. Managing data must consider both the professional designs and the integration with subsurface information. A common way of managing subsurface information is through a borehole database software program such as gINT. This paper focuses on i) the management of 3D design and subsurface information, and ii) methodologies for the integration of gINT borehole data to build 3D geotechnical conceptual models for subsequent numerical modeling.

2.0 3D MODEL BUILDING METHODOLOGIES

Geotechnical numerical analysis of 2D slope stability by the limit equilibrium analysis was pioneered in the early and mid parts of the century (Petterson, 1915; Fellenius, 1936; Bishop, 1955; Morgenstern and Price, 1965; Fredlund et al., 1981). The focus in numerical model creation was on the use of vertical cross-sectional profiles that had been established as a hybrid of engineering design drawings and borehole fence diagrams to enter the stratigraphy. The continued use and value of 2D vertical cross-sections is readily apparent in the industry.

3D slope stability analysis is also not a new science with the methodology being established decades ago (Howland, 1977; Hungr, 1987, Hungr et al., 1989, and Fredlund, 1977). Such 3D analysis focused on simplistic and idealized models which were largely comprised of simple embankments or simple homogeneous earth dams. As such, the focus was on modeling simple and geometrically precise shapes. The shapes analyzed more represented the clean lines of models such as represented by machine parts in mechanical engineering.

Advancements in the modeling of regional groundwater flow led to the numerical modeling of geo-strata over large areas by the finite difference or finite element methods in the early 1980s. Modflow-based interfaces generally adopted a "layer cake" approach of stacking surfaces on each other to form geo-strata. Early geometry paradigms required all surface definitions to extend to outer limits of the modeling domain. Revisions to the "layer cake" approach allowed successful pinching out of surfaces and a loosening of the requirement that all layers extend to the boundaries of the model.

The mining field has introduced advanced concepts such as folded bedding lithologies and mineral formations with volcanic origins which are zones which can only be described with fully formed 3D meshes. Faults can also create breaks in strata layerings and severely complicate their representation in 3D numerical models. (Figure 2).

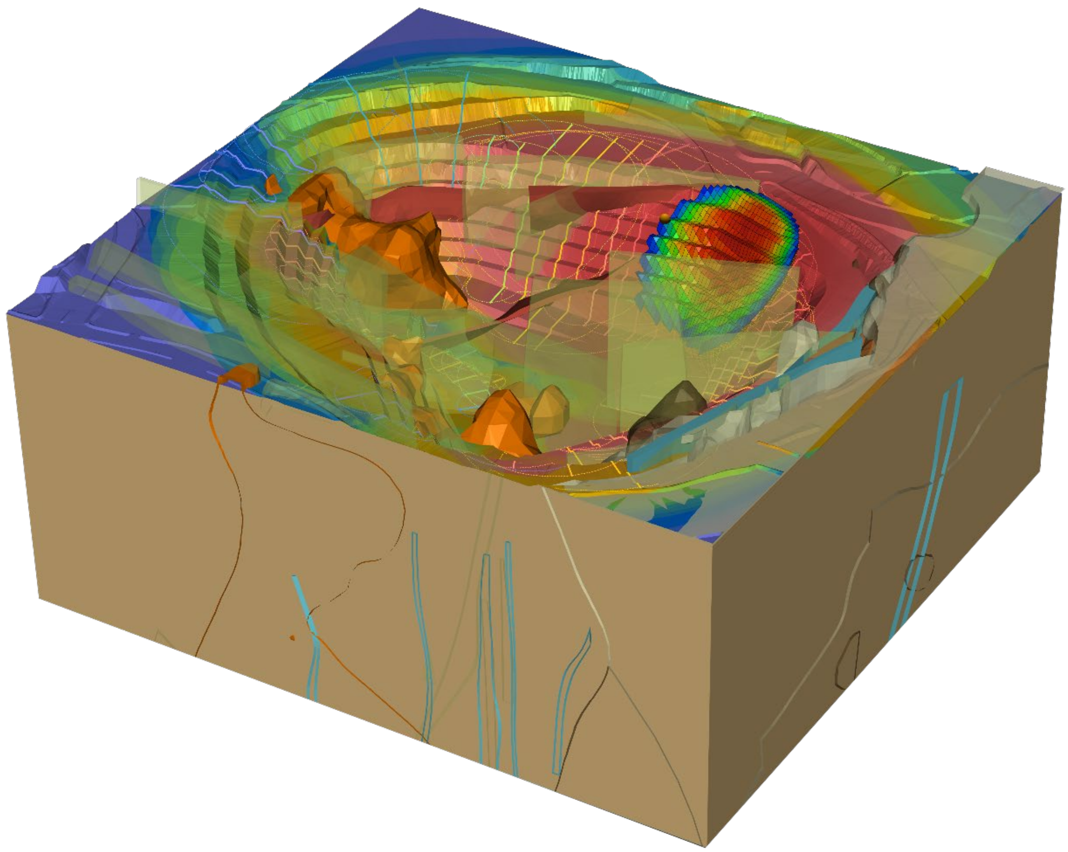

Figure 2 Example of complex enclosed volumes

The difficulty is that the geotechnical modeling industry cannot be provided a single paradigm of building 3D numerical models as the scenarios and the data methodologies are historically varied and complex. Therefore the building of 3D models has evolved into the following basic methodologies:

1. Extrusions from 2D profiles: simple 3D models can be extruded from 2D cross-sections. The tops of regions are converted to surfaces and conform to the "layer cake" geometry paradigm. Surfaces cannot "fold back" on each other so some regions need to be cut with additional surface lines in the process.

2. Profile stitching: 3D models can be built from a series of parallel 2D profiles which can be stitched together to form a 3D conceptualization of the model.
3. Layer cake: In this paradigm the 3D model is build from stacking of surfaces defined by grids or meshes. Grid/mesh objects need not extend to the boundaries of the model and pinchouts are allowed. The extents of the model can be arbitrary.
4. Borehole interpolation: This paradigm allows the subsurface geostrata to be interpolated based off of borehole measurements. Such borehole data can be imported from gINT databases.
5. Material volume meshes (MVMs): These are fully enclosed 3D volumes made from triangulated mesh objects sometimes referred to as TINS (triangulated information networks). MVMs override Layer Cake region definitions and can have a hierarchy of definition. Such objects can be adapted to form complex engineering structures.

The use of such advanced paradigms has resulted in a dramatic increase in the complexity of 3D structures which can be digitally represented in a 3D numerical model. The paradigms have also greatly reduced the time required to build 3D numerical models and thus brought such efforts into the realm of mainstream analysis with geotechnical consultants. Such an application of the aforementioned geometry building paradigms may be seen in the following case study.

3.0 CASE STUDY - EARTH DAM

The methodologies of building a geometrically complex 3D tailings dam are illustrated in the following case study. Tailings dams can be geometrically complex and have historically exceeded the ability of geotechnical software to model them in 3D. The following case study illustrates the methodology behind the building and analyzing of a tailings dam including the proposed tailings dam design integrated with the surrounding topology and subsurface stratigraphy.

3.1 Building a 3D Model

To build the Tailings Dam 3D model, information from a number of sources was used to create the model including: Pre-construction LiDAR, Digitized Foundation approval surfaces, as-build geometry and 2D and 3D CAD designs.

Geological interpretations and borehole data can be included in the modelling process however, for this model a simplified geology was assumed as preliminary stability analysis indicated that upstream (US) stability at the dam bend was controlled by 20 m thick layer of soil immediately under the dam at the location of the bend.

The 3D model was built entirely within SVDESIGNER, a 3D conceptual modeling software package (SoilVision, 2018). Pre-development LiDAR was used to define the both the topographic surface and translated 20 m down to bound the bottom of the controlling soil layer in the simplified geology. A DXF surface of the digitized foundation approvals were imported and intersected with both the topographic and subsurface surfaces to replicate excavation of the foundations. The foundation approval surface was also used to create the blanket filter surfaces by translating the surface up the width of the filter and trimming it to the filter extents. As-built dam geometries we imported from Surpac^{TM} and AutoCAD^{TM} with surface mesh refinement editing Performed. Future design stages were either extruded from 2D neat line sections or imported directly from AutoCAD.

To simplify their modelling, many of the surfaces described above where modelled using a special subset of 3D surfaces called 2.5 dimensional (2.5D) surfaces. In 2.5D surfaces are defined in 3D space with each point having an X, Y and, Z coordinates, but with two limitations: 1) the surfaces must be continuous between all adjacent points and 2) the surface can only contain one Z coordinate for each unique X,Y coordinate. This means that unlike a true 3D surface, 2.5D surfaces cannot fold over themselves or allow true vertical faces.

While many of the dam components can be built up with layers of 2.5D surfaces, there are some dam components which could not be modeled as 2.5D surfaces. For these surfaces Material Volume Meshes (MVMs) were needed.

3.2 Material Volume Meshes

MVMs are not restricted to 2.5D and exists as enclosed 3D surfaces defining a volume of material. An MVM overrides the materials defined by the layered surfaces of geotechnical conceptual model. This feature is useful for modelling geological layers with extremely complex geometry that usually can't be represented by 2.5D surfaces in a 3D model.

The compacted clay core transition from an upstream (US) inclined configuration in the central of Dam 1 to a central core configuration at the right abutment (RA). This transition is problematic when using 2.5D surfaces exclusively, for 2 reasons: 1) The downstream face of the core and filters will invert resulting in a location where the surface will be vertical and 2) The order in which 2.5D surfaces would be layered from an inclined core (downstream (DS) rockfill first, then the chimney filters and core followed by US rockfill) is different than the order for a central core (combined DS and US core and chimney filters first followed by US and DS rockfills).

To solve this problem with the geometry an MVM was constructed the available geometry data. The top of the filter blanket was used to the define the base of the Core and chimney filter. The previously designed US and DS surfaces for the core and chimney were imported from AutoCAD and Surpac and used for the sides of the MVM. The top of each stage was created natively within the software. Each individual surface was then tied together like assembling the faces that make up a cube to construct the completed MVM.

Figure 3 illustrates the Tailings dam view with the length of the MVM used.

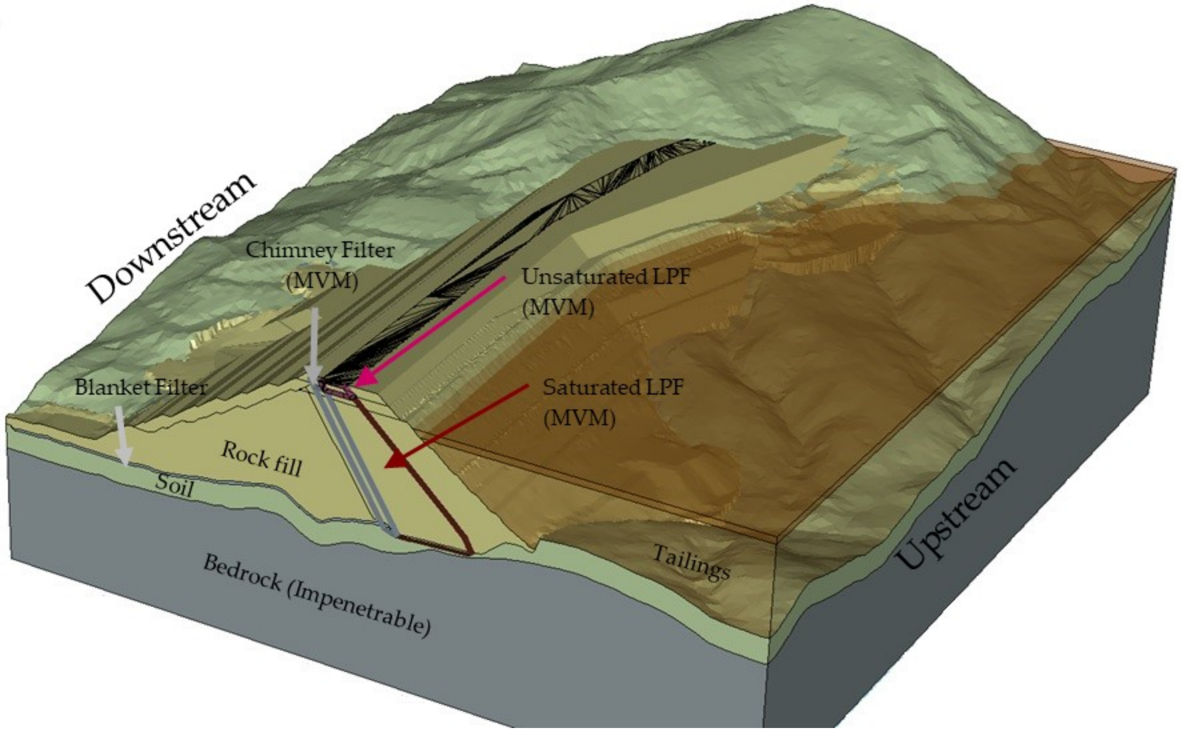

Figure 3 3D Model of Dam 1, exterior surface for MVM of LPF and Chimney Filter shown

3.3 Slope Stability Analysis

The overall stability analysis of Dam 1 includes a number of 2D cross-sections along the dam profile that were analysed to asses the stability of the dam under drained, undrained, and seismic loading cases in both the US and DS direction. The results were compared with established stability criteria. Where this established criterion was exceeded the design was accepted; where the criteria was not met, modifications in the design were made until the criteria was met.

In most cases the conservative 2D analysis exceeded the design criteria and were excepted. However, in the case of US stability at the bend in the RA, 2D sections could not reasonably resolve the pseudo-static seismic stability and a 3D stability model was required. To analyze the LEM slope stability analysis in 3D, the software SVSLOPE (SoilVision, 2018) was used which is integrated with the conceptual modeling software, providing an improved interaction between geometry building and analysis in the final solution.

The 3D analysis illustrated in this paper aimed to verify the US factor of safety under pseudo-static seismic conditions. Based on the site-specific seismic assessment available at the time of the analysis, a seismic yield co-efficient (k_y) of 0.08 or greater was found to meet/exceed the displacement criteria regardless of the height or average shear wave velocity of the slip surface when analyzed using Bray and Travasarou (2017). An orientation analysis was considered to identify the direction of the critical slip surface. Orientations between -40° to 40°from the bisect of the US crest bend angle were considered.

Pore-water pressures (PWP), were modeled within the software using a spatial function. The values of PWP were determined based on which portion of the model was being considered and what PWP primary influence was at that location. e.g. Pond elevation in the US, Filter location in the DS, and construction and pond loading in the core. Exact details of PWPs are beyond the scope of this paper.

The material strength parameters for the foundations and the fills are based on a large number of in-situ and laboratory testing completed as part of a number of site investigation and material characterization programs. Testing includes but is not limited to: Index testing, SPT, direct shear and triaxial tests. Rockfill properties were estimated using the Average Leps shear normal function (Leps, 1970). Tailings were assumed to liquify for seismic analysis. This meant that it had to be modeled using the software fluid model type to allow for the correct material density without being incorporated in the sliding mass.

4.0 gINT SUBSURFACE BOREHOLE DATA

Large amounts of borehole data have been collected in the last number of decades. Such data has been stored in a variety of formats but is ideally stored in a database of some type. gINT was one of the early and popular borehole packages due to it’s flexible database design and manages significant volumes of borehole data in North America and around the world. It is a desireable geotechnical process to be able to move from the borehole data in to a 3D geotechnical numerical model such that the value of the borehole data can be used as the basis for the geotechnical stratigraphy.

The methodology of importing gINT data is not straightforward and involved the following steps. Firstly the variable format of the gINT database required the implementation of an import / mapping functionality such that the proper fields in the gINT database can be matched with the fields which the software is expecting in order to locate each borehole in 3D space and provide a depth description of layers. Once the mapping is done the data may be imported. The boreholes can then be visualized in 3D space or in plan view. All the boreholes must be scanned for all materials present at the site and “missing” soil layers presented in each borehole. The reasonable order of all layers must be preserved.

The raw data must then be interpolated onto 3D surfaces. In theory this can be accomplished through linear, nearest neighbor, krigging, or a host of other interpolation methods (Kessler, 2008). In practice however, this process of interpolation is often accomplished through manual intervention of controlling the interpolation of certain layers through known points. Therefore the software implementation must ultimately be comprised of a hybrid of manual drawing of known layers on fence diagrams (Figure 4) as well as interpolation methods. Such a hybrid method was implemented in software in order to allow flexibility of the ultimate development of 3D surfaces in a model as illustrated in Figure 5.

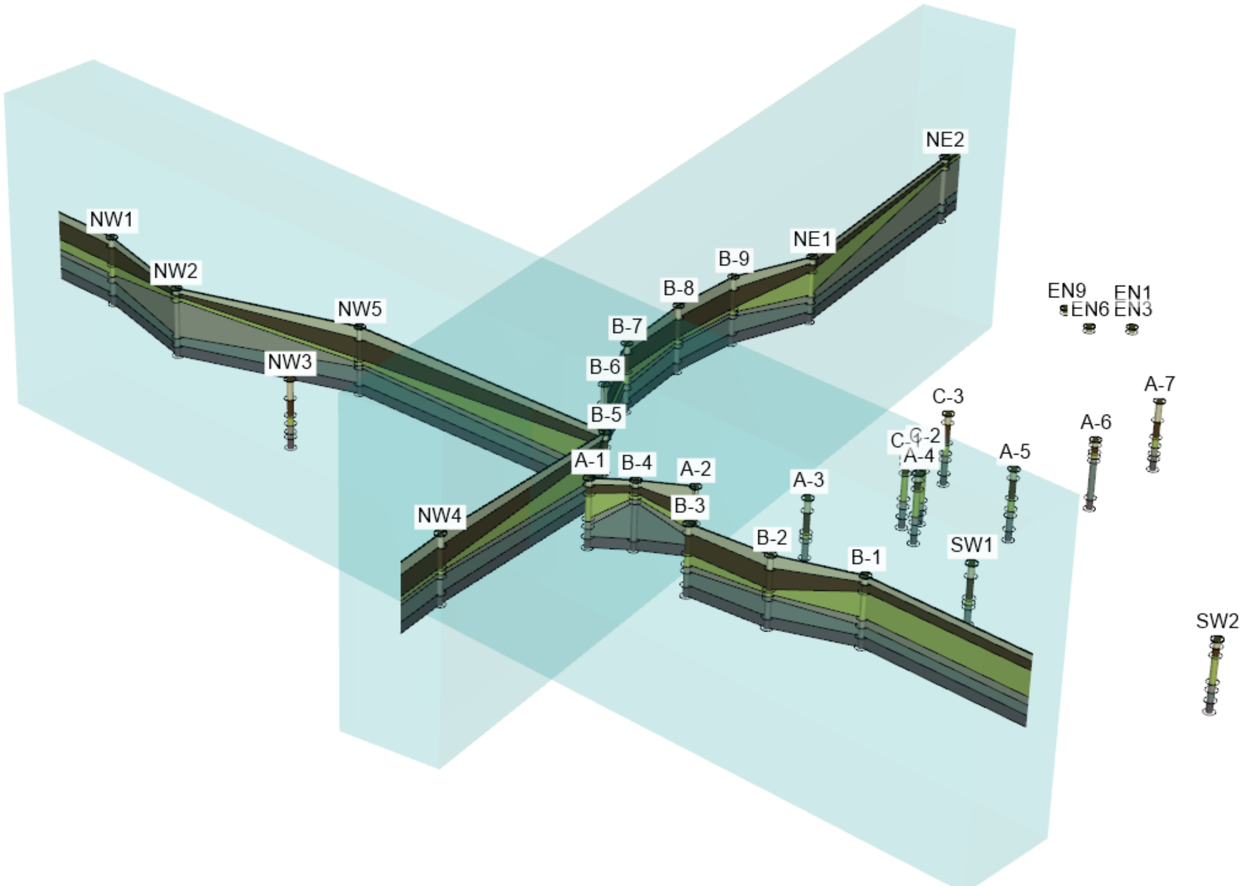

Figure 4 Fence diagram representation of layers between boreholes

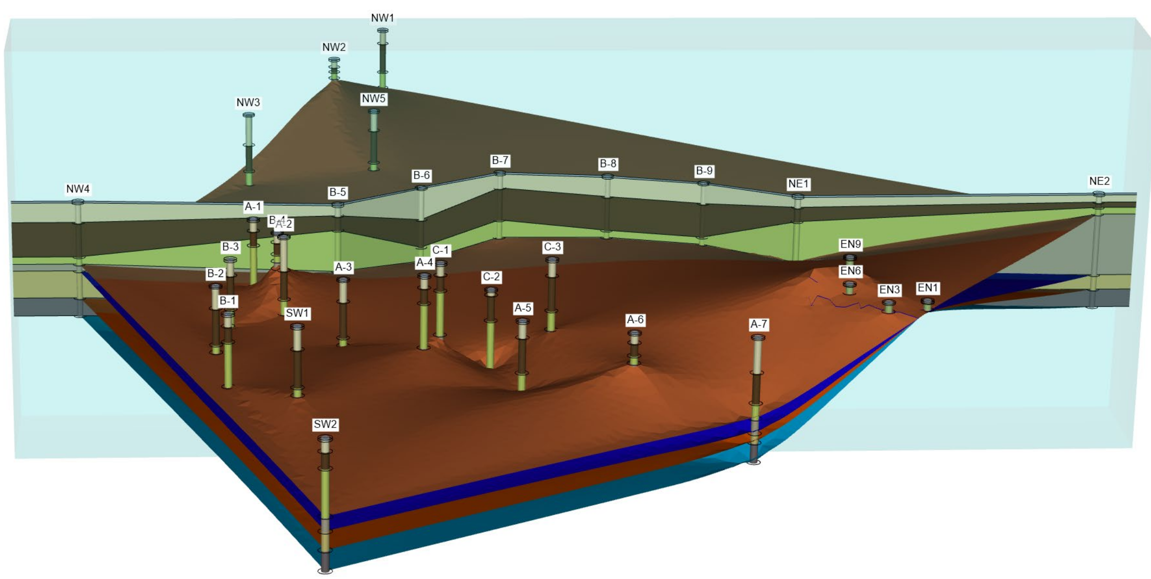

Figure 5 Illustration of fence diagram and single interpolated 3D surface

Once imported and interpolated, surfaces then conform to the Layer Cake geometry paradigm and can be modified or integrated with the engineering drawings of a related earth structure.

5.0 SPATIAL SLOPE STABILITY ANALYSIS

One of the secondary issues with a standard 2D geotechnical analysis is that the geotechnical engineer may not know the correct location of the 2D plane which produces a critical factor of safety. A classic example of such a problem was presented by Jian (2003). The example presents a simple slope to illustrate two problems with conventional 2D plane-strain stability analysis; namely that the location of the slip as well as the correct factor of safety can be difficult to determine from this relatively straightforward example.

Multi-plane analysis (MPA) allows the engineer to quickly perform hundreds or thousands of analyses around a slope quickly using parallel computations. In the 2D MPA analysis method the slope is sliced into 2D profiles each of which is a full 2D LEM analysis. Each slice is analyzed, and the results are then plotted over top of the original 3D slope therefore giving a spatial perspective to the many 2D slices. Each slice is oriented such that the primary slip direction is the steepest slope. Since the slip may not happen on the steepest slope the MPA analysis method can be specified such that multiple orientations, such as +/- 10 degrees can be analyzed. In this way the most likely slip orientation can also be determined.

The analysis of slope can be seen in Figure 6. From the analysis we can see the critical zone clearly outlined as to the left of the nose of the hill. This is counter-intuitive from the sense that most engineers would feel that the point of the nose of this model would yield the lowest FOS value. Therefore, this illustrates the value of using analytical procedures to determine the correct location of a probable failure zone in an irregular topology. This result must also be noted that it is only the result of 2D slices through differing spatial locations in the 3D model. There is no relation implied or computed between the slices so the 3D lateral effects on the slope are not considered. Therefore, the model must be considered as an indication of a probable failure zone but not a definitive analysis which considers 3D effects.

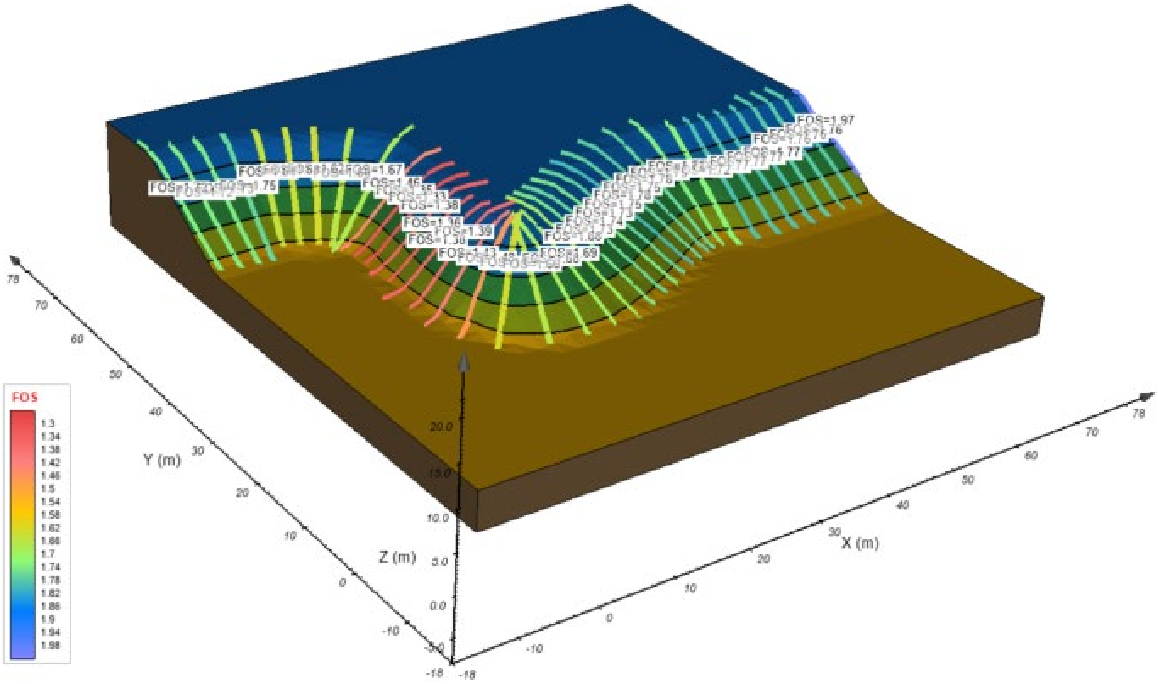

Figure 6. Example of slope difficult to analyze in 2D plane strain (Jiang, 2003) – analysis by 2D MPA.

5.1 3D Spatial Stability Analysis

The benefit of the multi-plane analysis is that it can easily be applied in 3D space using the same slicing planes established for the 2D analysis only with the analysis of a 3D ellipsoid at each slicing plane location. Similar searching techniques such as Entry & Exit, Cuckoo Search, Slope Search, or Auto Refine methods can be applied to the searching technique. The aspect ratio of the ellipsoid as well as faults and fractures can be considered as well in the analysis.

An enormous amount of information is generated with each slice being considered as a full 3D analysis. The 3D results can therefore be presented as a series of individual critical slip surfaces or contoured to produce a contoured map of the relative factor of safety over an area. The results of such an analysis for an open pit are shown in Figure 7. It can be seen that MPA is a useful methodology for i) understanding the relative factor of safety of a large spatial area as well as ii) locating potential zones of instability which may exist. The 3D results also provide a higher and computationally more realistic analysis of the true 3D FOS.

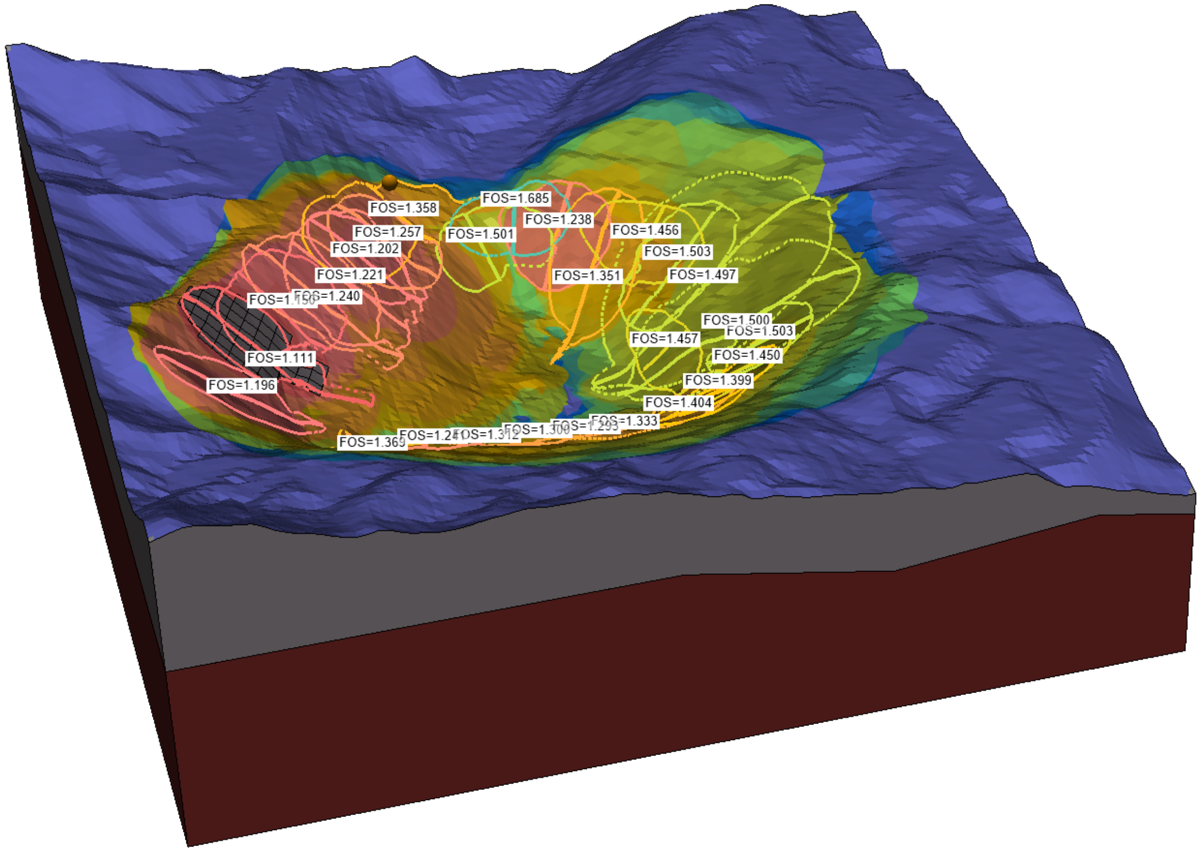

Figure 7. Example of 3D MPA applied to the analysis of an open pit.

6.0 SUMMARY

The ability of the present geotechnical engineer to model the real-world in 3D is greatly enhanced. Data collection methodologies allow for collection of enhanced site data through remote and subsurface sensing techniques and facilitate the creation of digital twins of the geotechnical site. Such digital twins can yield more comprehensive geotechnical analysis that more closely resembles the real world.

This paper focused on the specifics of updated geometry paradigms which facilitate the faster creation of 3D numerical models. A number of current geometry paradigms were presented which facilitate the entry of both subsurface and design information into a numerical model. A particular focus was the utilization of gINT borehole databases in order to assemble and build 3D subsurface geotechnical layerings. The resulting 3D models can then be analyzed in the context of spatial 2D or 3D slope stability analysis, groundwater seepage, or stress/deformation.

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