Numerical Modelling – Prediction or Process?

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Introduction

Geotechnical software, often referred to as modelling software, is now being used routinely in geotechnical practice. In spite of the extensive use, there seems to be some confusion as to what is meant by the word *model*. Does it refer to a numerical simulation, as in the phrase, 'a finite element *model*'? Taken in this context, modelling is simply the operation of a numerical tool. This is not only too narrow a definition; it also diverts us from a deeper understanding of modelling as a fundamental engineering problem-solving methodology.

In this paper, we explore the definition of the word *modelling* in some depth. We review the purpose and benefits of modelling to the engineer and introduce a conceptual framework that guides us through the modelling process.

Modelling Defined

The role of modelling within geotechnical engineering practice was clearly illustrated by Professor John Burland from Imperial College, London in his 1987 Nash Lecture, entitled *The Teaching of Soil Mechanics – a Personal View* (Burland 1987). In this lecture, he presented the view that geotechnical engineering practice is comprised of three parts: establishing the ground profile, defining ground behavior, and modelling – all interlinked and supported by experience consisting of empiricism and precedent. He linked these three parts into what has now become referred to as the *Burland Triangle*. Morgenstern (2000) also discussed the Burland Triangle at some length in his keynote address entitled *Common Ground* at the GeoEng2000 Conference in Melbourne, Australia. Graham (2003), in his Hardy Address at the Winnipeg Canadian Geotechnical Conference, concentrated on the soil behavior and ground profile apexes of the Burland Triangle.

The Burland Triangle has been discussed widely and expanded on considerably since it was first introduced. The expanded version of the Burland Triangle as presented in the Ground Engineering magazine (Anonymous 1999) is shown in Figure 1. Burland envisaged geotechnical practice as requiring a clear understanding of the ground profile established from a site investigation, the definition of soil behavior provided from field and laboratory measurements, and then the application of this understanding through the use of modelling. It is important to note two features of this triangle: first, that all three steps are interlinked and second, that they are all tied together by experience.

An important idea in this representation is how the process of modelling is integral and integrated into the entire engineering process. It is the point at which our understanding of site conditions and soil behavior are developed

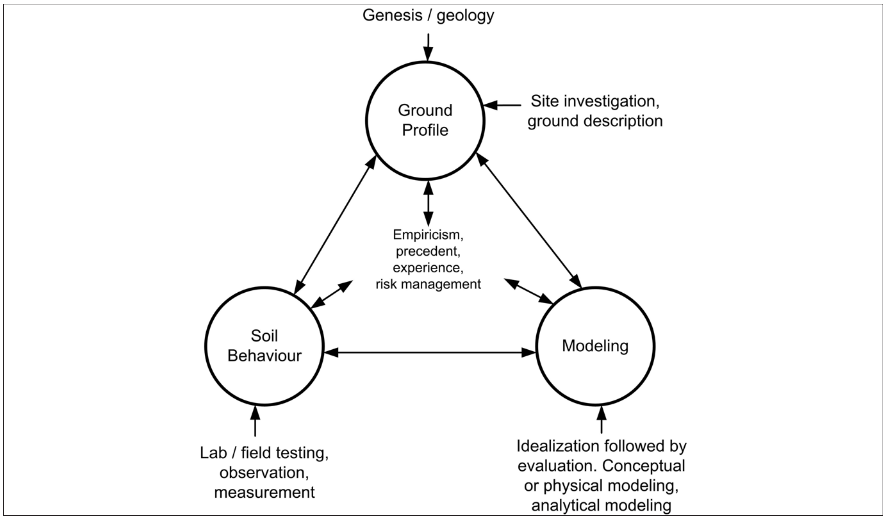

Figure 1. Expanded Burland Triangle (Anonymous 1999).

into an idealized conceptual model, which can be drawn upon through the use of analytic techniques (numerical models) or physical models to assist us in interpretation and design. The development of appropriate conceptual and analytic models is interlinked with, and relies heavily on, the information obtained from the other parts of the triangle. In addition, the development of the models themselves is strongly dependent on the experience of the individual engineer and the precedents of the profession as a whole.

In addition to providing perspective on the place of analytic models within geotechnical practice, the Burland Triangle also opens our eyes to a broader definition of modelling. As geotechnical engineers, we work with some of the most difficult materials and conditions in any field of engineering. Unlike many engineering professions, we cannot simply specify the types of materials or material geometries with which we would like to work. We live with what nature provides. In fact, developing an understanding of what nature has provided is a major portion of the engineering challenge. We deal with an extremely complex physical reality. And yet, to engineer with this reality means we have to try to make some calculations. We must turn a complex physical reality into some mathematical system to quantify our designs, and to understand our risk and uncertainty.

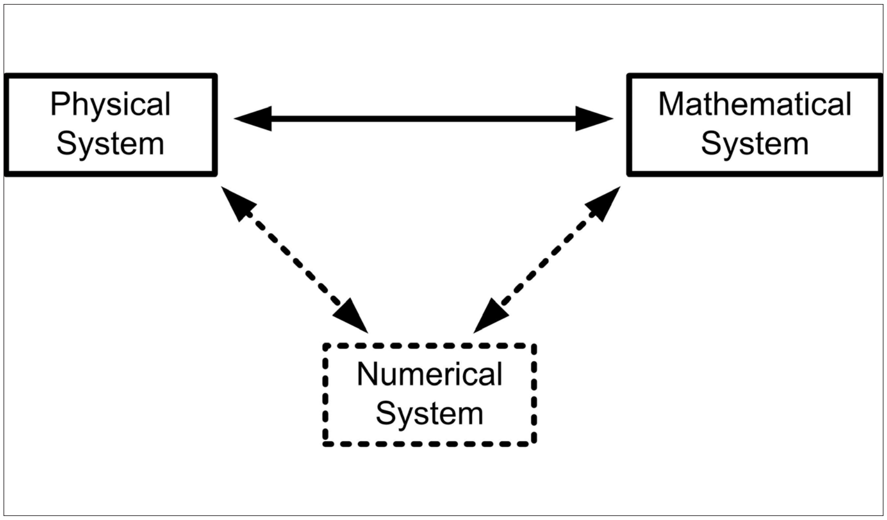

Figure 2. Simple definition of modelling.

The National Research Council (1990) report on modelling describes this concept as follows: '*A mathematical model is a replica of some real-world object or system. It is an attempt to take our understanding of the process (conceptual model) and translate it into mathematical terms*'. As depicted in Figure 2, the simplest definition of modelling is this: the process by which we extract from a complex physical reality an appropriate mathematical reality on which we can base a design. The role of the *numerical model* is simply to assist us in developing the appropriate mathematical abstraction.

Modelling Complexity

Modelling, then, is the process by which we construct a simplified mathematical reality from a more complex physical reality. In this process we often make use of numerical methods (or models) in order to more fully describe a complex physical reality. A short review of some of these complexities might help us appreciate the challenge we face in the modeling process. So what are some of the complexities we face in the development of our modelling exercise?

In geotechnical engineering, our medium consists of natural geologic materials that are notoriously variable, both in terms of their properties and their spatial distribution. Since soil behavior is governed by effective stresses, the behavior of these geologic materials is intrinsically linked to the pore-water pressures within the soil. Consequently, we not only have geologic complexity, we must also deal with complex hydrogeologic systems.

We also deal with complex behavioural processes. The primary goals of any geotechnical design are often related to one of three general types of behavior (and properties): deformation (compressibility), stability (strength), and seepage or groundwater flow (hydraulic conductivity). Each of these processes can be extremely complex, and the mathematical descriptions of this behavior often result in non-linear numerical solutions.

On top of geologic and behavioral complexities, we also must work with complex designs and design methods. The development of a final design often requires that we evaluate the performance of numerous alternatives in terms of their constructability, performance, and risk of failure. This process requires that we quantify the performance of hundreds, if not thousands, of different design scenarios.

Finally, we have to communicate and steer our designs through complex decision-making processes. This may appear trivial at first glance, but often we must find ways of communicating our designs effectively to decision makers, including the public. This can often be facilitated through the use of visual computer graphics that can be produced from many of the numerical tools currently used in analyses.

Homer-Dixon (2001), in his book entitled *The Ingenuity Gap*, highlights how the demand to deal with increasing levels of complexity continues to accelerate in our modern society. This complexity occurs not only due to our awareness and potential ability to deal with increasing levels of complexity in physical processes, but also because of increasingly higher demands from society that these complex interactions be considered in design. He also points out that in many cases we are reaching a limit to the level of complexity with which we can deal:

"Another way to estimate a system's complexity is to measure the difficulty of creating a mathematical model of it. ... Some systems are extremely difficult to model because they have so many components; to use the specialists' awkward phrase; they are "mathematically intractable". As the number of components, variables, or "dimensions" in the equations goes up, the length of time it takes to work out, or solve, the equations rises even faster. ..Although modern supercomputers can help solve this problem, even the fastest computers are often quickly overwhelmed. As top experts, Joseph Traub and Henryk Wozniakowski, say, ..Even though scientists have computers at their disposal, problems can have so many variables that no future computer speed will make it possible to solve them in a reasonable amount of time" (Homer-Dixon 2001 p. 116).

In an attempt to deal with this complexity, we continue to extend the complexities of our modelling tools. This rapid expansion in the use of increasingly complex modelling tools is occurring not only in engineering, but also in financial markets, global warming, and the management of social programs. Homer-Dixon points out that, while these computer tools are increasingly being used by young, computer literate professionals, they are often too intimidating for older, experienced professionals. This results in a situation where the people running the models do not have the professional experience or wisdom to use the tools effectively. He writes:

"Says Gene Rochlin, a professor of energy and resources at the University of California, Berkeley; 'As skill with the computer and its models becomes more important than accumulated experience, power and influence are shifting to a generation of younger traders more familiar with electronics than trends, less concerned with preserving long-term market stability than with developing and mastering better, quicker models with which to outmaneuver the competition.. ...We are now acutely aware how (in many fields) more experienced managers are actually intimidated by a younger generation steeped in the arcane of computers and their magical, number-crunching software. Experiential knowledge consists of intuitions, subtle understandings, and finely honed reflexes gained through years of intimate interaction with a given natural, social or technological system. ...When we fragment management expertise into subspecialties and squeeze out broad experiential knowledge, we become more vulnerable to unknown unknowns" (Homer-Dixon, 2001, p. 177-178).

Although his quote is written in the context of the near failure of the stock markets during the October 19 and 20, 1987 crises, it sounds all too familiar to our own engineering practice. In the next section, we discuss how to include both the computer hotshot and the sage in the modelling process.

Application of Models

Recognizing that we use numerical tools to deal with complexity, the next questions we address are ones of expectation. How do we use these models? What is the primary strength of the modelling process in general, and the application of numerical tools such as computer models in particular?

One could classify the use of models in many ways, but we suggest three generic categories:

- **Interpretation**: This is the use of models to help us interpret field or laboratory data. For example, the development of a model to help back-analyze a suite of monitoring information.
- **Design**: In this application, we develop models to help compare the relative performance of various design alternatives, with less emphasis on the final predicted performance.
- **Prediction**: Finally, we may have to use a model to provide a final, quantifiable prediction of actual field behavior.

It would be interesting to ask a group of engineers to assign percentages to each of these applications in terms of the effort they expend in each type of exercise. The response could be compared to a survey of the general public as to how they perceive engineers make use of models. Although we can only speculate on the actual numbers, we suspect that most engineers would allocate the majority of model application to the categories of Interpretation and Design – let's say 90 to 95% between the two. Most of us would be very uncomfortable with assigning more than 5 or 10% of the modelling effort to prediction. However, one might suspect that the general public would see most of what we are trying to do as prediction.

This is a significant point because, if we don't believe we can predict, then why would we engage in the modelling process at all? Let us address this issue directly. How well do you believe we can make predictions in geotechnical engineering? In many of our estimates (note the softening of the word), we would be happy to be within an order of magnitude. We would be extremely pleased if we had predicted 10 cm of settlement behind a retaining structure only to actually measure 1 cm. (We would likely not be quite as happy if the situation was reversed but we suspect we would still be satisfied with our estimate.).

Maybe we can't really predict at all! If that is the case, then why do we go to all this bother? Let's look at an example of how well we predict. Carter et al. (2000) presented an example from the German Society of Geotechnics in his Keynote address at GeoEng 2000 in which a number of different groups had been asked to predict the deflection of a tie-back retaining wall. The groups were all given the same site information (e.g. ground profile and ground behavior).The results of the various predictions are shown in Figure 3 along with the actual monitoring data. The dashed dark heavy line is the actual inclinometer data. The solid dark heavy line is the inclinometer data shifted to the left to account for an estimated base correction.

There may be a few readers who will be quite concerned about the lack of agreement between the predictions and the monitored reality and possibly even more so about the lack of agreement between the various predictions. In fact, the accurate prediction of actual field performance is extremely difficult. We

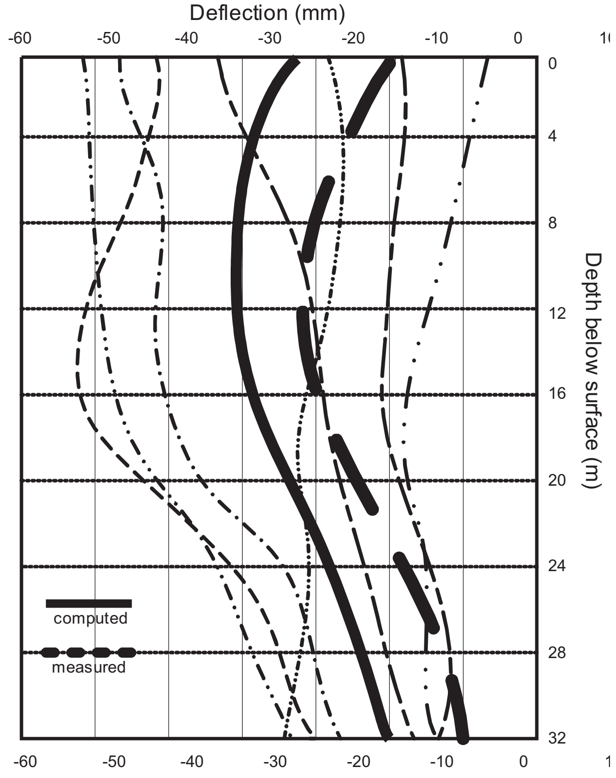

Figure 3. Predicted and measured deflections of a tie-back wall (Carter et al. 2000).

may try to predict the amount of settlement or seepage, the first arrival of a contaminant, or the stability of a slope; however, the accuracy of those predictions are often overwhelmed by difficulties in fully characterizing the geologic setting (in three dimensions), in providing appropriate theoretical descriptions of soil behavior, in uncertainties in measuring soil properties, and in numerical problems with analytic tools. Because of these difficulties, modelling, and particularly the use of numerical models, is often dismissed as useless due to lack of predictive accuracy.

In fact, we would contend that we can take a lot of encouragement from the predictions shown above. In nearly every case, the general pattern of movement was correctly predicted and the magnitude of the movement was well within an order of magnitude. The predictions were all wrong, and yet they provided considerable insight into the performance of this structure. Moreover, the predictions provide sufficient insight so that the structure could have been designed safely and economically.

This is a critical lesson in modelling and the use of numerical models in particular. We previously ascribed the majority of engineering use of computer models to the categories of interpretation and design, not prediction. It is an important distinction because we believe that the key advantage of modelling, and in particular the use of computer modelling tools, is the capability it has to *enhance engineering judgment*, and *not* the ability to enhance our predictive capabilities. Although the use of more sophisticated computer tools does allow us great advantages in prediction over other methods such as hand calculations, graphical techniques, and analytic solutions, this is secondary to the capability of models to enhance engineering judgment.

The reason for this is because modelling is primarily about a process, not about prediction. Anderson and Woessner (1992) provide this insight: "*The attraction of ... modelling is that it combines the subtlety of human judgment with the power of the digital computer*." The primary role of the modelling process as described by Burland and others, which is the one we espouse in this paper, is that it is a *process*. When this process is entered into correctly, it incorporates and enhances the essential component of engineering design that cannot be replaced by a computer: experience and judgment.

There is no question that the complex numerical tools we have today do provide us much better predictive capability than we have ever had before. And yet, this is not the primary benefit we have from the modelling process. The modelling process is most powerful when it is used as an aid to our own judgment. As we will see later, it also allows us immense freedom. It allows the freedom to model even when we can only guess at geology and material properties, and the freedom to reconnect the wise, old, seasoned professional with the young computer guru. In the end, modelling, done correctly, helps ensure that we have not only extracted an appropriate level of complexity from the physical reality in our mathematical model, it teaches us and helps us develop a sound understanding of the physical system so that we can, and as we inevitably must, exercise our engineering judgment.

Taken in this light, we can see how we receive the maximum benefit from modelling when it incorporates and is applied to the entire process of data gathering, interpretation, design and final prediction. The modelling process must envelop site investigation (ground profile), field and laboratory testing and monitoring (ground behavior), as well as theoretical idealization and numerical analyses. Let us now move on to look at a possible model for this modelling process. In the next section we develop a series of generic steps to describe this process, outlining the activities, challenges and pitfalls facing us in each step.

A General Methodology for Modelling

There are relatively few references in literature that describe a model for modelling. Some references are provided at the back of this paper if you would like to read further in this area. A typical example of a modelling methodology would be one proposed by Mercer and Faust (1981) for groundwater modelling. They suggest the following steps:

- Develop an understanding of the physical system (Conceptual Model)
- Translate physics describing your understanding into a mathematical system (Mathematical Model)
- Develop a solution of the mathematical model using numerical, analytic, graphical, analogue or other techniques (Numerical Model)

Some other references could be cited here, but like the example of Mercer and

Faust, they all tend to have common steps such as:

- Conceptualize: Geology and the physical processes
- Define: Behavioral processes and material properties
- Formulate: Numerical descriptions and solutions for these processes
- Solve: Obtain an accurate numerical solution
- Interpret: Validate, calibrate and interpret the solutions in the context of the physical system

We could also develop a modelling process along the lines of an engineering design process. A colleague at the University of Saskatchewan, Professor Jerry Huff, describes the design process to undergraduate students as being comprised of combinations of the following four words: *generally*, *specifically*, *what*, and *how*. These words are combined into four questions, to be addressed in order, to move us towards a final design.

- **Generally – What?** This is a statement of work. What, in general, are we trying to build? What general objectives do we have? What is the general characterization of the physical environment (e.g. geology) in which we must work?
- **Specifically – What?** What are the specifications for performance? What are key processes and properties with which we must work? What are the quantitative inputs and outputs we will need?
- **Generally – How?** What analytic tools can we use to quantify behavior? To which input parameters are the behaviours of interest sensitive? What is the relative performance of various design alternatives?
- **Specifically – How?** What will be the final recommended design? What are the final predictions and what aspects of the design are essential to the accuracy of these predictions?

Another approach to this process is to look at it in terms of a simple version of the scientific method: observe, measure, explain, and verify. These are most commonly defined as part of the scientific method as follows:

- **Observe** – Definition of the problem statement based on general observations
- **Measure** – Collection of problem specific data
- **Explain** – Development of a hypothesis explaining the behavior
- **Verify** – Validation of the hypothesis by comparing the explanation to the data

When adapted to the modelling process, these four steps become:

- Step 1: Observe – Develop a conceptual model of the ground profile and the project objectives
- Step 2: Measure – Define appropriate theoretical models that describe the key processes operative in the problem.
- Step 3: Explain – Develop a mathematical description of these processes and verify that it provides an accurate solution.
- Step 4: Verify – Interpret the results of the mathematical description in light of the observed physical reality. Prove the hypothesis, obtain additional measurements, improve the complexity or accuracy of the mathematical solution, or change your conceptual understanding until you are satisfied that you have a full understanding of the physical reality.

Each of these steps are discussed in more detail in the following section including a description of typical activities conducted during each phase of the modelling process along with warnings about potential pitfalls. The reader is also directed towards a useful illustrative example of this process provided in the National Research Council (1990) booklet entitled *Groundwater Models: Scientific and Regulatory Applications*.

Step 1: Observe – Develop the Conceptual Model

There are three key activities for this step of the modelling process. First, it is important to clearly define the purpose of the model. What are the 'generally – what?' questions you are concerned about?

The second activity is to begin to gather existing general information for your site. In some cases, you will only have access to existing background information from geologic maps or reports. In other cases, there may have been some preliminary site investigation. It is essential at this stage to begin to develop a conceptual model of the geology and hydrogeology of the site. In the case of new construction, you will also need information on the proposed development such as potential depths of excavation, loadings, sequence of construction and so on.

Finally and most importantly, you must use your engineering experience to begin to develop a conceptual model of the physical environment. Examine and interpret the *existing data* into some sort of coherent conceptual model. Keep in mind that this model is likely to evolve repeatedly over the course of the modelling process as it is challenged by new data, simulation results and monitoring information. However, you must begin with a commitment to some initial conceptual model. Being wrong at this stage is not a problem; being lost or noncommittal is a problem. The central component of this conceptual model is your understanding of the geologic and hydrogeologic framework of the site.

It is essential that Step 1 be undertaken carefully since it serves as a foundation for Steps 2, 3 and 4. Major errors at this point can hopefully be overcome as we iterate through the four steps; however, the old adage, 'garbage in = garbage out' is quite appropriate at this stage. A somewhat simplistic initial conceptual model based on existing data is not fatal; misinterpretation of the data entirely may be.

It is also important to *start simple*. Keep in mind that the modelling process is iterative. Increasing the complexity of the initial conceptual model may be required as the model evolves; however, speculating on high degrees of complexity in the absence of supporting field observations is not only problematic in developing a clear understanding of site behavior, it will also make the remaining processes more difficult. Don't use too complex a conceptual model too soon.

We think it is obvious that it is important to have the sage professional fully involved in this initial step. The computer skill of the young engineer is no match for battle scars at this modelling step. We would encourage a young engineer faced with a modelling task to seek out the sage in your company to guide you at this stage.

Step 2: Measure – Define the Theoretical Model

An appropriate theoretical description of the important processes must now be selected based on the problem definition and conceptualization provided in Step 1. The key material behaviors that will need to be understood must be identified and likely some homework will have to be undertaken to ensure that the theory describing these processes is fully understood.

Each of the constitutive relationships describing these processes will have material properties associated with them. The solution will require that we utilize these theoretical descriptions to develop governing equations that can be solved, subject to appropriate material properties and boundary conditions. Most of these formulations are based on key assumptions, the ramifications of which need to be appreciated in light of our specific problem.

We can also begin to develop an appropriate data set that we can use in solution. Initially, these might simply be guesses. Often we are reluctant to guess; but keep in mind, the goal of this modelling exercise is to enter into a process in which we can improve our judgment and understanding of the response of the system, it is not to be simply predictive. Professors John Burland and John Carter both advocated the idea of starting with a guess in their keynote addresses at GeoEng2000 in Melbourne. Professor Burland notes that this is where they began as they tried to solve the important problem of correcting the increasing lean of the Tower of Pisa.

We may rely solely on reasonable guesses of material properties and boundary conditions during our first pass through this iterative process. The results of our analyses and interpretation will guide us towards understanding which parameters are of greatest concern and in which areas our greatest uncertainties lie. Additional field work or laboratory testing can then be directed towards to resolving some of the most important uncertainties, and our mathematical descriptions of the physical reality can then be improved.

It is important also to realize that existing field monitoring can be an important source of information to describe material behavior. We can begin with a guess, but then use actual monitored field responses in space and time along with the completion of Steps 3 and 4 to back-analyze guesstimates of appropriate material properties.

The most common sources of error in this step are primarily related to *theoretical awe*: our tendency to accept without question the theory incorporated in the most readily accessible mathematical solution or numerical model. It is important to do your homework at this step. Make sure that you are comfortable with the fundamental theory being used in the mathematical description of your system. We are not sure whether the sage or novice engineer has a greater advantage here. The sage has had years of practice but faces the challenge of staying current with the latest theoretical developments, while the novice has had the most recent formal education, but is now regretting they didn’t pay more attention in class. In either case, the only solution is to return to the books and study.

Step 3: Explain – Develop and Verify the Analytic or Numerical Model

Now that the physical reality has been observed and conceptualized, and the relevant processes have been theoretically and mathematically defined, it is now time to test these descriptions by committing them to a mathematical solution.

In many cases, the solution takes the form of a boundary value problem. This type of mathematical problem is defined by the following components. First a domain (geometry) must be defined within which we will seek the solution to a set of governing equations. These equations will be solved subject to a set of boundary conditions applied to the domain and in concert with a set of material properties specified within the domain. The method of solution can be quite varied, encompassing analytic solutions, graphical techniques (e.g. flownets) or numerical solutions such as finite difference and finite element techniques.

An appropriate method of solution for the equations laid out in Step 2 is selected. In most cases, it is important to select more than one method of solution, such as an analytic solution and a numerical solution. The complexity of the model may eventually require the use of a numerical model such as a commercial software package; however, it is important that even these models be verified against other solutions. This might require that a simpler conceptualization be used initially or that simpler versions of similar problems be compared. The purpose of this exercise is twofold. It verifies that the more complicated numerical model used by the engineer is working correctly, and it also familiarizes the user with the particular features and peculiarities of the software (input and output) to ensure they are using the software correctly.

If this is the first time you are using this particular method of solution, then we would encourage you to check the method against known analytic solutions, other known numerical solutions and even other case histories of field studies from literature or your own files.

The goal here is not simply to get a solution to your particular modelling problem. It is to develop confidence in the limits of the solution. This is of particular concern with numerical models where numerical problems of roundoff, convergence, spatial and temporal discretization, numerical oscillation, or dispersion, may occur. These errors are not always as easy to identify as the limitations of an analytic solution.

A useful metaphor might be to compare the engineer with a numerical solution to that of an artisan or workman with his tools. You must have confidence with the tool in order to work freely and confidently on the project.

Step 4: Verify – Interpret, Calibrate, Validate against the Physical Reality

Once a mathematical solution is obtained, the results must be carefully interpreted and checked against the physical reality. Typical exercises might include a comparison against field monitoring in which the conceptual and mathematical models are adjusted until there is good agreement between the physical and mathematical systems. It is important to realize that these calibrations are always non-unique. We can improve our confidence in the calibration if we have a series of readings that are taken at different locations and at different times, including both pre-construction and during construction. However, keep in mind that we are like the young student trying to solve for four unknowns with three equations. There is no unique solution and any solution we can obtain will rely heavily on experience and engineering judgment.

We can also conduct sensitivity analyses as an aid to our interpretation. This is a series of simulations in which we vary only one parameter at a time and then review the effect of these variations against key performance (e.g. pore-water pressure at particular locations, factor of safety, deformation along a retaining structure, etc.). The goal of the sensitivity study is to help us understand which element of the conceptual and theoretical models (e.g. boundary condition, material property) are of particular importance to field performance.

It is important at this stage to retain one of the key personality traits of all good engineers: skepticism. All solutions should be only considered to be *conditionally valid*. That is, they are only as good as our conceptual model, mathematical description, and numerical solution. Consequently, it is important that the sage and the novice be working in concert at this point.

The greatest danger at this stage is blind acceptance of the solution, a problem that is often associated with the use of commercial software. It is important to keep in mind that the solution provided by the software is only one step in the modelling process. It is not design software, only analytical software. The design only comes from the clear thinking and judgment of the engineer.

This leads to the Golden Rule of the modelling process. Consider suspect any model results that contradict sound engineering intuition. The basic question remains, 'are the results reasonable?' In the early stages of the modelling process it is not uncommon to see results that don't make sense. Often it is because of errors in one of the previous stages of the process: poor conceptualization, inappropriate material descriptions, or even mistakes in running the numerical software. However it may also be due to the fact that it takes some time to train our own thinking as to why the predicted behavior is reasonable. Remember, one of our objectives is to train our own thinking and improve our judgment.

Key Points

There are a number of features of numerical models that must be appreciated to make effective use of these analytic tools in the modelling process. These features include the fact that all models are only simplified abstractions of a complex reality. It is important to keep in mind that the purpose of modelling, particularly in the use of numerical models, is not to try to replicate all of nature's complexity. The genius in modelling is the ability to only develop as complicated a representation of the physical reality as required to sufficiently understand the behavior required for a particular design.

Understanding this simple concept helps the engineer appreciate why the modelling process always begins with the simplest possible conceptual model, and then adds complexity incrementally until the level of complexity is sufficient to represent the material behavior of interest. This is very much in keeping with Occam's Razor, often called the principle of parsimony, ascribed to the English philosopher William of Occam (or Ockham) (1285-1347/49), which states *'plurality should not be assumed without necessity'* or more simply stated: 'When there a number of possible explanations for a phenomenon, generally, the simplest explanation is the best'.

Ironically, the basic reason we use complicated numerical models is so that we can sort through the complexity of the physical system until we isolate one or two simple issues on which we can base our design. Inevitably, as you begin to reach the end of a long and lengthy modelling project, you will find that your understanding of what appeared to be a complex enigma will suddenly boil down to one or two central, simple ideas. In many cases, there is almost a sense of personal embarrassment that you didn't grasp these simple principles from the beginning.

This is a critical lesson in modelling and the use of numerical models in particular. The key advantage of modelling, and in particular the use of computer modelling tools, is the capability it has to enhance engineering judgment, not the ability to enhance our predictive capabilities. While it is true that sophisticated computer tools greatly elevate our predictive capabilities relative to hand calculations, graphical techniques, and closed-form analytical solutions, prediction is not the most important advantage these modern tools provide. As noted earlier, numerical modelling is primarily about *process*, not about *prediction*.

Keep it Simple

The first lesson is this: *start simple and then add complexity in increments*. This applies to all steps of the modelling process. Begin with the simplest geologic and hydrogeologic conceptual model that is consistent with the available data. Start with a simple theoretical model. For example, never initiate a non-linear elastic-plastic stress deformation model until you have fully explored the implications of simple linear elastic behavior. Begin with the fewest elements and least number of materials possible in your first finite element solution. Add more elements and materials only as you understand the behavior of your simpler system and only until adding additional elements or materials continues to make a difference to the behavior of the system.

A supplementary principle to starting simply and increasing complexity incrementally is to keep in mind that all models are data deficient. If you don't believe that, then ask any geotechnical engineer whether they wouldn't like another one or two boreholes for their project. What this means is that we are always working with under-constrained systems with more unknowns than equations. Sherlock Holmes, the great detective (modeller) once said: "It is a capital mistake to theorize before one has data. Insensibly one begins to twist the facts to suit the theories, instead of theories to suit facts". Dealing with data deficiency means that we must never increase the complexity of our theories beyond the level of our data sufficiency and secondly, we have no possible solution without the liberal use of engineering judgment.

There are also a number of practical advantages to starting simply and adding complexity incrementally. First, it is much easier to spot errors in your numerical model when you begin simply. Errors in specifying material properties or in mesh creation can be seen more readily. One of the first tasks a modeller faces once they have completed their first set of simulations is to verify that what they thought they specified as input was actually used. This is much easier to do when the initial complexities are minimized. When you start with a very simple model you are often able to make initial checks on your results with simple hand calculations or analytic solutions.

The second advantage of beginning simply is that you are able, in a sense, to begin running sensitivity analyses. You begin to develop an intuitive feel as to when the system begins to change quite dramatically to changes in level of discretization, or the location of a particular boundary condition, or the addition of a different soil property. You lose this intuition when you simply dump all your complicating factors into your simulations at the same time.

Questions and Answers

To reinforce the central ideas behind the modelling process, let us consider some complaints or questions a young engineer might have as they begin the modelling process.

Observe

- Problem: "I really don't understand the geologic or hydrogeologic system".
- Answer: Find a sage, talk to senior staff. At one of our workshops, we spoke with a consultant who designed their offices so that pairs of junior and senior engineers sat at desks across from each other. Conceptualization requires experience: find an old engineer!

Measure

- Problem: "I don't think we really understand this process".
- Answer: Do your homework. Study, read, take a class, and/or attend a workshop.
- Problem: "I don't have very much real data".
- Answer: Start with a guess and then do sensitivity analyses to see which parameters are important.

Explain

- Problem: "How do we know if we have enough time steps or elements for example?
- Answer: *Change it.* If it makes a difference, then it was important.
- Problem: "Is my boundary condition far enough away?"
- Answer: *Change it.* If it isn't a *real* boundary condition (symmetry or geologic control) then simply move it farther away. Keep moving it back until it has no further incremental effect on the solution.
- Problem: "Should my constitutive model be linear, non-linear, or coupled?"
- Answer: *Change it.* Start with a simple enough model so that you are able to understand the results, and then change it in small increments of complexity.

Verify

- Advice: Verify, verify, verify….
- Verify your input data. Did you get the result you thought you assigned for material properties, boundary conditions, etc.?
- Verify your output. Did you get a result that you expected? Is it reasonable? Can you approximate the same result with a hand calculation or simpler analytic solution? Does it agree with other numerical solutions?
- Advice on calibration: When you compare your simulation to the results of monitoring (pore-water pressures, deflections, etc.), don't just compare the specific numbers, compare patterns. If the numbers are similar but the pattern (spatial and temporal variation) is completely wrong, then you likely have something wrong with your model. If the numbers are different but the patterns are similar, then you likely have the process sorted out, although your parameters may be off. (Although getting an exact match can be a case of diminishing returns. There is an Irish saying: 'The devil is in the details'.) In the case of calibration the pattern, not the number, is the detail.

How Not to Model

Just in case the above advice falls on deaf ears, let us try some reverse psychology. Here is an example of how NOT to model effectively: Create a HUGE mesh and include the highest degree of complexity you can. Dump all your information into the model and hope that somehow the software will magically sort everything out. In short, the hope is that software will do your thinking for you. This simply will not happen!

Concluding Remarks

Our hope is that these informal comments will provide some perspective, particularly to younger engineers, as they begin to use the vast power of numerical tools. Keep in mind that the ability to model effectively is an acquired skill. It is an art, not just a science, and like any art form the only way to learn is to practice. Remember that modelling takes time, time to think, time to try and experiment. There is no such thing as running a 'quick model'. That is an oxymoron, like 'good grief' or 'designer jeans'. If you ask anyone with a considerable amount of modelling experience, they will assure you that any modelling exercise is likely to involve hundreds, if not thousands, of simulations. It is often difficult to keep track of all of these trials (and errors), so we would encourage you too keep a journal of your thinking and simulation trials.

In the end, the answer to the question posed in the title is that modelling is more about process than prediction. The modelling process is indeed a journey of discovery - a way of learning something new about the complex behavior of our physical world. Furthermore, it is a process that can help us more fully understand highly complex real physical processes, and that can help us exercise our engineering judgment with increased confidence to make predictions.

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