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The management of advanced numerical modelling in geotechnical engineering: good practice

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The management of advanced numerical modelling in geotechnical engineering: good practice

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Summary

Numerical modelling is now routinely carried out in geotechnical engineering. Producing a numerical model is not straightforward and if not used properly can be dangerous. However, if used with skill and care there can be enormous benefits.

This guide has been written for those who commission and manage numerical modelling, not specifically those who undertake it. The aim is to provide a framework for those who oversee the process, provide the information needed for this task and use the results of the numerical modelling.

This guide aims to outline the information that the project manager (PM) needs to assemble, and the processes that need to be put in place for a successful outcome: the 'ten steps to better numerical modelling'.

By following this guide, those producing a numerical model will, we anticipate, be given the quality of information and the time needed to successfully produce a model that can be relied upon by the design team as a whole. Those managing the process have a vital role to play in producing a reliable numerical model and ensuring that maximum benefit can be obtained from it.

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Following CIRIA's usual practice, the project was guided throughout by a project steering group (PSG) comprising:

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Rachel Monteith	BuroHappold
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Stephen Thomas	OGI Groundwater Specialists
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Executive summary

Numerical modelling is now routinely carried out in geotechnical engineering. Producing a numerical model is not straightforward and if not used properly can be dangerous. However, if used with skill and care there can be enormous benefits.

This guide has been written for those who commission and manage numerical modelling, not specifically those who undertake it. The aim is to provide a framework for those who oversee the process, provide the information needed for this task and use the results of the numerical modelling.

Providing accurate information for those building and running a model is essential, without it the results obtained could be misleading. This guide aims to outline the information that the project manager (PM) needs to assemble, and the processes that need to be put in place for a successful outcome: the 'ten steps to better numerical modelling'.

This guide sets out to explain that, however simple the engineering challenge might be, numerical modelling is an intrinsically complex process. Those commissioning or managing it should understand what is required in order that they can provide those responsible for producing the model (building, running, checking and reporting) with the information that they require and with sufficient time to do the modelling. A means of assessing the importance of the outputs from the model for supporting design decisions is defined as the 'application category'.

This publication starts by explaining, in broad terms, what numerical modelling is (**Chapter 2**). It does not suggest that numerical modelling should be used in favour of traditional methods of analysis because they have successfully been used for many years by engineers and, in many instances, they are still appropriate (**Chapter 3**). However, numerical modelling has become an important tool in an engineers' toolkit. It has many benefits but there are risks. In 2004, during construction, there was a collapse of a section of the Nicoll Highway in Singapore. One of the primary causes of the collapse was found to be the erroneous application of numerical methods. Such an example should serve as a warning to those who do not adequately apply these methods to real engineering problems.

Following this general discussion, the guide outlines the roles and responsibilities of the different parties involved in the process of producing a valid numerical model (**Chapter 4**). A description of the process involved in developing a model from specifying the objectives follows (**Chapter 5**), acquiring the information needed for the model (**Chapter 6**), and building (**Chapter 7**), running (**Chapter 8**), calibrating (**Chapter 8**), and checking it (**Chapter 9**). Some approaches provide greater certainty in terms of the accuracy of the solution than others. So, the degree of checking might be greater for some approaches than for others. Accordingly, the project manager and advisors should be aware of this requirement and allow sufficient time in the programme to ensure that the outputs are robust and adequate for the purpose intended.

An important aspect of this process is reporting the results of the model. Any assumptions or idealisations have to be communicated to the design team as a whole so that they can assess how the results of the model may be used. This guide makes recommendations as to how this should be done and who should do it (**Chapter 10**).

By following this guide, it is hoped that those producing a numerical model will be given the quality of information and the time needed to successfully produce a model that can be relied upon by the design team as a whole. Those managing the process have a vital role to play in producing a reliable numerical model and ensuring that maximum benefit can be obtained from it.

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Glossary

Client	The client commissions the design delivery co-ordinated by a project manager, where numerical modelling is one of the key elements of the design and often as part of a multi-disciplinary scope of work. Typically, they can be in an external organisation (from the numerical modelling team) and will usually not have any technical knowledge of numerical modelling.
Designer	Often the outputs from numerical modelling will be passed onto others for subsequent application, either to complete a design or to make decisions on project planning. Note the 'user' of the numerical model's output is termed the 'designer'.
External party	When existing infrastructure is affected and needs to be included in a numerical model, it may be necessary for the relevant external party (eg the asset owner) to provide appropriate input data.
Independent checker	For large complex projects an independent checker (IC) may be appointed who will be independent of the project team (PT).
Modeller	The user of the software, the modeller constructs the numerical model, runs the analysis and generates the output. They need to have a sound knowledge of geotechnical engineering and numerical modelling. The qualifications for this role are discussed in **Section 4.7**. For smaller projects they may also be fulfilling the function of a geotechnical engineer, carrying out conventional analysis and design work with input from the senior modeller (SM). However, for larger projects their role may be limited to building the numerical model, running it, interrogating it and reporting.
Numerical modelling	A mathematical solution to a geotechnical problem. In this context, numerical modelling refers to numerical analysis methods used to numerically solve the equilibrium equations for a soil mass, while at the same time satisfying the condition of compatibility. This relates to mechanical, hydraulic and thermal behaviour for given boundary conditions. Numerical modelling could refer to any one of the following approaches: ● finite element method (FEM) ● finite difference method (FDM) ● discrete element method (DEM) ● boundary element method (BEM) The most commonly used form of analysis in mainstream geotechnical engineering is the FEM, and this guide has been written with this form of analysis in mind. However, the comments and explanation provided in this guide could equally apply to the other approaches. Throughout this guide there is reference to individuals involved in commissioning, performing and using the results of numerical analysis. It is important to understand the roles of these individuals and their responsibilities. These are discussed in subsequent chapters. In summary, the roles are as follows:
Peer assister	This is a senior role and peer assist (PA) provides proactive independent guidance and technical challenges to the PT. Typically, they will consider the objectives, available information and the interpretation and practical application of the numerical model's outputs, and assess if they are appropriate in the context of project risks and opportunities. An experienced PA can play a key role in ensuring that expectations are reasonable, the numerical model's application is appropriate and that risks/opportunities are balanced. This role is additional to that of a checker.
Project manager	The PM is in overall control of project delivery, typically controlling and co-ordinating the work of several different teams with varying technical/commercial skills. For the purposes of this guide the term project manager (PM) is assumed to be the individual with overall responsibility for design co-ordination and liaison with the client and acts as the link between the numerical modelling team and the rest of the PT. For smaller projects the PM will often carry out numerous co-ordination roles (**Figure 4.1**), but for

	larger projects the PM functions will often be split, with a design manager (DM) and design team leaders (DTL) assisting the PM (**Figure 4.2**). The PM (and DM, DTL) will usually be responsible for co-ordinating the work of several different specialist teams (eg structural, geotechnical, mechanical/electrical), and even if they are civil engineers and have an awareness of different design/analysis methods they will usually not have an understanding of numerical modelling.
Project team	The project team (PT) will usually comprise several different disciplines (eg structural engineers, planners) depending on the project types. Usually, some of these other parts of the team will need to contribute to the modelling. For example, at the early stages, providing information for use in the numerical model. At a later stage they will be using the outputs for design or making planning decisions. For design/build projects, the contractor will need to define a construction sequence for use in the numerical model (this is often a critical part of a numerical model).
Principal designers	In the UK, for projects falling within the scope of the Construction (Design and Management) Regulations 2015 (CDM 2015), then a principal designer (PD) has to be appointed. They will then be involved in the numerical model if the outputs have a potential impact on their responsibilities (both in terms of agreeing key inputs/ assumptions and subsequent use of outputs).
Senior geotechnical engineer	The senior geotechnical engineer (SGE) will have overall responsibility for all geotechnical inputs into the project and have extensive geotechnical design experience. The roles of SGE and senior modeller (SM) may be carried out by the same person, depending on their expertise and the overall project requirements.
Senior modeller	The senior modeller (SM) will provide the modeller with technical guidance, mentoring their professional development, and will liaise with other senior staff in a PT. They discuss and agree the objectives of the numerical modelling, review the numerical model input data and interpret the results. They need to have a sound technical understanding of engineering principles and have extensive experience of numerical modelling and of applying numerical modelling for design. For smaller projects they may also act as the lead geotechnical engineer, providing conventional geotechnical design advice for the project and provide advice to the modeller. For larger projects, they may be focused solely on numerical modelling and support several geotechnical teams.

Abbreviations and acronyms

BEM	Boundary element method
CDM 2015	The Construction (Design and Management) Regulations 2015
EP	External party
FE	Finite element
FEA	Finite element analysis
FEM	Finite element method
FDM	Finite difference method
DEM	Discrete element method
DM	Design manager
DTL	Design team leader
FOS	Factor of safety
GI	Ground investigation
IC	Independent checker
M	Modeller
PA	Peer assist
PD	Principal designer (CDM)
PM	Project manager
PT	Project team
SGE	Senior geotechnical engineer
SLS	Serviceability limit state
SM	Senior modeller
TBM	Tunnel boring machine
ULS	Ultimate limit state

1 Introduction

1.1 PURPOSE OF THIS GUIDE

The aim of this guide is to provide those commissioning or managing advanced numerical analysis with the opportunity to understand, in simple terms, what is involved in undertaking these analyses and how to effectively manage the process. Well-managed numerical modelling can provide significant benefits, but there are also considerable risks if it is poorly managed and implemented. Numerical modelling is a specialist task, but PMs can make a positive contribution. Outcomes from a numerical model can be improved, provided PMs are aware of the key issues. This guidance is targeted at, and written for, those non-specialists commissioning numerical modelling as a stand-alone package of work undertaken by a specialist company or by a PM within an organisation carrying out numerical modelling as part of a design package.

In addition, guidance is given on:

- a framework for effective management of numerical modelling
- defining the scope of work, by ensuring that there is clarity on the objective of the numerical modelling
- the type of information that is needed for building and checking a numerical model
- the types of checks that should be carried out – it is important that managers understand these, to avoid a 'black box' mentality, which can have potentially serious safety implications (in addition to various technical and commercial problems)
- the range of skills and expertise that may be needed for building and checking a model
- the necessary reporting to ensure that there is clarity across the PT on the assumptions and choices that a modeller has made in building a model and how the factual outputs should be interpreted for subsequent practical applications.

The potential issues in managing numerical modelling have become a concern for many clients. These challenges include non-specialist matters such as the supply of relevant information and subsequent interpretation and application of the outputs. The guidance is not intended to provide the user of numerical analysis (known as the 'modeller') with a guide to undertaking analysis or to explain how to validate analyses or software as there are other publications that do this (eg Naylor *et al* (1981), Potts and Zdravković (1999a and 1999b), Lees (2016)).

In reality, few individuals have an in-depth understanding of the use of these methods of analysis. Now, with increasing reliance placed on this type of complex modelling, effective procedures to manage the use of these methods is needed, particularly when those managing analysis and design are not necessarily acquainted with these methods.

It is hoped that, by following this guide, the process of undertaking analysis of this form will become more efficient, more reliable and ultimately will provide clients with more cost-effective solutions. After reading this guide, clients, PMs and those overseeing geotechnical design elements who are not familiar with numerical modelling, should be able to appreciate when advanced numerical analysis is appropriate, what is involved, why it is required and how the work should be checked to ensure that output is reliable and relevant for subsequent application for design or planning.

1.2 THE CURRENT POSITION

For many years, traditional methods of analysis and design have been successfully used. For example, up to the extension of the Jubilee Line (circa 2000), the whole of London's underground system was designed without the use of numerical modelling but still involved the construction of some very complex structures such as Piccadilly Circus Underground Station in central London (**Figure 1.1**).

In the last decade or so, numerical modelling has become a far more popular geotechnical design tool. This may be because of the availability of user-friendly software and the development of more powerful computer hardware.

In the past, numerical analysis was predominately undertaken by specialists who were familiar with the principles of geotechnical engineering and numerical analysis. The same is not necessarily true today. The benefits of numerical modelling include the assessment of structural forces and displacements in a consistent way (rather than trying to combine different simplified methods which have different assumptions) and the assessment of the impact of construction on adjacent infrastructure and utilities (which is often critical in dense urban areas).

Figure 1.1 Piccadilly Circus Underground Station (courtesy London Transport Musesum)

Today, many users do not have a full understanding of the geotechnical and numerical principles involved. Some may use the software as a black box where data is input and output follows, ie the principle of 'rubbish in, rubbish out' applies. However, decisions are often made on the basis of these results. This may substantially increase project risks, especially if the assumptions and limitations of the analyses are not understood by decision makers (or, in the case of a black box approach, even the 'modeller' may not understand the limitations of the model!).

To the uninitiated the process of undertaking such analyses appears relatively straightforward – a unique answer can be obtained for a given set of inputs. However, as this guide discusses, nothing could be further from the truth.

There are many pitfalls and dangers that have to be avoided when using advanced numerical methods and, as for any other form of analysis, assumptions and approximations have to be made (which may or may not be justifiable). Whether or not these assumptions can be justified, the analysis can be undertaken and answers, reasonable or not, can be obtained, but using such methods without sufficient scrutiny can be very dangerous. For example, the Nicoll Highway collapse in Singapore (Magnus *et al*, 2005, **Figure 1.2**), should be a stark reminder of the consequences of erroneous outputs from numerical analysis. The background to this failure is briefly discussed in **Chapter 9**. It should be noted that some simple checks could have identified the flaws in this analysis.

Figure 1.2 The Nicoll Highway collapse, Singapore (courtesy New Civil Engineer)

1.3 LAYOUT OF THE GUIDE

Table 1.1 summarises the overall layout of the guide, the key points covered in each chapter and the primary readership. **Figure 1.3** provides a flow diagram which summarises the key tasks involved in numerical modelling, starting from a kick-off meeting through to preparation of reports and application of outputs. For each of the main tasks (eg 'design team organisation' or 'checking') a chapter reference is provided where more detailed guidance is given. Also shown are the activities that a PT needs to undertake (eg 'agree roles/responsibilities' and 'calibrate') to effectively control the numerical modelling. Checking needs to be carried out, and the key questions which need to be asked are outlined in **Figure 1.3**.

Changes frequently occur during a project and it is important that there is effective communication of any changes, and the implications of any changes on the numerical modelling are assessed, as illustrated in the flow chart. Recommended deliverables are summarised in **Figure 1.3**. Those who wish to understand the practical application of numerical modelling should read the whole guide. **Chapters 2 and 3** provide useful background and explain, in a simple way, 'What is numerical modelling?' and 'Why use numerical models?'.

For PMs **Chapters 4 and 5** are considered to be particularly important – the guidance in these chapters should help them improve their management of numerical modelling and their control of risks and opportunities. **Table 4.1** outlines the 'Ten steps to better numerical modelling' which will help PMs organise the tasks involved in managing numerical modelling, so it is more cost-effective. Inputs are often needed by others in the PT, not just by the 'modellers'. An example RACI table (responsible, accountable, contribute, inform) is provided in **Table 4.2**, which illustrates the team effort usually needed. There is often confusion about the type of information that is required to build and check a model.

Chapter 6 discusses the breadth of information that may be required, and all those involved in planning surveys and investigations (of various types) should read this chapter. Checking is a critical task. PMs need to be confident that the scope of checking is appropriate (and consistent with the objective and subsequent application of output) and that it is being done properly by specialists with the appropriate experience and expertise. **Chapter 9** outlines the key principles for checking.

Table 1.1 Layout of the guide

Chapter	Topic	Key points	Primary readership
1	Introduction	Purpose of this guide, and the current state of numerical modelling practice. Example given of serious consequences of poor checking. **Figure 1.2**	All
2	What is numerical modelling?	Basic explanation of numerical modelling. A distinguishing feature is that the results are very sensitive to how the model is designed and built by the modeller. Each model tends to be unique. A modeller has to make many choices, each of which can affect the outputs. **Box 2.2, Figure 2.3**	PM
3	Why use numerical modelling?	It is a powerful tool when used properly. Stability and ground deformation can be calculated in a coherent consistent manner, but it is relatively expensive and time-consuming to carry it out properly. Conventional analysis methods still play a vital role, especially during early project phases. **Figure 3.1**	PM
4	Organisation, roles and responsibilities	Recommendations for: team organisation, how PM can start and control the process – the 'ten steps' are outlined. Roles/responsibilities need clear definition. Common challenges are outlined. The technical staff needed to carry out checks and the competency/training required for modellers are summarised. **Tables 4.1, 4.2, Figure 4.3**	PM
5	Specifying the objective and application category	To ensure that the correct type of model is built in a cost-effective way, a clear objective needs to be specified. A key step in managing risk (and the necessary scope of checking) is to define the 'application category'. Application of outputs needs consideration at the start – generic issues (such as code requirements) are discussed. **Figures 5.1, 5.2, Table 5.1**	PM
6	Information for model	A wider range of information is needed (compared with conventional analysis), and a multi-disciplinary effort may be required. Many GIs are not carried out with numerical modelling in mind, so additional GI may be necessary to provide adequate input for numerical modelling. The scope of information required is dependent on the specified objective and application category. Relevant case studies, large-scale trials/loading tests play a vital role in model calibration. **Figures 6.1, 6.2, Table 6.1**	SGE
7	Building a model	Four main components to any model: 1 Definition of mesh geometry and types of elements within it. 2 Creating relevant *in situ* stress conditions. 3 Selection of appropriate stress–strain models for ground layers and structures (basic or advanced), which will depend upon the objective, geology, design situation. 4 Defining the sequence of steps in the analysis, including the construction sequence. **Figures 7.7, 7.8, Table 7.1**	SGE
8	Running the analysis	Running a numerical model comprises several tasks to ensure output is reliable: checking solution stability, correcting errors, refining mesh, calibrations (various types) and checking sensitivity/robustness of outputs. Calibration, ideally against relevant case history data, is a key step. **Figures 8.1, 8.2**	SGE
9	Checking, key principles	How checking should be organised-checking plan (concepts/principles/detail), timing, scope, selection of stress–strain models. Examples are given, including the Nicoll Highway collapse. **Figures 9.1, 9.2, 9.3, Tables 9.1, 9.2, 9.3, 9.4**	PM
10	Reporting	Three components: 1 Key assumptions and information available, assumed construction sequence. 2 Factual output. 3 Interpretation of output and guidance on application of output (this is often forgotten but is essential if output is to be used safely). **Figure 10.1, Table 10.1**	SGE
11	Conclusions and recommendations	Numerical modelling is a powerful technique, but must not be used as a black box. If this guidance is used, then the black box can be eliminated.	All
Appendix A1	Checking, technical issues	Several technical issues that can be challenging and require careful checking are discussed. Some common scenarios are also discussed.	SGE

Figure 1.3 Numerical modelling – tasks and deliverables

2 What is numerical modelling?

There are many texts that describe in detail what numerical modelling is (eg Naylor *et al* (1981), Potts and Zdravković (1999a and 1999b), Lees (2016) etc) but these are highly technical. Obviously, if the reader is interested and wants to explore the subject further, reference can be made to one or more of these texts.

In simple terms, in the context of geotechnical engineering, a numerical model is a numerical representation of the ground and structures within it or founded upon it.

The components are:

- a mesh subdivided into elements
- the initial stress condition – the state of stress in the ground at the start of the analysis, which is usually a 'greenfield' condition
- constitutive models that are assigned to sections (elements) of the model to represent material behaviour (stress, strain, strength etc)
- boundary conditions (displacements, pore water pressures, forces, temperature, accelerations etc) which are applied to the mesh (or sections of it) to represent fixity or changing conditions (see **Box 2.1**), and which may change at different stages in the analysis.

The analysis is broken down into a series of steps or increments. Because it is sequential, representing different events or activities, it models in turn what has happened and what will happen within the geometry represented. As such, these models are very complex, and a great deal of skill is needed to successfully run them and to interpret the output.

An important feature of numerical modelling which distinguishes it from conventional analysis is that the modelling results, or outputs, are very sensitive to how the model is designed and built by the modeller. Two different modellers analysing the same problem can, by virtue of the models they produce, come up with very different answers (eg Schweiger, 2002). Also, the model design and construction sequence will usually be unique for each application, and so this is highly dependent on the modeller's skill and expertise.

Because of the complexity of numerical modelling, from the outset, decisions have to be made about the form of the numerical analysis (eg discontinuities such as fractures in rock can be explicitly modelled by one approach but not by others), how it is carried out and what it is being used for. Any approximations have to be carefully considered.

These early decisions will dictate the form of the analysis, the information needed to perform the analysis and the resources needed to undertake it. Many choices have to be made about how the modelling is carried out and, as the example of the bridge pier shows (**Box 2.2**), these choices can affect the reliability of the analysis as well as the cost and the duration. The form of the analysis is something that has to be agreed between all parties involved at the start of the process and needs buy-in from all concerned.

It is important that those managing numerical modelling understand that there are two different forms of FEA computer programs – explicit codes and implicit codes:

- **Explicit.** This method does not enforce equilibrium at the end of each increment and, if the number of increments is not sufficient, errors can result.
- **Implicit.** Equilibrium is enforced within specified tolerances at the end of each increment. It is usually more accurate than an explicit approach, but it can be computationally costly.

Although an explicit analysis may run much faster than an implicit analysis, because of the way equilibrium is dealt with, much more effort is needed to check the analysis once completed. Overall, the apparent savings in terms of time taken to run the analysis may be more than offset by the time taken to validate the analysis. Sufficient time has to be allowed for design management, allowing for validation (more likely explicit codes), or for the analysis to run (more likely implicit codes).

Box 2.1 Example of boundary conditions applied to the analysis of a footing on an elastic foundation

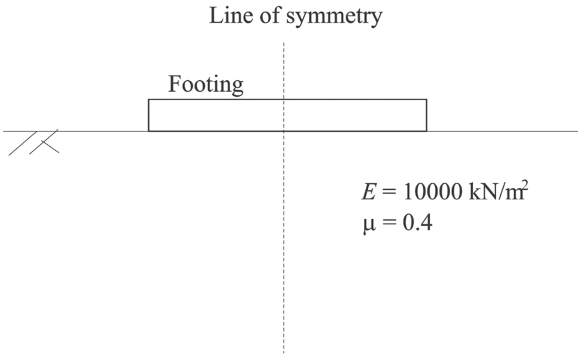


Figure 2.1 Footing on an elastic foundation

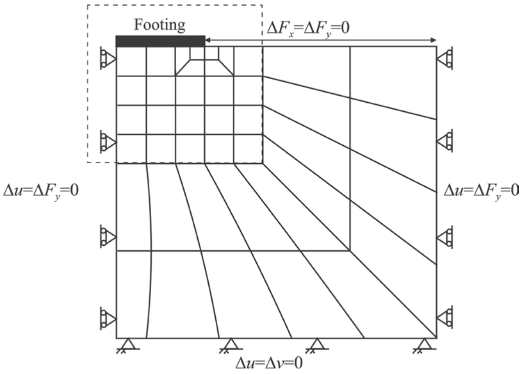


Figure 2.2 Finite element mesh, representing a footing on an elastic foundation

Figure 2.1 shows the issue of a footing resting on the ground – a drained material (Potts and Zdravković, 1999a). Because of symmetry, this can be simplified by generating a mesh to represent the geometry which in this case can be half the problem (**Figure 2.2**). The boundaries of the mesh have to be sufficiently far from the footing so that any constraints applied do not influence the results of the analysis. The boundary conditions applied are as follows:

- There is no change in vertical displacement along the base of the mesh (Δv).
- There is no change in horizontal displacement along the vertical boundaries and base of the mesh (Δu).
- There is no change in vertical force (ΔF_y) along the vertical boundaries.
- There is no change in the horizontal force (ΔF_x) or vertical force (ΔF_y) along the top of the mesh outside the loaded area.

Having set up the analysis, loads are applied to the footing to determine the load displacement response. Stresses, stains and displacements can be tracked at any point within the mesh at any stage in the analysis.

Box 2.2 Design of the mesh for the analysis of a bridge pier

a **b**

Figure 2.3 Analysis of a bridge pier – coarse mesh (a) and fine mesh (b)

Figure 2.3 shows an example of how dependent the results of the analysis are on the skill of the modeller. The example is of a numerical model for a bridge abutment foundation. The figure shows points at which yield has occurred within the soil.

- **Figure 2.3a** shows a relatively coarse model was built and a settlement of 10 mm was calculated.
- **Figure 2.3b** shows a more refined model was built, and the calculated settlement was double that calculated from the poorly built model.

It should be emphasised that the only difference between the models was the level of skill and care which went into building the model. The coarse model was relatively quick and cheap to build and run but it proved to be unreliable and unsafe. This highlights the need for careful checking and management of numerical modelling.

3 Why use numerical models?

For many years, geotechnical engineers have successfully used conventional analytical and empirical methods. Such methods still play a vital role in geotechnical engineering and should always be considered before carrying out numerical modelling. Nevertheless, under various conditions, their use might be considered inappropriate or at best limited. For example, there are many methods for the design of a single tunnel (eg Muir-Wood, 1975). However, where two (or more) tunnels are in close proximity conventional methods may be considered inappropriate because of interaction between them.

In terms of the problems that can be addressed, numerical analysis can be used for a range of soil–structure interaction problems and situations were deformations are important, such as the effect that the construction of one structure has on another structure (serviceability limit state, SLS) or where stability (ultimate limit state, ULS) is critical. The following is not an exhaustive list, but it illustrates the versatility of this approach in which linked thermal, hydraulic and mechanical (THM) behaviour can be considered:

- cut-and-cover tunnels, bored tunnels (segmental, brick etc) and cast *in-situ* tunnels
- onshore and offshore slopes and cuttings
- embankments including embankment dams
- onshore and offshore foundations
- pipelines
- earth retaining structures including embedded structures, anchored walls, gravity structures, reinforced earth structures
- nuclear storage facilities
- sustainable building foundations such as thermal piles.

The US Army Corps of Engineers (1995) prepared a report explaining how numerical analysis could be used in design. It compared the traditional methods of analysis (closed form solutions, limit equilibrium, beam string approaches etc) with the use of finite element (FE) analysis (one of the four forms of numerical modelling previously defined). They explained the situation as follows:

> *"Traditional methods of analysis often use techniques that are based on assumptions that oversimplify the problem at hand. These methods lack the ability to account for all of the factors and variables the design engineer faces and may severely limit the accuracy of the solution."*

They went on to say:

> *"The finite element method can overcome many of these shortcomings, thereby offering many advantages over conventional approaches."*

There are advantages and disadvantages to all methods of analysis. Some are easier to use than others and the necessary assumptions are more or less reasonable under different circumstances. **Table 3.1** summarises the capabilities of different forms of analysis when applied to the design of a retaining wall.

It is apparent that numerical modelling has a number of advantages over other approaches – there is consistency in the calculations. Engineers have recognised these advantages, which is partly why the use of numerical methods has become commonplace. This approach overcomes some of the limitations of traditional approaches and can be used to examine situations that are not well understood or go beyond the limits of normal design/construction practice.

Because of the complexity of numerical analysis, it needs to be demonstrated that their use is appropriate (ie calibration of the input data derived from testing or from case histories). It should also be emphasised that the results of the analysis are dependent on the quality of investigations and testing used for deriving input parameters.

Table 3.1 Summary of capabilities

Method of analysis	**Design requirements**						
	Stability			***Walls and supports***		***Adjacent structures***	
	Walls and supports	***Base heave***	***Overall***	***Structural forces***	***Displacements***	***Structural forces***	***Displacements***
Closed form (linear elastic)	No	No	No	Yes	Yes	Yes	Yes
Limit equilibrium	Yes	Separate calc.	Separate calc.	Yes	No	No	No
Beam-spring approach	Yes	No	No	Yes	?*	No	No
Full numerical analysis	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Note

* Displacement can be calculated but will often be misleading due to intrinsic limitations of method.

Perhaps the most powerful use of these techniques is to identify the sensitivity of predictions to variations in different parameters, ground conditions, the behaviour of structural elements, imposed constraints (thermal, hydraulic, stress or displacement), or methods of construction or construction sequences. Critical aspects of a design that require further development to obtain a robust solution can then be identified. As such, they are a design tool that can be used to assess risks in construction and to identify opportunities for value engineering, eg can props with minimal forces in them be omitted?

Compared with using traditional methods, undertaking any numerical analysis can be relatively expensive and time-consuming. Resources will be required to compile the information needed to define the model, to decide on the form of analysis required, to decide on what output is required, to check the analysis, to report it factually and to interpret the results. However, even considering this, the benefits of running a numerical analysis can be significant and cost-effective if the process is managed correctly.

Figure 3.1 is a flow chart that can be used to assess the need for carrying out numerical analysis. Typically, project requirements plotting to the right-hand side of the flow chart will benefit from the use of numerical analysis.

There are cases where the economic benefits of undertaking these analyses have been demonstrated. For example, Higgins *et al* (1998) described the analysis of the A406 road tunnel (**Figure 3.2**). They were able to show that a modest cost spent on undertaking numerical modelling provided a 15 per cent saving on the overall tender sum (in excess of £60M at 1998 rates). This was a significant sum compared with the comparatively modest cost of undertaking the analysis.

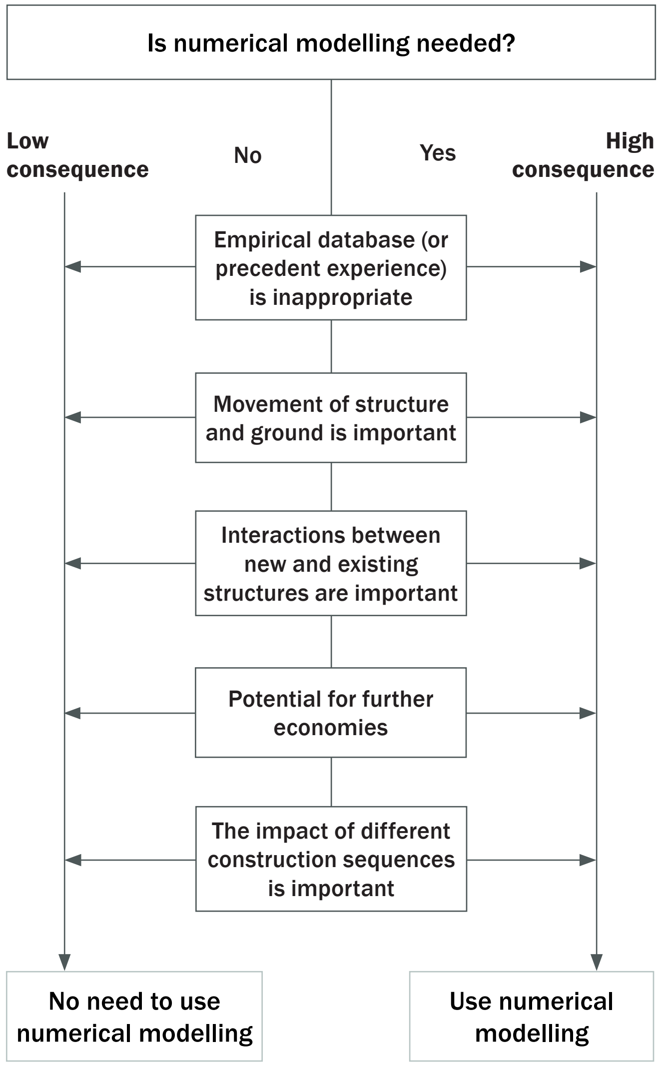


Figure 3.1 Flow chart for 'why undertake numerical modelling?'

Figure 3.2 A406 road tunnel

It was the use of numerical modelling to prove that an alternative, more easily buildable, structure was technically feasible that initiated most of the cost savings made. From a purely geotechnical standpoint, the modelling was able to demonstrate that T-shaped diaphragm wall panels could be replaced with piles with a reduced penetration and that alternative propping arrangements proposed by the contractor were feasible. The approach was subsequently validated by comparing the behaviour of the structure during construction with the predictions.

Recently, for a deep shaft for Crossrail, the use of numerical modelling, together with the application of the Observational Method, enabled more than three months to be saved from the construction programme for a key part of the works at Liverpool Street (Farooq *et al*, 2016). The calibrated numerical modelling demonstrated that planned modifications to the shaft construction (sequence and temporary supports) would not have adverse effects on sensitive infrastructure adjacent to the shaft.

Numerical modelling is able to identify mechanisms that can be used to inform design and to provide a focus for further investigation. However, it is a tool that should only be used to inform judgements. If used properly, it is an extremely valuable weapon in an engineer's armoury, but any tool can be misused and, when used poorly, this can be an extremely dangerous approach, as the Nicoll Highway collapse demonstrated.

It is important that everyone involved in the process recognises the potential risks and opportunities of using numerical methods and the requirement to have an effective management and checking process to ensure that they are used properly.

4 Organisation, roles and responsibilities

4.1 INTRODUCTION

Experience has shown that the way in which a team is organised and operates is key to obtaining a successful outcome from numerical modelling.

This chapter gives recommendations for the organisation and operation of PTs to facilitate more effective use of numerical modelling. This chapter also highlights some common challenges when using numerical models.

The terminology used to describe different roles in a project is defined in the **Glossary**.

4.2 GETTING STARTED

Some of the questions that the PM needs to answer before starting to build a numerical model are similar to other design activities:

- What is the objective ('why do we need to do this?'), and what are the associated risks/opportunities?
- Is there sufficient information and, if not, what extra information is needed (and costs/time to get it)?
- Are the appropriate staff available to carry it out, and to check it?
- What are the costs/timescales for carrying out the work?
- How will the results be reported?

The PM also needs to be aware that numerical modelling is different from many conventional design activities for the following reasons:

- A wide range of information is needed (as discussed in **Chapter 6**) and data from specialist investigations may be needed. Outputs can also be very sensitive to assumed construction sequences – so is project planning sufficiently advanced to define these for analysis purposes?
- The choices and assumptions made in building a model dictate the outputs and their reliability. It is important that an experienced specialist is involved right at the outset, to review the work and ensure that appropriate choices are made. Key assumptions should be communicated with the rest of the PT and with the client to ensure that there is a consensus that assumptions are appropriate. There needs to be buy-in from all parties.
- The level of effort needed to check the inputs and outputs is far larger than for conventional analysis. Typically the cost and time to check a model is several times larger than the time needed to set up and run a model (between two and five times larger, depending on the model complexity or the nature of the code, implicit or explicit). Senior staff are usually required in this checking process.
- Numerical modelling is highly specialist, and there is a danger of poor communication between specialists and non-specialists (as for other specialist activities). The PM should ensure that there is a senior geotechnical engineer (SGE) involved (who has sufficient breadth and depth of experience) to 'translate' or interpret the specialist work, so that the key practical implications are understood by the rest of the PT.

The PM should:

- have a kick-off meeting – agree the objective and application category, key activities and scope of work, use the 'ten steps' process for initial planning (see **Section 4.3**). The flow chart (**Figure 1.3**), summarising the main tasks, is also helpful for initial discussion and planning
- define roles and responsibilities necessary for executing the work (see **Section 4.4**), a RACI table should be prepared for the detailed execution of the work
- ensure a checking plan is prepared and agreed (see **Chapters 5 and 9**)
- implement effective change control, communicate any change that may impact on numerical modelling, across the team – note that the first three points should be reviewed to check if any change has a significant impact on the numerical model
- before completion of the work, ensure that the checking plan is audited, signed off and stored with the modelling files.

The checking effort is mainly dependent on the 'application category' (**Chapter 5**) – this term is used to define the importance of the numerical modelling output for project decision making and design. Is the design wholly reliant on the numerical modelling output or is the design based on simpler calculation methods (and numerical modelling being used to provide supplementary information for the designer)? The answer to these questions will dictate the application category.

4.3 TEN STEPS TO BETTER NUMERICAL MODELLING

Table 4.1 provides a simple summary of the key steps involved in carrying out numerical modelling – 'ten steps to better numerical modelling'. This framework is helpful in demystifying the numerical modelling process, and has helped PMs to:

- ask the right questions to numerical modellers and others in the team before carrying out numerical modelling
- understand the actions they need to carry out to improve the reliability of numerical modelling
- improve communications across the team and help the numerical modelling team obtain appropriate support, for example, obtain appropriate input data and get agreement on key assumptions for the modelling.

It is recommended that **Table 4.1** is used for initial planning, which acts as a useful checklist for all involved and will help the PM focus on the key issues. **Figure 1.3** is also useful – it summarises the sequence of tasks and how they are interlinked.

The ten steps are discussed in greater detail in other chapters of this guide, as indicated in **Table 4.1**.

Table 4.1 Ten steps to better numerical modelling

Step	Description	Comment	See chapter
1	Set objective	Specify why modelling is needed, and which output is critical for design. Discuss with experienced modeller. Assess options and limitations (**Box 5.1 and Figure 5.1**).	3 and 5
2	Select application category	May vary from low risk (informative) modelling through to higher risk (critical) modelling (see **Figure 5.2**, **Table 5.1**, also refer to notes for this table). This will affect the necessary level of checking and seniority of staff involved. Previous experience in the type of modelling and specific application being considered is an important factor.	5
3	Design team organisation	Agree roles and responsibilities, eg **Table 4.2**. Is the modeller also the designer? Information flow across the PT etc. Who checks/approves? The time and budget available are also key factors.	4
4	Competencies and training	Define necessary skills/experience (**Figure 4.3**). Manage future training needs.	4
5	Information for model	Surveys, ground investigations, design/site information, construction scenarios etc. Adequate for scope/complexity of modelling? (**Figures 6.1**, **6.2**)	6
6	Simplifications and assumptions	Some idealisations are always necessary and need to be stated clearly. All assumptions and data sources should be described, communicated/agreed across PT and with the client (**Table 7.1**).	7
7	Calibrations	What type of calibrations will be carried out, eg element, component or case history checks. Important to assess model output reliability	8, 9, Appendix
8	Robustness	Some sensitivity studies are necessary to check for 'cliff-edge' effects.	8 and 10
9	Checking	Both of inputs and outputs, independent of originator (**Tables 9.1 to 9.3**).	9
10	Reporting	Broken down into three parts: assumptions, factual reporting of the analysis, and interpretation of output (often this will be the most complex task!).	10

Notes

Suggested project application

Stage 1 – Use 'ten steps' for 'kick-off' meeting. Assess the application category – see Note – and level of PA required.

Stage 2 – Define roles and responsibilities, prepare a RACI table, for execution of the work (**Table 4.2**).

Stage 3 – During initial model development, a checking plan is prepared.

Stage 4 – Review regularly through project, especially if changes occur.

Stage 5 – Before completion, the checking plan is audited, signed off and stored with modelling files.

Application category – how critical is the modelling?

There are three different categories: informative, important and critical.

- **Informative.** The modelling is being used as a secondary tool for decision making, and alternative conventional methods are being used to produce the design or project assessment.
- **Important.** The modelling is a primary tool for decision making. However, extensive precedent experience is available, or simple methods are also relevant to independently check key issues. For example, structural stability ULS, checks can be carried out by conventional analysis, and modelling is being used to assess deformation SLS or potential effects of various construction sequences.
- **Critical.** A complex modelling application, with little specific precedent experience – simple methods are not appropriate. For example, for structural design, both stability (ULS) and deformation (SLS) are reliant on modelling results.

Depending on the modelling category, the necessary level of checking, testing and validation will vary and will influence the seniority of the staff involved. Critical is the most challenging application category and will require considerable PA input and extensive cross-checking of assumptions, inputs, outputs etc.

4.4 ROLES AND RESPONSIBILITIES

A RACI table is often used by PMs to allocate the roles and responsibilities of PT members. **Table 4.2** provides an example of a RACI table for carrying out numerical analysis for a large project. The terms used, defined in the table, are:

R – Responsible

A – Accountable

C – Contribute

I – Inform

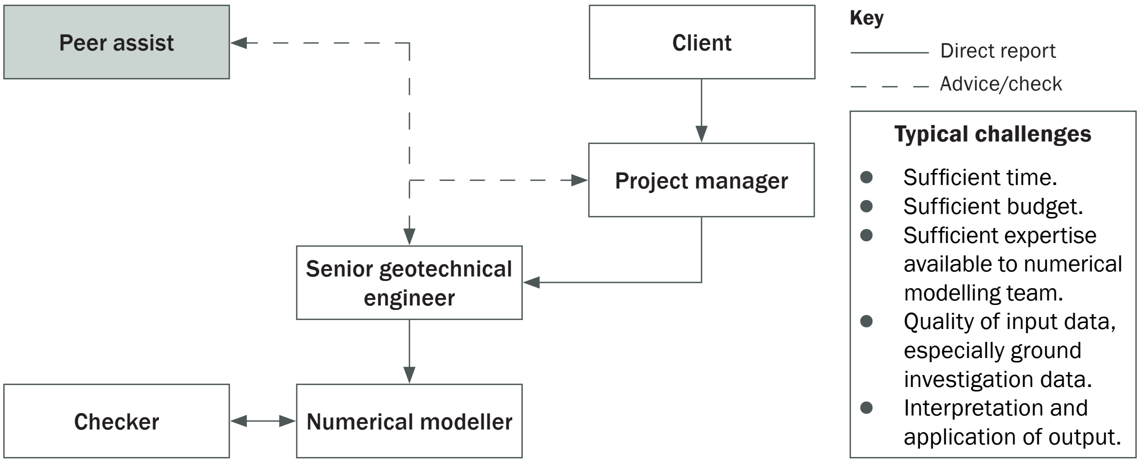
It is worth noting that several disciplines within a PT may have to 'contribute' to the numerical model. Also, if the project falls within CDM 2015, and the outputs will be used for subsequent design, then the PD (as defined within CDM 2015) may need to be involved in the modelling, to agree inputs/assumptions and subsequent application of outputs from a numerical model. For complex projects, PMs have sometimes found it helpful to prepare flow charts after a RACI table has been agreed to clarify the flow of information (before, during and after the numerical model has been completed) between the different parts of a PT, and between the PT and relevant external parties.

4.5 SOME COMMON CHALLENGES

Common challenges for all projects that use numerical models include:

- the specialist nature of numerical modelling (and senior staff with specialist expertise are relatively scarce)
- the need for a wide range of information to be available, in order to build a reliable numerical model, compared with conventional analytical and empirical design methods
- the potential for a 'generation gap' between (often) relatively inexperienced professionals who carry out numerical modelling (who may be technically skilled in numerical modelling but may lack the broad awareness of design/construction issues) and more experienced professionals who may be leading design teams or acting as PMs (but who often lack specialist knowledge of numerical modelling)
- the high risk of abortive work if the objective for the numerical model is poorly defined, if input data, eg historic construction, ground investigations, details of structures etc (**Chapter 6**), is inadequate, or the construction sequence changes.

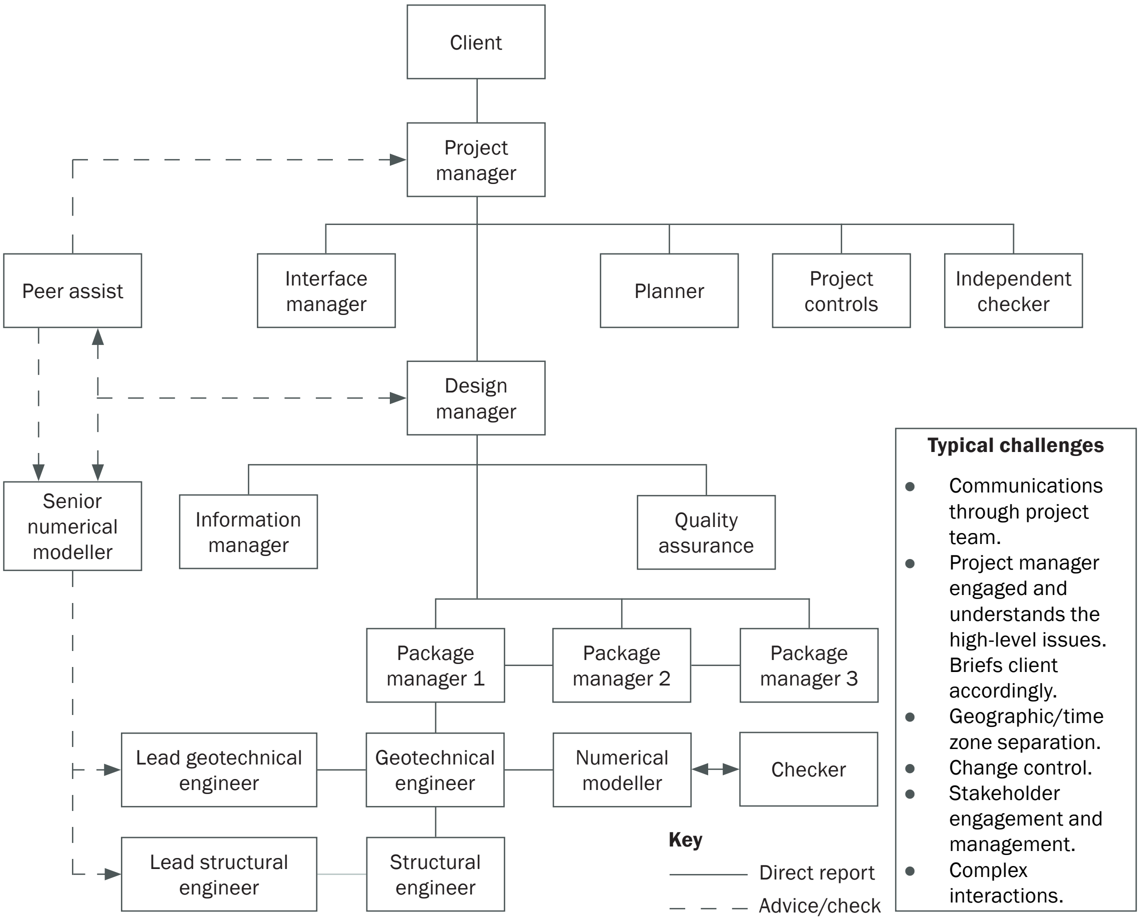
Teams can be organised in many different ways, depending upon the scale and complexity of the project. For the purposes of illustrating some of the issues, **Figures 4.1 and 4.2** provide organisation charts for a 'small' and a 'large' project, respectively. These are briefly discussed in the following subsections.



Typical challenges

- Sufficient time.
- Sufficient budget.
- Sufficient expertise available to numerical modelling team.
- Quality of input data, especially ground investigation data.
- Interpretation and application of output.

Figure 4.1 Example of an organisation chart for a small project



Typical challenges

- Communications through project team.
- Project manager engaged and understands the high-level issues. Briefs client accordingly.
- Geographic/time zone separation.
- Change control.
- Stakeholder engagement and management.
- Complex interactions.

Figure 4.2 Example of an organisation chart for a large project

4.5.1 'Small' projects

Small projects will typically be characterised by limited time and budget, perhaps one or two months for analysis and design team input, or even less. The geotechnical team is likely to be relatively small, for example, a numerical modeller (who is also carrying out more routine geotechnical engineering) and a SGE who is also supervising the numerical modelling (**Figure 4.1**). This may be a major constraint for checking and review of the numerical model, particularly if the senior engineer does not have modelling expertise and cannot properly check the numerical modeller's work. Such circumstances might arise in a small organisation where the available specialist resources are limited. Experienced input is necessary from the start, so the appropriate numerical modelling strategy is selected and adequate checking of the initial run. Late identification of errors or a flawed strategy would be a serious challenge for project delivery, because there would be inadequate time for corrections to be made at a late stage. The quality of ground investigation may often be a problem, typically the GI will not be designed with numerical modelling in mind. For this situation, it will be important to set a realistic objective and application category (**Chapter 5**). Ideally, the geotechnical engineers with appropriate experience in numerical modelling will be involved in reviewing available information and specifying additional ground investigation, if deemed necessary.

4.5.2 'Large' projects

The geotechnical team is likely to be supporting multiple design 'packages' (**Figure 4.2**) and communicating with several different 'package managers' or design team leaders (who typically will be co-ordinating multi-disciplinary inputs to deliver a specific part of a large project). They report to the DM or to the PM. Ensuring that there are effective communications – both upwards to the PM and client and downwards from the PM to the specialist modelling teams and across the different disciplines – can often be very challenging.

Change control can also be challenging, eg ensuring changes to construction sequences are communicated to the modelling team. The PM of a large project will have many responsibilities (and often may not be a chartered engineer), and so it may be difficult for the PM to engage with, and understand, the numerical modelling being carried out. In this situation, the SM or senior engineer carrying out peer assist (PA) needs to have appropriate authority and good communication skills to be able to highlight the key issues to the PM, so that the practical implications can be understood.

4.6 TECHNICAL STAFF TO BUILD AND CHECK A NUMERICAL MODEL

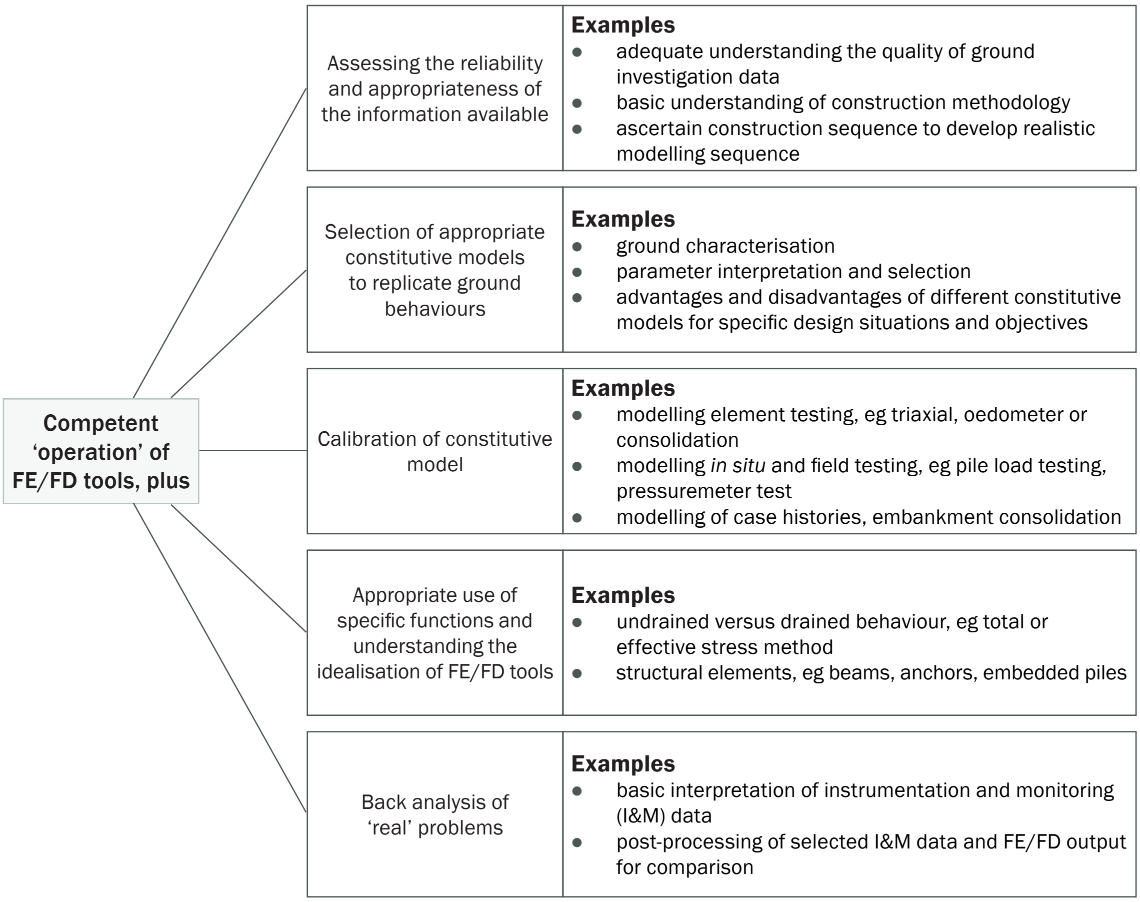
In addition to the modeller, the following technical staff are typically required:

- **Senior geotechnical engineer (SGE).** Typically the SGE will be chartered and have a broad range of geotechnics experience. The SGE will be responsible for specialist input to a project.
- **Senior modeller (SM).** If the SGE does not have specialist expertise in numerical modelling then it is important that they have support from a SM with the necessary expertise to review and check the work of less experienced modellers.
- **Peer assist (PA).** For numerical modelling that is categorised as important and, particularly, critical (see **Table 4.1 and Chapter 5**) it will also be important to identify a senior engineer who can act in a peer assist role (see **Glossary**). It is important for them to have experience in the practical application of numerical modelling and have a breadth of expertise in geotechnical design. They should be involved at the early stages to challenge the team on the objectives, the available input data and assumptions, the calibration of the model and to provide proactive guidance.

The geotechnical triangle

1. Geology and hydrogeology site and surroundings, depositional environment.
2. Soil/rock behaviour – fundamentals: stress/strain/time
3. Analysis/calculation – simplification/assumptions, methods/models/parameters
4. Judgement/well winnowed experience – case history data, technical literature, reality vs. assumptions, consequences of failure
5. Site verification (feedback loop) and construction process.

Figure 4.3 The geotechnical triangle, foundation engineering applications



Assessing the reliability and appropriateness of the information available	**Examples** ● adequate understanding the quality of ground investigation data ● basic understanding of construction methodology ● ascertain construction sequence to develop realistic modelling sequence
Selection of appropriate constitutive models to replicate ground behaviours	**Examples** ● ground characterisation ● parameter interpretation and selection ● advantages and disadvantages of different constitutive models for specific design situations and objectives
Calibration of constitutive model	**Examples** ● modelling element testing, eg triaxial, oedometer or consolidation ● modelling *in situ* and field testing, eg pile load testing, pressuremeter test ● modelling of case histories, embankment consolidation
Appropriate use of specific functions and understanding the idealisation of FE/FD tools	**Examples** ● undrained versus drained behaviour, eg total or effective stress method ● structural elements, eg beams, anchors, embedded piles
Back analysis of ‘real’ problems	**Examples** ● basic interpretation of instrumentation and monitoring (I&M) data ● post-processing of selected I&M data and FE/FD output for comparison

Note

Required skills/knowledge based on the geotechnical triangle (**Figure 4.3**), ie three key components: geology/hydrogeology, soil/rock behaviour and analysis idealisation/applied mechanics, together with adequate understanding of the construction processes and ‘well-winnowed’ experience.

Figure 4.4 Additional skills and knowledge required for numerical modelling

4.7 COMPETENCY AND TRAINING OF NUMERICAL MODELLERS

Currently, no means of assessing the competency of numerical modellers (recognised and accepted across the industry) is available. An EU-funded research project (a part of the Leonardo Da Vinci Transfer of Innovation research programme, known as competency in geotechnical analysis [COGAN]) has provided a basis for future objective assessments of competency in geotechnical numerical analysis. It is a comprehensive system that can be used by numerical modellers through various stages of their career, from early 'novice' level through to reaching 'expert' level skills. The competency system is now maintained by the NAFEMS Geotechnical Working Group. The group is developing the system, so that it is easier to use for those who wish to develop a basic level of competence.

The COGAN initiative can be found at: **http://cogan.eu.com/**

Training in numerical analysis usually begins during postgraduate studies (masters, but more often as part of PhD research) in soil or rock mechanics (following graduation in civil engineering). However, there is an important transition from academic numerical analysis to practical applications which requires the aspirant modeller to be mentored by a SM (in the author's experience over a period of several years). A competent SM would typically have more than ten years' experience in practical applications of geotechnical numerical analysis. There are several short industry courses (several days' duration), but attendance at one of these, although helpful, does not mean that an attendee would be described as 'competent' to undertake analysis unsupervised. Some of these courses are simply aimed at allowing a user to run a particular software package (which buttons to press) and do not provide a clear understanding of the theory behind the code.

It is the authors' view that a high level of understanding in soil/rock mechanics (typically obtained from masters or doctorate level studies) is a prerequisite for carrying out numerical analysis – a first degree in civil/structural engineering alone does not provide sufficient knowledge.

The range of knowledge required for a numerical modeller can be illustrated through a modification of the geotechnical triangle. (**Figure 4.3** illustrates the geotechnical triangle discussed by O'Brien and Burland (2012) for geotechnical engineering.) **Figure 4.4** has been developed specifically for assessing the training needs and competence of numerical modellers. Numerical modelling software should not be used as a black box with little understanding of the inputs and outputs. So, only being able to operate the software and produce results is insufficient. Competent numerical modellers need to have several additional skills, as outlined in **Figure 4.4**, and they should be able to:

- assess the reliability and appropriateness of the information available
- select appropriate constitutive models to replicate ground behaviour for specific applications
- calibrate key behaviour of a constitutive model to represent ground behaviour and key components (such as anchors/piles etc)
- use specific functions appropriately and understand the idealisation of the modelling tools
- carry out back analysis of 'real' problems (typically well-instrumented case histories reported in the technical literature).

Geotechnics is both an art and a science, and the geotechnical triangle provides a summary of the skills and knowledge needed for successful geotechnical engineering. Numerical modellers will tend to focus on the science (eg soil/rock mechanics) during the early phases of their development, but it is essential that they develop their skill in the art of geotechnics (well-winnowed experience, case histories and construction processes) in order to make good judgements about how best to build, test and calibrate a model and how to interpret the output.

Table 4.2 RACI table – example for an numerical modelling application for a large project

Task		Responsible	Accountable	Contribute	Inform
1	Why?	Lead geotechnical engineer	DM		
2	Agree application category	DM	PM	PM/senior numerical modeller/PA	Client/PT
3	Agree budget	PM	Client	Lead geotechnical engineer/senior numerical modeller/PA/DM	
4	Agree programme	PM	Client	Lead geotechnical engineer/senior numerical modeller/PA/DM	
5	Communication process	DM	PM	Lead geotechnical engineer	Client/senior numerical modeller/PA
6	Select numerical model team – delivery	Lead geotechnical engineer	DM	Senior numerical modeller/PM	PA
7	Agree checking	Lead geotechnical engineer	DM	Senior numerical modeller/PM	PA
8	Identify PA	DM	PM	PA/lead geotechnical engineer/DM	Senior numerical modeller
9	Agree key inputs/assumptions	DM	PM	PA/lead geotechnical engineer	Client/PT
10	Agree outputs and criteria for application	DM	PM	PA/lead geotechnical engineer/ senior numerical modeller/PD	Client/PT
11a	Information for model – site ground and groundwater conditions	Lead geotechnical engineer	DM	Senior numerical modeller/PM	
11b	Construction sequence	DM	PM	Senior numerical modeller/PT/PM	
11c	Structural inputs (if applicable)			Senior numerical modeller/PD/PM	
11d	Existing infrastructure (if applicable)			Senior numerical modeller/EP/ PT/PM	
12	Build model	Senior numerical modeller	Lead geotechnical engineer	PA	DM/PM
13	Carry out calibrations	Senior numerical modeller	Lead geotechnical engineer	PA	DM/PM
14	Test model	Senior numerical modeller	Lead geotechnical engineer	PA	DM/PM
15	Produce outputs	Senior numerical modeller	Lead geotechnical engineer	PA	DM/PM
16	Carry out in-house checking	Senior numerical modeller	Lead geotechnical engineer	PA/DM	
17	Prepare numerical model report	Lead geotechnical engineer	DM	Senior numerical modeller/PA	Client/PT/PD/IC
17a	Assumptions				
17b	Factual summary	Lead geotechnical engineer	DM	Senior numerical modeller/PA	Client/PT/PD/IC
17c	Interpretation of outputs				
18	Application of outputs for planning and design	DM	PM	PD/client/lead geotechnical engineer/PT	Senior numerical modeller/IC

Notes

Responsible. The role or person or entity that is assigned the role type 'responsible' is the one who performs the work, ie they are the 'doer' of the task or activity. The person who is 'responsible' does not need to be accountable for that task.

Accountable. The person or role who has the final authority and accountability for a given task. For any given task, there is only one role/ person accountable. Accountability cannot be delegated to other roles or individuals or entities.

Contribute. The people/roles who contribute and provide advice before and during the task. When there are many people who are assigned 'contribute' roles, the time taken to accomplish the task increases. However, too few or no 'contribute' roles assigned to a task means that the task has the risk of being under-performed.

Informed. The people/roles who are informed after the task is completed. 'Informed' roles should be assigned properly, otherwise there is a risk of miscommunication and delays. The responsible team member need to ensure the right people are informed after a task is successfully performed.

PT: other members of the PT, which may include other disciplines (eg structural engineers, planners), contractors (if design/build).

PD: if outputs from the numerical model are used for design then CDM 2015 may apply (UK projects), and a PD will be appointed.

IC: for large/complex projects an independent checker (IC) may be appointed (ie organisation independent of the PT).

5 Specifying the objective and application category

5.1 INTRODUCTION

A numerical model needs to be built in the computer, as discussed in **Chapter 2**. For the numerical modeller to build the correct type of model it is important to set a clear objective at the start, ie produce a specification and agree this with the team.

This chapter discusses:

- specification of the numerical modelling objective
- selecting an appropriate application category
- application of numerical modelling outputs, especially code requirements (many codes were written before numerical modelling became common, and there can be specific challenges which PTs need to be aware of).

5.2 SPECIFYING THE OBJECTIVE

Numerical modelling may be required for a wide range of reasons (as discussed in **Chapter 3**) during different phases of a project, for example to:

- calculate the settlement of a building foundation or ground movements adjacent to earthworks
- calculate forces in a new foundation, props, retaining wall or a tunnel lining to enable structural design to be completed
- assess potential interaction effects between new and existing infrastructure to determine the impact of construction on these assets (forces, displacements etc)
- assess potential cost/time savings, if conventional calculation methods are deemed to be over-conservative
- decide whether a single 'best estimate' is required (this is generally unwise and not recommended) or, more sensibly, an examination of sensitivities
- decide whether analysis is required for planning purposes, ie to understand mechanisms of behaviour, based on an analysis of different scenarios, which may support preliminary design, planning of further investigations, or the instrumentation and monitoring of a structure.

A numerical model can produce a plethora of outputs, however, as outlined in **Box 5.1**, for a model to be built and checked cost-effectively it is necessary to specify at the outset which output will be important for subsequent design work. Once the objective is specified then the modeller can build the model and make the appropriate choices to ensure that the required output is as reliable as possible (eg the design of the mesh might be finer where results are required and coarser elsewhere – see **Box 2.2 and Figure A1.2**).

If several different objectives are specified, the PM needs to appreciate that the model will often be more expensive and time-consuming to build and check. Also, further ground investigations (or other surveys) may be necessary, depending on the specific design situation and specified objective. So to avoid wasted effort it is sensible to have a clear and realistic objective.

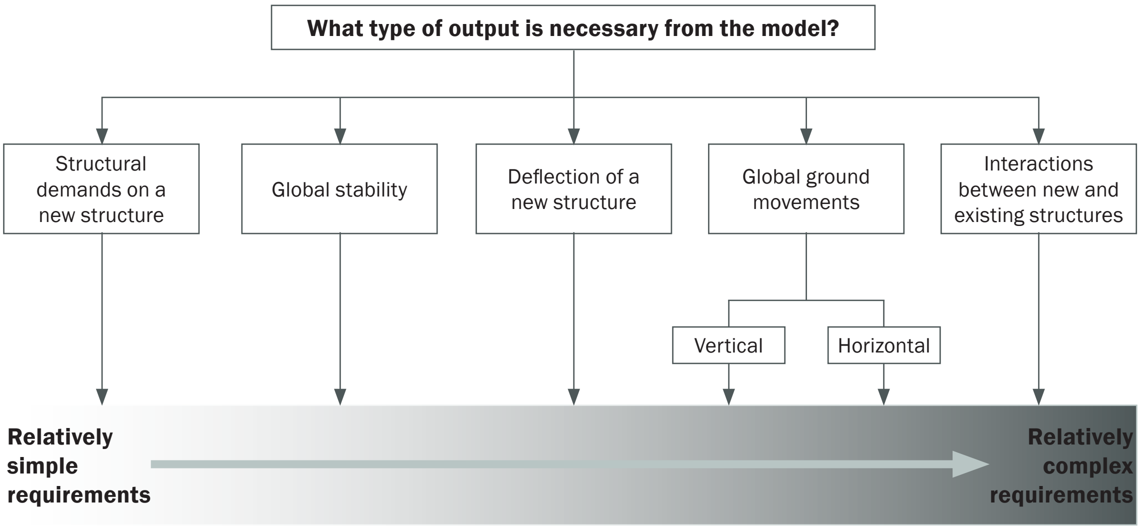
Box 5.1 Why specify the objective for numerical modelling?

Issue	Comment
Why specify the objective for numerical modelling?	A numerical model needs to be built in the computer, and similar to physical construction, choices and compromises need to be made, depending on the specified objective, due to, for example, limited time and budget, limitations in available ground investigation data and limitations in how ground–structure interaction and ground behaviour can be simulated. Depending on the objective a model can be built in many different ways. If the objective changes, then there is a high risk that the numerical model will need to be rebuilt. Depending upon how the model is built, some of the outputs that are not the main focus of the analysis may be unreliable and could be wildly misleading (this applies for most models, due to intrinsic limitations, and is not necessarily a reflection of the quality of the model or of the competence of the modeller). A model will be built in all cases for a specific purpose. It should be assumed that it only produces specific outputs, that are consistent with the specified objective, for use only by others in the PT.

All practical numerical modelling applications will involve a trade-off between simplicity and complexity. Typically, part of a model will be quite refined, and other parts will be relatively crude, based upon the modeller's judgement of what will be important or not for the specific objective. As such, the model may be inappropriate if the objective changes during project development. If the objective changes, then it may be necessary to:

- rebuild the model – different parts of the model may need to be reconstructed, eg a finer mesh built or a different element type selected
- rerun the analysis using a different set of input parameters
- rerun the analysis using a more sophisticated stress–strain model for a soil layer (or a structural component) possibly requiring an additional ground investigation to obtain the necessary parameters
- change the structural details to reduce any adverse effects
- build a three dimensional (3D) model, rather than rely on a two dimensional (2D) model.

Figure 5.1 gives a simplified summary of the relative complexity of different objectives for numerical modelling, based on the authors' experience. It should be borne in mind that this is a generalised indication only, and there can be site-specific exceptions. However, it is usually the case that an assessment of interaction effects between new and existing structures is more demanding than an assessment of structural demands on, for example, a proposed retaining wall. The reason for this is that calculation of interaction effects usually requires more sophisticated stress–strain models, the mesh will usually need a greater level of refinement, and the existing structures will need careful modelling as well as the proposed new structure.



Notes

- General guidance only, project specific issues may change level of complexity.
- Typically, short-term behaviour is less challenging than long-term behaviour (due to reliability of data usually available, eg consolidation/swelling/creep characteristics, availability of case history data) and associated model calibration difficulties.
- Experience indicates that the reliable calculation of interaction effects between new and existing structures requires the use of well-calibrated advanced constitutive models.

Figure 5.1 Relative complexity of numerical modelling objectives

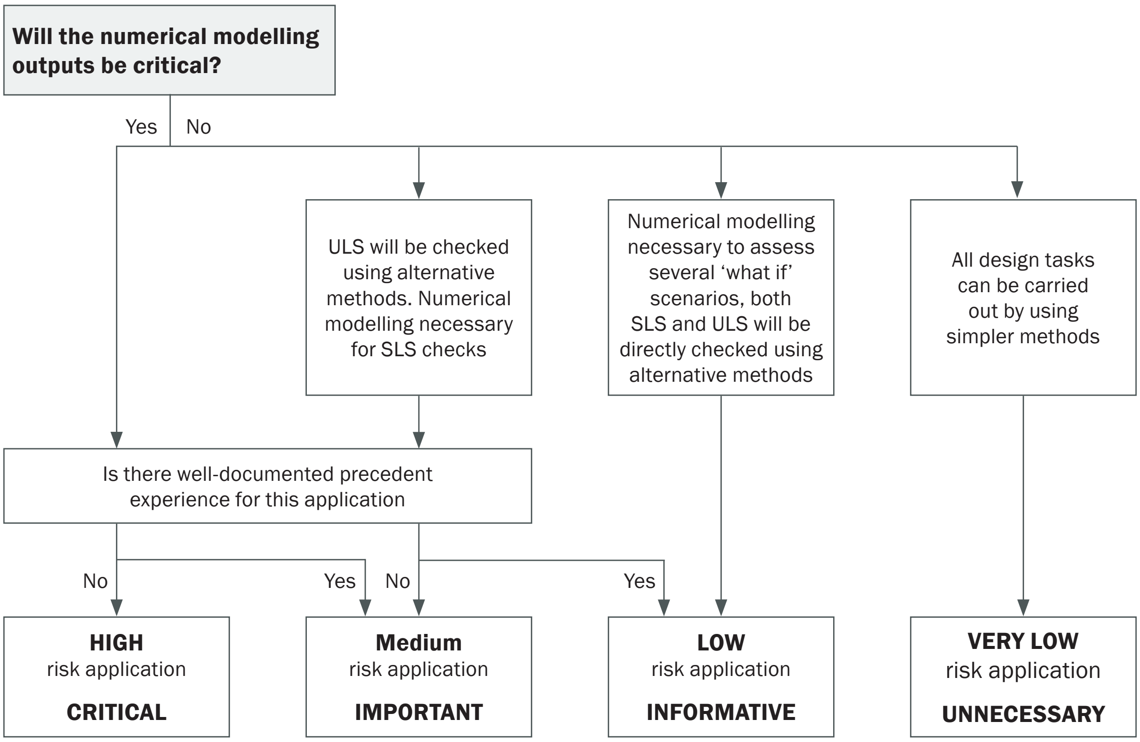
5.3 APPLICATION CATEGORY

To ensure that the scope of checking is adequate, it is strongly recommended that the PM (following consultation with the SGE) uses **Figure 5.2 and Table 5.1** to assess the appropriate application category for the numerical model. The application category simply defines the level of importance of the outputs for supporting design decisions. Deciding upon the appropriate application category is a key step in managing risk and in properly identifying the necessary scope of checking and the seniority of the staff who should be involved.

There are three different categories, 'informative' (low risk), 'important' (medium risk) and 'critical' (high risk), see **Figure 5.2**. Questions that should be considered before agreeing the application category include the following:

1. Is there well-documented experience (eg relevant case histories) for the particular application (considering the proposed works, site geology, hydrogeology etc)?
2. Can simple conventional calculation methods be used to independently check the reliability of the numerical model outputs either in whole or in part?
3. Will the design be based on simple conventional methods for ULS checks or SLS checks?
4. Is numerical modelling just being used as a tool for judging sensitivity to various scenarios that cannot be assessed via conventional methods (eg different construction sequences)?
5. What are the consequences if the output from the model is unreliable? For example, if a calculated ground movement is too high or too low what are the practical consequences likely to be?

Based on careful consideration of these questions the numerical model application should be categorised appropriately. Ultimately, it is a matter of judgement by the senior professionals responsible for the project. This is a key PT decision and should be communicated across the PT, and the PM should be involved in the decision.



Notes

1. The application category dictates the level of checking necessary, and the scope of documentation to assess and verify that the model outputs are reliable. The application category will also dictate the seniority of the staff involved in reviewing and checking the model outputs.
2. Where feasible, conventional methods (analytical or empirical) should be used for preliminary estimates before numerical modelling.

Figure 5.2 Defining the application category for numerical modelling

Table 5.1 Application category, risk and checking effort

Risk level	Typical applications	Checking effort
'Informative' low risk	Assess behaviour trends. Qualitative comparison between different scenarios, eg construction sequence A vs. B.	Comparisons between simple analytical/empirical methods versus selected numerical model output. Qualitative judgement and experience by SGE (or SM). Spot-checking of inputs and outputs by independent modeller.
'Important' medium risk	Quantify some aspect of behaviour or design component, eg movement calculation only. ULS will be checked using conventional methods. Well-documented precedent experience exists.	Comprehensive and formalised checking of inputs and outputs by SGE (or SM). Document model calibration and relevant experience. Independent PA necessary.
'Critical' high risk	Design decisions totally depend on model outputs, eg movement, geotechnical and structural strength checks, ie all ULS/SLS checks. Conventional methods have limited applicability or there is limited precedent experience.	As for 'medium risk', but more extensive independent PA (may need several senior staff to review multi-faceted aspects of a large complex model) is necessary to challenge the project and numerical model team. Several components of model should be tested, calibrated and verified. Full documentation necessary to support the credibility and reliability of output. Extensive sensitivity studies are typically required to understand failure modes or 'cliff-edge' effects.

Notes

The application category dictates the level of checking necessary, and the scope of documentation to assess and verify that the model outputs are reliable. The application category will also dictate the seniority of the staff involved in reviewing and checking the model outputs.

'Cliff-edge' effects refers to a situation when the numerical model calculates large changes in output values for small changes in input values.

If the numerical model is to be used in a low risk application, it will be inappropriate to involve senior staff in comprehensively checking and documenting the model calibration. However, if the numerical model is a high risk application, it will be essential to have a senior engineer with the relevant expertise review and challenge the numerical model (and any associated design) so that the checking and calibration process is comprehensive and fully documented.

An example of a low risk application is shown in **Figure 5.3**. This involves the construction of a highway embankment on a compressible layer of clay. It is a greenfield site, remote from any sensitive infrastructure. The important project issue is the long-term residual settlement, after the highway embankment has been constructed. For this situation, there are conventional methods of calculating total settlement and rate of settlement based on 'textbook' consolidation theory. It is also possible to check short-term and long-term stability by using conventional (and relatively simple limit equilibrium) methods. Numerical modelling is not essential, but it can be helpful as a mean of checking a number of different situations (eg influence of different construction periods or relative effectiveness of different techniques to reduce residual settlement, such as deep drainage or ground improvement). Technically, this might be challenging, but it would be classified as low risk or informative because there are several conventional methods of assessing the key output, and the consequences associated with erroneous output are not particularly severe in terms of serviceability.

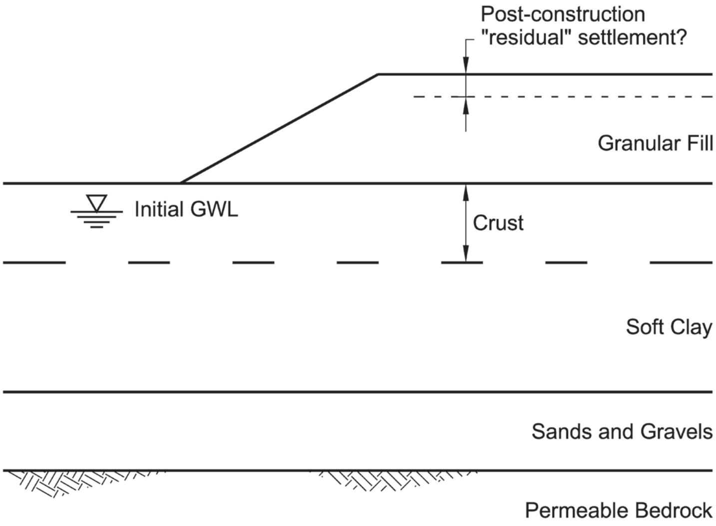


Figure 5.3 Example of low risk numerical modelling application – residual settlement of highway embankment

A high risk example is shown in **Figure 5.4**, which involves the structural design of a tunnel lining for a non-circular sprayed concrete lined tunnel to be built in close proximity to existing tunnels and a new shaft, as part of an underground station. The tunnel is located beneath a densely populated urban area. The key output is the structural force in the tunnel lining, which will be used for the final structural design of the tunnel. There is no precedent experience for a tunnel of this shape and depth at this location. Conventional analytical methods are inappropriate because they cannot account for interaction between the different sub-surface structures. So, this application is considered to be a high risk or critical application, because there are no simple ways of checking the reliability of the output, and the consequence of erroneous output is very severe.

Figure 5.4 Example of high risk numerical modelling application – structural forces in SCL tunnel lining

5.4 SPECIFYING THE NUMERICAL MODEL OBJECTIVE – AN EXAMPLE

Figure 5.5 shows an excavation supported by a propped embedded retaining wall. This is the type of situation for which numerical modelling might be required. However, there could be several different objectives for the analysis, such as:

1. Calculating displacements of, and structural forces in, the wall and support systems (props etc).
2. Calculating the greenfield settlement trough and lateral movement behind the wall.
3. Calculating long-term heave at the base of the excavation (assuming that a void is left below the base slab).
4. Modelling the interaction between the proposed works (deep excavation/embedded retaining wall) and the existing infrastructure (building and utility) explicitly (ie the utility and building are included in the model), to calculate the distortion of the building and utility.

Table 5.2 provides a commentary on the modelling considerations for each of the objectives (or outputs) listed here from a numerical model.

As outlined in **Table 5.1**, each of the objectives would require different choices to be made by the modeller, in order to obtain reliable model outputs. The choices may include:

- selecting different types of stress–strain model
- building a larger and more refined model
- selecting different types of elements to include in the model.

Depending upon which of the four objectives is required will also have a major effect on the type of information that needs to be obtained (there may be a need to obtain additional survey data, for example). The cost and time required to build, test and check the model will also vary significantly from, eg Objective 1 (relatively cheap) to Objective 4 (relatively expensive). So, careful specification of the objective for the numerical modelling is essential if the analysis is to be carried out efficiently, reliably and in a timely and cost-effective manner.

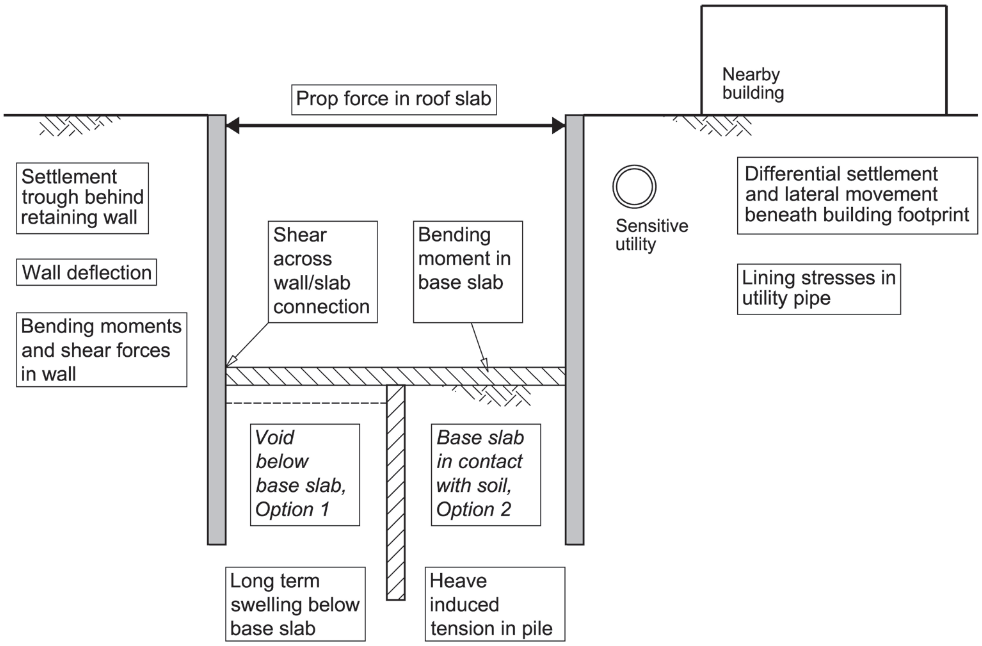


Figure 5.5 Specifying numerical modelling objective example – propped retaining wall in over-consolidated clay in urban area, also refer to Table 5.2

Table 5.2 Examples of some modelling considerations for Figure 5.5

Required objective from numerical modelling	Comments
Bending moments/shear forces in wall Wall deflection	Typically, the simplest requirement, adequate outputs can usually be obtained from relatively simple stress–strain soil models, especially for 'stiff' walls, when critical stages are short-term. Care is needed for multi-propped/anchored flexible walls when soil arching becomes more significant, and/or if transient time-dependent soil behaviour is important (eg partial consolidation/swelling during critical construction stages).
Prop force	Level of complexity will depend on several factors. See Powrie and Batten (2000b) and Twine and Roscoe (1999). Should check outputs against empirical methods and relevant case history data. Temperature effects can be important. If multiple levels of temporary props, then critical stages can occur during removal of props. Simulation of prop/wall connections, and structural load transfer system (eg waling beams) can be challenging, especially within 2D models.
Settlement trough	Simple, and commonly used, linear elastic perfectly plastic soil stress–strain models will be inadequate and will give misleading outputs. Will be necessary to use non-linear small strain stiffness model for 'competent' soils (over-consolidated clays, dense sand, weak rock).
Differential settlement and lateral movement beneath building footprint	Building will influence differential movements, relative to greenfield, depending on the nature of foundation/sub-structure configuration and structural strength/stiffness. It may be necessary to also include the building in the numerical model.
Lining stresses in utility pipe	Stiffness and configuration of lining (presence of joints etc) will significantly influence lining stresses. Condition of utility pipe (deterioration?) will be a key consideration.
Long-term swelling below base slab	For 'competent' soils, which are typically heavily over-consolidated with anisotropic stiffness (higher in horizontal than vertical direction), the modeller will normally need to make a choice (if, as is usually the case, the soil model is isotropic) to either select input parameters to simulate horizontal behaviour (eg wall bending moment/deflection) more accurately (and accept vertical behaviour will be incorrect) or vice versa.
Shear across wall/slab connection Bending moments in base slab Heave induced tension in pile	Base slab bending moment and shear force across wall/slab connection will depend not only on careful selection of vertical stiffness and soil strength in triaxial extension, but also on appropriate simulation of structural restraints and boundary conditions (eg rotational stiffness of wall/slab connection, load–deformation behaviour of tension pile, and simulation of pile stiffness within 2D model, selection of structural element type, ie plate or solid element).

5.5 APPLICATION OF OUTPUT, GENERIC ISSUES TO BE CONSIDERED

Some of the key issues that need to be considered when a numerical model is deemed to be required are discussed here:

1. **Use of output from numerical models.** Once the objective has been specified, the SGE (or SM) can discuss with the PM (or design team leader, depending upon project organisation), if any points of detail need to be clarified. A common scenario (especially on larger projects) is for the output from the model to be passed on to a separate design team or organisation. Understanding how the output will be used and communicated to others is important. The likely limitations of the model should also be discussed and communicated. If the output is likely to be used for design of component(s) for the proposed construction, then some thought is needed. Currently (2020), most international codes being used for structural and geotechnical design were not written on the basis that numerical models would be used for design. This is discussed in more detail in point 2b.
2. **Code requirements.** Some code requirements cannot easily be included within a numerical model. Some examples include:
   a. Applying partial factors to ground strength for stability (or ULS) checks – when and how these are applied can make a significant difference to the outputs of the numerical model. Applying a factored soil strength at the start of an analysis may not be compatible with other assumed inputs, such as *in situ* stresses or soil stiffness, which may result in unrealistic deformation/failure modes being calculated. Usually, it is better to run an analysis with all soil inputs unfactored, and then only apply factors to soil strength for a construction stage of interest (rather than at the beginning). An alternative is to run the whole analysis with unfactored parameters throughout, and then apply code-required factors to outputs (Potts and Zdravković, 2012).
      Figure 5.6 illustrates these 'input factoring (at key stages)' and 'output factoring' approaches. Lees (2016) recommends that both factoring methods are applied to assess the most critical scenarios for structural and geotechnical design. Input factoring tends to be most onerous when global deformation (ie when 'weaker' ground) is significant and dominates the critical failure mechanism. In contrast, output factoring tends to be most critical for checking piles, anchors etc, where the interface strength (between ground and the resisting structure) dominates the critical failure mechanism. Output factoring often provides the critical design forces for structural design, although this is not always the case. It should be noted that input factoring may only be practical when relatively simple failure criteria are used (eg Mohr–Coulomb).
      Although, theoretically it may be possible with more advanced models (where the ground strength evolves during the analysis, depending on the stress path or effective stress), it may not be practical to use input factoring, and some programs do not allow this to be done. If this is the case, alternatives then need to be considered, eg just relying on output factoring or using an advanced model for SLS checks and a simple model for ULS checks.
   b. Applying minimum water pressures, minimum earth pressures for earth retaining structures, applying maximum shear resistance or end-bearing resistance for deep foundations. Many codes of practice or standards specify minimum disturbing forces/pressures and maximum resisting forces/pressures. The applied pressures and the resistance developed evolve during the numerical analysis, as a result of the interactions that develop within the numerical model. Under some circumstances it may be possible to apply limits in a model but this is a complex process and it is not always possible or sensible to do so (because of adverse side-effects which may be generated). Some programs do this automatically and it is another instance where the black box approach can be dangerous, and the consequences of imposing artificial limits need to be carefully scrutinised.
   c. Applying partial factors to a part of the ground/structure resistance – some codes require a partial factor on resistance, eg a partial factor on passive earth pressure. As for point 2b, it is usually unwise (and often impractical) to attempt to apply this type of requirement within a numerical model.

If numerical modelling outputs are to be directly used for design, then before running a model, the specific requirements of the relevant code need to be reviewed and considered. The extent to which code requirements can be met will need to be assessed, recognising that not all requirements can always be dealt with directly within a model. Usually it is possible to accommodate these requirements, either by reviewing and modifying outputs, by modifying the design of the model or, if the code is sufficiently flexible, using the outputs slightly differently from those obtained from conventional analytical methods (or design software written specifically for particular codes).

When numerical modelling is being relied upon for ULS checks, the SGE (supported as necessary by an SM) needs to carefully consider how code requirements can be practically implemented, and brief the rest of the PT. It is important that this is done at an early stage. Occasionally, it may not be possible to use numerical modelling for ULS checks if the code is particularly restrictive. The way in which particular code requirements are interpreted is subjective and, if ICs are involved, it would be worthwhile discussing and agreeing an approach beforehand to avoid abortive work or contradictory interpretation.

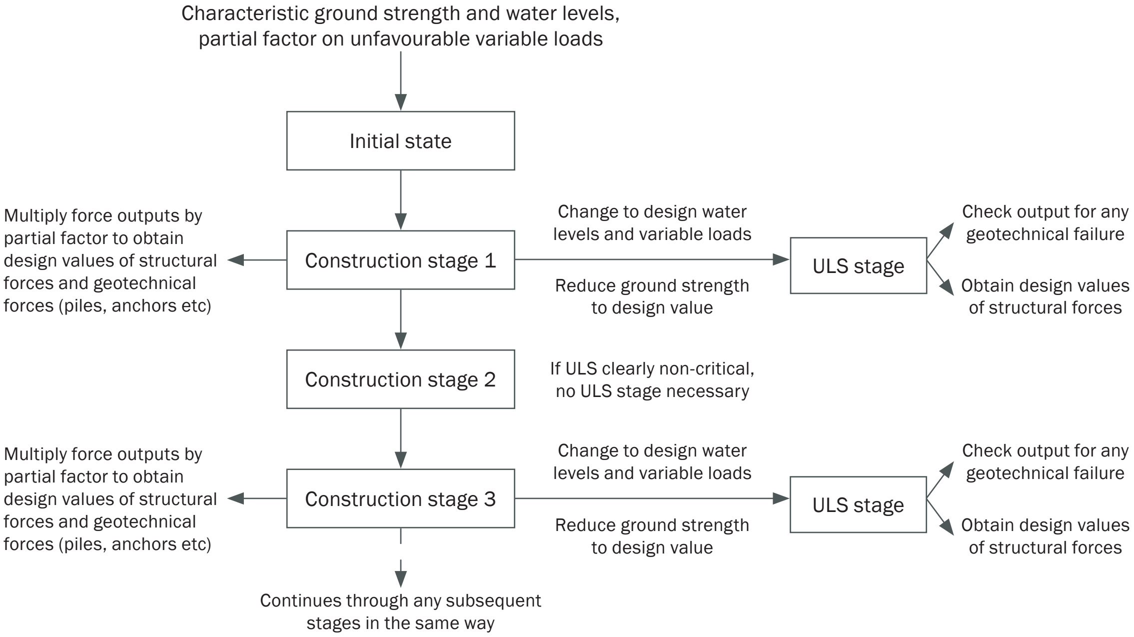


Figure 5.6 Dual factoring approach with strength reduction at key stages during numerical modelling

6 Information for model

6.1 INTRODUCTION

The need for suitable information should be recognised right at the outset of the numerical modelling process, because this impacts on the reliability of any outputs.

A critical review of available information should be made once the objective of the numerical model and application category have been specified. It is often the case that the organisations carrying out numerical modelling are different from those who have carried out initial surveys and ground investigations (and they may not have been aware of either the requirement for numerical modelling or the type of input data that would be required). So, data gaps can often be apparent before carrying out numerical modelling and, in some cases, further investigations may be required (see box above **Section 6.2**).

Sophisticated analysis is not a substitute for reliable information for the site, its environs and the proposed works.

A wide range of information may be required (**Figure 6.1 and Table 6.1**). Similarly, when project changes occur, and if the objective of the numerical modelling changes, then it may be necessary to revisit the scope and adequacy of available data for deriving appropriate inputs into the model.

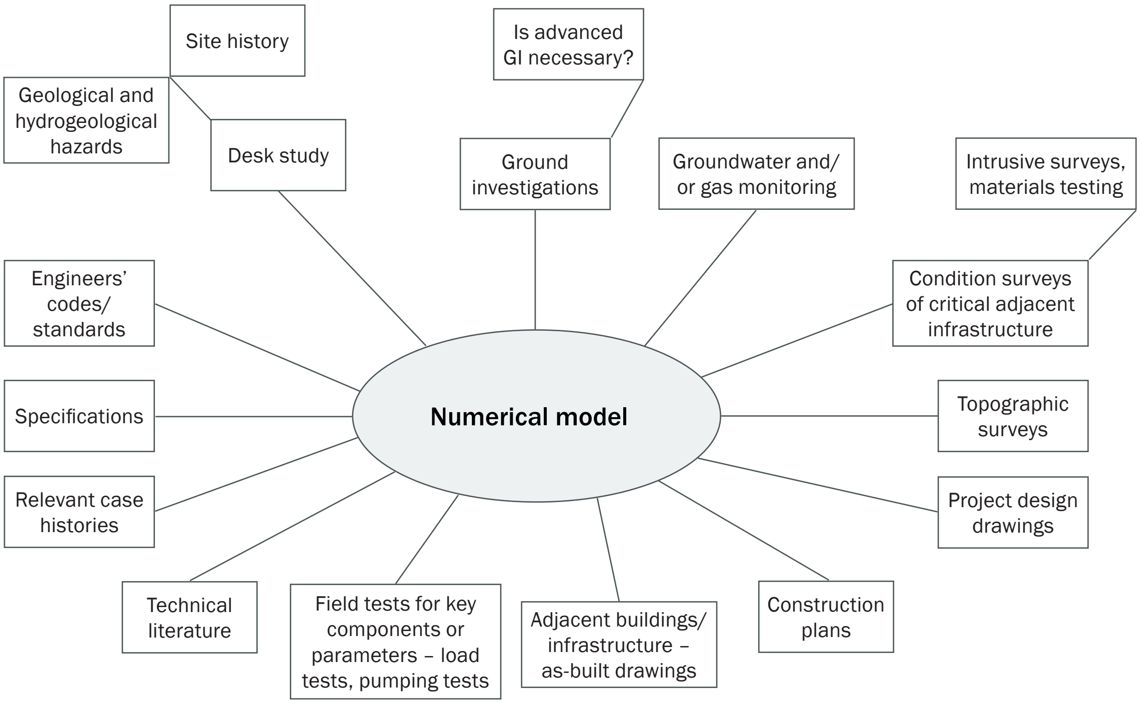


Figure 6.1 Example of information sources for numerical model

Figure 6.2 provides an example of some of the factors that may influence the scope and complexity of the information required for a numerical model. If several of the information components plot towards the right-hand side of **Figure 6.2**, then the information requirements are likely to be relatively challenging. The scope of investigations and surveys required for numerical modelling may need to exceed those required for conventional calculations. Each of the main factors that normally need to be considered are discussed in the following sections.

Less challenging		Type of information		More challenging
Short-term behaviour (during construction). Stability or deformation of proposed structure.	←	Analysis objective	→	Long-term, time-dependent behaviour. Differential movements around proposed structure. Interactions between new and existing structures.
Homogenous deposits, eg marine clays. Well researched and documented.	←	Geology	→	Heterogenous deposits, eg glacial deposits. Little research data or documented experience. Past instability.
Hydrostatic conditions, low water table, low permeability ground.	←	Hydrogeology	→	Artesian conditions. Hetereogenous ground profile. High permeability layers.
Greenfield site. No historic activities.	←	Site and adjacent area Current conditions and site history	→	Heavily developed urban areas, numerous surface and underground structures, some in fragile condition. Complex site history.
Relevant case history data available (same form of structure, construction processes, geology etc). Published research on ground behaviour and ground–structure interaction.	←	Case histories and technical literature	→	Relevant case histories and technical literature unavailable. Proposed project 'pushes boundaries' of what has been attempted previously.
Robust, multiple load paths, ductile behaviour. Tolerant of differential movement. New build structure.	←	Proposed structure	→	Prone to progressive failure, potential for brittle collapse. Sensitive to small differential movement. Historic structure (more challenging if suffered deterioration).

Figure 6.2 Example of factors which may influence scope of information required for numerical modelling

Table 6.1 Possible information requirements for numerical model

Required Inputs	Typical information source	Implications for management and checking	Implications for numerical modelling
Site topography	Surveys, existing and historic maps	Sufficient, consistent, up to date?	Surface geometry
Geological profile	Desk studies, ground investigations	Adequate Interpretation, reliability?	Stratigraphy
Geological history	Desk studies	Past instability, faulting, local weak zones?	Stress history
Site history	Desk studies	Infilled quarries, historic mining, non-engineered fills, old basements/ foundations?	Stress history
Hydrogeology	Desk studies, ground investigations	Adequate interpretation, non-hydrostatic groundwater regime?	Groundwater regime (and *in situ* effective stress)
Geotechnical parameters (strength, stiffness, *in situ* stress). Groundwater pressure etc	Technical literature Back analysis of case histories Advanced ground investigations	Relevant precedent experience? Advanced investigations, field tests/ trials required? Site-specific stiffness and permeability data available?	Inputs for constitutive model for ground behaviour (and calibration). Hydraulic gradients, flow, effective stress.
Proposed earthworks/ structures	Project design drawings	Design development, adequate communication across PT if changes?	Inputs for earthworks, structures within model.
Construction sequence	Construction plans	Changes? Adequate communications?	Analytical sequence/stages.
Duration of key phases	Construction plans	Changes. Potential for increase/ decrease in mobilised ground strength. Adequate communication	Selection of undrained/ drained or coupled analysis.
Structural parameters, strength, stiffness	Codes/standards/specifications	Non-standard materials? Prone to long-term creep? Potential for brittle behaviour?	Inputs for structures within model.
Load displacement of key components, eg piles, anchors	Technical literature, field tests	Significant influence on overall response? Behaviour replicated in numerical modelling?	Calibration of components in a model.
Structural connection details	Project design drawings	Rotational stiffness, strength, adequate load transfer?	Inputs for structures within model.
Adjacent infrastructure – above ground	Historic drawings Condition surveys	Foundations and sub-structures – details known? Sensitive to damage? Current condition?	Inputs for structures within model.
Adjacent infrastructure – below ground	Historic drawings Condition surveys	Underground utilities, tunnels Sensitive to damage? Current condition?	Inputs for structures within model.

It is essential that the client and PM recognise that reliable outputs can only be obtained from a numerical model if the available input data is reliable and sufficient (in terms of both extent and quality), given the type and complexity of the numerical model being carried out.

The client and PM should also ensure that sufficient resources are made available to obtain additional information, if it is demonstrated that the available data is inadequate.

6.2 DESK STUDY AND GROUND INVESTIGATION

A comprehensive desk study is a fundamental requirement for any geotechnical engineering effort and is a code requirement in many parts of the world, eg EC7 (BS EN 1997-1:2004+A1:2013). In addition to collating information on the site's geology and hydrogeology, the desk study should also summarise the site history. For urban development projects, an understanding of the site history is often important and may need to be considered carefully in the context of building a representative numerical model. Here are two examples:

1 Historic excavations, basements, tunnelling etc, in the vicinity of the site will influence *in situ* stresses and stress history, and locally may lead to lower mobilised strength and stiffness, **Figure 6.3** (also, **Chapter 7** shows the effect of modelling historic construction on the wall displacements for Westminster Underground Station).

2 Historic filling activities, foundations etc, in the vicinity of the site will influence *in situ* stress and stress history, and locally may lead to higher mobilised strength and stiffness.

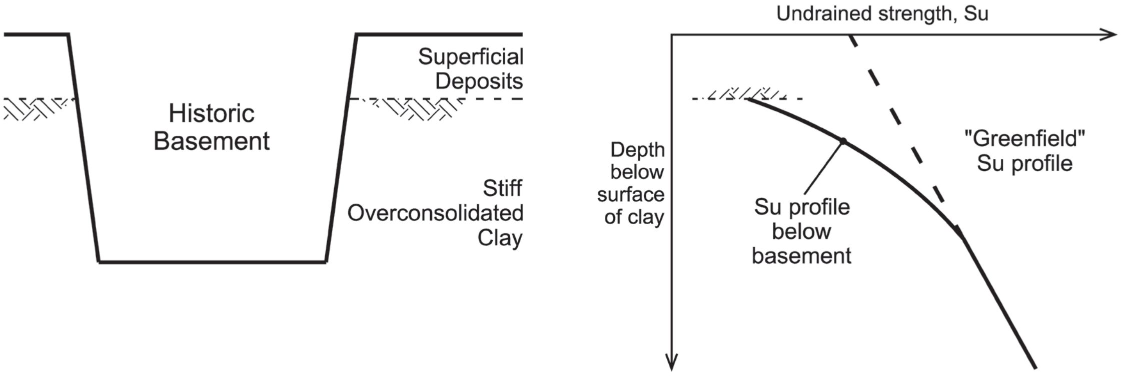


Figure 6.3 Example of influence of site history on mobilised undrained strength for a stiff clay

Both examples may lead to local increases in differential movement (and it should be noted that it is differential, rather than total, movement which causes damage to infrastructure).

The majority of ground investigations, if properly supervised, can enable good estimates of shear strength to be made by experienced geotechnical professionals. At the current state of practice, reliable data is usually lacking for:

- **Ground stiffness/compressibility** – for stiff clays, weak rocks and dense sands, bulk modulus, shear modulus, undrained and drained Young's modulus etc, and its variation with depth and strain amplitude. For soft clays, the pre-consolidation pressure, compressibility following yield, and consolidation (both primary and secondary) characteristics are usually critical inputs – sampling disturbance can lead to unsafe estimates of deformation (eg **Figure 6.4**).
- **Groundwater pressure** – seasonal variations and variations with depth and permeability (and variations with stress level and with depth).

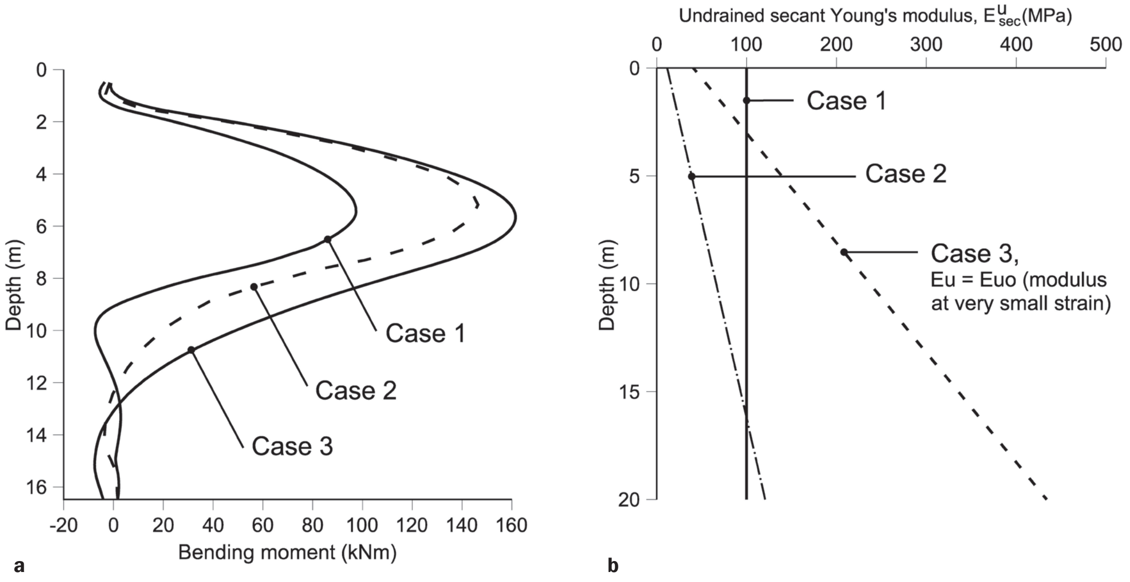
Note

p'_c = pre-consolidation pressure.

Figure 6.4 Soft clay – example of influence of sampling disturbance on pre-consolidation pressure and compression index

Appropriate techniques are available for obtaining reliable data for ground stiffness/compressibility and groundwater pressure, however they are often considered to be too expensive/time-consuming. Often this turns out to be a false economy.

When simulating the behaviour of over-consolidated soils, reliable ground stiffness profiles are a prerequisite for reliable predictions of ground movement and ground–structure interaction (**Figure 6.5**). As discussed by Clayton (2010), the use of field geophysics testing is particularly valuable in assessing appropriate ground stiffness profiles.



Case 1 Linear elastic Mohr-Coulomb soil , with Eu = 100MPa, and Su = 100kPa.

Case 2 Linear elastic Mohr-Coulomb soil, stiffness increasing with depth.

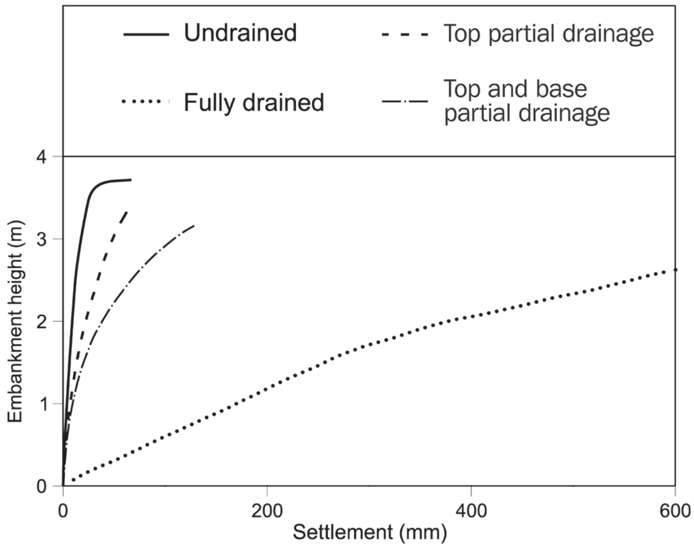
Case 3 Non-linear elastic Mohr-Coulomb soil, stiffness increasing with depth and decreasing with mobilised strain amplitude. Stiffness degradation with strain (see Clayton, 2010).

Figure 6.5 Example of influence of stiff clay stiffness on wall bending moment. Predicted bending moment in the wall for three different soil models(a) and comparison of undrained secant Young's moduli for three different soil models (b) (modified after Clayton, 2010)

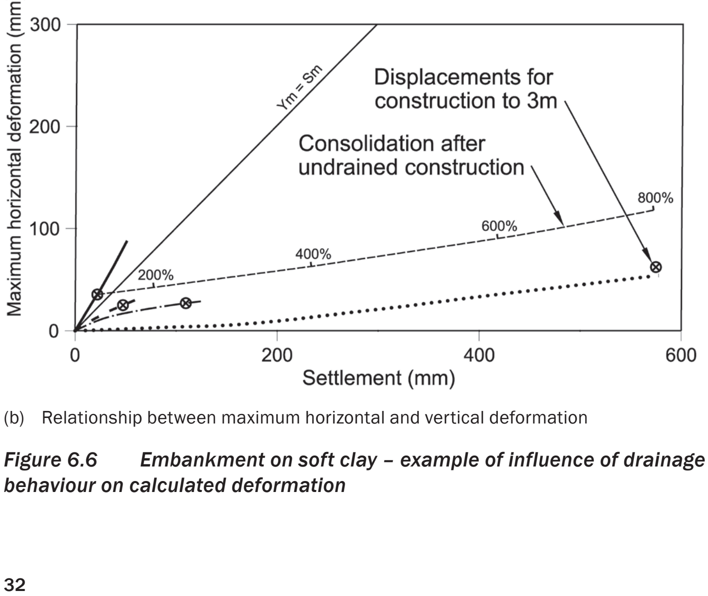
In some urban areas, such as London and Singapore, back analysis of well-instrumented construction activities has provided important insights into mobilised stiffness and strength. Nevertheless, site-specific variations occur and residual uncertainties can remain if direct site-specific measurements of stiffness are absent, eg Hight and Higgins (1994), even for urban areas where there is significant case history experience.

For soft clays, the degree of drainage that occurs during construction (ie the speed of construction versus the clay's consolidation characteristics) is particularly important in controlling stability and horizontal and vertical deformation (eg **Figure 6.6**). So, advanced ground investigations are often necessary, usually through a combination of *in situ* and laboratory testing, to evaluate the appropriate consolidation parameters – some of the challenges in determining appropriate soft clay consolidation parameters are outlined by Rowe (1972), Symons and Murray (1975), and LeRoueil *et al* (1990). The accuracy of any time-dependent analysis will depend upon determining absolute values of permeability, this is often challenging and will usually require field tests, eg Preene *et al* (2016).

Unforeseen groundwater conditions are a very common cause of project delays and cost increases. Groundwater variations with depth are often non-hydrostatic, and the common assumption of a hydrostatic variation with depth may lead to considerable errors in *in situ* effective stresses (and consequently mobilised strength and stiffness). Under most circumstances this might be considered to be conservative, but there are situations where this is not the case. Variations of groundwater pressure with depth can be assessed, via numerical modelling of groundwater flow, although these analyses will depend upon appropriate boundary conditions and spatial variations of ground permeability (especially changes in permeability with depth). If implemented in a numerical model, then the variations of groundwater pressure with depth should be consistent with the depth-dependent variation in ground permeability.



(a) Settlement vs. embankment height



(b) Relationship between maximum horizontal and vertical deformation

Figure 6.6 Embankment on soft clay – example of influence of drainage boundary conditions and undrained/drained behaviour on calculated deformation

6.3 CONDITION OF SITE AND ADJACENT AREAS

The nature of the site and adjacent areas and their current condition and history will be important considerations when assessing the information required for building a numerical model. Many urban areas have had a complex history due to past buildings or industrial activities (such as quarrying, mining, construction and removal of old foundations and basements). Some of these activities may have led to changes in ground behaviour or changes to the groundwater regime, some parts of the site may be weaker or stronger than a greenfield site. As such they should be included in the model construction and the early part of a simulation (for example, to recreate an appropriate *in situ* stress regime), and it may be important in the selection of appropriate strength/stiffness parameters, and this is essential when using any non-linear soil models.

In urban environments the impact of new construction on existing infrastructure is often the main reason for carrying out numerical modelling. The following information may be needed for existing structures:

- structural strength
- effective structural stiffness, defined by the stiffness of a number of components (propping systems, tunnel linings etc)
- overall configuration
- nature of any structural connections (eg **Chapter 7**)
- type and geometry of foundations
- any deterioration (steel corrosion, masonry or concrete degradation etc).

This data may be equally as important as the modelling of the ground and the proposed structure in the overall analysis. It is often particularly challenging to obtain good information on the current condition of an old structure (and the current owners may not be prepared to approve intrusive surveys). A key unknown may be the magnitude of deformation that a structure has suffered in the past (and consequently the residual deformation before significant damage occurs).

An increasingly common activity is the modification of an existing structure – for example, an existing bridge or port structure to accept heavier loads – which results in the need to construct new foundations or retaining walls. Again, obtaining detailed information on the existing structure will be important, especially the extent of any deterioration.

6.4 PROPOSED STRUCTURE

The proposed structure or earthworks will be specified and the relevant properties should be relatively easily defined for the purposes of numerical modelling.

However, there can be significant challenges in deciding how best to idealise the proposed structure, for example the behaviour of structural connections, thermal effects etc, can be difficult to model correctly. These idealisations may lead to some uncertainty in the model outputs.

6.5 CASE HISTORIES AND TECHNICAL LITERATURE

Reliable numerical modelling relies to a large extent on the availability of monitoring and full-scale performance data of similar forms of construction, as discussed by O'Brien (2015) and Jones *et al* (2008). The value of precedent experience, and 'calibration' of numerical models against case history data cannot be over-estimated.

> The availability of relevant case history data may be one of the most important considerations when assessing the adequacy of available information.

It is essential for the modeller to obtain all relevant case history data and to use this data when building, calibrating and checking a model.

If relevant case history data is unavailable, the scope of ground investigations may need to be more extensive than normally required, and advanced testing (both *in situ* and laboratory, together with high quality sampling) may be necessary.

6.6 LARGE-SCALE TRIALS AND LOADING TESTS

If case history data of similar forms of construction are not available for any reason, then the reliability of any outputs will be far more uncertain. The lack of case history data may justify the requirement for a large-scale instrumented trial or load test, eg for key components, such as piles/anchors, or mass permeability from pumping tests, or mass deformation characteristics from trial embankments or trial excavations (**Box 8.2 and Chapter 9**).

Trial embankments/excavations can be particularly valuable if time-dependent behaviour (such as consolidation or swelling characteristics) are important. Preliminary trials can also be important when ground improvement is a critical component of the proposed works. Back analysis of monitoring data can provide valuable insights into large-scale behaviour, facilitate calibration of a numerical model and provide more confidence in subsequent output from the numerical model.

7 Building a model

7.1 GENERAL

Chapter 6 outlines the information needed to build a numerical model. This chapter explains how that information can be used.

Construction of a model can be a lengthy process. Before doing so, the reasons why the model is needed have to be established and all the data on ground conditions, the form of structures (new and old), construction sequences (historic and proposed) and other features have to be collated, correlated and checked for consistency. A remark attributed to Einstein (and others) is a useful maxim when setting out to construct a numerical model:

> *"Everything should be made as simple as possible, but not simpler."*

The geometry has to be defined, the means of representing the behaviour of the ground and structures have to be established and the boundary conditions have to be defined, bearing in mind that they should not directly influence the outcome of the analysis. **Table 7.1** provides a summary. Inevitably, in building the model, a number of assumptions and idealisations have to be made. It is vital that these are clearly communicated.

The model should consider the whole life history of the site. After any existing above and below ground structures have been constructed, the site cleared for the proposed scheme and, in line with an agreed sequence, the foundations have to be constructed, and any structures built. In most cases the long-term, post-construction, effects are then generated.

The design team, with advice from the technical experts (SGE, SM etc), has to decide on the form of the analysis, which will depend on the objectives and the quality of the available information.

For example, the numerical model could be axially symmetric, and it could assume 2D conditions (plane stress or plane strain), in which case the analysis assumes semi-infinite loading and geometry or fully 3D conditions could be considered. Even with a 3D analysis, assumptions and simplifications are inevitable.

In the past, 3D analyses were only undertaken in exceptional circumstances or they were simple enough that the modeller could understand how the analysis performed. More recently, the use of 3D analyses has become routine, and modellers sometimes attempt to analyse some very complex geometries such as that shown in **Figure 7.1.**

The issue is that although the results produced from such an analysis might appear impressive, they may be very unrealistic – the modeller producing the analysis cannot reasonably understand the implications of the assumptions that have been made. To speed up the analysis, several shortcuts may have been taken which, although they may have seemed reasonable at the time, greatly influence the outcome (eg the use of linear elasticity to determine building damage or movements remote from an excavation). Such approximations may render the results unrealistic.

In the 2017 Harding Lecture, Dr Barry New (New, 2019) highlighted the complexity of numerical models now being produced. He questioned the ability of modellers to undertake analysis of such complex structures and to provide sufficient confidence in the results (eg the case shown in **Figure 7.1**). Unfortunately, because it is possible to run analyses such as these, it does not mean that the results are accurate or reasonable. However, it is possible to generate a mesh (usually quite coarse), and the use of certain solution strategies means that the analyses can be run much quicker than if other more accurate solution strategies are adopted (see **Chapter 2 and Appendix A**).

Note

Proposed works shown in yellow, existing infrastructure in blue and grey.

Figure 7.1 Existing underground station with proposed upgrades

Building highly complex 3D models is becoming a more common situation and the 'client' and the 'PM' should be aware that however impressive the output from an analysis might be, the results may be worthless. It is often better to rely on a series of less complicated analyses that are easily understandable and allow a framework to be developed that can be sensibly validated, and more easily understood. For example, before building a 3D model, it is strongly recommended that several simpler 2D models are run first and the outputs from these are interpreted and understood. Only then should a 3D model be built and run, the results from the 3D model should then be compared with the 2D models.

7.2 BEFORE BUILDING THE MODEL

As previously observed (**Table 5.2**), before starting to develop a numerical model the objective has to be clearly defined, because the objective will define the form of the model. The analysis will need to focus on certain aspects of behaviour and not on others, as discussed in **Chapter 5**.

The form of the model will also be dictated by what is sensibly achievable, and the results viewed in that context. The time available to undertake and report the results of the numerical model is a factor that has to be considered. There is no point in building a highly complex model that takes time to develop, run, check and report if there is simply not enough time available to do so. The client has to be aware of these limitations and expectations have to be managed.

7.3 BUILDING THE MODEL

Once all the available information has been collated and the form of the model has been defined, the model can be constructed. There are five components to the model:

- The definition of the output requirements ensures that sufficient accuracy can be obtained.
- Initial stress conditions. The initial stress conditions define the stress field at the start of the analysis. These may be uniform or vary spatially.
- The mesh defines the geometry of the model representing ground conditions (stratigraphy) and any structures that will be included in the analysis.
- The definition of constitutive models and boundary conditions. The data input file defines how the ground and structures will respond to imposed conditions and the constraints or boundary conditions imposed in the model.
- The sequence to be followed in the analysis. This usually has to be idealised and activities broken down into a series of unique events as defined by the application of loads, displacements, constraints etc.

Table 7.1 shows the components needed to generate a model, including the inputs to the analysis, once the objectives and the form of the analysis have been defined.

Table 7.1 Synthesis (inputs) and definition (outputs) for model construction

Synthesis	Definition
Historical data (events)	Geometry
Ground investigation data and supplementary information (records of previous investigations)	Initial stress conditions
Construction sequence	Idealised sequence
Form and properties of existing structures	Constitutive models (includes checking and validation)
Form and properties of new structures	Boundary conditions
	Load cases (SLS and ULS)

7.4 DEFINING THE GEOMETRY

The basic geometry is defined by the following:

- **Geology.** The geology and the geological processes that have caused the ‘current’ ground conditions to develop have to be understood. In many cases, a simplified or idealised soil stratigraphy is developed for the purposes of the analysis. However, in other cases the spatial variation of stratigraphy may be important, eg where the stability of slopes is being considered – the presence of deep filled hollows or other features may influence spatial variation in soil properties across the site.
- **Structures.** The form of any structures (new or old) to be modelled requires careful consideration. If the analysis is intended to predict how these structures behave, they have to be represented realistically in the model. Apart from defining the form of the structures and their foundations, the loadings that they apply and how these loads are transmitted to the ground all require consideration. In some cases, it is possible to smear the effects of the foundations, in other cases they have to be represented individually. A particular problem that is sometimes overlooked is the connections between different structural elements. How these are modelled can have a significant influence on the behaviour of a structure (Higgins *et al*, 1999). **Figure 7.2** shows a simple underground structure built by installing the roof slab before excavation. The difference in the displacements of the wall resulting from a difference in connection (full moment and rotation) between the piled wall and the roof slab is apparent (**Figure 7.3**). The effect on the bending moment diagram (left wall) demonstrates the possible impact on the structural design of the wall (**Figure 7.4**).
- **Output.** The model should be sufficiently detailed to ensure that the results obtained are accurate.
- **Influence of boundary conditions.** The mesh should be sufficiently large to ensure that the imposed boundary conditions do not influence the behaviour of the ground or structures for which results are required.

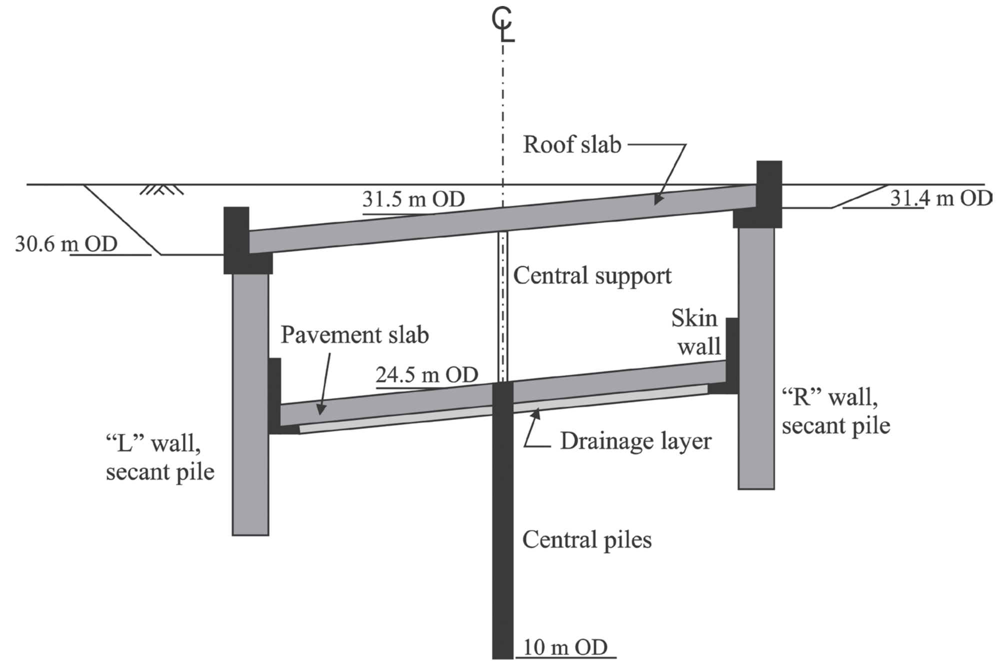


Figure 7.2 *Cross section through a road tunnel constructed top down*

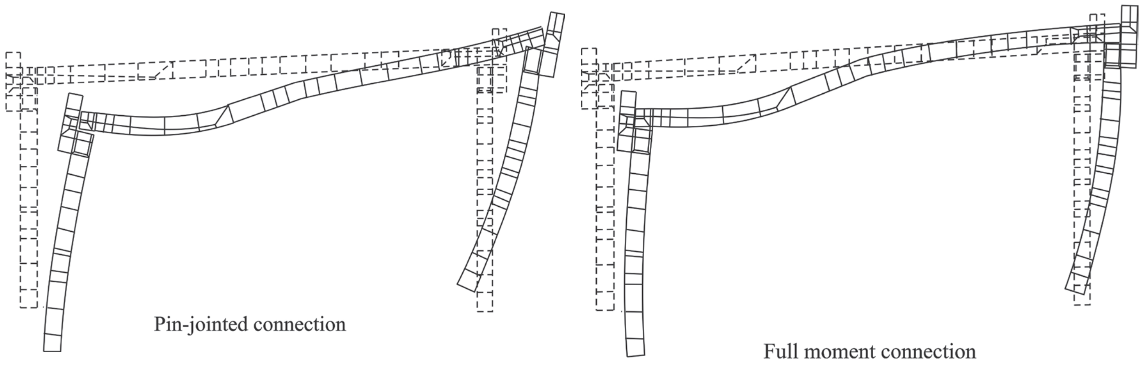


Figure 7.3 *Displaced shape of walls and slab following completion of excavation*

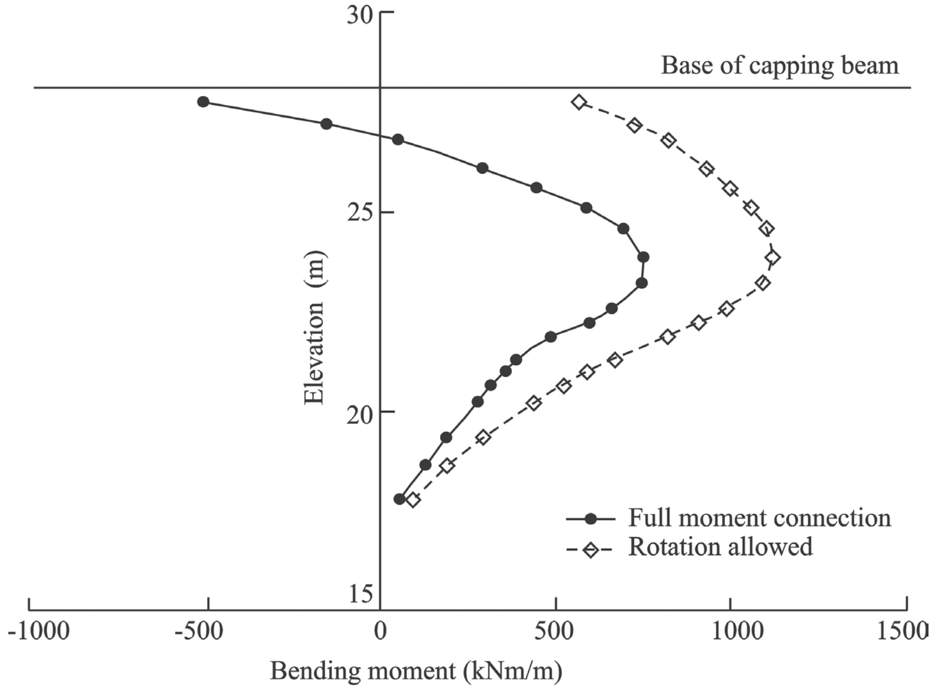


Figure 7.4 *Bending moments left wall – full moment connection and pinned connection*

There may be other factors that have to be considered for specific cases, but for most situations the geometry is defined by a FE mesh that should account for the following:

- the topography and the soil stratification
- the dimensions of the structures to be analysed and any sub-surface structures such as pipes and tunnels
- the spatial variation of the constitutive models used to represent the behaviour of the ground and structures
- the connections between structural elements (as above)
- the construction sequence, including the position of any temporary works, the configuration of any excavations including supports such as walls, props, anchors etc, and it may be necessary to allow for any hold points during the excavation or construction process
- the position of foundations
- the points at which loads are applied and where constraints are applied, taking into account their influence on the output
- groundwater conditions, the presence of any drains and the need to dewater
- the output required.

Figure 7.5 shows a 3D mesh used to model a deep excavation. The size of the mesh, and how large the elements are, is dictated by the need to ensure that any imposed boundary conditions do not unrealistically influence the outcome of the analysis.

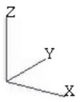


Figure 7.5 Three-dimensional finite element mesh for a deep excavation

A common mistake is for the boundaries of the mesh to be too close to the areas of interest and for the boundary conditions to effectively dictate the outcome of the analysis (eg Potts and Zdravković, 1999b). Potts and Zdravković (1999b) describe a study undertaken to demonstrate that by placing displacement constraints along a boundary that is too close to an excavation the displacements of the retaining wall can be affected. They give surface settlements for an excavation in front of an embedded retaining wall (**Figure 7.6**) where the base of the mesh was varied (**Figure 7.7**) and the width of the mesh was varied (**Figure 7.8**). It is apparent that the proximity of the boundary where these constraints are applied has to be carefully considered and can be influenced by the soil model chosen (Potts and Zdravković, 1999b) has details).

The mesh should be sufficiently refined to ensure that any stress concentrations or gradients in quantities such as displacements, pore pressures, temperature etc, are smoothed between parts of the mesh. Critically the form of the mesh will also depend on the form of the output required, ie it may need to be finer in certain areas to ensure that abrupt changes in quantities (loads, displacements, pore water pressures etc) are avoided. Economies in the number of elements needed to define the problem, or to obtain a high degree of accuracy, may be achieved by using high-order elements (**Chapter 2, Box 2.2, and Appendix A**).

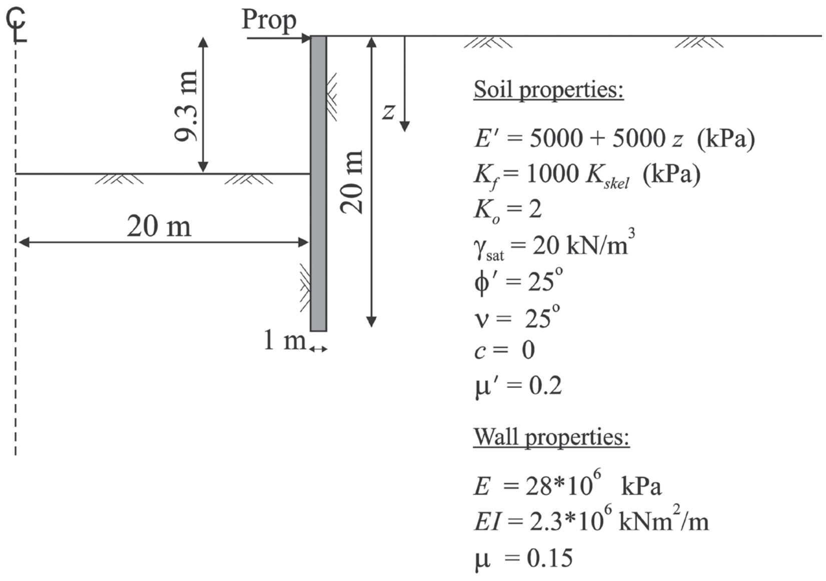


Figure 7.6 Embedded retaining wall retained by a single prop

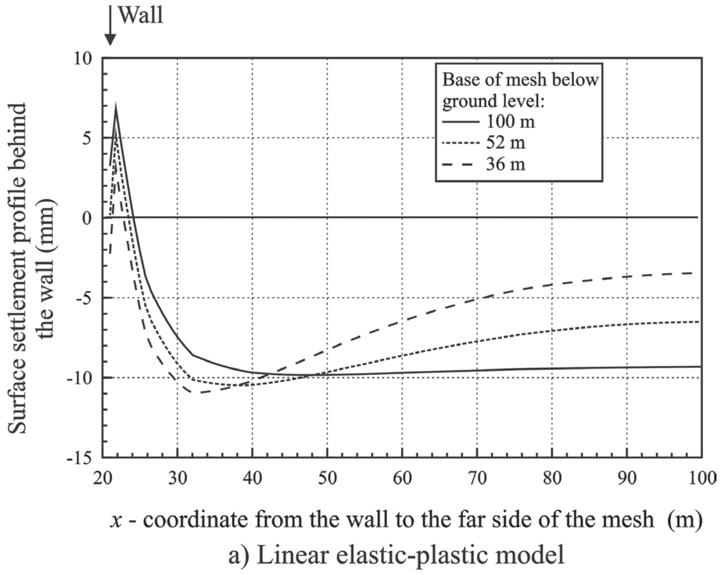


Figure 7.7 Surface settlement, 100 m wide mesh, bottom boundary varies

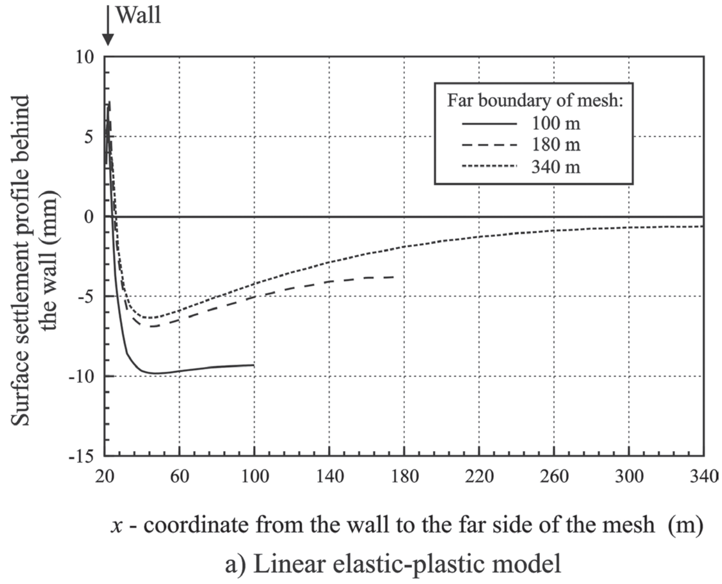


Figure 7.8 Surface settlement, base of mesh fixed, far vertical boundary varies

7.5 INPUT DATA

Having developed a mesh, properties are assigned to different parts of it. These properties or constitutive models define how the soil or structures that are present behave. The sequence of events or construction sequence and the constraints then have to be defined.

Initial stresses

The analysis usually starts by defining the initial stresses. These stresses normally relate to a 'greenfield condition' representing a time when there was no construction activity. On a time-related basis, the construction history of the site is followed to reach a point where 'current conditions' exist. This represents a stage where the analysis mirrors the stress state in the ground before the proposed construction starts. This process is essential if non-linear material behaviour is being modelled.

The initial stress conditions may be based on the results of the ground investigations through direct measurement or on theoretical considerations. They may vary spatially but they should be consistent with the geometry at the start of the analysis.

Constitutive models

Constitutive models are used to define the behaviour of the ground, and any structures modelled.

For the soil, the constitutive models may be based on the following:

- **Ground investigation.** If a ground investigation has been undertaken at the site the results of that investigation may be used to develop appropriate constitutive models to represent the behaviour of the ground. A NAFEMS publication (Lees, 2012) considers how to derive suitable properties from *in situ* and laboratory tests.
- **Back analysis.** There may be measurements relating to similar forms of construction in similar ground conditions that could be used to develop constitutive models for ground response.

Not all geotechnical software packages model structures particularly well. For example, some structures may not be able to sustain tension, in which case a tension cut-off has to be used. Other structures have features that have to be modelled, such as tunnels and pipes, where modelling the joints between segments may be important. In these instances, simply applying an overall stiffness for the lining may not be sufficient. It is often a question of appropriate detail. Advice to the modeller from members of the design team who will use the results of the modelling might be beneficial in this respect.

Historic and future construction (idealised sequences)

A timeline needs to be developed for historic and future construction activity, and suitable 'at rest' periods need to be allowed between events.

Because most geotechnical analyses undertaken have to consider non-linear behaviour of the ground (the behaviour of soil is highly non-linear), the past construction activity has to be modelled. **Figure 7.9** shows a cross section through the excavation for the Underground Station at Westminster including the Jubilee Line platform tunnels and running tunnels (Higgins *et al*, 1996). **Figure 7.10** shows the stress field in the ground before and after the tunnels were dug.

Two analyses were undertaken, one ignoring tunnel construction and one including tunnel construction. The resulting wall displacements are shown in **Figure 7.11**. The influence of the initial stress field is apparent (Potts and Zdravković, 1999b). So, it is important to define and understand historic processes that are liable to affect a new structure.

The sequence for future construction has to be defined, and in most cases idealised. In reality, events occur concurrently whereas in most cases it is desirable to consider a consecutive series of events. So, the dominant activities need to be identified and approximations or idealisations have to be made. Again, such approximations have to be communicated and agreed by the design team.

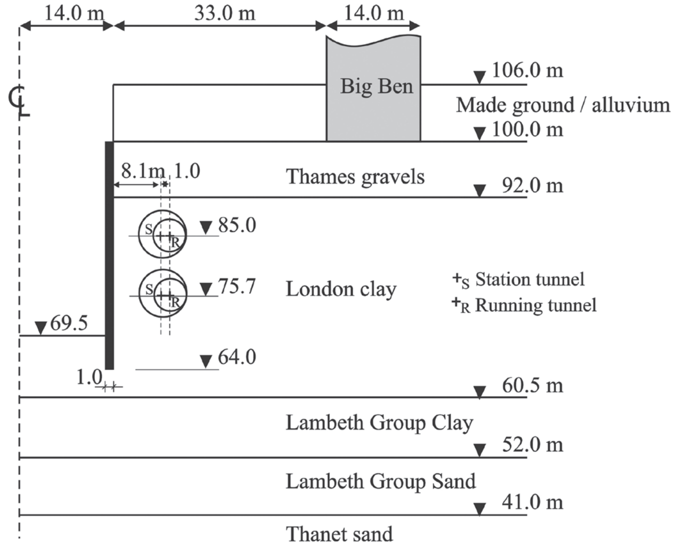
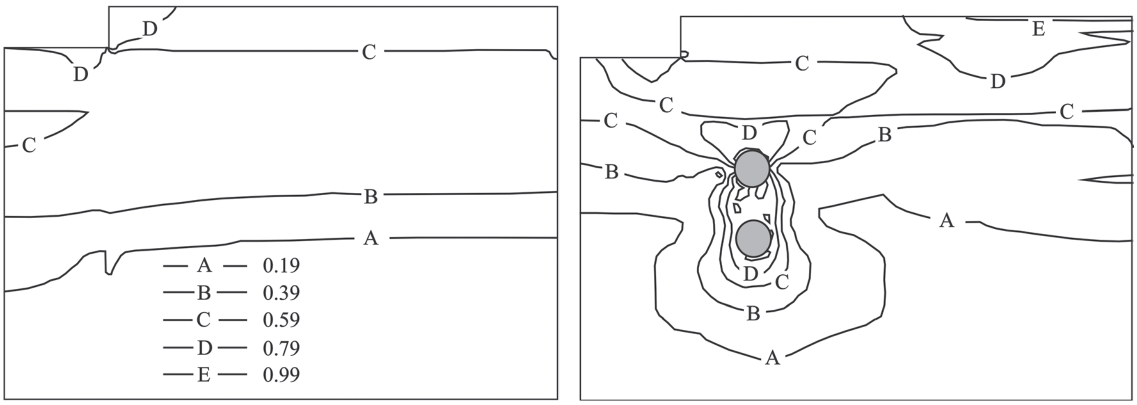


Figure 7.9 Cross section through Westminster underground station



a **b**

Figure 7.10 Stress field without tunnels (a) and with tunnels (b)

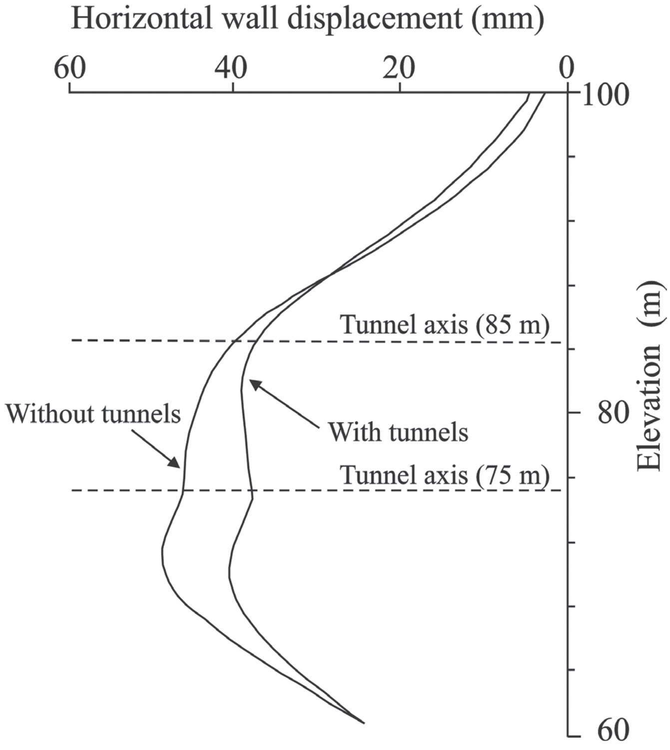


Figure 7.11 Wall displacement upon completion of excavation with and without tunnels

8 Running the analysis

8.1 INTRODUCTION

The modeller and the SM undertake the task of running the analysis. It is beyond the scope of this document to explain how the analysis should be run. However, those not involved in this process need to understand that this is not a straightforward process, and that it should only be undertaken by those who understand the computational mechanisms and the engineering principles involved.

Unfortunately, analyses are often run by individuals who do not have the necessary knowledge, and who treat this as a routine process, ie they simply input data and present the results without question or critical review – the black box approach. More sensibly, analyses should be run by someone who continually critically checks and reviews the results to understand what the analysis is doing to confirm that this is as intended (see **Chapter 4**).

Some programs do not present the user with sufficient information to confirm that the solution has converged within defined tolerances and is numerically valid. Some programs adjust the increment sizes (size of the steps in the sequence) to provide a valid solution, but others provide the user with enough information for them to check that the solution is valid and convergence has been achieved. Depending on the form of the analysis, this may include checking that convergence has been achieved for the following:

- deformation (displacements and rotations)
- stress (moments, loads and forces)
- hydraulic (pore pressures, flows and seepage)
- thermal (temperature, flux and conductivity)
- general (work).

It may be difficult to achieve convergence on all these factors at every step in the analysis. This is where the skill and experience of the modeller is important as they may conclude that a divergent solution is acceptable or that the limits on convergence can be relaxed.

Ensuring that the solution is valid may involve rerunning certain stages, to obtain a better solution or to correct any errors in the input. Ultimately, it may even require that the model is rebuilt and rerun. Sensitivity checks will often be needed to ensure that the model is robust.

It is important that the team as a whole understands that running an analysis is not a passive process and requires extensive review and checking to ensure that the output from the analysis can be relied upon and used for the intended purpose.

Subsequent chapters of this document discuss the processes involved in checking and validating models and reporting the results.

Calibration and checking of a model have similar aims, ie they are both processes that are intended to confirm that the model is providing results that are numerically accurate and that they realistically represent the behaviour of the ground and any structures within it.

In simple terms, calibration can be thought of as occurring before the analysis is undertaken and that checking occurs afterwards. Both procedures provide confidence that the analysis undertaken is providing reasonable results, but they are not simple exercises and they may be time-consuming. So, both calibration and checking have to be planned and allowed for during the design process in terms of cost and programme.

8.2 WHAT IS CALIBRATION?

Calibration might be thought of as undertaking an exercise to demonstrate that the whole or part of a particular aspect of behaviour can be realistically reproduced. Parameters or boundary conditions might be adjusted to reproduce measurements or empirical solutions. However, a model might be calibrated for a particular purpose, eg to reproduce displacements of a retaining wall, but the same calibration may not be applicable for other purposes (eg pile design, tunnel movements).

In order to calibrate a model, the following may be used:

- measurements of similar construction on similar ground conditions
- *in situ* measurements of soil behaviour, or load–deformation behaviour of key model components, such as piles anchors etc
- laboratory test data
- analytical solutions.

On occasions, there is confusion about what is being calibrated. It is not the calibration of a program, but it might be the calibration of a particular constitutive model coded into the program. Many programs allow a user to define their own soil models, which means that there may be different versions of a particular program, ie the coding of one soil model could be different between different versions of the same program.

There are many constitutive models available for analysis, but there are no universally applicable models. Models that perform well for some situations do not perform well for other classes of problem. It is important to consider which issues are critical and to choose a model accordingly. It is pointless using a model that will predict settlements accurately when lateral movements are an issue. Likewise, certain models may predict the behaviour of a structure reasonably well, but they do not predict remote movements well and so potential damage of remote structures can be under-predicted.

Apart from the software, the calibration process may be used to test the ‘modeller’. The ‘modeller’ may be asked to reproduce predefined examples and to demonstrate that they can define a problem and solve it with a suitable degree of accuracy. This process adds confidence that the ‘modeller’ has a suitable level of understanding when using advanced numerical analysis (eg Schweiger, 2002).

8.3 CALIBRATION AGAINST CONSTRUCTION MEASUREMENTS

Where there is experience of similar forms of construction in similar ground conditions, that experience may be used to demonstrate that the analysis is capable of reproducing realistic behaviour in terms of the required outputs, such as ground movements, movements of the structure and stresses and forces acting on the structure.

This process involves reanalysing the original scheme to reproduce the measured behaviour. Doing this is not straightforward – there has to be confidence that the measurements are realistic (data may need to be reviewed and validated) and the sequence of construction also has to be known in sufficient detail to undertake an analysis.

For large projects it is not unusual to initiate a trial to study certain aspects of behaviour and to back analyse it to gain confidence that the techniques used for analysis are valid. Two examples are provided (**Boxes 8.1 and 8.2**).

These examples both show the importance of using the results of measurements or known performance to gain confidence in the numerical models. Obviously, for other projects, a trial of this magnitude may not be economic, but there are published case histories that can be considered.

Box 8.1 The Jubilee Line trial tunnel at Redcross Way, London (from Kovacevic et al, 1996)

A trial tunnel was constructed to demonstrate the feasibility of certain construction techniques, but it also showed that certain analysis methodologies could be used to reproduce the measurements, thereby validating the modelling approach chosen.

The aim of the analysis was to confirm that the lining stresses could be reproduced reasonably well through the use of a particular soil model, but as **Figure 8.1** shows, the procedure used was also able to reproduce the measured ground surface displacement. As such, there was confidence gained that future predictions would be reasonable and could be relied upon.

Figure 8.1 Example of numerical model calibration – tunnel induced ground surface settlement

Box 8.2 Saint Alban trial embankment, Quebec (from Zdravković et al, 2002)

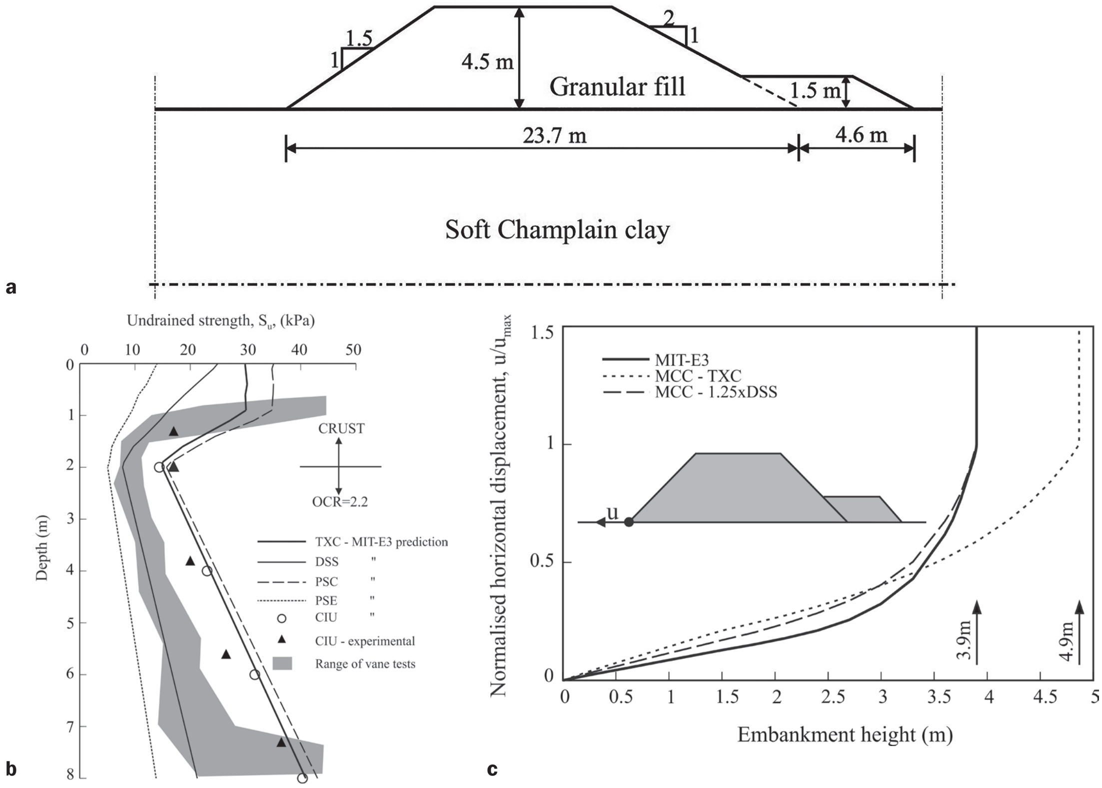


Figure 8.2 Example of numerical model calibration – geometry of trial embankment (a), strength anisotropy of a soft sensitive clay (b), and embankment stability on soft sensitive clay (c)

A granular fill embankment was built on top of a sensitive, strongly anisotropic, soft structured clay 13.7 m thick (**Figure 8.2a**). A detailed ground investigation had been undertaken, but because of the complexity of the soil models used, some judgement had to be used when selecting input parameters.

Figure 8.2b shows a profile of undrained strength for the clay. This figure shows theoretical strength profiles obtained using a particular constitutive model (Whittle, 1993) for different forms of laboratory tests. Also shown on that figure are the results of tests on high quality samples (denoted by triangles), together with simulations of those tests (open circles).

Construction of the embankment was modelled, and failure was predicted to occur at a height of 3.9 m, which was the height at which the trial embankment failed. **Figure 8.2c** shows the horizontal displacement of the toe of the embankment plotted against the height of the fill at stages in construction.

For comparison, an additional analysis was run using another constitutive model in which the undrained strength profile in triaxial compression agreed with the experimental results. This time the embankment was predicted to fail at a height 4.9 m. To predict the correct failure height, it was necessary to adjust the input parameters.

It was concluded that the anisotropy of strength in soft clays was important in determining stability, and that isotropic strengths derived from back analysis can be misleading when extrapolating to new geometries. For this type of problem, models capable of reproducing strength anisotropy are used in analyses.

8.4 TEST DATA

As the second example (**Box 8.2**) has shown, one means of calibrating a model is the use of test data – the chosen model can be used to reproduce test data, *in situ* or from the laboratory. As the St Alban example shows, some models will reproduce certain aspects of behaviour better than others. So, the modeller will have to consider which aspects are more important and use a model capable of reproducing the dominant or most important behaviour.

The third example shows in simpler terms how different soil models might perform. In this case, results from a simple oedometer test were used to demonstrate that the chosen model would reproduce a specific aspect of behaviour.

Box 8.3 Oedometer test on London clay (from Hight and Higgins, 1994)

When clays are unloaded, there is an initial undrained response and then, as excess pore water pressures dissipate, they swell in response. This behaviour is reproduced by an oedometer test, where the sample is loaded and then unloaded. **Figure 8.3** shows the results of the test data (oedometer data, shaded) and two simulations. One simulation was based on using a linear elastic–plastic model, which is commonly used for numerical modelling, and the other simulation was based on a more complex (small strain) model, originally developed to reproduce ground movements around deep excavations in stiff clay. It is apparent that the more complex model reproduces the test behaviour better than the simpler model, which confirms the need to use such models when wanting to reproduce this aspect of behaviour.

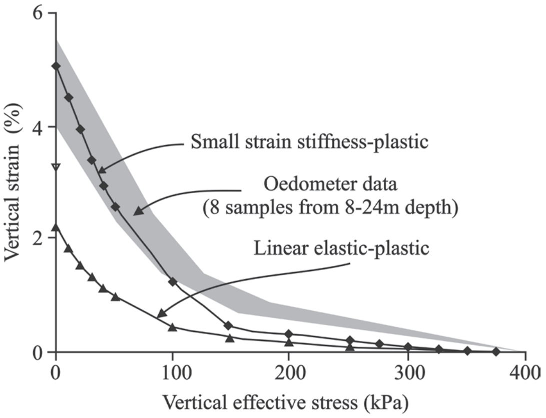


Figure 8.3 Example of numerical model calibration – swelling of an over-consolidated clay

Field tests, such as pile load tests, can also be used as a mean of verifying the behaviour of a key component of a large model (eg pile behaviour, within a pile group or piled-raft, is being simulated correctly).

8.5 ANALYTICAL SOLUTIONS

Apart from trying to reproduce test data or measurement, models can be tested against analytical solutions for example (eg Jefferies and Knowles (1994). However, these analytical solutions are simple, and normally only consider one activity such as tunnel construction or pile loading, whereas most numerical analyses consider multiple activities – no one model can account for all activities, as they all have their strengths and weaknesses.

Judgements may have to be made to use models that reproduce the dominant aspects rather than all aspects. However, it is still necessary to examine all aspects of behaviour to understand where weaknesses exist.

8.6 TESTING THE MODEL

As **Box 2.2** (**Chapter 2**) shows, the design of the mesh can be critical – different results are obtained with different meshes. Accordingly, in order to demonstrate that the solution is valid, sensitivity checks have to be made by rerunning the analysis with different models (finer and finer meshes) until similar results are obtained. Obviously, this is a laborious and time-consuming process which can only be avoided by careful mesh design undertaken by an experienced modeller.

Another example might be the analysis of an excavation. When tracking the displacements of a wall, a significant increase might be detected for only a small increment of excavation. Although the process is not linear, such a result might seem strange and could be the result of an error. However, the wall could be failing and the excavation of such a depth might not be feasible, and it could have reached a tipping point. However, without tracking the displacements, such effects would not be detected, and valuable insights into the issue not obtained.

8.7 SENSITIVITY CHECKS AND ROBUSTNESS

Demonstrating that the analysis is valid and robust is an extremely important part of the process. A good modeller should remain sceptical until it can be proved that the results of the analysis are valid. The other members of the design team should adopt a similar attitude.

There are instances where small changes in the input parameters or boundary conditions can have a significant impact on the results of the analysis. This may be real or it may be that there is an error in the input data but, without checking or undertaking sensitivity analyses, uncertainty will remain over the robustness of the output.

9 Checking – key principles

9.1 INTRODUCTION

This chapter provides key principles for the checking of numerical models. If checking is inadequate, there may be severe consequences – an example is given. Some key technical issues that need to be carefully checked are discussed in **Appendix A**. The requirements for formal independent checks – in the UK often known as 'Cat 3 checks' – are not discussed here.

It should be emphasised that calibration is a different activity from checking. Calibration (as discussed in **Chapter 8**) should be carried out by the team who are building and running the numerical model, so that they have confidence that they are producing reliable output. Checking is carried out by different individuals working separately from the modeller who built the numerical model (although still part of the same organisation).

9.2 DEVELOPING A CHECKING PLAN

The SGE (supported as necessary by the SM) should prepare a checking plan. This should be prepared after the kick-off meeting with the PM (following the ten steps in **Table 4.1**) and agreement on the objective and application category for the numerical model (**Figures 5.1, 5.2 and Table 5.1**). The SGE, supported by an SM, should identify the right people (on the basis of their specialist expertise) to carry out and document the checks. It is critically important that there is a proper assessment of the skills and expertise of the engineers who may be available. For more complex work, it may be necessary to bring additional expertise into the PT. Checks typically comprise two different levels:

- Concepts and principles by senior staff, eg for the agreed objective and application category are the following appropriate:
    - input data and assumptions?
    - type of stress–strain model(s)?
    - model built correctly and calibrated?
    - output reasonable (compared with past experience and case history data)?
    - interpretation and application of output appropriate?
- Detailed checks of inputs and outputs can be mainly done by junior staff, but if the type of modelling is particularly unusual (given the modelling team's experience) or complex, then larger inputs by senior modelling staff may also be needed. This involves a line-by-line check of inputs and of outputs (outputs often need further manipulation to be of further use) to ensure that errors have not been made in setting up, running the model and extracting outputs.

The checking effort depends upon the application category (**Figure 5.2 and Table 5.1**):

- **Low-risk applications.** The check may only need input from a geotechnical engineer, with appropriate numerical modelling experience, to do the detailed checks (independent of the originator), with the SM (who may also be the SGE for the project) reviewing the concepts and principles. PA may be judged to be unnecessary.
- **Medium-risk applications.** In addition to the detailed check, there would need to be independent review of the concepts and principles by a senior engineer (to carry out PA).
- **High-risk applications.** The checking team would be larger and may need to be multi-disciplinary (complex models often require detailed modelling of several different features or components, eg ground, groundwater, structures etc, perhaps using several advanced material models for ground and structural behaviour).

9.3 TIMING OF CHECKS

Checks should be carried out at three stages (whatever the application category):

- early phase – review of available data, selection of software and key assumptions, such as stress–strain model(s), based upon the agreed objective
- middle phase – building and calibration of model
- final phase – review of outputs and their application.

The early phase check is particularly important to avoid wasted effort and rework. For many projects, changes occur as the project develops, and the implications need to be carefully reviewed by the numerical modelling team and the checkers (including PA). If the objective changes, and the model has not been modified, there is a serious risk of misuse of the output.

9.4 SCOPE OF CHECK BY SENIOR SPECIALISTS

Example checklists are given in **Tables 9.1 to 9.3** which cover the early, middle and final phases of checking. Essentially, the following need to be checked by senior staff with sufficient specialist knowledge and expertise:

- right people
- objectives and application category appropriate
- adequate information
- analysis strategy correct – including the use of simplified conventional methods at an early stage, selection of right type of model and modelling assumptions
- robust change control and effective communication
- sufficient evidence of detailed checks of inputs and outputs
- outputs reasonable and sufficiently reliable for subsequent use
- adequate reporting of numerical modelling– including assumptions, factual outputs, interpretation of outputs (and guidance on limitations for subsequent use).

Appendix A discusses some of the technical issues that can often be challenging. The examples indicate that a good understanding of soil/rock mechanics is fundamentally important, together with an understanding of the stress–strain (constitutive) models used in the numerical modelling. Checking the detail of how the model has been built (selection of element types, design of mesh etc) and how it has been calibrated are also important.

Table 9.1 Organisation, role and responsibility – example checklist

Topic	Comment	Recommendation	Action By
Roles and responsibility	Proper allocation of roles and responsibility, recognising competency of available resource and staff location.	Discussion needed between PM and SGE/SM. A checking plan is prepared.	See, for example, **Table 4.2**
Roles and responsibility	Define who will 'check' and 'authorise' modelling outputs and reports? Who will 'PA'?		
Roles and responsibility	PA required at early stage (and well before issue of reports), eg objective versus time/budget, input data and assumptions, together with interpretative report review.	PM to plan ahead and ensure effective communications to right people at the right time.	
Roles and responsibility	Clarify who will be 'designer' (ie to translate modelling output into practical project implementation).		
Timescale and budget	Time should be allowed for checking, testing and validation.	Prepare realistic programme and budget.	See, for example, **Table 4.2**
Timescale and budget	PM should discuss with senior modelling specialists, before finalising the programme/ budget for modelling.	SM needs to be proactive and discuss with PM.	
Timescale and budget	Balancing programme/cost versus model accuracy – if only limited time/budget, then need to outline practical implications/ limitations associated with a 'simple model'. More conservative design/project planning will likely result.	Mature and realistic discussions needed, at an early stage.	See, for example, **Table 4.2**
Communications	Two-way regular communication is essential. Do not rely solely on email! Verbal communications (phone) and face-to-face meetings are essential.	SGE/SM needs to be proactive.	See, for example, **Table 4.2**
Communications	How will changes within project (eg geometry, construction timing/sequence, use of outputs) be effectively communicated?	PM to consider, ensure effective communication.	
Communications	Modellers need to attend selected project meetings, so they have a good understanding of what modelling output will be used for.	PM to encourage active involvement by SGE/SM.	
Communications	Reduce 'specialist jargon' – to communicate effectively.	SGE/SM to action.	

Table 9.2 Objective, information, model building – example checklist

Topics	Comments	Recommendation	Action by
Key inputs/ assumptions	Critical inputs/assumptions should be identified as early as possible, and independently checked, especially for projects where consequences may be severe.	PM to discuss with SGE. For major projects, critical inputs may need independent review by the senior challenge team (multi-discipline PA team).	See, for example, **Table 4.2**
Numerical model objective	Identify the key objective of using a numerical model.	Specific unambiguous statement of the primary objective. If multiple objectives, then these should be prioritised so that primary objective is recognised.	See, for example, **Table 4.2**
Numerical model objective	How will required output be used? If output required for design, then potential challenges with code requirements need early assessment.	Associated design standards, codes and specifications should be stated. Discuss with designer (or end-user) how required output will be used. Depending upon numerical model objective, SGE/SM needs to communicate model limitations or constraints.	
Information	A comprehensive review of all available information is required.	SGE to carry out review, identify limitations (may affect appropriate objective and application category). Prepare scope of additional work (investigations/monitoring/ surveys etc) to solve data gaps.	
Numerical model application category	Application category appropriate?	PM and SGE to carefully consider, seek PA view if necessary.	
Analysis strategy	Use simple conventional analytical/ empirical methods, whenever feasible, at early project phases to get approximate estimates.	Before numerical modelling begins, the SGE should ensure that simple conventional methods are used to give preliminary 'ballpark' estimates of required output.	
Model building	Selection of software (what software and why).	Software selection, assumptions and input parameters and design of model (mesh geometry etc) check by SM. Detailed modelling should not start, until the conceptual design of the overall model is deemed to be robust and appropriate.	
Model building	Model design (key issues, mesh geometry and boundary conditions).		
Model design	Conceptual design of numerical model.		
Model design	Modelling of behaviour, selection of constitutive models.		
Model design	Previous experience with selected model and proposed application, and its associated reliability.	SM and PA review.	
Model design	Appropriate level of complexity.		

Table 9.3 Calibration, checking and interpretation of outputs – example checklist

Topics	**Comments**	**Recommendation**	**Action by**
Calibration	Calibration is essential to assess likely reliability of outputs for 'real-world' behaviour.	Calibrate against case-history data whenever possible (if not, risk of unreliable modelling outputs should be highlighted in modelling report). Review by PA.	See, for example, **Table 4.2**
Calibration	Critical components of model should be cross-checked against laboratory, physical modelling, empirical, or full-scale field tests to check that a separate computer model of the component provides reasonably realistic calculations of behaviour.	Computer simulations of critical components (eg piles/anchors) should be carried out, particularly for large complex models.	
Input data checking	Input files.	Detailed independent check of all inputs needed[1]. Should be documented and signed off by checker and originator and available for review by SGE. PM should ensure that final set of assumptions (and previous assumptions) are documented and communicated to PT, before outputs used for decision making/ subsequent design.	See, for example, **Table 4.2**
Input data checking	Control of model files.		
Input data checking	Interim hold points needed for large models.		
Input data checking	Source data should be comprehensively documented, plus any changes/corrections (for traceability purposes).		
Application of output	Which output is critical?	Designer to confirm and communicate to SGE/SM.	See, for example, **Table 4.2**
Application of output	How will critical output be used?	Discussion between SGE and designer.	
Interpretation of output	What are the consequences of real behaviour being different from model output?	Designer to consider. Ensure that engineering design or project planning is robust, given reasonable variations in model output.	
Interpretation of output	Sensitivity checks. Identify which inputs/assumptions have the most impact on output.	SM/SGE needs to discuss with designer.	
Interpretation of output	Sensitivity checks. Are changes in outputs reasonable, given changes in inputs?	SGE/SM to consider.	
Model outputs	Given modelling and input data limitations, associated uncertainties. Is the key output being interpreted and applied appropriately?	Review by PA.	

Note

1 Input checking includes meshing and boundary conditions, constitutive model selections and associated input parameters, groundwater conditions and drainage boundaries (short-term and long-term), initialisation and *in situ* stress, inputs for structural components, construction sequence.

9.5 SELECTION OF APPROPRIATE GROUND MODELS

This is a task which is often not given adequate attention, however the type of ground models that are used (together with selection of appropriate input parameters) can fundamentally affect the reliability of the numerical modelling output (eg O'Brien, 2015, Schweiger, 2015, Lees, 2012, O'Brien and Liew, 2018). Specialist expertise and experienced judgement are needed to make the most appropriate choices (eg **Box 8.2**). The right type of ground model for a particular design situation will depend upon a range of factors, including:

- the objective
- the nature of the geology and hydrogeology
- the type of loading which will be applied to the ground and structure
- the type of ground–structure interaction and the nature of the deformation/failure mechanism which may develop.

It is important that this selection is carefully reviewed by the senior staff involved in checking the model.

Table 9.4 provides some examples of the complex behaviour of natural soils and rocks. It is usually impractical to attempt to include all the complex facets of ground behaviour into a numerical model. Because of practical constraints (time, budget, limited ground investigation etc) the modeller may need to select relatively simple stress–strain models to simulate the ground behaviour, but this will mean that the outputs have to be interpreted carefully. There may also be severe limitations in how the output can be used for subsequent design.

Past experience and the use of relevant case history data is vitally important (eg Jones *et al*, 2008 and O'Brien, 2013). For some situations, depending upon the objective and the ground conditions, it may be necessary to use more advanced ground models (eg including non-linear stress–strain behaviour) in order to obtain reliable outputs. Calibration and checking of the model inputs/outputs is then likely to be more demanding, but the outputs may be more useful for subsequent design.

Table 9.4 Some examples of complex ground behaviour

Feature of behaviour	Comments
Non-linearity of stiffness	Natural soils exhibit significant non-linear reductions of mobilised stiffness (typically a factor of 10 or more) between true linear elastic region (at strain amplitudes of less than 0.01%) and mobilising peak strength.
Anisotropy of stiffness	Stiffness in horizontal direction (at a mobilised strain) will generally be different from that mobilised in the vertical direction. For some heavily over-consolidated soils horizontal stiffness may be more than double that mobilised in the vertical direction. Undrained stiffness anisotropy is not equal to drained stiffness anisotropy.
Anisotropy of strength	Mobilised strength will often differ, depending upon shearing direction. For soft clays and laminated deposits, strength in triaxial extension may be less than half that mobilised in triaxial compression.
Discontinuities/joints/low strength layers	Many natural soils and rocks have a pronounced macro-structure, with the mass strength being mainly dependent on the strength mobilised along joints, fissures and low strength (pre-sheared?) layers. For some situations, continuum models will not be suitable.
Yield	For soft clays and silts, loading may lead to their yield stress (often referred to as pre-consolidation pressure) being exceeded, and then stress and strain increments and principal stress and strain directions will not be directly related via elastic parameters (eg Young's modulus, Poisson's ratio). Sensitive clays will de-structure, and will exhibit viscous, strain rate dependent behaviour.
Variability of permeability	Natural soils often have a pronounced fabric, which means that mass permeability can be sensitive to a small number of local lenses or laminations. During swelling or consolidation, permeability may change significantly.
Anisotropy of permeability	Due to depositional environment and post-depositional processes, vertical permeability may be quite different from horizontal permeability.
Stress path direction and principal stress rotation	Both soil strength and stiffness may be influenced by the overall stress path direction, and by changes in stress path direction, which may be imposed by construction processes.
Creep (secondary consolidation and secondary swelling)	Soft clays/peat can exhibit large creep deformation (secondary consolidation), and stiff clays/mudstones can exhibit large secondary swelling. Coarse grained soils (sands, gravels) can also exhibit significant time-dependent deformation.
Post-peak strain softening and progressive failure	Once peak strength is mobilised, strength will drop towards critical state strength, and then residual strength at larger displacements. The drop from peak to critical state, and then to residual can be extremely large for some soils/weak rocks. Failure modes often involve progressive failure. For some situations and geologies, this can be of significant practical importance.
'Fatigue' under cyclic loading	Depending upon the magnitude and nature of the cyclic loading applied, soils can exhibit a considerable loss of strength/stiffness.
Unsaturated soil behaviour	Soil behaviour (strength/stiffness/permeability), once unsaturated, is fundamentally different from saturated soils (eg collapse settlement of unsaturated soil, induced by wetting, compared with swelling of saturated soils). Unsaturated behaviour can be important, even in temperate climates, for many groundwater flow problems. Permeability reduces as a soil desaturates and exhibits hysteresis during wetting/drying.
Strength/stiffness during earthquake shaking	Some soils can liquefy or suffer considerable loss of stiffness/strength during earthquake shaking. Following an earthquake, ground movements may be strongly affected by migration of excess pore water pressure (and so are influenced by local permeability changes and layer boundaries) and local topography.

9.6 EXAMPLES

One well-known case of a high-consequence failure that could be significantly attributed to poor checking of numerical modelling is the Nicoll Highway collapse of April 2004. **Figure 1.2** shows the catastrophic collapse of this 30 m deep excavation. Fundamentally the choices made in selecting the model inputs led to the undrained strength of the soft clay being significantly over-predicted. There were two aspects, firstly, combined with a Mohr–Coulomb failure criteria, a simple stress–strain model (linear-elastic), was selected. Second, the clay strength used effective stress parameters together with assuming that the clay was undrained during construction. **Figure 9.1** illustrates how the adoption of undrained conditions combined with effective stress strength parameters within a simple stress–strain model led to a significant over-prediction of the undrained shear strength. Below the excavation the simple stress–strain model follows the path A–B, hitting the failure envelope at B. The resulting undrained strength calculated by the model is much larger than the correct undrained strength, given by point C.

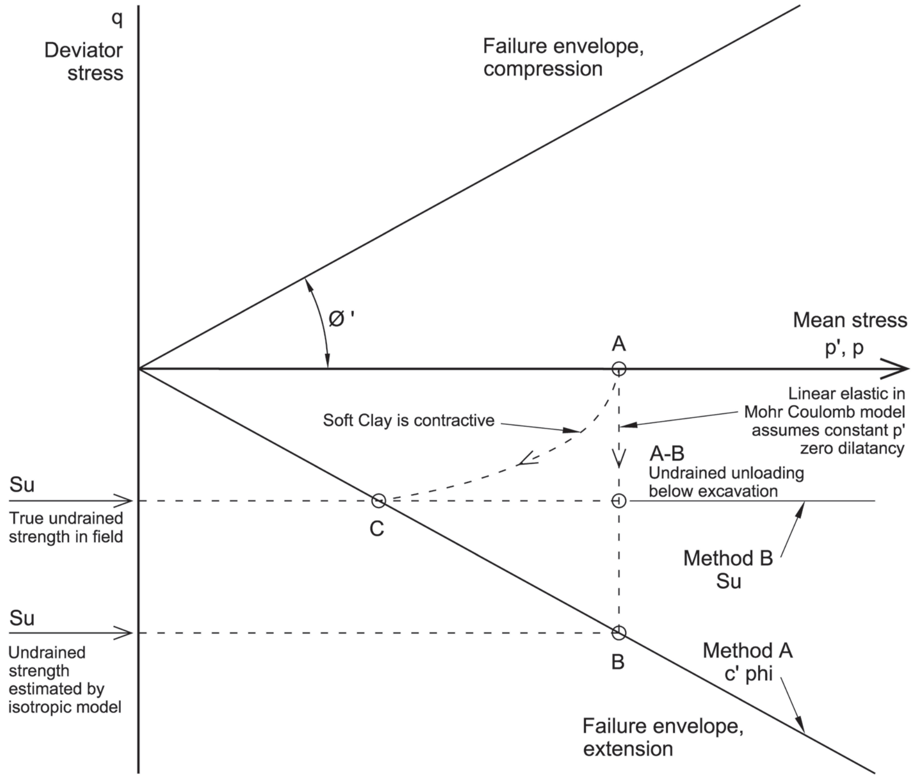


Figure 9.1 Assumed (method A) and more realistic shearing behaviour (method B), Nicoll Highway, Singapore

Fundamentally, shear strength is governed by effective stresses. In saturated soils, however, in order to calculate the correct value for effective stress under undrained conditions it is necessary to adopt an advanced stress–strain (constitutive) model that is capable of correctly calculating the undrained changes in pore water pressure.

The Mohr-Coulomb model adopted for the Nicoll Highway modelling was not capable of calculating the correct value for effective stress under undrained conditions and over-predicts the short-term soil strength. **Figures 9.2 and 9.3** show the significant effect that the different ways of defining the soil's shear strength had on the calculated wall movements and bending moments. The method adopted for design calculated wall movements and bending moments which are only about half of those of a more realistic soil model.

A simple check could have been made that would have highlighted the potential error. This would have involved setting up a computer simulation of an undrained triaxial extension test (using the same software and inputs as for the full numerical model).

The undrained shear strength calculated by the model could then have been compared against the ground investigation data.

Figure 9.2 Predicted wall deflections (method A vs. method B), Nicoll Highway, Singapore

Figure 9.3 Predicted wall bending moment (method A vs. method B), Nicoll Highway, Singapore

Boxes 9.1 and 9.2 give examples of errors that were identified during checking by a SM. **Box 9.1** indicates that some software can assume soil behaviour that is different from that originally intended, because of software-specific definitions (which are not necessarily logical). The issue was identified because the SM had sufficient experience to recognise that the output was unrealistic. **Box 9.2** illustrates the importance of careful soil characterisation and taking into account the effects of local stress history. For this example, the GI data was mainly obtained from areas beyond the existing embankment footprint. Below the embankment, the clay had consolidated and was stronger than that beyond the embankment footprint. Well-established empirical relationships between undrained strength and vertical effective stress for soft clays were subsequently used (after the SM had identified the issue) and this led to more realistic calculated behaviour.

Box 9.1 Drained or undrained calculations (and software specific definitions)

FE analysis was carried out to design a cantilever sheet-pile wall for an existing stiff clay (embankment fill) with an undrained shear strength of 50 kPa and modelled as undrained. The results showed very large horizontal movements for the 4.5 m deep excavation, which was inconsistent with past experience and case history data. After further investigation by the SM, due to the low water level, the modeller had set all the clay layers above the water level as 'dry'. This meant (due to the software-specific definitions) that the software ignored the undrained behaviour of the clay fill that had been defined as 'dry'. This layer was simulated by the model as 'drained' (even though the modeller had not intended this to occur), resulting in excessive horizontal movements. This simple example illustrates the importance of checking by an SM, and for modellers to be aware of (sometimes obtuse) software-specific definitions and the implications for material behaviour simulated in a model.

Box 9.2 Importance of good soil characterisation

FE analysis carried out to design a cantilever sheet-pile wall for an existing clayey embankment fill overlying soft clayey alluvium and stiff clayey glacial till strata as shown in the figure. The sequence of construction was as shown above. The proposed design was challenged by the SGE because the calculation indicated that an excessively long embedment was required (17 m embedment from top of the embankment for a backfill retaining height of only 1.5 m).

The modeller had carried out a c′-phi reduction after stage 3, adopting both undrained and drained properties. It showed that the long embedment is required for the undrained case only, to ensure the required factor of safety (FOS) of 1.25 is achieved. When drained properties were adopted, the FOS can be achieved with a very short embedment (consistent with past experience). This outcome is unusual in this geology because drained cases are generally more onerous. The failure mechanism for the undrained case was investigated, and it showed that the FOS was highly sensitive to the undrained shear strength (Su) of the alluvium. The Su adopted for the alluvium was obtained from data that included very soft offshore sea bed alluvium. So, Su values input into the model were excessively low. When Su was back-calculated for the material under the embankment using a well-established empirical correlation between Su and vertical effective stress for normally consolidated clay, this showed that the Su value below the embankment should be higher than assumed. Using this empirically estimated Su value demonstrated that the FOS could be achieved with a shorter embedment, and the FOS for both undrained and drained cases were comparable.

10 Reporting

10.1 GENERAL

Communication between the client, the design team and through the lead geotechnical engineer or SM is vital. From the outset, all parties have to understand why an analysis is being undertaken, how it is being done and what will be achieved by doing it. Essentially, this is managing expectations in terms of the outcome and the timescales taken to achieve an end result.

Once an analysis has been completed, who reports the outcome and how it is done is crucial to a successful result. This might be likened to reporting a ground investigation – there is a factual element and there is an interpretive element, although in the context of EC7 (BS EN 1997-1:2004+A1:2013) it would form part of the geotechnical design report. The factual report and the interpretation of the analysis can be combined into one document or they may be two separate documents.

Figure 10.1 summarises the overall process, showing the various steps in communicating what is required through to reporting and interpreting the results of the analysis. **Table 10.1** highlights some general issues which need to be checked when preparing numerical modelling reports.

10.2 SPECIFICATION AND APPLICATION CATEGORY

Before starting any analysis, a specification has to be developed to tell the modeller what the analysis should achieve. This should detail the information that the analysis should be based upon and the results required. It should include the following:

- purpose of the analysis
- agreed application category
- geometry
- ground investigation information (stratigraphy, soil properties, groundwater conditions etc)
- stress history (previous construction activity affecting the site)
- proposed construction sequence
- results required
- any simplifications or assumptions that can be made, and the reasons for doing so, eg idealisation of the construction sequence.

As outlined in **Table 10.1** it is helpful, especially when carrying out major modelling activities, to prepare a preliminary report that describes the key assumptions, the input data and any associated limitations and practical implications. This should be circulated across the PT as early as possible, and ideally before the modelling is completed. This can highlight potential misunderstandings within the PT, which can then be addressed before completion of the numerical modelling.

10.3 FACTUAL INFORMATION

Any analysis has to be based on the information provided to the modeller. So, it is usually beneficial to summarise the available information used to create a model, to describe the key assumptions and the associated input parameters when factually reporting the results of the analysis (the original agreed specification should also be included in the report).

Figure 10.1 Numerical model reporting – typical contents

When constructing the model the modeller may have to make a number of further assumptions or simplifications, which have to be communicated. There may be insufficient information or there may be a very large amount of information, some of it possibly contradictory. If additional results are required that were not initially envisaged (not included in the specification), the report should identify this.

In terms of who should produce the factual report, the only person who can really do this is the modeller. They are the only person who will fully understand what was analysed and know why it was done. The report should include the following details:

- reasons why the analysis is required
- information used and who provided it
- basis of the analysis and assumptions made including, ground conditions, groundwater conditions, site history etc
- summary of the mesh and element types used
- constitutive models (soil and structure) used and the basis for deriving parameters to describe material behaviour
- description of the idealised construction sequence followed
- details of the relevant results
- limitations of the analysis.

Before interpreting the results of the analysis, the SM has to review the details of the analysis and confirm that the analyses undertaken are valid and meet the specified objectives. In effect, they have to confirm that the specification has been met. This process is likely to involve the design or assessment by the whole team – not just an individual – the SM may simply co-ordinate this process. Once that is done, an interpretive report can be produced.

10.4 INTERPRETIVE REPORTING

Having concluded that the analysis was completed in accordance with the specification, the interpretation of the results can be undertaken and reported. An interpretation of the analysis is effectively a translation. It takes the results of the analysis and puts them into context, providing a commentary on the implicit conservatism of the analysis (if any) and a discussion on where and when the results of the analysis can be used.

This is not a straightforward process because it requires an understanding of the analysis and of the design process (ie the bridge between the two). Care has to be taken to ensure that the results of the analysis can reasonably be used in the design or assessment process and, perhaps more importantly, how they will be used. Certain assumptions may be conservative in terms of the numerical model but they may not be conservative in the context of the overall design process. The user of the results has to understand when, and how, the results can be applied. So, the report should include a discussion on issues such as – but not limited to – the following:

- how conservative the analysis is
- how various quantities have been derived from the output of the analysis and how the data has been manipulated, eg how a radius of curvature has been derived from an analysis in which 'constant strain' elements have been used
- approximations made in deriving quantities and what additional information has been used to derive these quantities, eg how wall installation effects have been simulated or have underground structures been 'wished-in-place'. If they have been wished-in-place is it reasonable to do so and how might any associated ground movements be added and what does that do to the assessment of ground movement?
- implications of the results, eg what building damage category is predicted, and a commentary on how these results might be modified if building stiffness is accounted for
- what has been ignored, is it reasonable to assume that a pipe or tunnel moves with the ground or does the stiffness of a structure (if not modelled) change the pattern of ground movements?

- how the results might be used in further assessments or modelling that has been planned, eg structural analysis and modelling, and is it appropriate to do so?
- any pertinent observations or recommendations on how the factual information might be used
- any additional information needed to improve the reliability of the analysis.

The interpretation of the results of the analysis is a guide to the user. It has to be produced by the lead geotechnical engineer and the SM or modeller, who can jointly communicate this information to the design team. It is important to note that if the sequence changes or if more information becomes available that contradicts the assumptions made, then the analysis may be invalidated, for example:

- If a certain volume loss has been assumed when modelling a tunnel construction and measurements suggest that this will be exceeded, then the analysis (and all related reports) becomes invalid. This may seem obvious, but on major infrastructure projects and, in the past, this has been overlooked, with potentially serious implications for adjacent structures.
- The analysis of a propped retaining structure where the prop stiffnesses have been assumed. Despite advice at the time the analysis was undertaken, it subsequently became apparent that the assumed effective stiffnesses were not achievable, so the analysis could potentially underestimate ground movements behind the wall and lead to more damage to an adjacent structure than expected.

Given these possibilities it is important that the assumptions made are well documented and reviewed as the design progresses.

Table 10.1 Numerical modelling reporting – example checklist of issues

Reporting	Recommendation	Action by
Assumptions/input data	A comprehensive description of all inputs, material parameters, assumptions etc is essential. For major modelling exercises, an 'assumptions' preliminary report should be produced. SM needs to ensure that proper reporting of assumptions is carried out and communicated to the PT as early as possible. Ideally, it should be checked and agreed before modelling starts. Update, if there are subsequent changes.	See Table 4.2.
Factual report – a summary of the key numerical model outputs	Ensure that outputs are always linked to assumptions/inputs. Highlight changes to assumptions/inputs if several different runs.	
Interpretive report (can be most challenging aspect of modelling)	An interpretive report should be produced. Needs early discussion with PT. Needs to compare outputs with known real-world behaviour, and provide advice on how modelling outputs should be used for specific project applications. This requires considerable experience and, potentially, a broad range of technical expertise.	

11 Conclusions and recommendations

11.1 CONCLUSIONS

Numerical modelling is a powerful and versatile analysis technique in geotechnical engineering. If used wisely, it can provide significant benefits (**Chapter 3**). During the last decade or so, numerical modelling has become more widespread and is becoming a more popular design tool. However, conventional QA procedures are relatively ineffective in controlling the reliability of numerical modelling outputs. This guide has sought to outline good practice in the process of commissioning, managing and reporting the results of numerical modelling.

For PMs who are not familiar with the processes involved, there are additional challenges because:

- numerical modelling is highly specialist, and can appear to be a black box
- there is usually a need for a much wider range of information to build a reliable numerical model, compared with conventional analytical techniques
- there is the potential for a 'generation gap' between relatively inexperienced modellers and those with more experience acting as PMs or DMs, which increases the risk of poor communication and misunderstandings
- the modelling results are very sensitive to how the model is designed and built by the modeller (and the skill and expertise of the modeller). It is useful to think about a numerical model in the same way as construction on site – it is important that a clear specification is produced of what is required. The workmanship involved in building a numerical model is critically important and requires an appropriate level of checking and supervision.

11.2 RECOMMENDATIONS

With increasing reliance placed on the outputs from numerical modelling for design and project planning, it is important for a PM to have effective procedures in place to manage the use of these methods. This guide outlines a 'ten steps' to better numerical modelling (see **Figure 1.3 and Table 4.1**). This simple process can help to demystify numerical modelling. It enables the modelling to be well planned and organised and to facilitate an appropriate level of checking and review. It is important for the modelling objectives to be clear and for the 'application category' for the modelling to be selected properly – see **Figures 5.1 and 5.2 and Table 5.1**. A RACI table is a commonly-used project management tool, and this can be applied for numerical modelling (see the example in **Table 4.2**).

It is strongly recommended that 2D numerical models should be built, run and interpreted before 3D numerical modelling is undertaken.

It is important to have a pragmatic and realistic analysis strategy, it is recommended that analysis should start with simple methods and progress to more sophisticated analysis as the project matures. Where possible conventional methods of analysis should be used alongside numerical models. When using numerical models, a relatively simple model should be built, run and interpreted before more sophisticated models are used. The reasons for differences between outputs from different analyses need to be considered. This general approach is particularly important if 3D numerical modelling is being contemplated. This overall analytical philosophy will facilitate more informed interpretation of numerical models and minimise a 'black box' mentality.

The competency and training of modellers and their supervisors (**Chapter 4**), the information required for a numerical model (**Chapter 6**), the calibration (**Chapter 8**) and checking (**Chapter 9**) of numerical models are all vitally important considerations. These tasks may require more effort and more senior review than merely building and running a model (**Chapters 7 and 8**) and producing the factual outputs. Finally, the reporting of numerical modelling should include an 'interpretation' of the factual outputs from the model, to ensure that any outputs are properly used for subsequent design and planning. SGEs, familiar with numerical modelling and geotechnical design, should be involved in this task, as considerable judgement may be required. Unfortunately, the key task of interpretation is often forgotten, with the result that outputs can be misunderstood and misused. The consequences of erroneous outputs from numerical modelling can be very serious, for example, the Nicoll Highway collapse is a stark reminder of what can happen if modelling is not properly checked and understood by the PT.

For the Nicoll Highway collapse, the serious error could have been identified if some simple and relatively quick checks of the numerical model had been carried out. Sometimes numerical modelling is considered to be a black box. But this is unsafe, and the project management community should consider this type of approach to be unprofessional. If the guidance outlined in this publication is followed, then the black box can be eliminated. If numerical modelling is used for design decisions, then there should be no difference in the level of understanding between it and alternative engineering calculations. The respective strengths and weaknesses of the analyses need to be understood. The assumptions and inputs used in numerical models should be transparent and justified, and checking should be sufficient to ensure there is confidence in the use of outputs, consistent with the agreed objective and application category.

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A1 Checking

A1.1 INTRODUCTION

Numerical modelling usually requires several sets of runs, and so it is wise for checking to start as early as possible after the first run, and before subsequent runs begin. **Chapter 9** outlines some key principles for managing the checking process and gives example checklists for checking activities (**Tables 9.1 to 9.3**). This appendix discusses specific technical issues that can often be challenging.

Logically, the items requiring checking follow the considerations outlined in building the model given in **Chapter 7** and these are outlined as follows together with examples of errors that can occur.

There is no easy checking procedure – it is a process that requires careful inspection by a checker with suitable expertise and it needs discussion during meetings between the checker and the modeller, together with advice from the SM. If in doubt, more than one approach needs to be tested to check if there is a significant effect on the outputs of interest. So, the sensitivity of the issue to various assumptions needs to be tested.

It is recommended that a checklist is created (based on **Tables 9.1 to 9.3**) and is provided by the checker as evidence of a check performed during a run-through of the model creation. The items outlined here usually require detailed checking because they are a common source of errors.

A1.2 GEOLOGICAL PROFILE

The levels and strata of the input geological profile need to be checked against the intended profile. Material layer definitions typically have serial numbers assigned to them, and these can be activated on a view of the mesh to allow for checking. Views of certain input and state parameters can also be used to perform checks.

A1.3 GEOMETRY

Levels and co-ordinates of input geometry for geotechnical features and structures need to be checked for consistency with the intended geometry of the problem.

A significant amount of idealisation in input geometry is often required for numerical modelling. **The goal should be to achieve a model that is as complex as required, but no more.** There are often numerous ways in which to idealise a problem for model input, and it may be necessary to examine more than one approach to determine which is most appropriate.

A1.4 MESH DESIGN

The sizing of the elements for the mesh should be checked to ensure that they are appropriate for the particular model. Typically, mesh size should be finer in areas of interest and coarser towards the model boundaries. Meshes that are too fine can create unnecessarily long computations, while meshes that are too coarse in areas of interest risk producing unreliable outputs. The latter is a more common issue than the former. In addition to mesh density, the types of elements selected by the modeller can have a profound impact on solution accuracy and the reliability of outputs. **Table A1.1** summarises results for the calculation of the displacement and stress in a simple linear elastic cantilever beam from various numerical models using different element types (4 and 8 noded tetrahedral and 8 and 20 noded brick elements). This shows that the model using simpler element types (4-noded tetrahedral) calculates a beam displacement which is less than a quarter of the more sophisticated element type (20-noded brick). It should also be emphasised that this is a relatively simple elastic calculation, so for highly non-linear geotechnical analyses the solution accuracy can be far more severely affected by the type of element used. The calculation accuracy of different elements is usually indicated by the number of nodes or gauss points. (This allows the iterations to solve with a reduced error) or 'the order of an element', eg a fourth order element is more sophisticated than a second order element (a fourth order element will give a more accurate solution, but will require a longer time period to solve). **Figure A1.1** shows how element shape can influence solution accuracy, and for this example (for FLAC® software) solution accuracy is influenced both by mesh density and by the aspect ratio of the elements.

Table A1.1 Table comparing results for elastic cantilever beam using 4-noded tetrahedral, 10-noded tetrahedral, 8-noded brick, and a 20-noded brick element

Solid element used	No. of nodes	No. of degrees of freedom	No. of elements	Free end displacement (mm)	Principal stress (kP)
4-noded tetrahedral	415	1245	1549	0.72	16263
10-noded tetrahedral	144	432	61	2.98	44547
8-noded brick	343	1029	216	3.18	44898
20-noded brick	1225	3675	216	3.26	47265
Classical ('exact') solution				3.27	47886

Key

NTV = 10 – relatively coarse mesh.

NTV = 50 – relatively fine mesh.

Figure A1.1 Solution accuracy versus mesh density (NTV) and shape of element (aspect ratio)

It is important to emphasise that these issues can become particularly challenging for 3D analyses when a coarser mesh density and/or simpler element types are selected to speed up run times for a numerical model. Before building and running a 3D model it is recommended that a 2D model is used, because comparisons between the 2D and 3D outputs can help spot errors in complex 3D models and can also assist in interpretation of outputs from a 3D model, otherwise, there is a high risk that output from a 3D model will be misinterpreted. Tan *et al* (2012) provide an example of how 2D and 3D models used in combination supported an innovative 'trouser leg' diaphragm wall for deep excavation support in very soft Singapore marine clay.

Both interpreted geological profiles and input geometries can cause problems when creating the mesh, known as 'meshing'. Sometimes it may not be possible for the mesh to generate due to inconsistencies in the geometry definition or having geometries that are too close or that create awkward geometric shapes. Geological layer boundaries and geometries of included structures may need to be modified to avoid meshing issues. In some instances, it may still be possible to generate a mesh, but elements with extreme aspect ratios (ie long and thin) can cause issues (as illustrated in **Figure A1.1**) in the numerical solution, and should be avoided.

Figure A1.2 shows an example of the impact of meshing problems on an SCL tunnel analysis. In this example, the analysis was carried out with two different types of software, but all the inputs (SCL shape, boundary, ground and groundwater conditions, the excavation and ground relaxation stages etc) were identical. Note that the bending moment for different software is plotted differently and with different sign conventions. Both models showed similar bending moments from the axis to the crown. However, model B calculated a bending moment about 50 per cent higher than model A at the bottom corners. This is due to meshing problems around the bottom corners of the lining for model B, resulting in a series of corners made with a series of straight beams, hence the larger bending moment. When model B is refined by making it finer at the corners (with a larger number of straight beams), the maximum bending moment is reduced and was similar to model A.

(a) Geometry and Mesh for model A

(b) Geometry and Mesh for model B

Figure A1.2 Challenges with meshing in SCL tunnels (coarse mesh for model B calculation gave 50% higher BM than for refined mesh for model A)

Due to the iterative nature of the numerical solution adopted in the FEM, tolerances (ie the 'percentage error' allowed within each solution stage) adopted in the calculation need to be carefully checked. Sometimes small changes can lead to large variations in outputs due to the cumulative nature of errors at each calculation stage.

A1.5 BOUNDARY CONDITIONS

Boundary conditions at the model limits also need to be checked for appropriateness. In particular, for analyses involving groundwater flow or seismic loading, a careful consideration of the appropriate boundary conditions is very important.

To save computational time, modellers often choose to assume a plane of symmetry, such that only half a model is created and analysed. When appropriate this can facilitate much quicker modelling, but it can lead to erroneous outputs if there is asymmetric loading or interactions 'across' the plane of symmetry. **Figure A1.3** shows the loads applied to the top of caissons embedded in weak rock for a bridge. The caissons are built on a rock slope. In this example, a modeller might choose (inappropriately) to model one caisson with a plane of symmetry. Owing to the asymmetric loading conditions (applied to the top of the caissons, especially associated with the transverse rotation and shear applied to the top of the caissons) and the closeness of both caissons, it is actually necessary to model both caissons to obtain correct outputs. In this example assuming a plane of symmetry would be incorrect.

Note

Only modelling one caisson and assuming a plane of symmetry is incorrect, due to the nature of the applied loading.

Figure A1.3 Example for bridge caisson analysis

A1.6 MATERIAL MODEL AND GEOTECHNICAL INPUT PARAMETERS

Application of the intended stress–strain (constitutive) model for each material type in a model (ie ground layers, structures, ground improvement zones) and the correct input parameters for each geological unit requires careful checking. The appropriateness of the adoption of total or effective stress for the characterisation of ground strength also needs to be considered.

Advanced constitutive models are available, but it is critical that the model is appropriate to the problem being considered. Both the modeller and the checker need to have a detailed understanding of the formulation and features of any model adopted.

Typically, printouts of input parameters can be made from the software for inclusion in reports. These printouts should be used to check the input parameters one by one and be signed off by the checker.

> Constitutive models that use effective stress strength parameters for undrained conditions have to be carefully checked for all the relevant stress paths for the problem under consideration.

There needs to be model calibration against laboratory element testing (eg simulating triaxial tests and comparing against laboratory measurements), especially for undrained conditions, with different stress paths, to demonstrate that the effective stress strength parameters are suitable. It is difficult with a simple soil model, such as Mohr-Coulomb, (with soil strength defined by effective stress strength parameters) to match the appropriate undrained shear strength for the soil. A simple and useful check is to plot contours of mobilised shear stress (calculated by the model) and compare these with the estimated undrained shear strength of the ground. This may identify zones where the model is over-estimating the mobilised shear resistance of the ground.

A1.7 GROUNDWATER PRESSURES

A critical aspect of most geotechnical analyses is the response of the groundwater regime. This could be changes in groundwater flow due to long-term changes induced by new construction or it could be excess pore water pressures generated during construction in low permeability soil. Total stress characterisation of soil behaviour implies an undrained response. This can be a very useful simplification but is only appropriate for particular ground conditions, for limited time periods and under certain loading conditions.

Adoption of effective stress analysis where groundwater is present requires an understanding of the drainage conditions for the material. This is typically a function of the boundary conditions, the permeability of the material and the duration of loading. Whether to select fully drained (no excess pore water generation), fully undrained (excess pore water pressures can be generated) or coupled consolidation (ie time-dependent) conditions requires an understanding of these issues. There needs to be clarity about the key objective of the analysis – is it to assess 'short-term' behaviour (ie during construction) or 'long-term' behaviour? Coupled analyses are possible and these can theoretically link both short-term and long-term behaviour, but this type of analysis requires far more detailed knowledge of the hydraulic properties of the ground (permeability), careful specification of changes in boundary conditions and loading during construction and the use of advanced constitutive models (in order to calculate realistic excess pore water pressures). In simple terms, three different types of analysis can be selected for assessing short-term behaviour of low permeability soils, and these have implications in any subsequent assessment of long-term behaviour:

1. **Method A.** Effective stress parameters to characterise undrained strength – as discussed in the Nicholl Highway case study (see **Section 9.6**), this method can be dangerous if used with 'simple' soil models. Advanced soil models are usually required to calculate correct undrained strengths and excess pore water pressures for a range of different stress paths – careful calibration is essential.
2. **Method B.** As for method A, but undrained strengths are specified to limit mobilised shear resistance – this method avoids some of the risks associated with method A, but it should be noted that the excess pore pressures generated during a short-term stage will be highly inaccurate. So, it should not be used for 'coupled' analysis nor for assessing subsequent long-term drained conditions (if a consolidation stage is added after an undrained stage).
3. **Method C.** Total stress analysis and undrained strengths are specified- no excess pore water pressures are generated. So it should not be used as the start point for assessing long-term behaviour.

Figure A1.4 Groundwater pressure assumptions for a river wall

Assumptions regarding the simulation of pore water pressures are often of considerable importance, and simplified definitions of groundwater boundary conditions can produce unrealistic pore pressure distributions which may lead to unsafe design.

For example, for a quay wall, different active and passive groundwater conditions are sometimes adopted, to simulate in a simple way the effect of maximum tidal water level lag (**Figure A1.4**). The modeller may choose to assume hydrostatic conditions on either side of the wall, or the increase of groundwater pressure with depth on the passive side may be assumed to be greater than hydrostatic. Depending upon the wall geometry and the tidal lag, this may lead to unrealistically large differences in groundwater pressure on either side of the wall, or effective stress conditions approaching zero within some parts of a model. A rigorous fully coupled transient analysis could be attempted, but this would require a detailed knowledge of ground permeability in the various soil layers. The common approach of assuming hydrostatic groundwater profiles on both the active and passive sides of a wall (sometimes known as the Z-method), which avoids performing groundwater flow calculations, is only an acceptable simplification in a limited set of circumstances. A checker must be aware of the potential pitfalls associated with these simplifying assumptions and that some deformation and failure mechanisms would not be simulated correctly. For example, in layered strata where a low permeability layer is present at the base of an excavation (and overlies higher permeability layers) the application of the Z-method produces an inherently stable condition within the numerical model, whereas in reality there could be a high risk of base instability (due to high groundwater pressures in higher permeability layers). In these situations, considerable judgement and detailed checking of assumptions are necessary to avoid unrealistic outputs. In many cases a separate evaluation of the hydrogeology and groundwater seepage can be useful, before numerical modelling, to define appropriate groundwater boundary conditions within a model. For these situations the checker needs to have a broad understanding of geology/hydrogeology in addition to numerical modelling, or be supported by a suitably experienced geologist/hydrogeologist.

A1.8 INITIALISATION

Following creation of the model, the first step required is initialisation of the stresses either through an initial estimation of the stresses or the application of gravity loading. Initial stress calculation requires the input of a K_0 (coefficient of earth pressure at rest, which is the ratio of horizontal to vertical effective stress) value and this input needs to be checked. It should be demonstrated that equilibrium has been achieved in this stage and the output should be inspected to ensure that the initial stress distributions are as expected before the analysis begins.

It is possible that the K_0 provided may be unrealistically high (there is usually a high level of uncertainty associated with any estimate of K_0, especially in heavily over-consolidated ground). So it is wise to check the *in situ* stress state at the initial stage. **Figure A1.5** shows the effective minor and major principal stress states for selected elements for a weak rock plotted for both a lower and upper bound K_0 profile. The stress state is compared with the Hoek–Brown failure criterion used to characterise the rock strength. This demonstrates that, for the upper bound K_0, the stress states are close to the failure line, so any subsequent proposed works could result in large plastic deformation. Some thought is needed as to whether this is realistic or not, before embarking on a detailed analysis.

Figure A1.5 Checking initial stress conditions versus assumed ground strength

Many construction processes (such as ground improvement, installation of driven/bored piles, diaphragm walls) can lead to changes of *in situ* stress (usually reductions/increases in horizontal effective stress, depending on the construction activity). Often these construction activities are ignored and underground features (eg grouted zone, or a retaining wall) are 'wished-in-place'. It should be recognised that in some situations this assumption can lead to erroneous outputs from a model (O'Brien, 2010). **Figure A1.6 and Table A1.2** summarise the effects of diaphragm wall installation in an over-consolidated stiff clay and the associated effects on calculated prop forces. For the upper props the wished in place assumption led to prop forces being over-predicted by more than 50 per cent. As discussed by Powrie and Batten (2000a) the prop connection details (and associated effects on prop stiffness) can also be a significant factor in calculated prop forces. The simulation of construction processes can be very challenging, which is why they are usually ignored. However, experienced judgement is needed because in some circumstances the construction processes can have a dominant effect on outputs and will then need to be simulated in the model. Hsu *et al* (2009) describe how, even for complex construction processes such as TBM tunnelling, numerical models can be calibrated to provide reliable outputs.

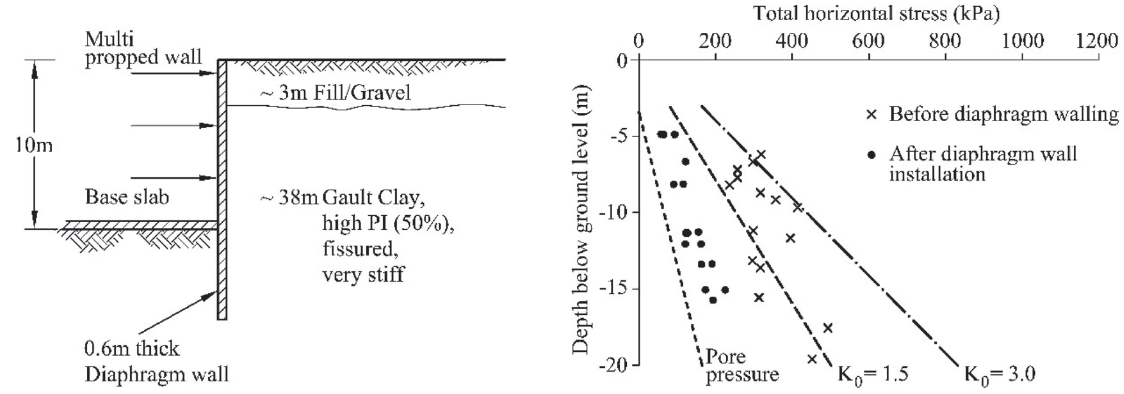

Figure A1.6 Horizontal stress, before and after wall installation, Lion Yard, Cambridge

Table A1.2 Prop forces, Lion Yard, Cambridge (from Ng and Yan, 1999)

Prop location	Measured prop force (kN/m)	Predicted prop force (kN/m)	
		WIP	*WIM*
L2	145	255	153
L3	119	216	155
L4	24	29	21

Note

WIP = wished in place

WIM = wall installation modelled

A1.9 ELEMENT TYPES FOR STRUCTURAL COMPONENTS

Table A1.3 gives examples of some element types that can be used to simulate behaviour of structural components in a model. **Fundamentally, there are two different types of element: zero thickness and volume.** Typically, zero thickness elements are quick and easy to include in a model and extract results (forces or bending moments, depending on element type, are directly produced by the software). However, there are often several limitations with these element types, eg the true volume/area is not represented in the model, the way in which interface friction, permeability, end-bearing (of a pile) can be simulated may be restricted or unrealistic for certain situations. For buried structural components that are wide (or large diameter) relative to their length the influence of interface friction (and the associated lever arm) in modifying, for example, wall (or pile) bending moment may not be calculated by zero thickness elements (depending on their formulation). In contrast, volume elements offer more flexibility in simulating, for example, interface friction, permeability and end-bearing and may be more appropriate to use in certain situations. However, they are more complicated to include in a model, and the outputs need to be manipulated after the numerical modelling is completed, in order for the outputs to be useful for subsequent use (eg wall bending moments need to be calculated from the stresses within the volume element). The pros and cons of different element types need to be considered when checking and interpreting the model outputs.

Table A1.3 Example of different element types for simulating structural components

Element type		Properties	Comment
1	Spring	Young's modulus (E)	Zero bending stiffness
2	Bar	Axial stiffness (EA)	Zero bending stiffness (2D or 3D)
3	Plate	Axial and bending stiffness (EA and EI)	2D
4	Membrane	Axial stiffness (EA)	Zero bending stiffness (3D)
5	Beam	Axial and bending stiffness (EA and EI)	3D
6	Shell	Axial and bending stiffness (EA and EI)	3D
7	Volume	True area/volume (for 2D/3D respectively) specified in model with appropriate properties and interface characteristics.	Complex setup, outputs need careful manipulation (eg from stress to bending moment). But potentially 'more realistic'

Note

Element types 1 to 6 are 'zero thickness' elements, which means that their true area/volume is not represented in the model. Typically, they are easy to include in a model, and structural forces are directly produced as outputs. However, they have several potential disadvantages depending on the design situation and numerical modelling objective (**Section A1.9**). The way in which different element types can be connected and forces transferred (free/fixed connections?) is also important. Depending on the software, element types and naming conventions can vary. 'Special' zero thickness elements are available in some software, eg to simulate pile behaviour. It is important for modellers and checkers to recognise the fundamental characteristics (and advantages/disadvantages) of different element types.

2D modelling is usually preferred because the models are quicker to run and easier to check. However, in a model, many structural components, such as piles and anchors/props, are 'smeared' in the 2D model. This means that their idealised behaviour (and interactions with other parts of a model) can lead to unrealistic model outputs.

Adoption of 2D modelling where three-dimensional elements such as foundation piles need to be represented can lead to compromises in the input, which can have unintended consequences. It is necessary to appreciate that a 2D model cannot adequately represent a 3D element, and compromises need to be made so that the most important aspect of behaviour (consistent with the specified objective) is reproduced by the numerical model.

The modelling of foundation piles (and other similar structural components) in 2D models typically requires 'smearing' of the element properties, such that the individual element properties are calculated and then divided by the element spacing to arrive at a unit length input required by the plane strain modelling assumption. The structural element is effectively simulated as a wall or slab in the 2D model. This can lead, for example, to the adoption of unrealistic interface element properties for piles as illustrated in **Figure A1.7**. Application of a smearing factor based on the surface area divided by the pile spacing can lead to low values of interface friction which can in turn lead to an under-prediction of axial forces in a pile.

Figure A1.7 Impact of smearing on interface properties for piles

Another source of incorrect input for structural elements can arise due to varying requirements for inputs of structural properties. For elements such as plates, it is common to provide the input on a unit length basis, which may or may not require the input of smeared properties, depending on whether the element being modelled is continuous or not. However, for elements such as anchors, the input is given on a per anchor basis, together with an input spacing.

Also, careful consideration needs to be given to the interpretation of output, recognising whether the forces obtained represent a unit length output which needs to be multiplied by the spacing, or a per element output which does not.

By default, structural elements usually adopt linear elastic properties. Deep excavation analyses typically require the modelling of struts, which, due to their method of connection to the retaining wall, are not capable of resisting tension forces, and the appropriate settings need to be adopted for the strut element.

It should be noted that when performing FOS calculations for slopes with reinforcing pile elements it is important to adopt elasto-plastic properties for the structural element with an appropriate ultimate capacity. If this is not done, the obtained FOS may be over-estimated and the critical failure mechanism may not be identified.

Figure A1.8 shows a sheet-pile river wall tied back to a pile anchor. In the plane strain FE model, the discrete pile bending and axial stiffnesses are 'smeared in 2D' by dividing by the spacing of the piles. This '2D smearing' develops a less stiff anchorage system, resulting in (a) larger lateral deflections of both anchor and river walls, (b) underestimating of the tie load, (c) excessive interaction between the anchor and river wall and (d) larger river wall bending moment. A single pile analysis was carried out where the lateral load–deflection response is plotted in **Figure A1.9**. This simple analysis showed that the pile anchor has a stiffer lateral response, and half the deflection is expected for the same tie load. As the tie load is underestimated due to a less stiff anchorage system, a fixed-end anchor analysis (without modelling the pile anchor wall explicitly) was carried out to obtain the upper bound tie load.

This example illustrates that, depending upon the objective, several sets of 'simpler' analyses may be needed to identify appropriate and conservative outputs for design.

Figure A1.8 Consequences of modelling anchor piles for a river wall in 2D numerical model

Figure A1.9 Lateral load–deflection of an anchor pile (anchor pile is a key component of the model shown in Figure A1.8)

A1.10 CONSTRUCTION SEQUENCE

Many geotechnical problems require staged construction and in reality some of these activities may be concurrent across a site. To make understanding easier the construction sequence is often idealised into a series of individual stages to simulate the construction sequence, eg progressive filling of an embankment or level by level excavation of a deep basement. Often different construction sequences may be investigated with the same model. So it is necessary to check that each analysis stage commences from the correct preceding stage.

Some software packages also have the facility to 'reset displacements' at the beginning of each calculation stage. This is a useful feature, however, careful attention needs to be paid when this feature is adopted because it may be possible to ignore cumulative displacement effects. Another issue is that while nodal displacements are reset with this feature, stresses and in particular forces in structural elements are not. This can lead to confusion and careful interpretation of outputs is required.

Figure A1.10 shows a typical construction sequence modelled for a tie-back river wall design, which considers the existing embankment condition. This representation, which reflects the assumed construction sequence in the model, shows the change of ground properties, excavation and backfilling operations, application of surcharges and structural components. This allows a checker to comment on the constructability and construction methodology. The structural loads and ground deformations for each stage can be collated to identify the critical stages and also to help develop a 'sense' check.

Figure A1.10 Review of overall construction sequence and applied surcharges assumed in numerical modelling

A1.11 MODEL VARIATIONS

Design development often requires multiple runs of the same model with variations in input geometry, eg thickness of ground improvement layers or properties. This makes it critical to check that this input has been defined and updated as intended.

For a port development project, a 'very soft clay' layer was identified during a relatively late stage, when the quay pile wall had already been installed. The FE analysis carried out with the original construction sequence showed a global failure mechanism due to the 'very soft clay' layer. This would lead to over-stress of the quay wall. So the sequence had to be modified and ground improvement implemented to improve the 'very soft clay' layer. The model was modified (see **Figure A1.11**) to include a new backfill sequence and the ground improvement (with stone columns) to prevent a global failure mechanism developing. This ensured that the structural loads for the quay pile wall remained acceptable. It is worth noting that this example highlights the advantage of using numerical modelling because a beam/spring type retaining wall analysis would not be capable of calculating the effects of this type of global failure mechanism. It also emphasises that important changes may occur during design development, and that 'checking' is not a one-off task, and needs to be maintained throughout the numerical modelling activity.

Figure A1.11 Modified construction/ground improvement for a quay wall

A1.12 THE 'STABILITY FALLACY'

Numerical modelling often focuses on predictions of SLS, so there can be a perception among inexperienced modellers that ULS failure should not occur. This might be termed the 'stability fallacy'. For FE calculations, the model will be unable to reach equilibrium if a failure mechanism occurs. This can be mistakenly interpreted as 'numerical instability' rather than the occurrence of a legitimate ULS. This can then result in the particularly hazardous practice of making inappropriate changes to a model to avoid the 'numerical instability' in order to allow the model solution to continue. This can then lead observers to the false conclusion that no stability issues exist for this model because equilibrium can be reached.

Examples of the 'stability fallacy' are as follows.

1. Slope stability, locally increasing soil strengths or lowering groundwater levels to avoid shallow slope failures may be a legitimate technique to investigate deeper failure mechanisms, but the possibility and consequences of the shallow instability mechanism still need to be considered. If the groundwater level has been reduced below prevailing levels to produce a stable solution, then this is not simply an expedient measure, but has real implications on control measures that will be required on site that need to be explicitly included in the design.
2. Similarly, undrained shear strengths may be adopted for 'temporary' slope stability issues, when permeability and groundwater conditions would dictate that an effective stress analysis is required.

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Numerical modelling is now routinely carried out in geotechnical engineering. Producing a numerical model is not straightforward and if not used properly can be dangerous. However, if used with skill and care there can be enormous benefits.

This guide has been written for those who commission and manage numerical modelling, not specifically those who undertake it. The aim is to provide a framework for those who oversee the process, provide the information needed for this task and use the results of the numerical modelling.

This guide aims to outline the information that the project manager (PM) needs to assemble, and the processes that need to be put in place for a successful outcome: the 'ten steps to better numerical modelling'.

By following this guide, those producing a numerical model will, we anticipate, be given the quality of information and the time needed to successfully produce a model that can be relied upon by the design team as a whole. Those managing the process have a vital role to play in producing a reliable numerical model and ensuring that maximum benefit can be obtained from it.

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