Annex 4 (by W. Bogusz):

Model uncertainty evaluation for pile foundations

While using LRFD method in accordance with Eurocode 7, the choice of the calculation model used to correlate predicted bearing capacity with soil test results is the responsibility of the geotechnical designer, who has to guarantee its validity. Vast majority of currently used calculation models, some of which developed decades ago, were based on empirical data gathered by performing static load tests on full-scale piles. To ensure the safety of the design, these models were provided with associated safety factors, most commonly, single global factors of safety covering all the uncertainties concerning actions and resistances. For example, Bustamante and Gianeselli (1981) proposed using factor of 3 for the base and factor of 2 for the shaft resistances, respectively, in association with their method. Moreover, those models are also often associated with additional rules (i.e. on embedment depth in bearing stratum) and limitations (i.e. maximum unit shaft friction or base resistance), which differentiate the reliability of different methods.

Model factor for piles

As different degrees of conservativism and calculation rules are associated with different calculation models, Bauduin (2003) states that it may be difficult to reach the required safety level linking these models with a set of partial factors provided in standards. These partial factors should be independent of the calculation model in use, and they should cover other sources of uncertainties. The main reason for the use of a model factor is to provide expected level of reliability of the prediction of calculated resistance value for specific model, to either provide accurate results or err on the side of safety. According to Bauduin (2003), model factor modifying calculation results should be used to address the bias of $R_{measured}/R_{calc}$ presented by the model and its variability. The main point of using this factor is to ensure, with given probability, that the resistance of the pile will be larger than the predicted value.

Two commonly applied calculation model types are used in practice for pile foundations when prediction is based on soil test results. Firstly, semi-empirical methods (i.e. model pile procedure in Eurocode 7), where pile shaft and base resistance is derived from the measured ground parameter directly for a specific location, where tests were conducted. The tests most commonly used to directly derive pile capacities are CPT, SPT and PMT. Secondly, analytical models (indirect methods; i.e. alternative procedure in Eurocode 7 if unit resistance for a stratum in not directly correlated to measured values of a specific profile) may be used, which are often based on soil strength parameters derived from aforementioned in-situ tests or laboratory tests, introducing additional uncertainty due to parameter identification error and subjectivity of the parameter selection. According to Bauduin (2003), those uncertainties are included into model uncertainty.

According to Bauduin (2002, 2003), model factor introduced in the design aims to provide a certain reliability of prediction using specific calculation model; thus, ensuring that there is

only *p%* probability that real value is lower than calculated one. In order to do that, model factor has to integrate both, the bias and the coefficient of variation.

$$\gamma_{mod} = \frac{1}{\left(\frac{R_{measured}}{R_{calc}}\right)_{p\%}}$$

It is possible to distinguish three main approaches of database analysis in order to derive model factor for a calculation method (Bauduin, 2002). First one considers very high level of detail of the analysis, where each type of pile can be calibrated for specific soil conditions. Second allows lower level of details grouping similar piles and soil conditions together. Third and last approach allows for larger generalization, treating all data as one sample, resulting in one calibration factor for the calculation method.

The choice of the approach should depend on the availability of data and the possibility of modification of other factors affecting the reliability of the design, namely installation factors and partial safety factors. In the best case scenario, when large and very detailed database is available, it may be more advisable to modify the installation factors instead of introducing additional model factor as a calibration method. On the other hand, if the database is considered as single sample due to limited amount of data, modification of partial safety factor for resistance may be required to differentiate i.e. between bored and driven piles.

Bauduin (2002) argues that simplified global calibration of the resistance is justified; however, having separate data concerning shaft and base resistance, their separate calibration is also possible.

$$R_d = \frac{R_{calc}}{\gamma_{mod} \cdot \gamma_R} = \left(\frac{R_{b;calc}}{\gamma_b} + \frac{R_{s;calc}}{\gamma_s}\right) \cdot \frac{1}{\gamma_{mod}}$$

Effects of installation, as well as small variations in pile geometry, are taken into account by the calculation rule or are included in the scatter of $R_{measured}/R_{calc}$ (Bauduin, 2003).

Existing databases with static load test results can be used to calibrate new calculation models. Additionally, to introduce a new type of pile, only 5 static load tests are necessary to establish its model factor (Bauduin, 2003). However, increasing their number lowers the uncertainty, allowing to lower its value. Appending new data of sufficient quality, gathered over time, would enable researchers and code drafters to regularly revise and possibly lower selected model factor values; this approach may give contractors an incentive to gather and share data as it might offer a possible cost reduction on future contracts.

Bauduin (2002) stated that an assessment of a calculation model for pile foundation should consider: soil type; method of pile installation, geometrical data of the pile, and the method of ground testing. It may be assumed that these data should also be included as basic information in any database of pile load tests.

Most of the older calculation models based on CPT results, used for bearing capacity prediction, utilized only cone resistance as an input value, while methods utilizing sleeve friction and pore pressure measurement (EN-ISO 22476-1) were developed relatively recently. However, it might be argued that the simplification of input data for the calculation model is a positive aspect, as it introduces some level of robustness to the design.

One of the important factors affecting the predicted bearing capacity is the filtration and averaging of the soil test results in order to eliminate extreme values, often done by the engineer responsible for prediction of pile capacity. It introduces additional bias that is not always directly related to the uncertainty of the method itself. Secondly, limiting the maximum unit bearing capacity to a specific value, used in some of calculation models, imposes additional margin of safety. Such uncertainties and limitations are a result of limited knowledge about the behaviour of specific model in certain conditions; potentially, it could be eliminated if additional data was available.

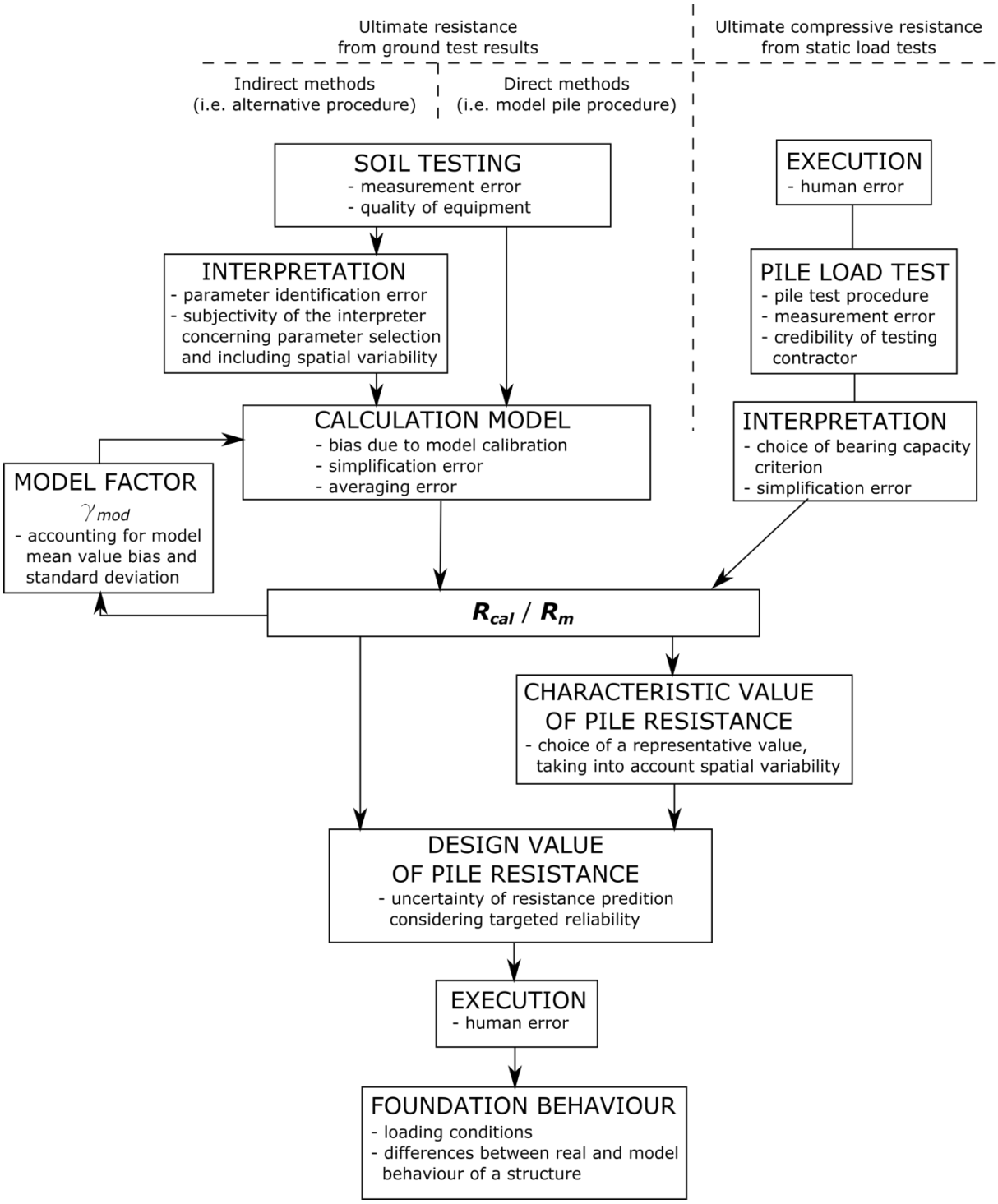

Figure 1: Pile design procedure with most significant uncertainty sources.

Database of static load tests

Although static load tests are considered as the most definite way of assessing pile capacity, they are not free of uncertainties. As the load measurement is done directly, the procedure used for the test (maintained load test, maintained rate of penetration, or creep test), measurement technique and the interpretation, introduce some degree of uncertainty.

Current assumption about ULS failure criterion provided in Eurocode 7 is that it corresponds to the settlement equal to 10% of the pile diameter. Although some calculation models assume even lower values (i.e. 5%), in fact, full mobilisation of end bearing capacity of a bored compression pile in sands can occur at settlement of approx. 20% of its diameter. Furthermore, due to high non-linearity of pile behaviour, often not exhibiting clear plunging failure, different criteria are available for the choice of ultimate bearing capacity. However, this is beyond the scope of this report.

Compiling databases of static load tests is necessary in order to upgrade existing and develop new calculation models for bearing capacity prediction of piles. Such databases are limited by the current technological advancement of both, ground and pile testing techniques.

As the best approach for model factor derivation, as well as verification of existing and development of new calculation methods, is to use statistical methods; it is advisable to create databases of static load tests serving as reference values for calibration. However, the quality of input data is of significant importance. Firstly, quality of site investigation has to be considered. Optimally, in-situ testing should limit the influence of spatial variability, measurement errors, and comprise of various techniques if possible. Additionally, test should be performed to sufficient depth to take into account any possible weak strata that may be located below the pile base in its influence zone. Secondly, sufficient quality of test loads should be provided by performing only static load tests to failure, desirably, with distinction between shaft and end resistances. However, due to the costs and time consumption, in many cases these types of tests are avoided by contractors. Moreover, seldom are such tests performed to failure on working piles. Usually, if performed only as a proof tests after pile foundation execution, maximum load of a static test rarely exceeds 150% of the design load value to avoid unnecessary costs; these are associated mostly with the loading frame and anchoring required for higher loads. If the pile design is based on a conservative calculation model, it will not exhibit sufficient settlement which would correspond to the ultimate load criterion. Performing proof tests in limited loading range instead of up-to-failure tests gives very little knowledge about pile behaviour (Paikowsky and Tolosko, 1999). Although there are methods of interpretation of non-failed static load tests, their use, especially as a basis for model calibration, is not recommended. Paikowsky and Tolosko (1999) analysed 63 load tests carried out to failure, disregarding final part of the load-settlement data to simulate non-failed tests; then after applying two already existing and one proposed extrapolation methods, they compared the extrapolated pile behaviour with the real one. Over-prediction of bearing capacity based on extrapolation could be as high as 50%.

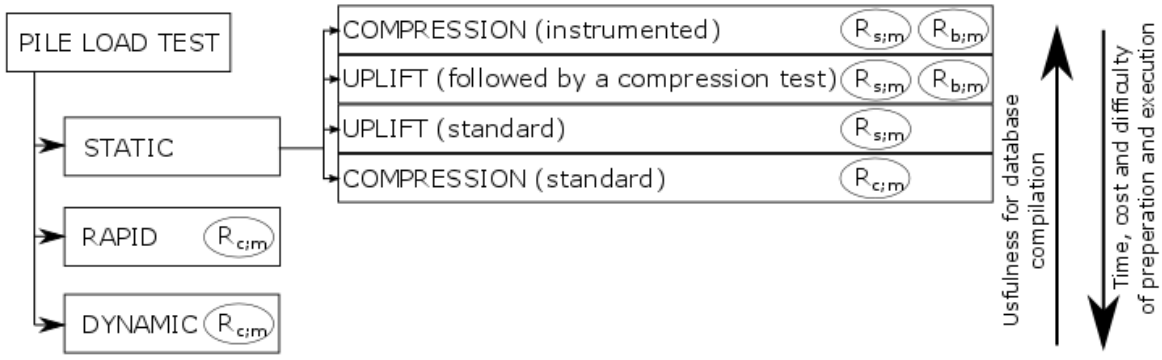

Fig. 2 Pile load test types used for verification of ultimate bearing capacity of pile foundations.

Advancement in data mining and data analysis techniques may provide more suitable tools, i.e. based on artificial neural networks, to eliminate model uncertainties or to take into the account additional factors. However, the use of these tools will still be limited by the amount and quality of available data.

Practical application of calculation model calibration

An example of development of a new calculation model, as an improvement of Bustamante method (Bustamante and Gianeselli, 1981), with its calibration to derive model factors was presented by Burlon et al. (2014). It was based on the database of 174 full-scale, mostly instrumented, static pile load tests, which had been performed over the period of 40 years in France. The model factor was introduced in French standard for pile design. Spatial variability was disregarded due to the location of test piles at the exact locations of corresponding soil tests.

Burlon et al. (2014) suggested two possible approaches for derivation of model factor. First by comparison of the dispersion of the former and new calculation models, assuming sufficient safety level of the former model, and the second approach as direct determination using statistical analysis. It is worth noting that for a group of piles, mostly including micropiles and injected piles, a high value of model factor is used due to insufficient sample in the database and to encourage full-static load testing of such piles.

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