Validation of geotechnical finite element analysis

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Validation d'analyse par éléments finis pour la géotechnique

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ABSTRACT: The use of the Finite Element Method for geotechnical analysis and design has become quite popular. It is often the younger generation of engineers who operate easy-to-use finite element programs and produce colourful results, whilst the responsible senior engineers find it difficult to validate the outcome. The NAFEMS Geotechnical Committee has concluded that there is a need for guidelines on validation of geotechnical finite element calculations. The first author is a member of this committee and the main author of a reference document on validation of numerical modelling in geotechnical engineering. This paper contains the highlights of the aforementioned document. After defining the term *Validation*, sources of discrepancies between a real project and its corresponding finite element model are described. In addition, the paper presents various methods to validate geotechnical finite element calculations. The paper ends with some conclusions and a list of references for further reading.

RÉSUMÉ : L'utilisation de la méthode des éléments finis pour l'analyse et la conception en géotechnique s'est généralisée. C'est souvent la plus jeune génération d'ingénieurs qui utilise des programmes d'éléments finis et produit des résultats avec des figures pleines de couleurs, quand les ingénieurs seniors trouvent difficile la validation de ces résultats. Le comité géotechnique NAFEMS a conclu que des recommandations pour la validation des calculs géotechniques utilisant les éléments finis sont nécessaires. Le premier auteur est un membre de ce comité et l'auteur principal d'un document de référence sur la validation des modélisations numériques en géotechnique. Cet article contient les points principaux de ce document. Après la description du terme Validation, les sources de divergence entre un projet concret et le modèle élément fini correspondant sont décrites. De plus, cet article présente des méthodes variées pour valider des calculs éléments finis en géotechnique. L'article se termine par les conclusions et une liste de références pour une lecture approfondie.

KEYWORDS: Finite element method (FEM), validation, verification, benchmark, numerical modelling, discrepancies.

1 INTRODUCTION

In the past decennia the Finite Element Method (FEM) has been used increasingly for the analysis of geotechnical engineering applications. Besides developments related to the method itself the role of the FEM has evolved from a research tool into a daily engineering tool. It has obtained a position next to conventional design methods, and offers significant advantages in complex situations. However, as with every other method, the FEM also has its limitations. These limitations are not always recognized by users of finite element software, which can lead to unreliable designs.

Despite the development of easy-to-use finite element programs, it is difficult to create a good model that enables a realistic analysis of the physical processes involved in a real project and that provides a realistic prediction of design quantities (i.e. displacements, stresses, pore pressures, structural forces, bearing capacity, safety factor, drainage capacity, pumping capacity, etc.). This is particularly true for geotechnical applications, because the highly non-linear and heterogeneous character of the soil material is difficult to capture in numerical models. When using the finite element method, soil is modelled by means of a constitutive model (stress-strain relationship) which is formulated in a continuum framework. The choice of the constitutive model and the corresponding set of model parameters are the most important issues to consider when creating a finite element model for a geotechnical project. It forms the main limitation in the numerical modelling process, since the model (no matter how complex) will always be a simplification of the real soil behaviour. Hence, some features of soil behaviour will not be captured by the model.

Considering the use of geotechnical finite element software, it is often the younger generation of engineers who perform the numerical modelling and produce colourful results; sometimes without fully understanding the backgrounds and limitations of the constitutive models and the numerical methods used in the software. Supervisors, i.e. project managers or senior engineers, often find it difficult to validate the outcome, especially when these do not match with what they would expect based on their experience. This leads to the conclusion that there is a need for guidelines on validation of geotechnical finite element calculations, which was the primary motivation for the NAFEMS Geotechnical Committee to write a publication on validation of finite element models for geotechnical engineering applications. This paper summarizes the main issues addressed in the NAFEMS publication.

The next chapter 2 starts with a definition of the term *Validation* and other related terms. Before elaborating various methods of validating finite element models for geotechnical applications in Chapter 4, an overview of possible discrepancies between a real project and the corresponding finite element model is presented in Chapter 3. The last chapter contains the main conclusions of this paper.

2 WHAT IS VALIDATION?

Validation is concerned with the accuracy at which a model represents reality. In order to use the results from a model reliably in the design process, a proper validation of the model is required. Another term that is often used in relation to validation is *Verification*. To give more insight in the meaning

of validation and verification, the modelling process of Reality is divided into four steps, as visualised in Figure 1.

In the first step (1) the complex physical reality is abstracted into a simplified conceptual model. The main aim of this modelling step is to determine the crucial processes and to reformulate reality in a conceptual model by applying valid simplifications such that the main phenomena as observed in reality are retained in the model.

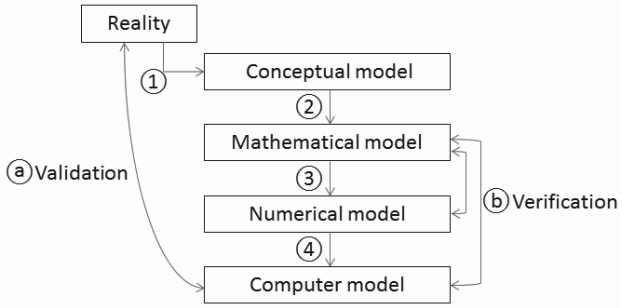

Figure 1. Visualisation of the modelling process from Reality to a Computer model, and the position of Validation and Verification.

The second step (2) is the translation of the conceptual model into a mathematical model. The mathematical model is the mathematical formulation of the processes identified in the conceptual model. Examples of mathematical models are the set of partial differential equations describing equilibrium in a continuum, and the constitutive model (stress-strain relationship) describing the soil deformation behaviour.

The third step (3) is the translation of the mathematical model into a numerical scheme. This generally requires a discretisation of the problem in space and/or time.

The fourth step (4) is the implementation of the numerical scheme into a computer model using a programming language or using a modelling package.

The process to verify that a model or method has been properly implemented in a computer program is called *Verification* (b). *Validation*, on the other hand, is the process to make plausible that a computer model includes the essential features for a real situation to be analysed and the results obtained with the model are representative for the situation in reality (a).

All the above steps may involve differences between the computer model and reality. Considering existing dedicated finite element software packages, it is the developers of such packages who take most of the above steps and decide about the mathematical formulation, the numerical schemes and the implementation of models in their software. Therefore, the responsibility of software developers mainly lies in the verification of the software and the proper documentation of the models and methods implemented in the software. For users of existing software packages the division of the modelling process into different steps is still relevant, although their position is different. Starting from a practical engineering problem, users first decide about the most relevant phenomena to be modelled (conceptual model). By using an appropriate software package, they select, apply and combine several of the implemented models and methods to create a computer model for their analysis. It is their responsibility to make plausible that the model is a good representation of reality. Hence, the process of validation is primarily their responsibility.

3 SOURCES OF DISCREPANCIES

In this chapter we will focus on the sources of discrepancies between reality and finite element models. Since a numerical model involves several components that may introduce approximations and errors, it is necessary to identify each of these components and their role in and contribution to the discrepancy as a whole. Identifying possible individual discrepancies may result in an improvement of the model and a possible reduction of the overall modelling error. It may also enable a quantification of the variation of design quantities by considering parameter uncertainties and their possible value ranges. Discrepancies may be divided into the following categories: Simplifications, Modelling errors, Constitutive models, Uncertainties, Software and Hardware issues and Misinterpretation of results.

3.1 *Simplifications*

Simplifications are the results of modelling choices made by the user of a software package. These are made in different parts of the modelling process. Examples of simplifications are:

- Geometrical simplifications
- Selection of model boundaries
- Simplifications in material behaviour
- Simplifications in the construction process

For every simplification of reality the user needs to be aware of its consequences.

3.2 *Modelling errors*

In addition to the aforementioned simplifications there is a variety of other sources of modelling errors. Some of these can be reduced when they are recognized; some can even be completely avoided. Examples of modelling errors are:

- Input errors
- Discretisation errors (meshing)
- Boundary conditions
- Time integration
- Tolerances (tolerated numerical errors)
- Limitations in theories and methods (e.g. small-deformation theory)

The process of validation can help to identify and quantify such modelling errors.

3.3 *Constitutive modelling*

Probably the most important part of the numerical modelling process is the selection of the constitutive model the determination of the corresponding model parameters. Real soil behaviour may involve several features that can be observed and measured in lab tests and in situ, but which are still difficult to capture in a homogenized continuum formulation. Apart from the limitations of the constitituve models themselves with respect to real soil behaviour, some typical issues related with different aspects of constitutive modelling are highlighted here:

- Non-uniqueness related to non-associated plasticity and strain-softening
- Undrained behaviour
- Unsaturated behaviour

Software developers need to properly document the constitutive models used in their software, whereas users need to be aware of the typical issues related to constitutive modelling in general and the possibilities and limitations of the models used in their applications.

3.4 *Uncertainties*

In the aforementioned sections it was assumed that the behaviour in reality would be fully known and that modelling discrepancies are the result of the modelling process only. The fact is that there are many aspects in a real project that are not completely known (yet) or which cannot be measured accurately. In other words, there are uncertainties about what we need to model precisely to reflect the real construction process and the conditions that are applied to the real structure during its lifetime. Examples of uncertainties are:

- Lack of soil data

- Spatial variation of soil properties
- Loading conditions during an earthquake
- Future developments around the project to be designed
- Design versus the actual construction

In order to deal with uncertainties, various methods are available, such as:

- Global safety factor approach
- Partial factor approach
- Probabilistic analysis
- Parametric analysis

Users of finite element models in which such methods have been implemented need to be aware of the possibilities and limitations of these methods.

3.5 *Software and hardware issues*

Although some models or processes may seem to be uniquely described by their mathematical model, the outcome of these models or processes, when implemented in computer software, might deviate from their original formulation; either deliberately or by accident. Here, the focus is on specific software and hardware issues that might lead to discrepancies in the outcome of a computer model which cannot immediately be influenced by users because they are

- result of specific implementations made by the developers of the software
- result of the used operating system
- result of the used computer configuration.

Examples of such software or hardware issues are:

- 'Bugs' (programming flaws in the application software)
- Specific implementations of models (for example rounding-off the corners of the Mohr-Coulomb failure criterion)
- Iterative solvers and their numerical solution tolerances
- Parallel solvers (solution differences depending on the number of threads or cores being used)

3.6 *Misinterpretation of results*

If the modelling process has been completed, the calculation has finished successfully and results have been obtained, it is not the end of the story. It should be realised that the computer model does not directly provide the answer to the original engineering problem. Therefore, a translation needs to be made from the results of the computer model towards the engineering and design issues. The translation and (mis)interpretation of results may also lead to discrepancies between the real situation and the computer model. Examples where misinterpretation of results might occur are:

- Interpretation of safety factors
- Structural behaviour (if the structure is too much simplified)
- Overlooking essential details (in particular complex 3D models)
- In general: Insufficient knowledge and understanding of the modelling software being used.

All this is subject of the validation process. In the next chapter, various methods of validation and other procedures are described in order to (im)prove the quality of finite element models and the modelling results.

4 METHODS OF VALIDATION

In the previous sections several sources of discrepancies between a real project and its finite element model have been identified. In order for a particular project to manage the uncertainties and to reduce the discrepancies, the finite element model must be validated.

Before considering validation of a computer model for a practical application, it is relevant to verify that the models and methods implemented in a software package are reliable. In the first place this is a responsibility of the software developers, but also users should consider performing a verification of models and methods that are relevant for the solution of their engineering problem. Verification is done by comparing the results of computer models for typical situations with known solutions. Examples of such solutions are:

- Analytical solutions of elasticity problems, plasticity problems, constitutive models, dynamic problems, bearing capacity solutions, solutions of flow and coupled problems.
- Limit equilibrium solutions (approximations) for global safety factors or bearing capacities.
- Upper and lower bound solutions (limit analysis).
- Benchmarks (see Section 4.5).

After a proper verification of the models and methods to be used in a finite element model, the finite element model itself needs to be validated. Validation of the model as a whole will not be enough to make plausible that the results that are obtained from the model are representative for the real situation. In fact, discrepancies in individual components may accidentally cancel each other out if they are not validated individually. The validation process should therefore also comprise the individual components of the modelling process in addition to validation of the integral model. This also gives insight in the accuracy of the individual modelling components. The following sections briefly describe the validation of individual components of a finite element model.

4.1 *Validation of constitutive models and parameters*

The selection of a constitutive model should be based on an evaluation of the capabilities (and limitations) that the model has to describe the essential features of soil behaviour for the application at hand. In that respect, the constitutive model provides the qualitative description of soil behaviour, whereas the parameters in the model are used to quantify the behaviour. The composition of the model plus parameters can be regarded as the 'artificial soil' that is used in the finite element model, which should be representative for the real soil behaviour in the application. Before considering the numerical model in full detail, it makes sense to evaluate the behaviour of the 'artificial soil' (= model + parameters) separately in particular stress paths. Therefore it is useful to check the behaviour of the soil in simplified soil lab tests simulations in element tests or using a single stress-point algorithm.

The results of the lab test simulations can be compared with real test data. This provides insight in the possibilities and limitations of the model to describe particular features of soil behaviour and the accuracy at which it does so. Moreover, parameters could be optimised to make a 'best fit' to the test data. However, it should be noted that the stress paths, stress levels and strain levels in the real application can be significantly different than those in the soil lab tests. Hence, a good fit between the results of a simulated test and the real test data is not a guarantee that the artificial soil is a good representation of the real soil in the practical application. Nevertheless, the numerical simulation of soil lab tests is, in any case, relevant to qualitatively understand the behaviour of the 'artificial soil' and should therefore be considered in the validation process.

In contrast to soil lab tests, in-situ tests cannot be simplified to a single stress point model. However, some in-situ tests can still be modelled as a simplified boundary value problem in the finite element method. The simplified modelling of in-situ tests can be used to optimise stiffness and strength properties, and they could be useful as part of the validation process. An example of such a model test is the pressuremeter test, modelled as a cavity expansion problem.

The validation of the selected soil model and parameters on the basis of soil lab tests is not sufficient to make plausible that the 'artificial soil' will sufficiently resemble the real soil in the

engineering application. Since the soil stiffness and strength properties are highly dependent on the stress and strain levels (or void ratio) encountered as well as the loading history and direction (anisotropy), it is necessary to estimate the stress levels, the stress paths, the strain levels (or void ratio) and the movement direction at different locations in the geometry and to relate these to the conditions for which the model parameters are deemed to be valid. The estimation may be based on engineering judgement, but it might also be considered to perform a preliminary analysis with a preliminary set of model parameters in order to support the estimation. If necessary, soil layers can be divided into sub-layers in which representative values of model parameters are used.

As part of the validation of model parameters for the engineering application it might also be considered to perform a preliminary analysis on a semi one-dimensional soil column representing the ground profile at the project location. In the case that the project involves mainly vertical loading, the soil column analysis can be used to check if the calculated settlements match the expected settlements (based on engineering judgement or conventional settlement calculations).

Some parameters will have a dominant influence on the outcome of the numerical analysis whereas other parameters may have little influence. In order to evaluate which parameters have a high influence, a parametric analysis may be performed. In a parametric analysis parameters may be varied individually in order to evaluate their influence on the results (sensitivity analysis), or combined in order to evaluate the variations in results. Parameters with a high influence need to be given most attention. Additional soil investigation may be required in order to be able to determine these parameters more accurately in an attempt to reduce the uncertainties in results.

After the final analysis with definite parameters has been performed it is necessary to validate the stress levels, stress paths, strain levels (or void ratio) and loading directions as obtained from the finite element model and to check whether these correspond with what has been assumed in the first place and what is deemed to be valid for the selected parameters.

4.2 *Validation of model boundaries*

Model boundaries are introduced to limit the extent of the finite element model and calculation time. It has to be validated whether the outcome of the finite element model is not influenced by the particular choice of the model boundaries (Figure 2a vs. 2b). This can crudely be done by redoing the analysis with model boundaries taken further away from the main modelling object and comparing the results, but that may be a time-consuming way of working. It should at least be verified after any finite element analysis that changes in stress and strain near the model boundaries are relatively small. This is not required near (vertical) symmetry boundaries. However, in the latter case it should be validated that the symmetry conditions are properly applied.

In the case of a dynamic analysis, users should check that there is no spurious reflection at the model boundaries. This is primarily of interest for the vertical model boundaries. The best way to check this is by creating an animation of the velocities in the model. If the bottom boundary is taken at the top of a bedrock layer, reflections may occur and are not unrealistic.

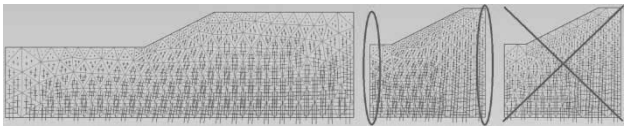

Figure 2. Generated initial stresses in a slope problem. a. Proper distribution based on 'Gravity procedure'. b. 'Gravity procedure' with inappropriate boundaries. c. Wrong distribution using 'K_0-procedure'.

4.3 *Validation of initial conditions*

In order to make an accurate prediction, it is necessary to initialise the stress in the model as much as possible in correspondence with the situation in reality (Figure 2a vs. 2c). The initial situation in the model may involve total or effective stress components, pore water pressures, pre-consolidation stress, void ratio and other state parameters, depending on the constitutive model(s) being used. Most soil constitutive models involve at least some sort of stress-dependency. Moreover, the initial stress state directly influences the forces in soil retaining structures. In the case of time-dependent behaviour, the initial state may have influence on the settlement rate. Therefore, the validation of the initial conditions is a necessary part of the validation process.

In an effective stress analysis, it is essential to create a realistic distribution of initial pore water pressures. Simple hydrostatic pore pressure distributions may be generated on the basis of a phreatic level (Figure 3b), whereas more complicated situations may require a separate groundwater flow calculation to be performed (Figure 3c). In the latter case, realistic hydraulic conductivities (permeabilities) are required, which are often difficult to obtain from soil investigation data. That is why modellers often 'abuse' the phreatic level tool to create more complicated pore pressure distributions based on non-horizontal level sections. Care has to be taken with such an approach, since in reality non-horizontal levels imply groundwater flow and possibly non-hydrostatic pore pressure distributions. A 'jump' in the phreatic level should definitely be avoided, since this would cause a similar jump in pore pressure all the way down in the layer, which is highly unrealistic (Figure 3a).

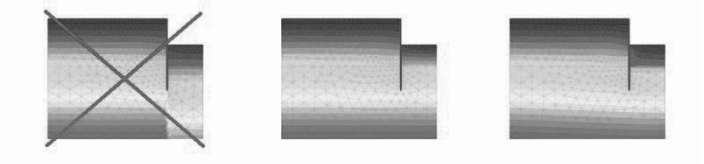

Figure 3. Generated pore water pressure distribution in an excavation problem. a. Wrong distribution based on a 'jump' in the phreatic level b. Improved distribution using interpolation between high and low head under excavation c. Distribution based on groundwater flow calculation (increased horizontal permeability)

Generated pore pressures should be validated against measured pore pressure distributions in the field. It should be validated that the pore pressure distribution is continuous and 'smooth'; jumps are suspicious and are likely to be the result of a wrong way of modelling.

4.4 *Validation of (the accuracy of) results*

The previous sections focused on essential components of the model that are part of the modelling process. It also needs to be validated that the finite element mesh is fine enough to produce sufficiently accurate results. In case of doubt, the model can be recalculated with a refined mesh. After the individual model components and the model as a whole have been validated, and numerical results have been obtained, there are various ways to validate the results for the practical problem as considered. The following methods can be used to validate the results of finite element models:

- Comparison with measurements (if the project is already under construction)
- Comparison with design charts.
- Comparison with experience and common practice
- Comparison with simplified models (e.g. reduced dimensions; 1D vs. 2D or 2D vs. 3D)
- Comparison with other software.

When considering a project in an urban environment, experiences with previous projects in the neighbourhood can be of great help in the validation of numerical models, since soil conditions may be quite similar. Here, it should be realised what

the differences are in loading conditions, duration of the construction process and influences from adjacent buildings, between the new project and the existing projects, and how that affects the numerical model.

Care should be taken to use common practice and experience to design a new project on a larger scale than the projects on which common practice and experiences are based. Because of the high non-linear character of soil behaviour, the design of a larger system is not simply an extrapolation from a smaller size project. This principle in the design process should also be realised when using finite element models.

It might be worth to model a project with different software packages and compare the results. No doubt, this will lead to different results, whereby the engineer should realize that the different packages may use different models and methods, and there could be differences in the way how these models and methods have been implemented. However, when it was intended to create very similar models, the results should be less than 10% different from each other to conclude that they are actually similar. This is a necessary condition for a positive validation, but it is not the only condition, since modelling errors can still be made in one or both software packages, such that the results are still within 10% difference from each other. It could be that two errors in one model accidentally cancel each other out and still lead to results that are more or less right. It can also be that errors made in both packages lead to similar results, which are both wrong. Therefore the validation of numerical models purely on the basis of a comparison with other software is not a sufficient validation. In fact, both models need to be validated individually and other types of validations (as described above) need to be performed as well.

Considering the modelling of the same situation in different software packages brings us to the issue of Benchmarking.

4.5 *Benchmarking*

A *Benchmark*, in the framework of validation and verification, is a well-defined example problem for which a reference solution exists, whereas the term *Benchmarking* can be defined as the process to evaluate the variation in results from different modellers or different computer software for a well-defined example problem. Although the latter definition is probably mostly related with how users translate the example problem into a computer model and how they interpret the results, it can also be used to benchmark different software packages against each other or against the reference solution. According to NAFEMS, a *Benchmark* is a standard test designed to probe the accuracy or efficiency of a finite element system or model (Baguley, 1994). This definition clearly addresses the role of the system (hardware + software), but also involves the role of the user in creating an appropriate and accurate finite element model.

The solution of a benchmark example is not a theoretical solution, but a reference solution that is considered to be 'a right solution' for that particular problem. Most benchmarks are simplified practical problems for which no analytical solution exists. Modellers can use a benchmark to check if they obtain a similar solution with their own software. Since the solution is obtained using numerical methods, a small deviation (few percent) from the reference solution is likely to occur and is quite acceptable. Larger deviations may still be acceptable, depending on the type of problem and the level of detail that is provided with the benchmark. Published benchmarks have shown that quite large differences can occur, which underlines the need for validation of numerical models.

A number of benchmark examples for geotechnical engineering have been defined and published (e.g. Jeffries, 1995; Schweiger, 1998, 2002, 2006; Andersen et al., 2005).

In conclusion, benchmarks are not only useful for verification purposes, but they are also relevant for the validation process. In summary, benchmarks can serve the following purposes:

- To verify computer software.
- To train unexperienced geotechnical engineers to help them becoming familiar with numerical analysis.
- To let modellers prove their competence in numerical analysis of geotechnical problems.
- To make modellers aware of differences in results for a well-defined problem, irrespective of their origin. This point highlights the importance of validation of numerical models.
- To highlight the importance to use appropriate constitutive models.
- To identify limitations of the present state of the art in numerical modelling in practice (Carter et al., 2000). To date this is still true.

4.6 *Checklists*

A checklist of the various sources of discrepancies, as described in Chapter 3, can be helpful to remind the numerical modellers of the possible modelling errors that they could make. Thinking about the various sources of discrepancies will increase the awareness of possible mistakes and will lead to better computer models. In the NAFEMS document (Brinkgreve, 2013) an extensive checklist is given, based on various sources of discrepancies. Moreover, a list of possible questions that modellers may ask themselves as part of the validation process is included in the document. The checklist and the list of possible questions may also be used by managers and supervisors to get an impression how well a model has been validated by the engineer.

5 NON-TECHNICAL ISSUES

In addition to the 'technical' issues related to the validation of finite element models for geotechnical applications, there are a number of non-technical issues involved with the validation process. Such issues include decisions, responsibilities and organizational issues, which are to be considered primarily by the management of a company or a project. Nevertheless, it should be realised by each individual working on numerical modelling that these issues exist.

5.1 *Availability of data*

Besides knowledge and experience, another key issue to be able to make an accurate finite element model is the availability of data. This involves:

- Geometric data
- Soil data
- Structural data (if structures are involved)
- Data of external conditions (loads, water levels, adjacent structures)
- Information about the construction process

Soil data is probably the most important, although this is not always recognized by project owners. In practice, there is often a lack of soil investigation data because it costs money. It is important to convince clients or project owners of the need of sufficient and good quality soil investigation. It does not only reduce the uncertainties in ground conditions, but it will also facilitate the validation of model parameters, thereby reducing the risk that the design is inadequate because it is based on insufficient or wrong geotechnical data.

5.2 *Responsibilities*

Regarding the use of numerical models for geotechnical engineering applications and the use of its results for geotechnical engineering and design, four main responsibilities can be identified.

- Responsibility of the *engineer* (user of finite element software)
- Responsibility of the *supervisor* (manager)
- Responsibility of the *organisation* (engineering company)
- Responsibility of the *software developer* (software company)

It is the primary responsibility of the *engineer* (user of finite element software) to create a computer model and to determine the required parameters such that the model accurately represents the real project and captures the phenomena that lead to the quantities that need to be determined or interpreted from the model (deformations, stresses, structural forces, flow, etc.). This responsibility includes a proper validation of the model and its components. It is also the responsibility of the engineer to report any lack of data and the consequences thereof to his or her supervisor or client.

It is the primary responsibility of the *supervisor* (manager) of the modelling engineer or the project manager to check that the model created and used by the project engineer is a reliable model on the basis of which the project can be properly analysed and/or designed with the required safety level. This responsibility involves a check on how and to what extent the model has been validated. For supervisors without advanced numerical modelling experience themselves this may be regarded as a difficult task, but it remains their responsibility. This NAFEMS book is intended to provide at least some guidelines for managers to discuss key elements of the numerical modelling process with their engineers. Together with his/her technical expertise and experience from other projects, the supervisor should obtain a good impression of the quality of the results obtained from a numerical model.

It is the primary responsibility of the organisation in which numerical models are being used to create an environment in which the importance and complexity of numerical modelling is realised on all levels. If numerical modelling is part of their activities, it should be included in their quality procedures. The organisation should be structured such that there is sufficient knowledge and room, not only to create numerical models but also to validate models and to control the process from the early stage of numerical modelling to the interpretation of the results towards the geotechnical design. Just like any other subject, numerical modelling is continuously evolving and new methods become available. This requires organisations to invest in facilities (literature, courses) to let their staff acquire the necessary knowledge to remain up-to-date in order to use numerical models with state-of-the-art technology in an appropriate way.

It is the primary responsibility of the software developer to produce software that has been sufficiently verified and that is (ideally) free of programming errors. Moreover, it is also the responsibility of the software developer to properly document the models and methods that are implemented in the software and make this documentation available to the user.

6 CONCLUSIONS

In this paper a summary is given of a NAFEMS document on validating finite element models for geotechnical engineering purposes (Brinkgreve, 2013). The document may be used by engineers who actually build the numerical models and interpret the results, as well as by supervisors and project managers who are responsible for the overall design of a project. Validation, in the context of this document, is the process to make plausible that a finite element model includes the essential features for a real situation to be analysed and its results are representative for the situation in reality.

After defining validation and related terms, the paper first describes sources of discrepancies between a real project and its finite element model. Insight in the sources of discrepancies is essential for a proper validation of the model and to reduce modelling errors.

The main chapter is devoted to the various methods of validation. The process of validation involves a validation of the model as a whole, as well as a validation of the various model components. Particular model components that need to be validated are the geometry, the model boundaries, the material (including soil) behaviour, the finite element mesh, the initial conditions and the calculation phases. Results obtained from the model should be checked against results obtained from other analysis methods, design charts, experience, common practice and measurements, if available.

The last chapter describes some non-technical issues related with decisions, responsibilities and organisational issues to control the quality of numerical modelling as part of the geotechnical engineering and design process. In the first place it emphasizes on the availability (or lack) of data and the need to convince the client or project owner of the essence of good quality soil investigation. In the second place, it highlights the importance to spend time and money on education and training. The latter is a common responsibility of the engineer and the organization in which he or she is employed.

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