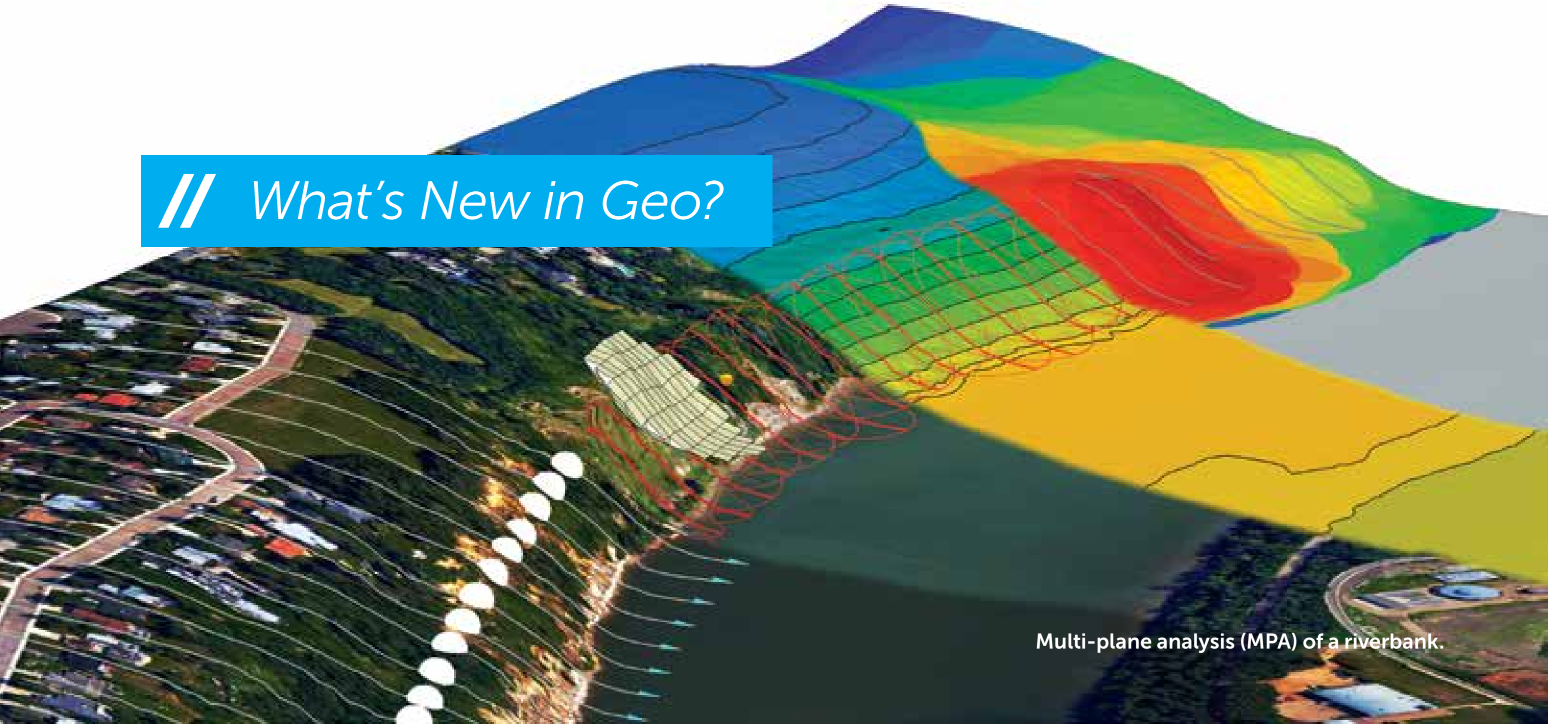

Multi-plane analysis (MPA) of a riverbank.

THE FUTURE OF NUMERICAL GEO-MODELING

IS 3D HERE TO STAY?!

MURRAY D. FREDLUND

By Murray D. Fredlund, PhD, P.Eng

Application of soil mechanics in engineering practice has undergone remarkable changes over the past 50 years as a result of developments in computer technology. Each improvement in computing capability, speed, and information storage has opened the way toward software solutions capable of analyzing problems of ever-increasing complexity. Not only have the size and complexity of the problems changed, but the modern computer has also opened up new approaches to addressing common problems in geotechnology.

Virtually every physical, flow, chemical, and thermal process associated with soils can now be simulated using a mathematical model. But exactly what is meant by a "mathematical model"? The U.S. National Research Council described it as "a replica of some real-world object or system. It is an attempt to take our understanding of the process (i.e., conceptual model) and translate it into mathematical terms." The processes associated with either single-phase or multi-phase materials in nature can be written in the form of a partial differential equation (PDE).

The PDE should embrace the physical behaviour of the material being considered in the form of a mathematical equation. The PDE can then be applied to an element of a continuum (i.e., a finite element of soil). Once the physical behaviour for one element is known, it can be applied repeatedly to the hundreds or thousands of adjacent elements of soil, thus reducing the entire continuum to the solution of a series of mathematical equations. And solving simultaneous equations is where computers shine. Today's computers have opened the way to addressing a broad spectrum of applications that were previously not thought possible.

The progression of science in any field involves focusing on specific hurdles that must be overcome in order to move the science forward. The current hurdles involve the following aspects of geotechnical numerical analysis:

- A movement toward 3D modeling
- Integrated hydrological and geotechnical numerical modeling
- Soil-structure interaction
- Large-strain analysis
- Stability analysis improvements
- Modeling of unsaturated soil mechanics

Historical Overview

Modern soil mechanics is a relatively young science, founded by Karl Terzaghi in the mid-1920s with his text *Erdbaumechanik*. Since then, changes in our understanding and application of soil mechanics have been dramatic. These advances have been made, in part, by the increased use and sophistication of computers; their impact on the field of soil mechanics has been substantial. In fact, computers have been recognized as leading a paradigm shift in many areas of engineering practice. Readers may find it valuable to understand the changes in our analytical capabilities over the past decades before attempting to visualize possible future changes that might be on the horizon.

The historical impact of computers on soil mechanics can be appreciated by dividing the decades since the discipline's infancy into the following eras:

1930s to 1960s – The era of the closed-form and graphical solutions, and simple, long-hand integration.

1960s to 1990s – The era of the development of digital computer hardware and geotechnical software. These were the decades when the computer was first used to assist engineers in solving soil mechanics problems. Early on, the computer was applied to slope stability problems using the limit equilibrium method (LEM) of slices. The "slices" were in essence a form of soil element to which the principles of static equilibrium were applied. Using the finite element (FEM) and finite difference numerical modeling methods was also introduced into soil mechanics, along with graphic output features to help users visualize and interpret the results.

1990s to present – This era witnessed the solution of a wide range of PDEs, along with the development of associated finite element solvers. The introduction of algorithms to solve partial differential equations became known as "PDE solvers." These PDE solvers are the basic computing algorithms, while information entry duties are handled by a graphical user interface or text-based input file. Of particular importance was the ability of the PDE solvers to ensure convergence of highly nonlinear equations. Techniques like automatic mesh generation and adaptive mesh refinement have stabilized computations by resolving issues related to insufficient mesh density.

Advancements in recent years have focused on our ability to build 3D numerical models quickly and efficiently. While we can now solve 3D models in a reasonable time, a lengthy process is often needed to create the model. Fortunately, 3D model setup times are significantly reduced these days. Conceptual modeling packages allow access to a range of geometry-related features, such as surface intersection, the management and integration of multiple data formats, the representation of water surfaces with time, the extrusion of engineering structures across uneven landscapes, and the interpolation of sparse datasets.

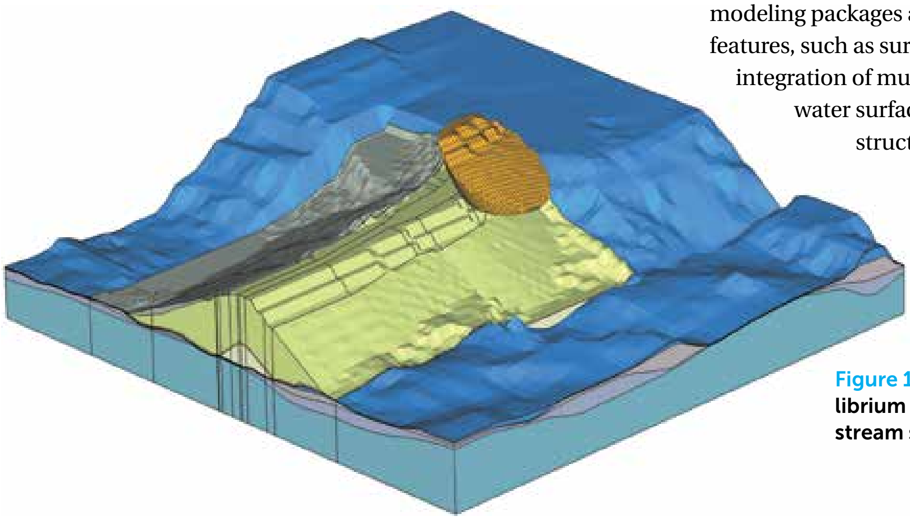

Figure 1. **Tailings dam analysis using 3D limit equilibrium methods to analyze upstream and downstream stability.**

Applications of Geo-Modeling

Geotechnical software advancements can be used to analyze embankments, retaining walls, tailings dams, heap leach operations, waste dumps, and landfills, to name a few. The broad scope of these and many other geotechnical problem solvers is made possible as a result of the modern computer's ability to handle complexity and a large amount of data (Figure 1).

For example, in order to model pollutants near the ground surface, close attention must be paid to near-ground-surface interactions of multi-phase materials. Near-surface contaminants are largely driven through the soil system in response to the imposed weather conditions. Consequently, it's important to understand the physical processes associated with both the saturated and unsaturated portions of the soil profile. Incorporating unsaturated soil above the water table introduces substantial complexity to the analysis of soil behaviour. However, it's the ability to analyse the near-ground-surface soil conditions that lends credence to possible engineering designs.

The design of covers (e.g., store and release soil covers) is another example of a geotechnical solution that focuses on limiting the movements of contaminants into the underlying environment. Cover design requires detailed analysis of past regional climatic conditions in addition to the assessment of suitable saturated and unsaturated soil properties to use as part of the cover design. As such, compiled historical weather station information is a valuable resource for future prudent engineering designs.

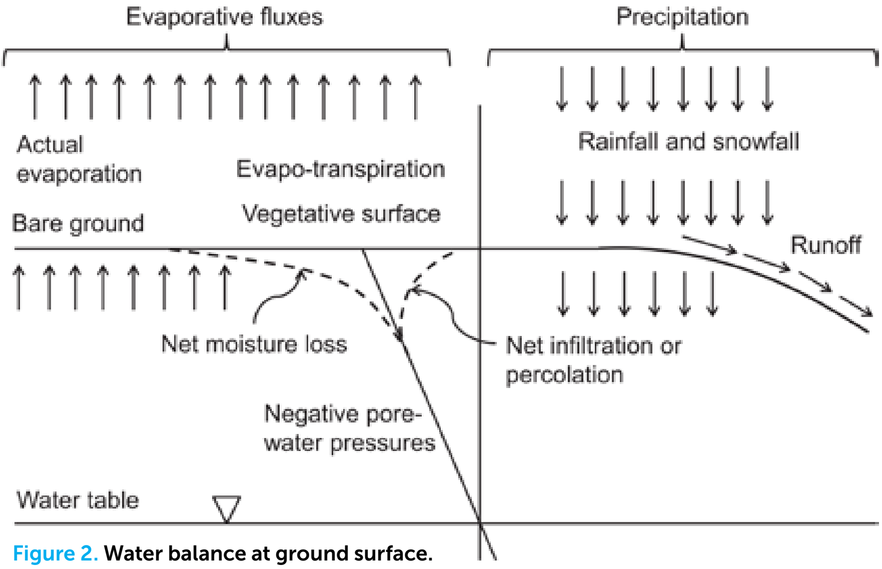

Figure 2. **Water balance at ground surface.**

Modeling Challenges and Solutions

Challenge: Modeling Unsaturated Soils Is Complicated

From the 1980s to present day, our understanding of unsaturated soils has grown dramatically. Over this period, there have been many national and international research conferences specifically devoted to addressing the special issues associated with applying soil mechanics principles to the unsaturated soil zone near to the ground surface.

Analysis of unsaturated zones of the soil profile brings with it some challenges. First, in most cases, the material properties of unsaturated soil are represented using nonlinear functions, which make the PDEs to be solved nonlinear as well. Additionally, the numerical modeling solutions must converge, and must do so at the correct solutions. Contributions from research in mathematics and computer science have led to the development of mesh refinement techniques that greatly assist in ensuring convergence.

There are also complications related to the quantification of the moisture flux boundary conditions that need to be imposed at the ground surface. Moisture is always moving across the ground surface in either liquid or vapor form (Figure 2). Moisture may be coming downward in the form of precipitation or moving upward in the form of evaporation and evapotranspiration. Three primary, but independent processes combine to produce an ever-changing "net moisture flux" at the ground surface. It is this "net moisture flux" that forms the boundary condition needed for modeling.

Data collected at weather stations provides the basic information required to assess each of the components of ground surface moisture flux. Total daily precipitation is recorded using rain and snow gauges. More frequent collection of rainfall intensity assists in the evaluation of possible runoff. Actual evaporation from the ground surface is the most challenging component to quantify; however, significant strides have been made in performing these calculations. Net infiltration is equal to precipitation minus evaporation (and evapotranspiration) and runoff.

Challenge: Ease-of-Use

The focus of much development in the past few years has been on reducing the numerical modeling times required. 3D slope stability is a good example of this. The methods for performing 3D stability analysis have been around for decades, but have not gained popular use until recently. That's because recent software advances have reduced the 3D numerical modeling time such that a 3D model can be set up in minutes or hours, and is therefore easy to perform in a consulting environment.

The downside of these simplified user interfaces is that the numerical modeling engineer doesn't need to understand the physics or limitations of the numerical model being utilized. Common sense and professional judgement must always form the context of a numerical modeling effort. A simple-to-complex numerical modeling approach is always recommended.

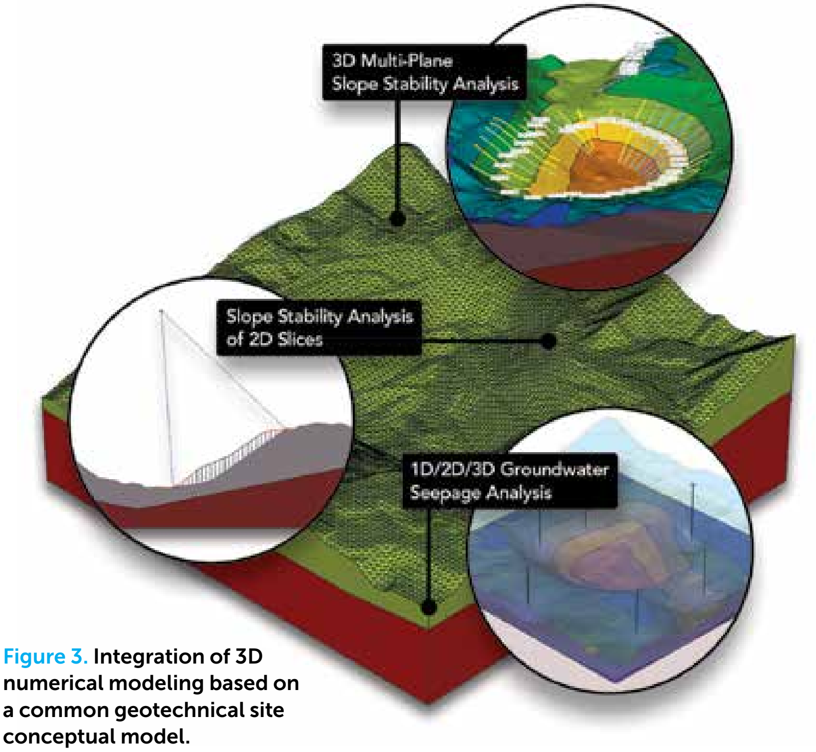

Figure 3. **Integration of 3D numerical modeling based on a common geotechnical site conceptual model.**

Challenge: 3D Models Are Time Consuming

The real world is described in terms of three Cartesian coordinate directions; however, it's possible to solve some engineering problems using a 1D or 2D numerical model. 3D numerical modeling was initially avoided because the numerical solvers were too slow. Since about 2008, greatly improved computer speeds and parallelization (i.e., solving large problems by dividing them into smaller ones that can then be solved at the same time) have allowed for solutions for extremely large models on laptops. There's now very little restriction in the solution times.

A second difficulty of 3D modeling involves the creation of a model that is suitably meshed and correctly represents the intersection of 3D features, such as a dam, and the 3D ground surface. This challenge is made even more difficult when groundwater is in the model. This limitation has been largely overcome with the creation of geometry conceptual model-building software. Conceptual model-building software focuses on a correct definition of the 3D geometry of a site at a reasonable accuracy such that the geometry is well-defined and all surface punch-outs are properly represented. 3D models can now be extruded from 2D cross sections or created from raw data in minutes or hours. The geotechnical engineer is now tasked with creating a 3D site model based on the assemblage of CAD designs, topography, and borehole data.

With these advanced, the paradigm for the modeling of a site has changed from the engineer requesting a few 2D planes from the CAD department for analysis to 1) building a comprehensive, 3D site conceptual geometry model, and 2) analyzing any set of 2D sections or 3D regions of the site with ease.

Conceptual models can form the basis of either spatially varying 2D slices or full 3D numerical models for slope stability, groundwater seepage, or stress/deformation numerical models (Figure 3). Once the 3D model is created, it may be analyzed through use of many hundreds of 2D slices. This process provides a more spatially representative picture of the stability of a site (Figure 4). Thus the time required for proper engineering design can be reduced and the quality of the design improved.

Such integration allows for simultaneous hydrological and geotechnical stability modeling. It also significantly reduces the geotechnical numerical modeling design time, as costly iterations between geotechnical analysts and CAD operators can be avoided.

Trends in Geo-Modeling

Trends in geotechnical numerical modeling over the next few years will be:

- A movement toward 3D modeling
- Integrated hydrological and geotechnical numerical modeling
- Soil-structure interaction
- Large-strain analysis
- Stability analysis improvements
- Modeling of unsaturated soil mechanics portion

Movement toward 3D

Two-dimensional numerical modeling is becoming more common in geotechnical engineering. Geotechnical engineers are beginning to realize that the numerical modeling of slope stability in 2D is often a poor representation of real-world conditions. 3D factors of safety are usually higher than 2D, but offer a more accurate factor of safety than a 2D analysis. Resistance to 3D numerical modeling has centered around the added time investment required; however, this additional effort has been reduced through the advancement of software tools.

A common thought is that a 3D analysis requires additional site exploration. But keep in mind that there are three aspects that make a 3D stability analysis different than a 2D analysis: 1) the shape of the slip surface, 2) the difference in topography, and 3) changes in stratigraphy, all across the third dimension. It must be realized that a 3D stability analysis can easily determine the difference that the first two items make in the analysis with no additional site investigation. The site investigation only influences the ability to more accurately assess the influence of stratigraphy in 3D. The influence of topography and slip surface shape can easily be determined with a 3D analysis, and therefore the true factor of safety can be approached.

Integrated Hydrological and Geotechnical Numerical Modeling

Many papers have been published related to the integration of hydrological regional groundwater models and related geotechnical slope stability models. It can be difficult to move the pore-water pressures from one numerical modeling package to another. Many consulting firms now have specialists in geotechnical and hydrological disciplines, which makes

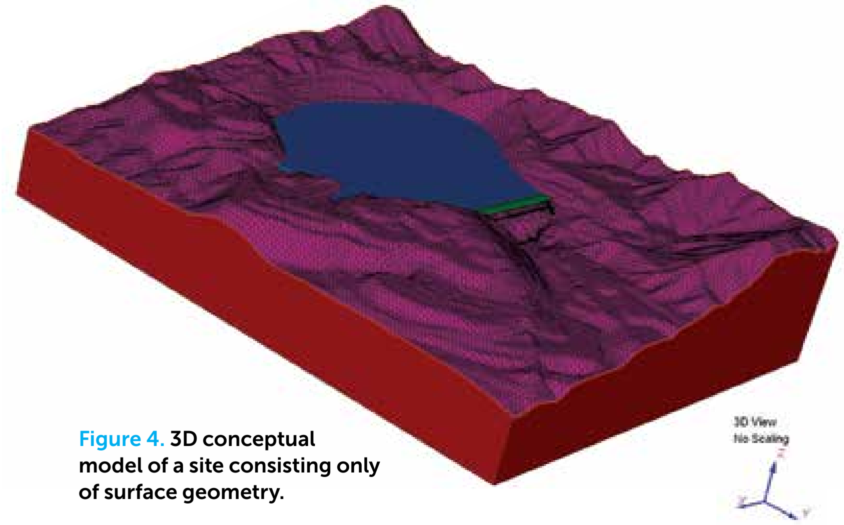

Figure 4. 3D conceptual model of a site consisting only of surface geometry.

it easier to import regional pore-water pressures into slope stability software packages.

Soil-Structure Interaction

Increasingly, geotechnical engineers are being challenged to model the interaction between geotechnical structure features and the soil. However, advancements now abound as numerical methods have been improved to analyze piles, spread footings, and anchored retaining walls. New methodologies will continue to be implemented to handle these interactions in both the LEM and FEM methodologies. In the context of seepage analysis software, the modeling of geomembranes is another area requiring additional research to properly handle.

Large-Strain Analysis

Analyzing soft soils and slurries often involves strains exceeding 10 percent. Such problems may involve the consolidation of mine tailings or the settlement of structures built over soft clays. Analyzing such conditions using traditional small-strain methods is not proper and will lead to an under-estimation of the time to dissipate pore-water pressures. Large-strain analysis is more difficult to implement and may involve a finite element mesh that changes during the analysis. Updating meshes offers accuracy advantages in the analysis of soft clays and tailings, and its use will continue to grow in the coming decades.

Stability Analysis Improvements

Recent research has involved a more accurate representation of soil stress-state in order to analyze a factor of safety. One method where detailed stresses can be considered is the shear-strength reduction (SSR) method. While the method is computationally intensive, it can provide additional insight into the factor of safety. Hybrid methods such as the Kulhawy method also provide insight and can result in the LEM being enhanced to consider complex stress states.

Unsaturated Soil Mechanics

Probably the most significant advancement in geo-modeling over the past few years has centered on realizing that the saturated and unsaturated portions of the soil continuum can be modelled as a single unit. However, appropriate application of these advanced numerical tools requires the assessment and selection of unsaturated soil properties. Moreover, inexperienced users can have concerns about solution convergence when unsaturated soil zones are included in numerical models. In these situations, it's prudent to seek assistance from experts experienced with characterizing and analyzing problems in unsaturated soil mechanics.

Vision for the Future

All evidence indicates that geo-modeling is here to stay, and that its application in geotechnical engineering is broadening and ever-increasing. Great strides have been made in the integration of topographic information with geotechnical designs from CAD. Available databases of relevant information are becoming an asset for the production of more comprehensive simulations of behavior.

Graphical representation of the physical problem geometry, and the computer results, are becoming increasingly impressive. Geotechnical engineers are rapidly moving beyond the constraints of 1D and 2D analyses, and making more use of 3D (real-world) geometries. Animations and video presentations illustrating historical or future performance assist the designer, other project professionals, and the public in understanding the results from time-based simulations.

The ability to model the complexity of real-world geotechnical sites has grown dramatically in the past few years. Computer hardware improvements now allow complex 3D numerical models to be solved on a laptop. We are seeing a global paradigm shift in which the geotechnical engineer has the ability to consider the 3D world as never before. Enhanced ease of collecting 3D site data with drones and LiDAR has further enhanced our ability to model in 3D. With this enhanced ability, however, it must be noted that numerical analysis still remains the tool of a capable professional geotechnical engineer. The tools will not replace common sense or good professional judgement. While failures are still possible, numerical computational tools are now available to help take our engineering structures to new heights – or "depths."

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