Guide to numerical modeling in geomechanics

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The present document is a quick guide to numerical modeling in geomechanics. It addresses some major issues about the general numerical approach, the choice of material constitutive model and different modeling steps. It is clear that the information given here provides only a general guideline which should be further adjusted for each specific problem.

1. Numerical modeling in geomechanics – Benefits and Risks

Modeling of geo-engineering problems often involves complex issues related to several geomechanical variables and the corresponding coupling effects. Compared to many engineering material, geomaterials exhibit a highly non-linear behavior. Often, there is no straightforward closed form analytical solution for such problems.

Furthermore, in many cases, the analyses of geo-engineering problems have to be done with little or no information about the in-situ geotechnical condition. This is often the case for tunneling or excavation projects where the design has to be verified or completed using the information from the encountered geotechnical condition. It is therefore important to have numerical modeling as a fast, reliable and powerful tool for a systematic analyses and design of the problem.

In general, numerical modeling in geomechanics MAY have the following main benefits:

- Fast and systematic solution
- Possibility of using more realistic non-linear material behavior
- Solution of coupled phenomena
- Fast parametric studies

The above mentioned features, among others, could in general result in cost reduction and optimization in geo-engineering problems.

On the other hand, however, blind using of numerical modeling could have catastrophic consequences. When running a code, it is always tempting to play with the parameters and get nice contour map results; but – Garbage in, Garbage out. Computers will unquestioningly process unintended wrong data and produce undesired wrong output. Here comes the important role of engineering judgment. Indeed, the engineering judgment should run through the whole process including data preparation, modeling procedure, and verification of results. It is therefore important to keep in mind that numerical modeling in geomechanics is more an Engineering Task rather than a Computer Operating Task.

2. General approach

In order to set up the model, three fundamental components should be defined by answering to the following 3W questions:

- What do we know? → Define the initial boundary value problem
- What are we looking for? → Define the type of analyses
- What are the materials → Define the constitutive models

2.1. Initial-Boundary value problems in geomechanics

Any geo-engineering problem can be converted into an initial-boundary problem for numerical modeling. This can start by answering "what do we know" in the project and drawing a global picture of the problem. Example for few engineering application are given in **Table 1**.

Table 1. Examples of Initial boundary value problems in geomechanics

No.	Application	Project concept: What do we know?	Modeling concept: Initial-Boundary value problem
1	Static analysis of double arch concrete dam	• Double arch effects • Seasonal water and air temperature variation • Water and sediment load	• 3D analysis • Varying temperature • Imposed load
2	Dynamic analysis of fissured gravity concrete dam	• Gravity dam with a given typical section • Seasonal water and air temperature variation • Water and sediment load • Earthquake load	• 2D plain strain analysis • Varying temperature • Imposed load • Imposed acceleration
3	Dynamic analysis of earth dam	• Earth dam with typical cross section • Water and seepage load (thermal effects neglected) • Earthquake load	• 2D plain strain analysis • Imposed water pressure • Imposed acceleration
4	Deep cylindrical shaft excavation	• Dual symmetrical shaft geometry • Dewatering • Stage excavation	• Axi-symetric analysis • Varying pore water pressure • Varying stress (unloading)
5	Large underground cavern excavation	• Large cavern with given geometry • Grouting, rock support and concrete lining • High in-situ rock stresses • Underground water, rock loads & operational loads	• 2D/3D analysis(as per geometry) • Varying water pressure • Varying in-situ stresses • Imposed load

2.2. Type of analysis

In general, initial-boundary value problems (IBV-problems) in geomechanics could be divided into two main groups: uncoupled and coupled problems.

Uncoupled problems involve only one primary variable:

• Mechanical	variable: displacement
• Seepage and hydraulic	variable: pore water pressure
• Heat transfer	variable: temperature
• Other, e.g. chemicals	variable: concentration, etc

Coupled problems involve more than two variables and their coupling effects:

• Hydro-mechanical	variables: displacement + pore water pressure
• Thermo-mechanical	Variables: displacement + temperature
• Thermo-hydro-mechanical	Variables: displacement + pore pressure + temperature
• Others, e.g. chemo-mechanical	Variables: displacement + concentration, etc

The answer to the question "What are we looking for?" helps in defining the required type of analysis. **Table 2** gives some examples.

Table 2. Examples of analysis type in geomechanics

No.	Application	Project concept: What are we looking for?	Modeling concept: Type of analysis
1	Static analysis of double arch concrete dam	• Temperature in the dam body • Stress and displacement in dam and foundation	• Coupled thermo-mechanical analysis • Output: stress, displacement, temperature
2	Dynamic analysis of fissured gravity concrete dam	• Temperature in the dam body • Stress and displacement in dam and foundation	• Coupled thermo-mechanical analysis • Output: stress, displacement (acceleration), temperature
3	Dynamic analysis of earth dam	• Stress and displacement in dam and foundation • Pore water pressure in the dam	• Coupled hydro-mechanical analysis • Output: stress, displacement (acceleration), pore water pressure
4	Deep cylindrical shaft excavation	• Displacement of the shaft and the diaphragm wall • Stress and strain state at the vicinity of the shaft • Pore water pressure in the shaft area	• Coupled hydro-mechanical analysis • Output: stress, displacement (acceleration), pore water pressure
5	Large underground cavern excavation	• Displacement of the vault, walls and bench • Stress and strain state at the vicinity of the cavern • Underground water pressure around the cavern	• Coupled hydro-mechanical analysis • Output: stress, displacement, structural loads, water pressure

2.3. Materials and constitutive models for geomaterials

An appropriate choice of the mechanical constitutive model for soils is the key issue for successful engineering modeling of geomechanical problems. In general, geomaterials exhibit non-linear behavior in a wide range of stress; thus, a realistic prediction/simulation of their behavior can be achieved by using constitutive models capable of addressing such non-linearity. However, the choice of constitutive model depends also on the specific application and requirements of the problem. **Table 3** gives a general guideline for the choice of constitutive model.

In general, the answer to the question "What are the involved materials?" helps in defining the type of constitutive model. Some examples for the previously mentioned engineering applications are given in **Table 4**.

Table 3. Constitutive models for geomechanics

Level of complexity	Model	Examples	General application
Basic	Linear elastic	• Linear elasticity • non-linear elasticity	• Foundation design • small displacement analysis
Standard	Elastic perfectly plastic	• Mohr-Coloumb • Hoek-Brown (Rock)	• Stability analysis • Basic displacement analysis
Advanced	Hardenning elasto-plastic	• Cam-Clay • Cap model	• Stress-displacement analysis • Stress history effects
Complex	Combination with other geomechanical factors: time, saturation, soil structure	• Swelling Cam-clay • Small strain hardening	• Specific applications, e.g, tunneling in swelling rock, partially saturated slopes

Table 4. Examples of constitutive models used in geomechanics

No.	Application	Project concept: What are the materials?	Modeling concept: Type of constitutive model
1	Static analysis of double arch concrete dam	• Homogenous concrete • Homogenous rock foundation	• Linear elastic concrete • Linear elastic rock
2	Dynamic analysis of fissured gravity concrete dam	• Homogenous concrete • Cracks in the concrete • Homogenous rock foundation	• Linear elastic concrete • Elasto-plastic interface • Linear elastic rock
3	Dynamic analysis of earth dam	• Soil in the eath dam • Soil/rock on the foundation	• Hardening elasto-plastic soil • Elastic-perfectly plastic foundation
4	Deep cylindrical shaft excavation	• Different geological soil layers • Concrete diaphragm wall	• Hardening elasto-plastic soil • Elastic concrete wall
5	Large underground cavern excavation	• Different rock formation • Rock support (shotcrete and anchors) • Concrete lining	• Elastoplastic rock • Linear elastic shotcrete and concrete • Elastic structural anchors • Elasto-plastic interface

3. Numerical methods

Once the general approach defined, an appropriate numerical method should be selected for the modeling. Numerical methods can be in general divided into two main groups:

a) Continuum methods:
- Finite element method (FEM)
- Finite Difference method (FDM)
- Boundary element method (BEM)

b) Discontinuum methods:
- Discrete element methods including:
- Distinct element method (DEM)
- Discontinuous deformation analysis (DDA)

The detailed description of these methods is beyond the scopes of the present document and can be found in the literature (also for few other methods not mentioned above). All the methods provide a rigorous solution by reaching equilibrium (within the defined tolerance); the difference lies only in the numerical method and algorithm employed to reach the equilibrium. Therefore, apart from some numerical preferences, the main choice is between continuum and discontinuum approach. Some general guidelines are given in **Table 5**.

Table 5. Choice of continuum versus discontinuum approach in geomechanics

Primary material / behavior		Numerical method	Example application
Soil		Continuum approach	Soil slope stability, excavation, earthdam
Rock	Homogenous Rock mass behavior	Continuum approach	Dam foundation, overall displacement of underground caverns
	Jointed rock behavior dominated by discontinuities	Discontinuum approach	Jointed rock slope stability, tunneling in fractured rock

4. Choice of numerical code

When dealing with numerical modeling, a significant time is usually spent on data preparation and post-processing. Therefore, apart from their technical capabilities, the numerical codes with more user-friendly pre- and post-processing interfaces are better accepted by the geotechnical engineers.

Among others, some of the most commonly commercial numerical codes can be listed (but not limited) as in **Table 6**. The choice of the numerical codes, more than anything else, depends on the following issues:

- Personal experience of the engineer in using the code
- Company and institute policy in buying the code and training engineers
- Some specific particular features of the code (e.g. large deformation interface, advance constitutive models, etc)

Table 6. Some of numerical codes used in geomechanics

Approach	**Code**	**Method**	**Developer**
Continuum	Plaxis 2D, 3D	FEM	Plaxis BV
	Phase	FEM	RockScience
	DIANA	FEM	TNO DIANA BV
	EXAMINE	FEM	RockScience
	ZSoil	FEM	Zace Ltd
	FLAC, FLAC 3D	FDM	Itasca cg
	ABAQUS	FEM	Hibbit, Karlson & Sorensen, Inc
Discontinuum	EDEM	DEM	DEM Solutions
	UDEC	DEM	Itasca cg
	3DEC	DEM	Itasca cg

5. Problem solving and modeling procedure

The procedure and numerical modeling in geomechanics, regardless of method and code, can be simplified in 8 steps as follows

5.1. Define the problem and objective

At the onset, the engineer should define the main problem and objectives based on the defined general approach. At this step, it should be decided if the modeling is used to predict or reproduce the soil/rock behavior. In many Often, the results are to be compared with monitoring data and the main objective would be to reproduce and understand the behavior and mechanism of movements rather than its prediction.

5.2. Prepare the Engineering sketch

Once the objective defined, an overall engineering sketch of the problem should be prepared. At this stage, decision should be made about the level of details which are to be included in the model. The critical assumptions and simplifications should be all addressed in this engineering sketch.

5.3. Prepare, run and verify simple models

The first models are to be prepared without the details and based on an idealized form of the engineering sketch. The numerical performance and results are to be verified. This can be done, for instance, by comparing the model results at given condition/points for which the analytical close form solution can be obtained (e.g. effective stress at the lower limit, pore pressure at the different seepage directions).

5.4. Assign appropriate constitutive model and parameters

Once the simple model is verified, the model should be enhanced by assigning the appropriate constitutive model and material parameters. Some hardening elastoplastic models need to be applied and verified at different steps to ensure a good numerical performance and predictions.

5.5. Fine-tuning the model

The last step before running the final model is to add the necessary details and fine-tuning the model. Some required geometrical details, final material properties, length of structural elements and etc are to be adjusted at this step.

5.6. Run and verify the numerical performance of the model

The final model is to run and its numerical performance is to be verified by checking different numerical aspects of the model. A good numerical performance is satisfied if a solution to equilibrium is achieved in a stable condition with reasonable numerical parameters (tolerance, stepping, time increments, etc.). If needed different numerical algorithms can be tested to ensure about the stability of the results within acceptable tolerance.

5.7. Get the numerical results

Once the performance of the model verified, the results can be taken for further analysis and problem solving. Based on the general approach and objectives previously defined, the results of main interest can be extracted in the post-processor (or from the log files) and presented for interpretation.

5.8. Interpret the results with engineering judgment

The final step in modeling is interpretation of the results in combination with engineering judgment. The issue of primary importance should be identified and sought in the results. The general trend of the results should be always compared with knowledge-based engineering expectation. If anomalies observed, the engineer should find out the numerical or physical reason behind it. If necessary, some or all of the above-mentioned steps should be then repeated to achieve enhanced model with realistic results.

6. Conclusion

The present document provides a general quick guide to numerical modeling in geomechanics regardless of the method and approach. Of course, it needs to be adjusted and further developed for each case according to specific needs of the corresponding geo-engineering problems. The above presented information can be summarized in the flowchart of **Figure 1**.

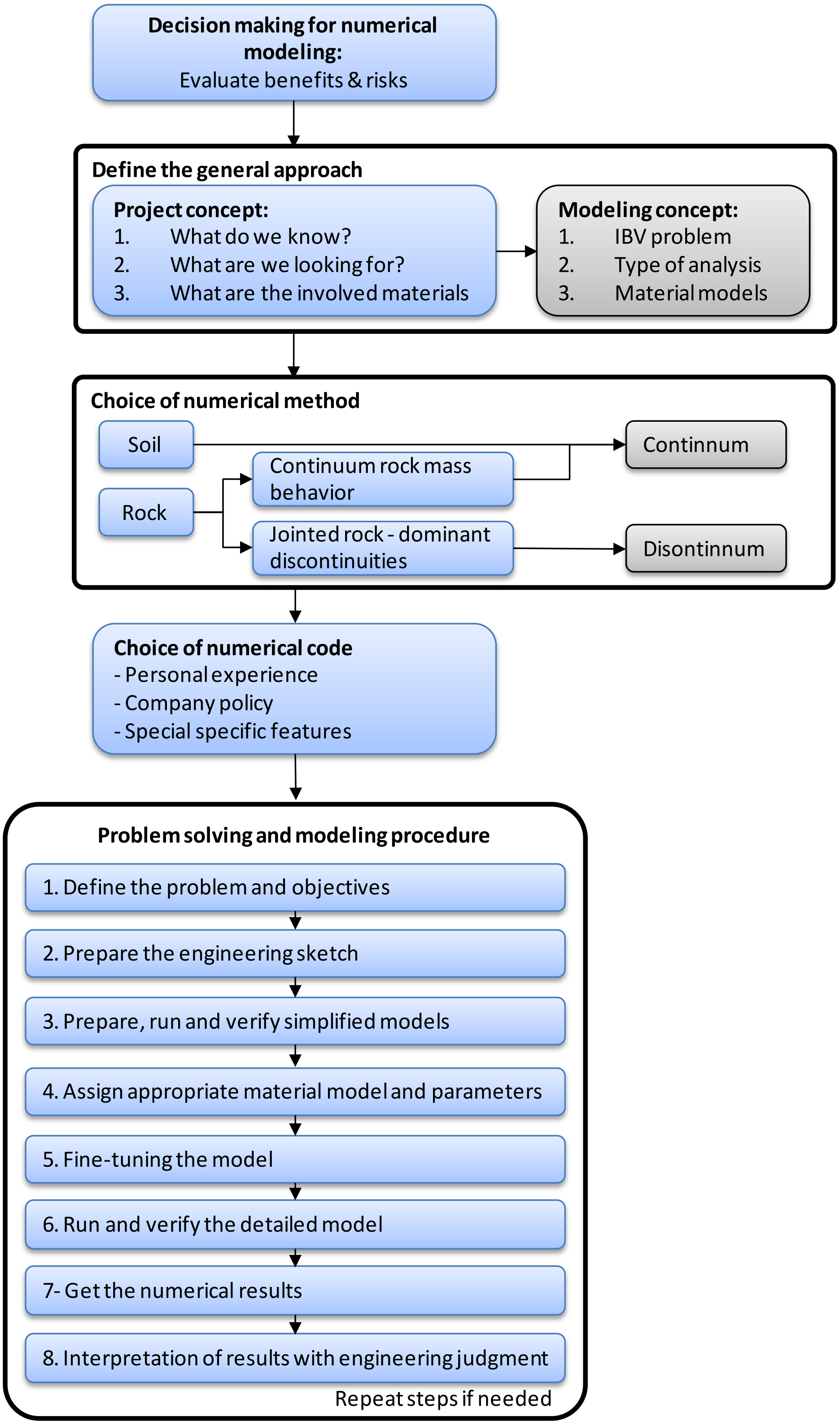

Figure 1. Recommended general procedure for numerical modeling in geomechanics