Evaluation and consideration of model uncertainties in reliability based design

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1. Introduction

The quality and reliability of geotechnical design depends among other aspects on the quality of the chosen design method. This can be a simple analytical or empirical equation or a sophisticated numerical model with different degrees of complexity and accuracy in modeling the behavior of a geotechnical structure. However, exact modeling of the real behavior is impossible and the deviation of the predicted from the real behavior is expressed by the model uncertainty. According to e.g. Nadim (2015) model uncertainty is of epistemic nature as it is based on the simplifications, assumptions and approximations made in the respective design model. It therefore can be reduced by improving the model. He also used the term transformation uncertainty for the uncertainties associated with the model as the model transfers input parameters to output parameters.

For geotechnical engineering design practice, as considered by Eurocode 7, calculation models in many countries were calibrated on the basis of an overall factor of safety resulting from previous standards and past experience leading to design approaches that are often regarded as being conservative. In such cases failures of geotechnical structures are usually attributed to insufficient ground investigation or external factors (human error, overloading, water levels exceeding design assumptions, etc.), but not to an insufficient calculation model.

However, derivation of partial factors with the aim of achieving a consistent reliability level within geotechnical design requires the separation of different sources of uncertainties and therefore establishes a need to analyze the uncertainties associated with the respective design methods.

This report presents the current status of the discussion on model uncertainty assessment for different types of geotechnical structures and calculation models.

2. Procedures of model uncertainty assessment

Eurocode 7 code drafters involved in the current revision process of the Eurocodes recently emphasized that model uncertainties shall only refer to the assumed calculation model and shall not cover (implicitly) other sources of uncertainties. For geotechnical design according to Eurocode 7 or other standards utilizing LRFD, a pre-defined target reliability shall be achieved by the combination of partial factors and model factors. The latter shall be used to calibrate specific calculation models to provide the same level of confidence in the validity of the prediction for possible design situations prior to the use of partial safety factors.

In regard to this, Phoon & Ching (2015) argued that simplified RBD methods such as LRFD with constant factors can only cover the design situations inside the domain the factors have been calibrated for. For other situations the target reliability may not necessarily be reached.

Consequently, the evaluation of model uncertainties as well must reflect all possible design situations to be covered by the code.

The way to introduce a model factor into design very much depends on the character of the design model used. For simple analytical, empirical or semi-empirical design methods, which result in a unique design quantity, model uncertainties can be considered relatively straightforward as shown in section 2.1.

For complex design models which do not result in specific design quantities or where results have to be interpreted from the calculation (e.g. FEM calculations) the evaluation of model uncertainties seems to be more difficult as outlined in section 2.2.

2.1 Model uncertainty expressed by model factors

A simple definition of the model uncertainty is given in (1), where the bias or model factor μ is defined as the ratio of a measured (e.g. in a load test) to a calculated quantity X.

$$\mu = X_{meas}/X_{cal} \tag{1}$$

The quantity X can be a load, a resistance, a displacement, etc.

The model factor itself is a random value which can be introduced in reliability analyses, where it is usually assumed to be log-normally distributed with a mean and a COV to be defined (e.g. Phoon & Kulhawy, 2005; Juang et al., 2012).

Literature review showed that the simple definition in (1) is often applied where the design problem can be reduced to one single quantity which is the result of the applied calculation model, e.g. pile bearing capacity or foundation bearing capacity. Accordingly, quite some references can be found on:

- Axially loaded piles (settlement prediction or bearing capacity prediction)
- Spread foundations (settlement prediction or bearing capacity prediction)

In case of pile foundations pile loading and pile capacity are usually treated as independent quantities, hence the bias can be clearly defined (though depending on the type of prediction model). In the case of shallow foundations the bearing resistance is not an independent quantity as it depends on the type of load. Therefore the bias cannot be unique.

2.2 Model uncertainty prediction for more complex design situations

For more complex design situations or design models not resulting in a unique design quantity model uncertainty prediction may be based on representative quantities which properly characterize the performance as well as the design of the structure.

For a cantilever wall Zhang et al. (2015) chose its top deflection as the representative quantity. The model uncertainty of the applied mobilized strength design (MSD) according to

Osman & Bolton (2004) is evaluated in two steps. First, a correction factor is defined as the ratio of the top deflection resulting from a FEM analysis to the one resulting from the MSD. In a second step, field measurements are used to define a model factor of the FEM calculations. The resulting model factor of the MSD is finally derived as the product of the MSD-FEM correction factor and the FEM model factor.

However, for complex retaining structures with several construction stages etc. it is questionable, if a single representative quantity sufficiently reflects the characteristic behavior of the whole structure that must be considered in the model uncertainty prediction. Further, design of such structures is usually based on various design proofs. Hence, the reduction to simple model factors in such cases alone cannot address the whole complexity of the design. Examples and case studies may help in the decision process.

Laterally loaded pile design is driven by the anticipated flexibility of the pile which determines the type of calculation model. For rigid piles evaluation of the model uncertainty related to the bearing capacity prediction is relatively straightforward and follows the procedure outlined in section 2.1. Phoon & Kulhawy (2005), for example, analyzed the model uncertainties of different earth pressure models by calculating the ultimate lateral and moment capacity which were the design quantities.

For flexible piles it is questionable, if the pile head displacement (or rotation) as a single representative quantity is sufficient or if the whole deflection curve is a better choice. On the other hand, it seems possible to compare measured and calculated load-displacement curves, but only very few load tests on laterally loaded piles are available. Such a work has been presented for axially loaded piles by Abchir et al. (2016) to assess the uncertainty of t-z curves obtained from pressuremeter test results.

A similar problem arises for settlement prediction of footings. In case of single rigid footings a representative settlement and rotation can be defined. In case of flexible footings this is at least difficult.

Another problem related to the design of axially loaded piles is the combination of axial and lateral loading. Available design methods cannot account for the effect of combined loading which is a typical design situation e.g. for offshore pile foundation structures. Hence, the interaction of the load components is usually neglected often by simply arguing that lateral loading only affects the upper part of the pile-soil system whereas axial loading mobilizes resistances in greater depths. The uncertainties related to such a design procedure can hardly be addressed by model factors.

2.3 Model uncertainty assessment by reliability based sensitivity analyses

Another procedure to assess the model uncertainty of a given design method is to perform a RBD based sensitivity analysis to evaluate the relative influence random parameters have on the reliability index or the probability of failure, respectively, when adopting a specific design method. Such a work was proposed e.g. by Teixeira et al. (2012) who analyzed the bearing capacity of piles calculated by an empirical method directly correlating the SPT-N values to

the pile capacity. The sensitivity analysis was based on FORM and MCS calculations. The soil variability expressed by N_{SPT}, model factors for base and shaft resistance of the pile and factors for load uncertainties were considered as random variables with statistical parameters adopted from literature. The resulting reliability indices were compared for different scenarios in which the different sources of uncertainties were considered or not. Such a procedure allows an assessment of the importance of different sources of uncertainties within design. For the investigated design method it was shown that model uncertainties were the predominant sources of uncertainties emphasizing the importance for appropriately considering them in design.

2.4 Difficulties in model uncertainty evaluation

Prediction of model uncertainties based on measurements of the real behavior as provided by the simple definition given in section 2.1 reveals some fundamental problems:

The bias cannot be separated e.g. from (1) the inherent variability of parameter values used within the model, (2) measurement errors, (3) definition and determination of X_{meas} from the test (e.g. consistency of failure criteria and its application to the test results).

The inherent variability of parameters refers on one hand to the way they are determined (from theoretical formulas, indirect correlations and in situ direct measurements). On the other hand the spatial variability of soil characteristics plays an important role.

Fenton & Griffith (2005) showed in an analysis of the reliability of traditional retaining wall design how the spatial variability of the soil affects the failure mechanism which in turn affects the uncertainty of the chosen design method assuming one particular failure mode. On the other hand, Teixeira et al. (2012) in their study on axially loaded piles showed that soil variability was not as important as expected. One may conclude that these different results are related to the fact that the assumed failure modes for shaft friction and end bearing of the pile are not or not as much affected by soil variability as in cases where large failure planes in the soil have to be considered as in the design of retaining walls or also in the design of shallow foundations. Nevertheless, especially in the latter case model uncertainty is intrinsically tied to the uncertainties related to the soil characteristics and cannot be separated.

Measurement errors are related to the experimental device used to measure the variables of the model and other related errors. On the other side, especially in the case of complex numerical calculations the prediction is also affected by other sources of uncertainties related to the modeling itself which indirectly contribute to the model uncertainty (e.g. user experience, choice of constitutive models, mesh generation procedures).

It may be concluded that there is no unique model uncertainty. Hence, as already stated above the evaluation of model uncertainties and the derivation of model factors shall cover all possible design situations.

3 Overview of existing work

3.1 Shallow Foundations

Annexes 1 and 2 summarize some work on model uncertainty prediction for bearing capacity calculation of shallow foundations.

Model uncertainty was defined in Annex 1 by $\mu = X_{meas}/X_{cal}$ as in (1) and by $1/\mu = X_{cal}/X_{meas}$ in Annex 2. The work presented in Annex 2 deals with vertically loaded foundations only, whereas the work in Annex 1 considers combined loading as well. Both used extensive databases including field tests only (Annex 2) and laboratory and field tests (controlled and natural soil conditions - Annex 1).

Both studies show an influence in the model factor or bias related to the size of the footing (effect of model scale), but this trend is not clear. In Annex 2 the bias according to (1) decreases for greater footing width. In Annex 1 a similar trend has been found for footings in natural soil conditions whereas the trend in controlled soil conditions is different (increase of bias for greater footings), see Figure 1. Hence, this confirms the earlier statement that the model uncertainty is affected among others by the variability of the soil especially under natural conditions and/or the derivation of the design parameters (here shear strength).

Annex 1 also reveals that the bias is not unique but depends on the type of loading. The research presented in Annex 1 also discusses the importance of defining an appropriate failure criterion to evaluate the failure load from load-settlement curves.

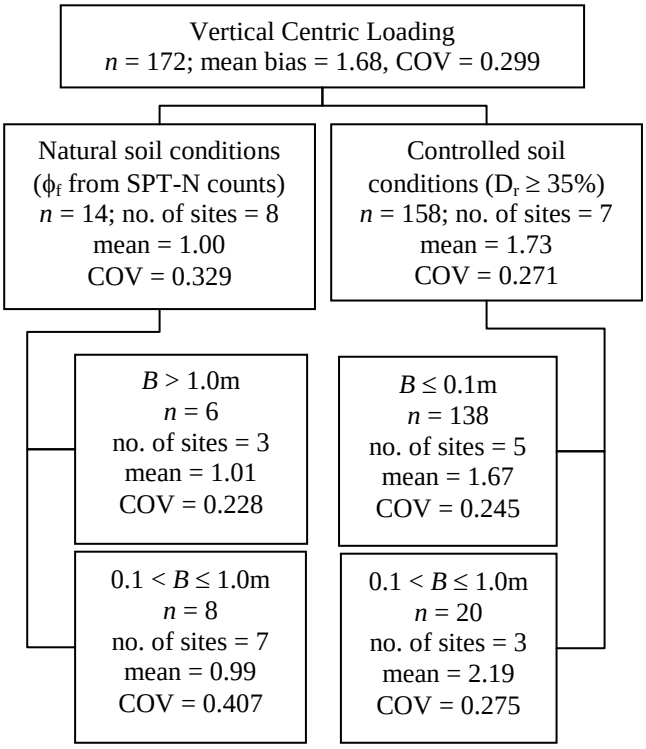

Figure 1. Biases for footings under vertical-centric loading differentiated according to soil conditions and model scale (Paikowsky et al., 2010)

Annexes 2 and 3 summarize some work on model uncertainty evaluation of settlement prediction.

The work presented in Annex 2 is based on an extensive database of 426 case histories to assess the model factor $1/\mu = X_{cal}/X_{meas}$ (where X is the settlement) for various calculation methods. The model uncertainty itself was considered as a random variable.

For those cases where a complete load-settlement curve was available instead of a single response point, the load and settlement values at the elastic limit were used to estimate the accuracy of the settlement estimation methods (see reference in Annex 2 for definition of elastic limit).

The study reveals that the overall accuracy of all methods is very poor with a very high COV and a high percentage of cases in which the calculated settlements exceeds the measured ones. It is also stated that a log-normal distribution can be assumed for the model factor $1/\mu$.

Annex 2 includes results of another study that was performed using a number of methods for predicting settlements based on SPT test results. The analysis procedure and the main conclusions are similar to the other study. Both studies investigated the influence of the inherent variability of soil properties, construction variabilities, and measurement errors on the model factor statistics related to instrumented structures and load tests.

Annex 3 uses the same definition of the model factor as in Annex 2: $R = 1/\mu = X_{cal}/X_{meas}$ (where X is the settlement). In the presented study a rigid footing under pure vertical loading was considered. To interpret the model uncertainty the following terms were used:

Accuracy = average value of R for all the cases in a database

Reliability = percentage of the cases for which $R \geq 1$

These information were combined in a **Ranking Distance RD:**

$$RD = \sqrt{[1-\mu(R)]^2 + [s(R)]^2} \qquad (2)$$

which can be displayed as a beam from the origin in a graph showing mean vs. standard deviation of R as displayed in Figure 2.

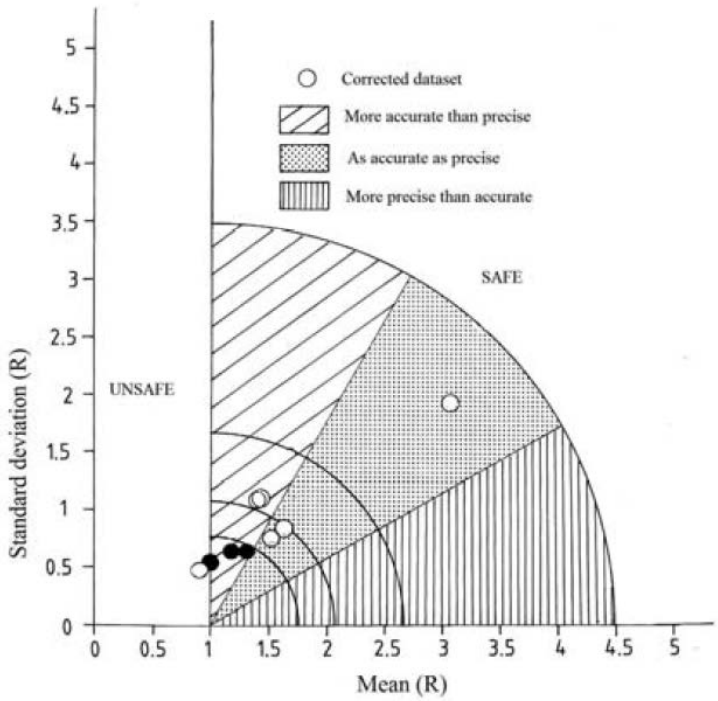

Figure 2: Mean versus standard deviation plot to be used in reliability based shallow foundation design with respect to settlement (Cherubini & Vessia, 2009)

Further on, entropy and the relative entropy (like the variance) are introduced to measure the dispersion of the R value.

Annex 3 then presents a procedure which is based on a study of nine settlement prediction methods that all used SPT data to derive soil parameters (some of these methods are the same as in Annex 2). In this procedure, curves of different levels of probability for settlement target values can be drawn for the different formulas. From these curves the engineer may derive the exceedance probability of a certain value of the measured settlement provided that the settlement value is known.

3.2 Axially Loaded Pile Foundations

Annex 4 addresses model uncertainties of the bearing capacity prediction of axially loaded piles.

Based on Bauduin (2002, 2003) the work presented in Annex 4 summarizes typical procedures to evaluate model uncertainties which are commonly expressed by equation (1). In this regard, Figure 3 highlights significant uncertainty sources within pile design.

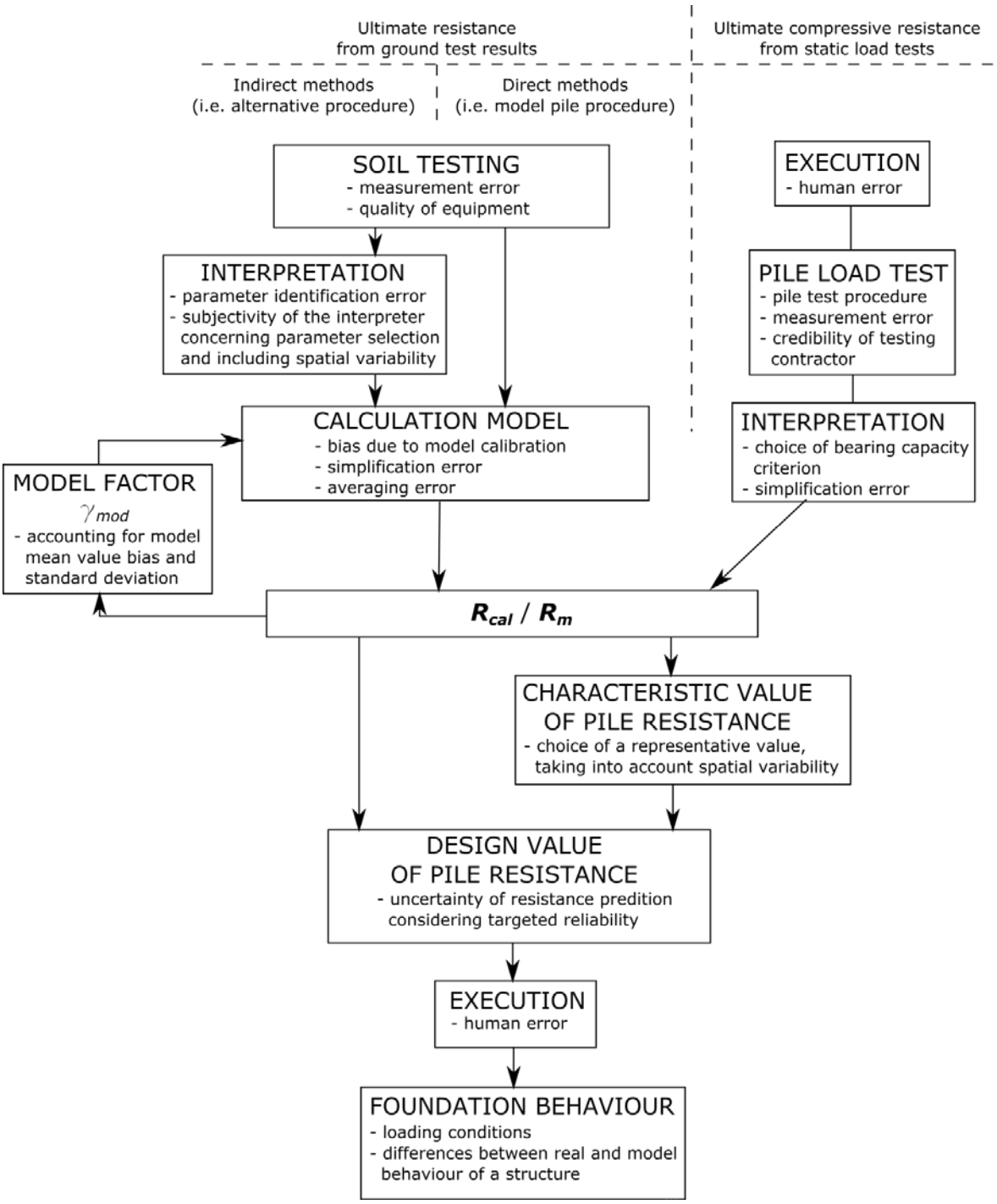

Figure 3: Pile design procedure with most significant uncertainty sources (see Figure 1 in Annex 4)

Annex 4 states that model uncertainty prediction for piles shall be founded on databases of static pile load tests which are especially useful also for analysing new pile types or calculation models. It is emphasized that the quality of the input data is of significant importance. In this regard the quality of site investigation (field or laboratory tests) and the test performance (testing depth, test load, measured quantities, e.g. separate measurement of shaft friction and end bearing resistance) are discussed. Annex 4 also addresses the problem of load tests not performed to failure and the possibilities and limitations of applying extrapolation techniques to determine the ULS failure load from a load-settlement curve of non-failed tests.

3.3 Retaining Structures

Hsiao et al. (2008) evaluated the ground settlement induced by neighbouring excavations. Similar to the study of Teixeira et al. (2012) the model uncertainty, considered as a model factor according to (1) applied to the settlement, was introduced as a random variable in a reliability analysis using FORM with statistical parameters adopted from literature. The analysis showed that the calculated settlement was highly sensitive to the model factor.

In this study the model factor was later updated by back-calculation from on-site measurements during several construction stages using the Bayesian updating technique, so that the calculated ground settlement finally approached the measured one. By doing so, the updated model factor reflects all other influences from the respective site, i.e. it is site-dependent and cannot (necessarily) be transferred to other design situations.

A similar study was performed by Juang et al. (2012) who evaluated the damage potential of neighbouring buildings due to excavation activities. The so-called damage potential index (DPI) was derived from the angular distortion and the lateral strain in the building due to excavation (DPI load) which was compared to a limiting value (DPI resistance). Model factors were applied to both, DPI load and DPI resistance, and were assumed to be log-normally distributed. The DPIs were derived from on-site measurements. Hence, model uncertainties only reflect the current status of information for the specific case. Consequently, Juang et al. (2012) used the term apparent model factor. Also this study showed a high sensitivity of the reliability analysis for model uncertainties.

A lot of other work could be analysed in order to give additional information. For example, the syntheses provided by Long (2001) or Moormann (2004) include many information about the behaviour of retaining walls. As outlined in section 2.4 the main difficulty remains the representative quantity to be considered, i.e. the maximum wall deflection, the wall deflection at the top of the retaining wall or any other.

4 Use of Databases

In general, definition and evaluation of model uncertainties must be seen within the context of the applied procedure and the related complexity (RBD, LRFD – research work or practical application). In this regard, comprehensive data bases with well documented field and laboratory test data can be a good tool to evaluate model uncertainties if they can be expressed by a model factor or bias as in (1). Therefore, this procedure is relatively popular and has been used frequently before. Phoon & Kulhawy (2005) give a short overview about the history of using databases for model uncertainty evaluation.

Bauduin (2002) distinguishes three approaches to use databases in model uncertainty prediction for piles (see Annex 4) leading to different quality levels in the derived model factors:

- very high level of detail in the analysis, each type of pile can be calibrated for specific soil conditions
- lower level of detail grouping similar piles and soil conditions together
- larger generalization, treating all data as one sample, resulting in one calibration factor for the calculation method

Databases typically include model and/or prototype field or laboratory tests under natural or controlled soil conditions for a specific design problem. Phoon & Kulhawy (2005) emphasized the use of scaled laboratory tests under controlled conditions (i.e. controlled loading, controlled preparation of uniform soil bed etc.) as the uncertainties resulting from the soil characteristics can be minimized. However, they further stated that such kind of tests possibly do not lead to representative mean model factors as they are not free of other extraneous uncertainties as well.

Field tests such as pile load tests have the advantage that they are conducted in real and diverse site conditions in full scale (no scale effects). But as mentioned above they are more or less affected especially by the spatial soil variability. Hence, only a combination of field and laboratory model tests allows reliable predictions of model uncertainties.

The main problem of databases often is the limited number of tests coming from very different sources each covering only a limited range of possible design situations. One needs to keep in mind that the application of the derived model uncertainty beyond the boundaries of the given database must be verified (ideally by more appropriate tests).

On the other hand, this requirement also depends on the complexity of the design and the degree of simplification implied in the respective design method, which determines the transferability to other boundary conditions. According to Phoon & Ching (2015) a sufficient number of tests is especially important also if parameters show influential statistics. This requires a subdivision of the database into segments with available data preferably being evenly distributed among each segment.

Another concern is the validity, applicability and uniqueness of failure criteria for definition of the ULS (or SLS) from the test result (e.g. the load-displacement curve). Especially field tests are often not run to failure. Extrapolation techniques may be considered, but their application is difficult (e.g. Paikowsky & Tolosko, 1999; Phoon & Kulhawy, 2005). Also in field tests the measured load-displacement curves often do not show a clear peak, i.e. failure is difficult to be interpreted and not all failure criteria lead to consistent results (see e.g. Paikowsky et al, 2010).

In summary, the following aspects have been identified to be important for establishing databases that can properly be used for evaluating model uncertainties:

- Availability of data (often propriety concerns)
- Minimum *representative* number of tests for a specific design constellation
- All geometric and geotechnical ranges according to possible design situations covered
- Test scale (prototype tests *and* scaled model tests to evaluate scale effects)
- Detailed information on geometry and installation procedure
- Detailed information on applied loading
- Detailed information on soil variability at the test site (especially related to field tests); quality and quantity of available soil information; test type for determination of soil parameters including test analysis and interpretation of results; influence of local or regional soil geology
- Detailed information on performance, processing and evaluation of load tests (in the field, in the laboratory)
- Detailed information on the failure criteria applied to define the ULS/SLS in the test

Other problems affecting the quality of the database input and its use are:

- Effect of nonlinearities in the limit state equations for extrapolation of derived model factors to other design situations
- Uncertainties in the prediction of loading

Furthermore, personal aspects shall be kept in mind. This includes the engineering judgement combined with human error and subjectivity and refers to the experience of the engineer who puts information into a database and later uses the database for evaluation. Here, especially the selection or filtration, the interpretation and analysis of the test results depend on experience and also on the applied accuracy.

5 Implementation in design

Phoon & Kulhawy (2005) stated that RBD is a helpful tool in geotechnical design as it ensures self-consistency from physical and probabilistic requirements. They argued that it is a philosophical question if there is the *willingness* to accept RBD as a necessary basis for calibrating LRFD factors.

In this regard, one should keep in mind that the assessment of model uncertainties related to a particular design method is not only important for the design of the single structure. Moreover, depending on the relevance of this single component for the whole construction it is important for assessing the overall uncertainties of the global design in the decision process.

Once the general concept of RBD has been accepted, the quantification of model uncertainties can be implemented in geotechnical design on different levels of complexity:

- Direct use in RBD as random variable (e.g. FORM, MCS)
- Use as constant value in LRFD (e.g. model factor)

For geotechnical engineers the acceptance of such concepts for daily design practice is strongly related to their practical applicability. This probably supports the use of model factors in LRFD design despite the disadvantages outlined above. In this regard, constant value means that a model factor is at least constant for a certain range of possible design situations.

During the revision process of Eurocode 7 the application of model factors within the limit state equation is currently being discussed. According to this, model factors shall be used to correct calculation models against a reference value, so that the model is either accurate or conservative. They shall be applied to actions, effects of actions, material properties or resistances.

Following the discussion in this report it needs to be emphasized here, that the reference value should be derived from appropriate test results preferably from databases fulfilling the requirements in section 4. The reference value shall not (only) be derived from another design method, just because it is assumed to be more sophisticated, thus representing reality, as this method itself may have (other) uncertainties.

As outlined before, the model factor will not be unique for many designs in order to cover as many design situations as possible. This will also affect the derivation of the partial factors. Hence, geotechnical engineers must accept a set of factors for different design situations. Nevertheless, one should keep in mind that the global aim of a constant reliability level for all designs still seems to be difficult if not impossible to reach. This especially applies for complex designs where model uncertainties cannot be reduced to single model factors.

6 Conclusion

The discussion illustrated the importance of evaluating and quantifying model uncertainties in geotechnical design due to the high sensitivity of many design models for this source of uncertainty. Databases of very well documented, high quality field and laboratory tests under diverse site conditions and under controlled laboratory conditions are a good tool for assessing model uncertainties. The main concern related to databases is the availability of a

sufficiently large number of tests among the whole design range to be considered. This is especially important as model uncertainties are difficult to separate from other inherent uncertainties such as the soil variability or uncertainties related to test performance.

The implementation of model factors in LRFD can provide a practical tool for considering model uncertainties in daily design practice. However, one should keep in mind that model factors are strongly related not only to the design method but also to the design situation. The use of single model factors is therefore (often) not correct.

The uncertainties of complex designs are difficult to be reduced to model factors in LRFD designs. In such cases model uncertainty assessment shall be performed by higher levels of RBD using e.g. various case studies for comparison.

The discussion on model uncertainties is not at the end so far and the present report shall be continued in the future. Readers of this report are therefore invited to send their comments to the discussion leader.

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Annexes

A1: Lesny, K.: Model uncertainty of bearing capacity analysis for shallow foundations

A2: Akbas, S.: Model uncertainty of bearing capacity & settlement analysis for shallow foundations on cohesionless soils

A3: Vessia, G.: Existing works on model uncertainty evaluation for shallow foundation settlement prediction on sandy soils and a new proposal

A4: Bogusz, W.: Model uncertainty evaluation for pile foundations

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