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Why Use Numerical Modeling to Make Dam Safety Risk Management Decisions?

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Numerical modeling is the computer simulation of the anticipated behavior of infrastructure. It is a valuable tool for identifying and managing risk, as it may warn of undesired scenarios long before they materialize.

Offering a wide range of possibilities and benefits, numerical modeling can help decision makers predict the expected behavior of a dam, its abutments, or its foundation during and after the application of specific loads, and at a fraction of the time and cost to develop a physical model.

It can support analyses at different times during the life cycle of a dam, from its initial design to construction and rehabilitation, to improve performance. The simulations can be a tool to evaluate the performance of the engineering design during construction by comparison to records of geotechnical instrumentation.

Looks Can Be Deceiving

The model must be developed and analyzed properly to ensure it yields reliable and actionable data, or it may result in colorful graphs that are not related to the behavior of the dam in the real world. It can also render results that “look” good because of biased model development, misunderstood data or numerical input, or simply because the modeling process exceeds the limitations of the numerical method or the code (software).

This means that a valuable tool that has not been properly conceived, developed, and analyzed may result in a false sense of safety and prevent a dam owner from implementing risk-reduction actions on time or meeting regulatory requirements.

Our experience shows that following the below milestones systematically leads to a scope that is aligned with the main objective of the numerical model, results in the efficient use of people resources and capabilities, and contributes positively to decisions on dam safety and risk management.

Defining the Origin of the Model and Main Objective

To determine the model origin, we must ask, "What is the main objective of developing the numerical model?"

Then we add questions to help frame the scope of the model, such as, "Why are we developing the model? What result will guide me on the next steps? Do acceptable thresholds exist for the expected result?"

This first step is the compass of the entire numerical modeling process and its importance cannot be understated. Modifying the objective during its development changes the actual direction of the scope and can also impact project stakeholder expectations.

Typically, the scope will be one of the following:

1. **Estimating a value or range of values.** Examples include maximum settlement, horizontal displacement, force, water pressure, seepage flow, etc. Value selection must be accompanied by its intended use, e.g., estimate the maximum settlement of the dam's crest after a maximum credible earthquake to evaluate the loss of freeboard and provide information on the dam's safety.
2. **Estimating the spatial distribution of a value.** Typical examples are the linear distributions of horizontal displacements with depth, which then can be compared to inclinometer data gathered in the field. Another example would be to estimate the spatial distribution of seepage to verify the adequacy of a drainage system. Alternatively, we could model the maximum shear strain in the core of the dam to understand the potential for cracking during a seismic event.
3. **Estimating behavior over time.** This is likely the most challenging type of result we can expect, as soil properties are inherently variable. Examples include:
    - Estimating the settlement of a dam's crest to evaluate the gradual loss of freeboard and inform on the safety of the dam.
    - Estimating the dissipation of excess pore pressure after an earthquake to identify areas at or near zero effective stress to inform on liquefaction potential.
    - Estimating excess pore pressure for undrained conditions during the construction of a dam's clay core to design the time required between compaction of lifts to safely raise the core.

Selecting the Numerical Method and Code

When selecting a numerical method and code, we typically choose from the finite element method (FEM), finite difference method (FDM), and discrete element method (DEM) and then decide which code we need to use.

For brevity, let's review the general characteristics of the methods to understand better the scenarios in which each might be used.

- **FEM** can provide sound, reliable results as long as the model is balanced at all times throughout the simulation. This means that the method is not reliable for simulations past failure of the model. In other words, it cannot simulate the full runout of a landslide, but can simulate maximum shear strain to define the initial sliding surface.
- **FDM** can explore the behavior of the earthen materials pre- and post-failure, which is a strong proposition when modeling for failure scenarios. This method follows a time-marching scheme, which results in fictitious inertial forces that must be interpreted and controlled to obtain meaningful results.
- **DEM** is based on separate elements interacting with each other, as opposed to a continuum of elements employed in the previous methods. DEM is a proven and valuable tool for modeling the propagation of cracks and simulating debris flow, which are examples of behavior beyond failure. The computational effort and soil properties available are currently limited, which generally implies long-running sensitivity analyses.

The constitutive model is an additional key component of numerical modeling because it is the set of rules conditioning the behavior of the soil in our model. It prescribes the relationship between stresses, strains, and the failure criteria. Some constitutive models are derived to simulate:

- Creep in rock.
- The undrained behavior of soils.
- Excess pore water pressure, which makes them the ideal choice for liquefaction studies.

The selection of the code is then controlled by the type of numerical method (FEM, FDM, or DEM) and the constitutive model that we need to use.

Developing the Model

The following are key components that inform the scope of the model:

- **Geometry.** Not all models require three dimensions to provide practical results. On the other hand, sometimes a 2D model introduces limitations that we need to understand. Also, not all soil units may influence the results beyond the precision of the model, and simplicity can do wonders for efficiency. Hence, the physics of the model, as well as experience, should dictate when the added effort of 3D modeling is required. Dams in narrow valleys or over a variable lithology could require 3D models, while simplified 2D models may suffice for dams over uniform geotechnical conditions.
- **Soil and rock properties, calibration, and validation.** The number and type of soil properties are functions of the constitutive model we plan to use, as well as the available data. This will inform the need for geotechnical exploration or an approach via sensitivity analysis. Calibration is a delicate process because it means adjusting inputs until the result matches a specific value. We must exercise care to avoid conditioning the results while modifying the inputs beyond reasonable estimates. Validation means having a reasonable comparison between the result from the model and the measured value in the field.
- **Boundary conditions and loads.** Boundary conditions, such as not implementing a reflective wave absorption boundary during seismic shaking, the use of interior outflow/inflow boundary conditions to simulate drains/water sources, or adding piezometric reference points that cause changes in water flow, should be used with special care to not inadvertently influence the results of the model. The loads should represent the condition we do know with full confidence that we want to evaluate.

Analyzing and Concluding Based on Model Results

Analyzing the results of a numerical model requires the highest level of expertise in the overall modeling process. Useful and meaningful results are realized when the modeling is conducted by experienced engineers who possess an expert understanding of numerical modeling and are well aware of its benefits and limitations.

An important step of the analysis is to interrogate the results to verify they follow the set of rules set forth during the development of the model. For example, stress and strain values should match the soil behavior prescribed by the constitutive model; boundary conditions are validated throughout the geometry and dynamic timesteps; loads are applied as prescribed, and the results are obtained within the convergence criteria.

The conclusion is the answer to our main objective of the scope, and it is perhaps the most straightforward task of the entire process because of the care and effort taken to follow the discussed milestones and steps.

About the Author

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