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Philosophy of geotechnical design in civil engineering – possibilities and risks

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Abstract. The European standards, developed extensively over last 30 years, are driven by the need for continuous evolution and their Authors' pursuit of better EU-wide quality in civil engineering – combining safety, economy, and sustainable development. The adoption of theory of reliability as the basis for design has played a major role in shaping current geotechnical practice. However, it requires from practitioners a greater understanding of underlying uncertainties. Furthermore, a number of alternative approaches, not generally used in structural design, are also allowed, as some situations in geotechnical engineering require an individual approach. Moreover, the current trends in geoengineering increase the importance of risk assessment and management. The paper presents general philosophy guiding the geotechnical design and pointing to some of the ideas introduced by Eurocode 7 and its requirements, in relation to preexisting practice of geotechnical design in civil engineering.

Key words: Eurocode 7, geotechnical engineering, limit state design, the observational method, reliability, risk management.

1. Introduction

Geotechnical engineering is a relatively new profession, which has been clearly distinguished as a separate branch of civil engineering in the early 20th century. Its guiding rules have been founded on the works of Karl Terzaghi and his successors [1]; advancements in various fields of technical sciences influenced the creation of a design framework tailored to deal with the particularities of the ground and uncertainties awaiting there.

What is now known as geotechnical engineering has been challenging every society and their endeavors of construction. The engineers of the past faced these challenges with the tools that are now known and defined as the observational method [2] and comparable experience; knowledge of soil behavior had been only empirically based and accumulated on a trial-and-error basis.

Nowadays, engineers have advanced tools at their disposal, as well as vast knowledge obtained during last few decades of rapid development in the field of geotechnical engineering. However, professionals are still faced with the difficulties resulting from the use of simplified calculation models, empirical correlations addressing complex physical phenomena, as well as lack of understanding exhibited by engineers of other professions.

Many opportunities for research and development, which may significantly improve daily design practice, still exist in geotechnical engineering. Especially, increased cooperation between engineers of different specializations, inside the construction industry, leads to better understanding of soil-structure interaction phenomena, as well as the consequences for design solutions. Some possibilities are associated with the adoption of reliability based design (RBD) and rediscovery of the observation- and experience-based design solutions. However, while the use of advanced numerical methods becomes more popular, simpler and more robust engineering rules of thumb often prove more popular than advanced scientifically based methods [3, 4], especially when it comes to their practical applications. They are often seen as having higher relative advantage in relation to the cost of implementation [5]. This is due to the fact that, for many practitioners, they are more intuitive in implementation and supervision of the calculation process. Further advancements, like Artificial Neural Networks [6], may never reach the necessary level of public acceptance to be used in practice.

The purpose of this paper is to describe the most important risks and possibilities that are associated with the field of geotechnics as an important part of civil engineering. This involves the evolving concept of reliability, its implementation in the design in regard to the past, present, and possible future practice, as well as still persistent uncertainties, by far outweighing those inherent in traditional structural engineering.

In addition to standard design practices, based on calculations, a number of different approaches exists and may be utilized by engineers for a benefit of a successful outcome. Similarly to the activities in civil engineering [7, 8], current trends in the field of geotechnics offer new paths that may lead to the improvement of engineering practice [9]. However, whether or not reliability based methods become more ubiquitous in civil engineering remains to be seen.

2. Reliability concept in geotechnical design

2.1. Reliability requirements. The main purpose of any design is to provide technical solutions for a structure, at a reasonable cost, which will allow for its safe construction and continuous maintenance of serviceability within assumed lifetime. Practically all projects in the field of geotechnical engineering consider reliability, in one way or another, to provide appropriate

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margin of safety and to limit probability of failure to a level acceptable by an investor and the society. In many cases, it may be defined as exceeding the maximum load-bearing resistance of a structure or one of its elements. At the same time, no less attention should be given to the serviceability in regard to the deformations that may affect the suitability of a building, or another structure, for the purpose for which it was intended [10].

According to Christian [11], engineer has to consider the nature of the input uncertainties, the methodology of reliability analysis, assumed geotechnical models, and interpretation of results, to properly evaluate the reliability of a structure. Therefore, the way in which the targeted reliability level is ensured is one of the most fundamental assumptions of a geotechnical design.

The margin of safety can be assured by means of global or partial safety factors (SF), as well as direct reliability analysis. Moreover, any reliability-based framework has to include relevant parameters such as physical properties, loads, geometry, and their inherent uncertainty. The evolution of philosophy of reliability in geotechnical design, in relation to national practices and standard evolution, is presented in Fig. 1. It shows the change of approaches from earlier national codes to the current basis of design in Europe [12], as well as the philosophies that may gain more support in the future.

In European countries following regulations of European Committee for Standardization (CEN), the main document providing guidance on the method of reliability assessment and the reference reliability levels are EN 1990 [12], as well as EN 1997 [13]. These standards are based on the semi-probabilistic concept of partial safety factors, but they are also implicitly open to direct reliability consideration [12]. In the next generation of Eurocodes [14, 15], these methods will be explicitly allowed as a mean of reliability verification. However, Bolton [16] argued that the decision-making in geotechnical design, based on deterministic calculations and observable mechanisms, is a more reliable approach than the processes of statistical inference.

The main aim of the Eurocodes has been to harmonize the design practice across Europe and provide unified framework for structural design of structures. However, they are mostly limited to the common type of buildings and structures. Unusual or high-risk structures, i.e. tunnels, dams, nuclear power plants, are beyond their scope, and they may be subjected to additional, stricter requirements.

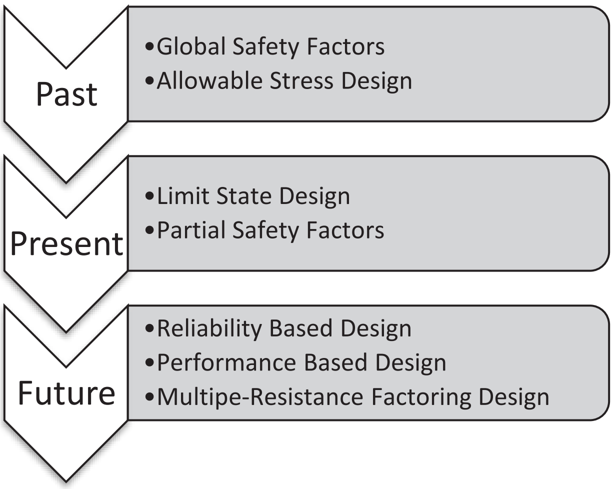

Fig. 1. Evolution of design methods in geotechnical engineering

Furthermore, there is no consensus on the choice of a commonly accepted targeted safety level. Even the European standards [12, 13] leave this decision to the CEN member countries. Although reference levels of safety factors are provided in them, they may be subjected to a change at a national level in the national normative annexes (NNA). Each country can either agree to accept the default levels or to modify them, either by offering more liberal or more conservative values, the latter being usually the preferred choice. Countries that decided to issue more detailed national standards, compatible with Eurocodes, usually include safety levels compatible with the values specified in their NNAs. In fact, this makes a national standardization bodies responsible for specifying prescribed margins of safety.

Although some flexibility of Eurocodes allows for the use of different approaches to ensure sufficient reliability level, the general framework has to be adhered to. Conversely, many developing countries are often not restricted by specific codes in regard to the adoption of design methods [17], and it is left to a designer to ensure that sufficient reliability is provided. It may be argued that, from a sustainability perspective, it would not be economically justified to specify safety factor levels used in developed countries to those still developing, as the costs would have disproportionate financial effects [18].

In addition to the choice of the reference safety level, it is a designer's responsibility to evaluate the reliability of the results obtained from the analysis. The assumption of a wrong design scenario (i.e. expected mode of failure) or the use of unreliable input data will make the results of the analysis unreliable. For this reason, when projects of higher potential consequences of failure are considered, often additional quality assurance procedures are implemented, which may include a review or checking of a design [19].

2.2. Global safety factor design. Traditionally, geotechnical design has been based on global safety factors, sometimes referred to as overall factors of safety (OFS). Their values for different applications were mostly empirically based, and they represented commonly accepted representation of the safety level for a given foundation type. Meyerhof [20] defined it as "the ratio of the resistance of the structure to the applied loads in order to ensure freedom from danger, loss or risks." Such OFS, defined in practice as the ratio of mean resistance to mean load (1) has been meant to account for all uncertainties [21], independent of their sources. The basic equation governing geotechnical design using OFS can be presented as:

$$OFS = \frac{R_k}{E_k} \tag{1}$$

where: R_k – characteristic value of a resistance; E_k – characteristic value of an effect of the actions.

High values of OFS, usually ranging from 2 to 4, as commonly encountered in geotechnical engineering, express the high overall level of uncertainty [22, 23].

For foundation design, the use of OFS has been associated mostly with Allowable (working) Stress Design (ASD) framework [24]. Nowadays, the global safety factor analysis is still often used outside the scope of Eurocode 7 [13], i.e. for slope stability analysis, when material properties are often a predominating uncertainty. Structures and problems that may by dominated by excessive soil straining (i.e. embankments, dams, levees, natural slopes, etc.) were usually the last to be harmonized with structural design principles set up in the Eurocode 0 [12].

Although this approach is intuitively understood by majority of engineers and non-engineers, it fails to cover safety of a structure in regard to different sources of uncertainties, as it may not provide sufficient margin of safety for every scenario. Due to that reason and generally high level of uncertainty involved in geotechnical design, providing overall safety level through the global SF often resulted in excessively high margins of safety in regard to the actual reliability. Due to this expected conservatism, in ASD framework, performance of the structure in regard to its serviceability had often been considered as satisfied through the use of sufficiently high OFS [24].

The use of OFS is not an objective measurement of reliability as it does not directly account for various uncertainties. In certain circumstances, it is possible to obtain higher value of an OFS, while reliability decreases and a probability of failure increases [25]. The report [17] confirmed this and concluded that the use of global SF does not reflect the reliability of a structure; it varies depending on a problem under consideration.

2.2. Limit state design. The concept of partial safety factors is based on the principle of diversification, as the sources of uncertainties do not contribute equally to the reduction of reliability; distinguishing separate partial factors associated with them is then justified [21]. These factors have been introduced within the limit state design (LSD) framework in Europe and Canada, as well as load and resistance factor design (LRFD) framework in the United States [24]. The purpose of using partial factors has been discussed by Simpson et al. [26] and Simpson [27]. Their fundamental role is to decrease probability of failure by modifying characteristic values of leading parameters, each with their associated uncertainties. In general, the basic equation governing geotechnical design using partial SF in limit state design [12] is expressed as:

$$E_d \leq R_d \tag{2}$$

where: E_d – design value of an effect of the actions; R_d – design value of a resistance.

In the simplest form, these partial factors can be obtained by redistribution of OFS into separate partial factors for loads and resistances [28]. They are often calibrated based on previous engineering practice and the expectation of providing the same safety level in future projects. Simpson et al. [17] stated that, in fact, almost all partial factors used in LSD-based codes of practice were calibrated based on previous experience and proven track-record of successful design.

Usually, larger SFs are assigned to more uncertain variables. However, Kulhawy & Phoon [24] argued that such approach may be misleading, and that the sensitivity of the performance function (i.e. equation used for bearing capacity prediction) to the parameter should also be considered. Furthermore, based on the analysis of benchmark examples [17], it has been concluded that caution is necessary while using LSD in the case of highly variable soils. Values of partial factors assumed in design codes may not be appropriate for parameters characterized by large coefficients of variation (COV).

Nowadays, global safety factors are often referenced to, as a mean of comparison of different calculation methods. Vardanega and Bolton [29] called it an equivalent factor of safety. Fenton et al. [21], after comparing the results of calculations with the use of five different codes used across the world, concluded that these codes were calibrated for the same global factor of safety; however, their distribution between effects of the actions and resistances differs.

Contrary to OFS approach when excessive safety level often implicitly accounted for serviceability criteria, LSD framework separated the analysis of ultimate limit state (ULS) and serviceability limit state (SLS). As the former deals with the possibility of failure, the latter mostly concerns an unsatisfactory performance of the structure.

According to Kulhawy & Phoon [24], a single resistance factor cannot maintain uniform reliability level over a wide range of design scenarios, especially, when different components contribute to the overall bearing capacity. Therefore, LRFA may be further extended by the concept of the Multiple Resistance Factor Design (MRFD), as it may be used for achieving more uniform reliability level [24]. Each component contributing to the resistance is given a resistance factor, related to its inherent uncertainty, and the limit state is verified as:

$$E_d \leq \sum \frac{R_{k;i}}{\gamma_{R;i}} \tag{3}$$

where: $R_{k;i}$ – characteristic value of the resistance from one of its contributing components; $\gamma_{R;i}$ – partial safety factor for the specific component contributing to the resistance.

This approach is especially beneficial for pile foundations, as it allows to differentiate between shaft friction (more certain) and end bearing (less certain) resistances, or in the case of uplift analysis, when variability of the self-weight of the structure is significantly lower than that of the resistance provided by anchoring piles or ground anchors.

One of possible downsides of LSD is the situation when a leading random variable dominates the uncertainty involved in the design. Sensitivity analysis to evaluate which variable contributes significantly, and which are negligible, may be necessary.

According to Kulhawy & Phoon [24], in LRFD framework, aside prescribed resistance factors, other parts of the design are left to subjective judgement of a designer. One of the main limitations of the LSD framework is the necessity of selection of characteristic values of geotechnical parameters. This step of the design introduces significant subjectivity and has an impact on overall reliability of the structure. The procedures for selecting the parameters are not well defined or followed uniformly. Due to that fact, the overall reliability of a design is highly dependent on the chosen characteristic values of parameters [30].

Additionally, the inherent variability of the ground in a LSD framework should be accounted for by selecting an appropriate characteristic value, depending on the failure mode considered and the extent of the failure mechanism [31]. According to Forrest & Orr [30], it is not enough to use mean value of parameters as it does not result in targeted reliability levels [12] in the case of shallow foundations, at higher variability levels. A lower estimation of a characteristic value should be considered for a foundation with a limited active zone. Conversely, the choice of a less conservative value, closer to the average, may be justified when a larger volume of soil is involved [31]. Due to that fact, a single characteristic value of a soil parameter cannot be explicitly defined, and it may be different for various limit states under consideration. This is one of the main differences between the geotechnical and structural engineering. For example, in European standards [12], even though 95% confidence level is expected when selecting a characteristic value of a parameter, in geotechnical design [13], its value defined as a "cautious estimate" is generally accepted. Although it is convenient from the point of view of code implementation by practitioners and, it results in some uncertainty regarding the real reliability level.

Where underlying uncertainties are higher than usually assumed in standard, most common design situations, probabilistically-based methods may be considered to evaluate reliability of a geotechnical structure. LSD framework may be insufficient to address soils (e.g. organic) which are characterized by very high coefficients of variation.

2.3. Reliability based design. The concept of reliability based design (RBD) is used in practically all fields of engineering. Among them, the most notable are: offshore petroleum industry, dams and embankments, seismic hazards, mining, nuclear power plants and waste repositories [11]. It is a way of handling foreseeable uncertainties by an explicit introduction of probability density functions (PDF) of know variables, i.e. relating to loads and material parameters. According to Lacasse & Nadim [25], probabilistic model can always be established wherever a deterministic one is available. This applies to classical safety calculations (e.g. bearing capacity) as well as serviceability considerations (e.g. differential settlement). One of the main differences is that parameters are defined over a range of values, not as a specific value, as in a deterministic approach. Moreover, a reliability analysis is not aimed to replace deterministic approach, but to complement it. The RBD is believed to be a rational framework that may improve current state of practice [24]. Furthermore, direct application of RBD is especially justified when LRFD framework may not provide sufficient margin of safety. This is often the case when inherent variability of the subsoil exceeds the variation that may be accounted for only by applying partial factors and by cautious estimate of characteristic values of parameters. However, even reliability-based methods may be insufficient when inherent uncertainties are very large or the underlying problem is not well understood [25]. Additional advantage that RBD has to offer is a possibility of identification of specific uncertainties guiding the design and quantifying their contribution to the overall uncertainty of this particular design. This may offer additional guidance for areas where further investigation efforts should be focused.

Reliability based design can be implemented with the use of various methods [25], i.e. such as:

- First-Order Reliability Method (FORM);
- Second-Order Reliability Method (SORM);
- First-Order Second Moment (FOSM) approximation;
- Monte-Carlo Simulation (MCS).

The safety level of a structure is defined by the reliability index β. Its targeted value may vary, based on expected reliability level, especially between ULS and SLS, and they are set for expected lifetime of a structure. The purpose of these targeted levels is to set up a margin of safety that may be considered as a balance between the cost of the structure and expected reduction of risk associated with its design, construction, and maintenance. For practical applications, targeted reliability levels can also be simplified into design rules, covering specific failure modes, as reliability-based partial safety factors. They may be also used to derive customized partial factors for specific applications [32] or to assess various design methods for code calibration purposes [33].

The reliability index is nonlinearly related to the probability of failure, and it is defined as the distance from a critical value in standard deviations [1], i.e. expressed as:

$$\beta = \frac{\mu_M}{\sigma_M} = \frac{\mu_R - \mu_Q}{\sqrt{\sigma_R^2 + \sigma_Q^2 - 2 \cdot \rho_{RQ} \cdot \sigma_R \cdot \sigma_Q}} \tag{4}$$

where: μ_M – mean value of margin of safety M; σ_M – the variance of M; μ_R – mean value of the available resistance R; μ_Q – mean value of the loading Q; σ_R – standard deviation of R; σ_Q – standard deviation of Q; ρ_{RQ} – correlation coefficient between R and Q (equal to 0 if uncorrelated).

One of the most important aspects of RBD is related to this definition of reliability and probability of failure that is associated with it. Intuitively, probability of failure is seen either as a chance that a single structure will fail during its design lifetime, or as a chance that one of a number of similar structures will fail. This may be related to both the resistance of the structure as well as maintenance of its serviceability. According to Baecher & Christian [1], probability may either reflect a frequency of occurrence in long or infinite number of trials or a degree of rational belief; therefore, a distinction should be made between estimated probability of failure and a real one, as they are not equivalent.

For a specific failure mechanism, an associated probability of failure can be directly estimated. This allows recognizing the most probable failure mode. However, identification and consideration of all modes of failure is required. Their interdependence may be of significant importance for the reliability of the design. Furthermore, unforeseen modes of failure or additional uncertainties, which have not been considered in the design, may result in a real probability of failure exceeding a predicted one by more than a factor of ten. Although in some circumstances RBD may be most advantageous, it should be used with caution. As with other advanced methods used in geotechnical engineering, an understanding of underlying principles is required in order to avoid coming to incorrect conclusions.

The main downside of this method is the lack of necessary data, especially, concerning PDFs of geotechnical parameters. Vardanega & Bolton [29] consider relying solely on published COV values from other soil deposits as unjustified; however, they can be used in conjunction with site specific data.

2.4. Reliability discrimination. Significant differences exist in expected levels of reliability across Europe and around the world. These differences stem from various reasons; some of them, are of philosophical, legal, procedural or even psychological nature. It is difficult to distinguish between acceptance of risk and excess optimism concerning probability of failure. A strong need for identification of these reasons exists to properly address the problem of varying level of safety in different countries to hopefully reach a common reference level, someday. Understanding these differences is also important in the light of harmonization of design rules, which is one of the main goals of European standards. In some cases, differentiation of safety levels may have its benefits. Even if not required by standards or regulations, designers sometimes provide additional margin of safety, anyway. This is often done informally, especially for structures characterized by high consequences of failure. Such considerations are in line with risk assessment and management approach. Although it is formalized by standardization [34] and widely accepted by the learned societies in geotechnical community [35], it is not a common approach in a design.

Using a single reference level of reliability for various types of structures constructed under various conditions is not cost-effective. Reliability discrimination, based on the expected consequences of failure and the complexity of the soil-structure interaction problem, is an effective way to balance safety with economy. According to Fenton et al. [36], the OFS in LSD framework should vary with uncertainty and consequences of failure.

The clear distinction between different sources of uncertainties allows engineers to provide less conservative design. This is due to increase in certainty concerning parameter estimation which follows the advancement of testing methods and procedures, as well as the level of understanding in regard to site conditions and underlying foundation behavior represented by the calculation models.

Differentiation of a reliability level should be based primarily on predicted consequences of failure, and the difficulty of repair. Factors affecting expected reliability can also include the type of failure, whether it is foreseeable and easy to notice, and whether it is brittle or ductile. Safeguarding against brittle failure that cannot be observed prior to occurrence may require appropriately higher margin of safety. Consequences of a failure may be of different nature concerning:

- Possible casualties – e.g. number of people subjected to injuries, fatalities, as well as psychological impact;
- Environmental consequences – e.g. release of hazardous substances, any significant damage to the natural environment;
- Economic consequences – e.g. cost of repair, expected loss of serviceability;
- Social consequences – e.g. damage to monuments and other objects of significant cultural value.

Further examples and more detailed descriptions of some of these consequences were presented by Janssens et al. [37]. Usually, consequences of failure are a more significant factor in reliability discrimination than temporary character of the structure [38].

The reliability discrimination can be introduced into the design in a simplistic, yet most practical manner by the means of varying deterministic factors of safety [39]. Fenton et al. [21] stated that in geotechnical design codes tuned towards reliability-based design concept, implementation in a LRFD framework can be conducted through variation in partial resistance factors. This approach has been already implemented in the current Australian Piling Code [40], as well as Canadian Highway Bridge Foundation Design Code [41]. Currently, the implementation of this approach is on track for the new version of Eurocode 7 [13].

Partial safety factors can be calibrated on the basis of reliability analysis and then introduced in the design in LSD/LRFD framework [32]. Fenton et al. [21] suggested that initial values for calibration should be based on existing codes, as they are commonly accepted and proven to provide sufficient reliability level. The next step is to adjust these values to account for underlying uncertainty. In comparison, Poulos [39] proposed a risk rating scheme which allows to estimate a safety factor by weighting it in regard to a number of different risk factors, in fairly intuitive manner. This method has been implemented later in an Australian standard for pile foundation design [40]. Furthermore, Kulhawy & Phoon [24] stipulated that the resistance factors should be calibrated as a function of soil data quality. However, this should be done also in relation to the quantity of data as well as its availability, as this allows for assessment of soil variability.

There is a significant trend in new standards and current standardization activities ([40]-[42]) to account for the extent of ground investigation in relation to complexity of soil conditions. The main purpose is to influence investors and designers to increase the amount of investigation in order to decrease the uncertainty caused by insufficient knowledge. This idea is supported by results of research into reliability-based methods.

2.5. Coordination of reliability. The reliability of a structure or its elements is often considered separately from other structures, elements, or the entire system of structures, even when reliability of service maintenance is the main consideration. When considering large-scale engineering systems (i.e. power distribution lines, pipelines, flood protection systems, etc.), overall reliability of the entire system should be the main concern, which requires coordination of reliability of all elements.

However, in the case of some structures, when reliability of a system is the major concern, a failure of a single element or a chain of elements should be considered as well; especially, when a cascading failure may occur as a secondary effect of the primary failure. In such cases, limiting the risk can be accomplished by limiting the possible consequences in regard to the cost and time of repairs.

Generally, the reliability of the system may be greater than the reliability of each element [25]. System-wide risk reduction can effectively be accomplished by focusing on strategically located components [43]. On the other hand, e.g. for flood defenses systems, where the weak link is responsible for the overall reliability level, targeted reliability of a cross section should be higher than that of a system as a whole [32].

2.6. Robustness. The subject of robustness is seldom covered explicitly by current standards and design codes of practice. Simpson et al. [17] presented the summary on the current understanding of this subject in relation to geotechnical engineering; however, it is concept that is not unique only to this field [44]. Although it can be understood in different ways, robustness was defined [17, 45] as the ability to accommodate events and actions that were not foreseen or consciously included in design. This definition includes primarily human errors. The basis for this definition is the general expectation of the society that some minor unforeseen actions can result in having a major impact on the structure in regard to any possible behavior or failure mode, both expected and unexpected.

However, proper quality control can lead to inclusion of some unforeseeable events into design process. Usually, sufficient robustness is provided by the use of LSD with experience-based calibration of partial factors of safety [17]. According to Simpson [38], a well designed and constructed structure should be sufficiently robust to withstand a major error or a series of a few minor ones. However, it should not be expected to withstand a catastrophic event or a significant number of minor errors. As robustness and cost are often conflicting goals of the design, their multi-objective optimization should be a result of a design [46]. So far, this is seldom done explicitly as a part of a design framework.

The idea of a robust design aims to lower the system response to some uncertainties rather than reducing their sources, as not always they are known or quantitatively identified. As uncertainty of primary factors of a design (i.e. actions, shear resistance of the soil, etc.) is usually directly accounted for in the design, either through safety factors or PDFs, the uncertainty in secondary parameters is seldom explicitly considered. It is usually assumed that their variation is of limited importance and their variation is rarely considered in the analysis or even investigated. Furthermore, for practical reasons associated with time constrains, sensitivity analysis is not performed, in most cases.

2.7. Quality assurance. Ensuring the reliability of the structure is not connected only to the targeted margin of safety (e.g. safety factors, reliability index) assumed in the design, but also to the quality assurance procedures and requirements implemented at all the stages of the project: design, construction, and maintenance. They should depend on the expected risk profile of the investment (expected complexity and potential consequences of failure). Rowe [47] distinguished three main project classes in that regard:

- Class A – Important and risky – complex geology which necessitates extensive investigation, great deal of information is required for design;
- Class B – Modest project risk and tolerable uncertainties;
- Class C – low risk and relatively straightforward ground conditions – little investigation is required.

These classes are equivalent to the qualitative risk assessment method used in Eurocode 7 [13], namely, the Geotechnical Categories (GC). Based on the proposals presented by Lambe [48] and the new Eurocodes [14, 15], Table 1 presents possible requirement variations in relation to assigned Geotechnical Cat-

Table 1
Design, verification, construction supervision, inspection, and performance control requirements

GC	Design and verification	Construction supervision and inspection	Performance and maintenance
GC3	– By qualified geotechnical engineer; – Based on measured site-specific data; – Complete quantitative assessment of geotechnical conditions. – Independent extended verification by a third-party; – Detailed evaluation of critical design assumptions and predictions.	– Full-time supervision by a qualified engineer; – Field measurement control; – Independent extended inspection by a third-party.	– Complete performance program; – Continuous maintenance.
GC2	– By qualified geotechnical engineer; – Qualitative assessment of geotechnical conditions. – Independent normal verification. – Evaluation of critical design assumptions and predictions.	– Part-time supervision by a qualified engineer. – Independent normal inspection.	– Periodic inspection by a qualified engineer – Few field measurements; – Routine maintenance.
GC1	– Design based on prescriptive measures – Self-checking	– Informal supervision. – Self-inspection.	– Annual inspection by a qualified engineer; – Maintenance limited to emergency repairs.
–	– No rational design. – No verification	– No supervision. – No inspection.	– No inspection or occasional inspection by a non-qualified person.

egory. Generally, such rules should allow for some flexibility, as they may have to be adapted to local conditions, type of the structure, as well as the risk tolerance of the investor or national regulations. The concept of qualitative risk assessment using GC gains wide acceptance even outside the scope of the Eurocodes; Stille and Palmstrom [49] proposed its application for tunneling in rock.

3. Geotechnical design uncertainties

Every analysis in geotechnics is based on a number of different parameters and factors influencing the overall reliability of a structure. All of them are affected by various uncertainties, always inherent in geotechnical design. Contrary to structures made of other materials, which behavior depends on properties subjected to extensive quality assurance during production, soils exhibit not only much higher variability, but often cannot be easily characterized just by assigning specific properties values in a dedicated standard.

Parameters presented in tables in various guidelines or codes of practice are often very conservative, as they are not based on site-specific data. Their applicability is often also limited to a specific foundation type or limit state under consideration. Furthermore, while considering the overall uncertainty of a design, actions acting on a structure or their effects, as well as a resistance to the effects of these actions have to be considered; these aspects can be strongly interrelated in geotechnical engineering.

Together with a strong non-linearity of soil behavior, high level of uncertainty is quite a common challenge for geotechnical engineers. Main sources of uncertainties are briefly described below.

3.1. Sources of uncertainty in geotechnical design. Geotechnical design may involve various issues contributing to the decrease of reliability of its predictions as well as the structure itself. Generally, the inherent uncertainty always remains significantly higher than in the case of other non-geotechnical structures. The complexity of ground conditions is associated with its heterogeneity, as well as highly non-linear and time-dependent behavior [23].

Soil, the main material that a geotechnical engineer has to deal with, is of natural origin rather than manufactured according to a design specification [1]; with the exception of engineering fill placed under controlled conditions, often very limited knowledge is available prior to conducting a geotechnical investigation.

Lack of awareness of the underlying uncertainties in geotechnical design can result in inappropriate design solution. At such circumstances, a designer is often driven by ignorance or fear, which can lead to over-conservatism and unjustified expenses. Kulhawy and Phoon [24] stated that absolute reliability is an unattainable goal in the presence of uncertainty. Exact natural conditions are never known and the understanding of the subsoil is limited by the number of observations (boreholes, tests, etc.). Small number of data points often encountered in geotechnical engineering can result in significant and unknown bias in the investigation of stratification and estimation of soil parameters [11].

Most uncertainties involved in geotechnical design are of epistemic nature, and are related to lack of knowledge, while others are aleatory, reflecting inherent randomness and natural variability [1], [50]; in practice, these two types coexist. Generally, the main uncertainties encountered in geotechnics are caused by [30]:

- Inherent soil variability;
- Limited information;
- Imperfect information.

The dominating uncertainty of geotechnical design can usually be attributed to inherent variability of the subsoil, and it can be evaluated at different scales, from micro-structural to geological (regional). While increased scope of site investigation can reduce uncertainty associated with soil variability (epistemic), it can only provide quantitative assessment of aleatory one. Furthermore, additional uncertainty exists in the case of special soils, i.e. expansive, collapsible, highly organic, etc., as well as in the case of behavior at unusual loading conditions, namely cyclic or dynamic.

Usually, only foreseeable uncertainties, which can be quantified, are considered in design by calculations. Their consideration stems from previous practice or has been introduced after some failure had occurred and had been thoroughly investigated. The uncertainties in the parameters propagate throughout design calculations and affect the final results. In the case of non-linear systems, a small change in initial conditions can lead to large changes in outcomes [1]; awareness of the uncertainties and their impact can be crucial for providing sufficient level of reliability.

Other uncertainties affecting the final reliability of a geotechnical structure, which cannot be easily quantified, often are implicitly considered in design. For example, the avoidance of human errors is accomplished mostly by means of proper quality control, which is often a basic requirement in standards and regulations.

It is virtually impossible to completely remove uncertainty inherent in geotechnical design; however, increasing awareness of these existing uncertainties and their consequences is a basic contribution of reliability concept [25]. Designers, both geotechnical and structural, need to poses knowledge of possible consequences of their design assumptions and awareness concerning their quality. This allows them to concentrate their effort on the matters of most importance.

If objectively insufficient investigation is conducted, some of practitioners tend to assume favorable conditions, unless higher risk of occurrence of differing ground conditions has been considered based on the previous experience or expert judgment. There are two main reasons fostering such practices.

First of all, in theory, geotechnical investigation should be conducted at different stages of the design. This would lead to the supplementation of knowledge at each stage of the project to obtain the most probable and reliable geotechnical design model. In reality, the problem with financing supplementary testing is a common issue worldwide. Designers, to avoid expenses in their own budgets are more conservative in the design or allocate additional responsibilities to the contractor.

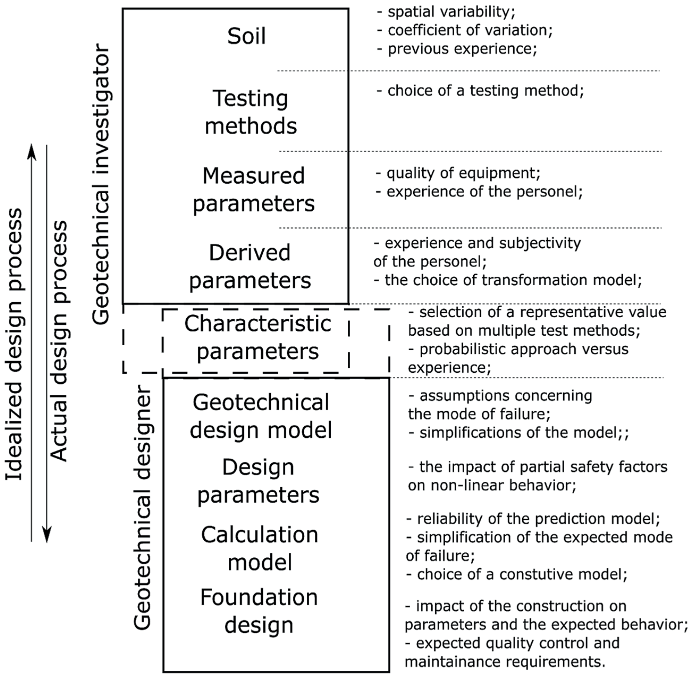

Fig. 2. Introduction of uncertainties in the design process

Secondly, when investigation is conducted by a subcontracted company, designers often do not consider the definition of appropriate ground model and the selection of the characteristic values of parameters to be their responsibility (Fig. 2).

3.2. Soil characterization and parameter estimation. Spatial variability may be of dual nature, either as continuous fluctuations of soil properties, including layers' boundaries and soil parameters, or discrete as local elements, which may include adverse geological conditions. As the former may be characterized through the mean and variation, the latter has to include prior experience and local geological knowledge [32]. The probabilistic approach to soil characterization has been a subject of studies for a long time [51, 52], which allowed for explicit modeling and consideration of soil variability in geotechnical design [53]. Such approach is of value for deterministic design as well as direct reliability consideration.

Parameters of the soil usually do not have constant values. They can be subjected to change due to natural (i.e. weathering) or anthropogenic processes. Assumption of soil parameters without the consideration of their stress- and time-dependence, although a common design simplification, may lead to mistakes.

Furthermore, while planning a scope of geotechnical investigation, consideration should be given to the type of a structure and results of the preliminary assessment of geotechnical conditions; particular effort should be focused on investigation of each strata that might guide the foundation design for every relevant failure mode.

3.3. Spatial variability of geotechnical strata. Soil variability is generally the most significant source of uncertainty [24]. In most cases of horizontally stratified soils, a much larger variation can be expected in the vertical direction; consequently, the effect of vertical variation usually dominate the failure mechanism [31]. According to Lacasse & Nadim [54], typical soil properties within distinct geological stratum can fluctuate approx. 10 to 100 m horizontally and 0.5 to 5 m vertically.

For all practical purposes, it is easier to assume random distribution and variability, even though the underlying caused were not, e.g. natural processes of sedimentation. However, lack of exact knowledge of geological history does not allow for precise description of the soil.

3.4. Measurement error. Measurement errors are introduced by the testing methods and procedures used to identify soil properties and derive their parameters. This type of error is also common in testing of other construction materials [55]. In practice, separation of a measurement error from spatial variability may be difficult [50]. Even isolating measurement error from transformation uncertainty during standard site investigation is impossible [56]. However, the measurement error can be negligibly small when a parameter is derived from accurate equipment and in accordance with relevant testing standard or procedure [31]. Measurement quality is affected by: appropriateness of the testing method for specific site conditions and soil types, as well as procedural control [57]. For most popular testing methods, measurement error is usually relatively small if regular calibration of the equipment is conducted. Furthermore, tests should be conducted according to accepted procedures. If these criteria are not met, values derived from the tests may be subjected to significant error, prior to the selection of characteristic value for design purposes.

3.5. Transformation error. Most parameters used in geotechnical engineering are seldom obtained directly as a measured value. Usually, some correlation between measured and derived values is used, introducing some level of uncertainty. According to Ching & Phoon [56], transformation uncertainties are typically fairly large. This is because empirical correlation models are often implemented, which are based on regression analysis used for fitting data and establishing a transformation function (Fig. 3).

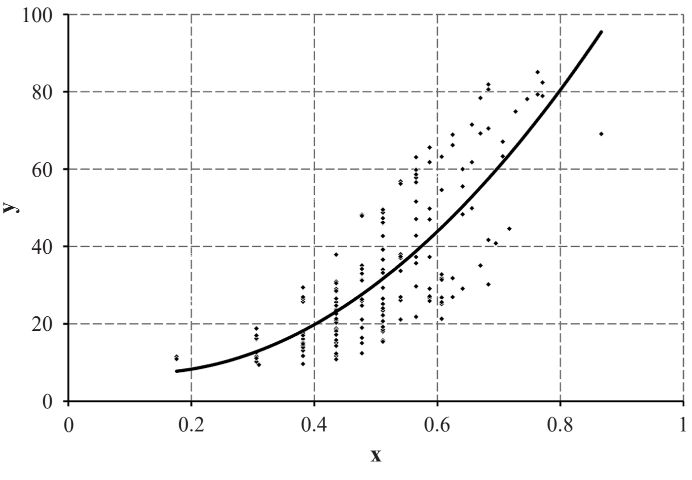

Fig. 3. Example of correlation uncertainty between two parameters

They may include significant level of subjectivity as estimation can be biased by the beliefs of the interpreter [1, 54, 58]. Generally, a characteristic of an underlying database has to be known for engineers to make a decision concerning the choice of transformation model to a particular problem.

Additionally, Ching & Phoon [56] distinguished between site-specific and global transformation models. The former are generally more precise but not applicable for another site without accounting for possible significant bias. These models should not be used indiscriminately, as most of them were developed for specific soil types and regions [56]. Their applicability is limited to the range of data contained in a database used for their preparation, and they must not be used outside their range of calibration. On the other hand, global models can accommodate broader range of soils. Therefore, it is a common practice to estimate parameters based on non-site-specific data [59]; however, the uncertainty resulting from such transformation is often relatively large.

Further uncertainty may be a result of discrepancy between the character of the testing method and the derived parameters. Based on the same testing method, transformation functions for some parameters are more uncertain than for others. For example, estimating Young's modulus E based on CPTU, will usually be more uncertain than estimating the undrained shear strength c_u [58].

3.6. Derived versus characteristic values of parameters. One of the main differences between the fields of structural and geotechnical engineering lies in the selection of material parameters, which are treated as representative in the design process. Selection process in the case of concrete [60] or steel [61] is mostly dependent on standardized characteristic values, converted into design ones with the application of partial safety factors; whereas in geotechnical engineering, it is based on values of parameters derived from various measurements (i.e. laboratory, in-situ). Eurocode 7 defines derived value of a parameter as a value obtained by theory, correlation or empiricism from test results. The methods of testing are presented in the second part of the Eurocode 7 [62]. The obtained values are often represented by significant variability [63] and seldom are directly applicable for design calculation purposes. This variability and other factors are accounted for through a process of selection of characteristic values, based on those derived from different tests. However, no explicit guidance on selection of characteristic soil parameters is given in most geotechnical codes, including Eurocode 7 [13], as this should be a responsibility of an expert geotechnical designer.

Generally, the derived value should take transformation and measurement uncertainty into account [31]. Then, inherent variability should be accounted when selecting characteristic values. A selection of a characteristic value of a material is essential in providing a targeted reliability level in a LSD framework [30]. Kulhawy & Phoon [24] argued that location of nominal values in regard to PDF has to be specified in LSD framework in order to provide specified targeted reliability level. Although the Eurocodes generally expect 95% confidence level in the characteristic values of material properties, this is not often the case for ground parameters. In Europe, it is defined as a cautious estimate of the value of a ground property that affects the occurrence of a limit state; this approach has been discussed by Simpson et al. [26]. In North America, on the other hand, characteristic values are usually assumed as somewhere below the estimated mean [36]. Furthermore, according to Orr [31] it is a responsibility of a geotechnical designer to determine characteristic values of parameters for each design situation, while site investigator provides derived values.

When choosing a value, Eurocode 7 [13] recognizes the difference between an amount of soil volume guiding the limit state under consideration. The averaging range should include the extent of geotechnical failure mechanism around the foundation, making the estimation of characteristic value dependent on expected type and size of the foundation [36]. Generally, the increase in the problem size decreases the uncertainty of the results due to shear strength variation [11].

Furthermore, as the conservatism is often exhibited when selecting characteristic values of parameters, it should be noticed that a low value of a parameter is not necessarily a conservative one [1]; it is important to ascertain a realistic range of values for soil properties.

A characteristic value of a shear strength parameter is just a mathematical approximation of estimated soil behavior under the assumption of Mohr-Coulomb failure criterion. A linear relationship between normal stress σ and shear stress τ is a simplification often adopted in geotechnical engineering as its use is justified in the ranges of stresses commonly encountered for most geotechnical structures. However, different soil behavior can be observed at small and large normal stresses, when a description of a curve line is more appropriate (Fig. 4). Moreover, it should be considered that effective cohesion c' obtained from laboratory tests may, to some extent, account for apparent cohesion caused by suction. As the soil is a three-phase medium (solid particles, fluid, and gas) [64], for practical purposes, often full saturation is considered in most laboratory tests, as it is often assumed in in-situ conditions below the water table. Although explicit consideration of unsaturated soil mechanics is

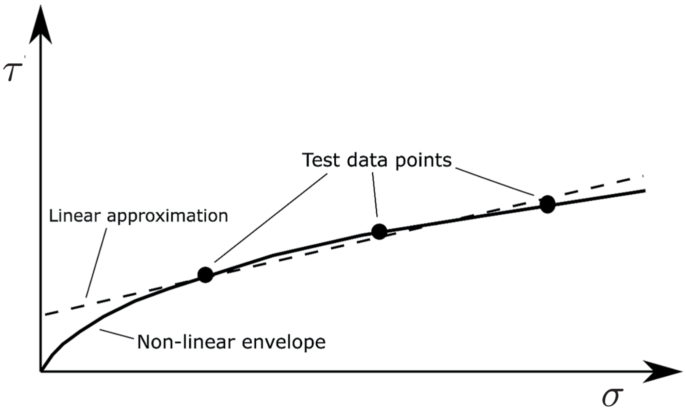

Fig. 4. Strength envelope approximation

possible in design [65], it is not a common practice, and it is still a subject of extensive research. In some areas of geotechnical practice, i.e. slope stability analysis, the assumed behavior can be crucial for the reliability of prediction.

The difficulty of selecting characteristic shear strength parameters is additionally complicated when large strains may occur. For a given problem at hand, it is important to identify whether pre- or post-yield behavior is of critical importance. Then a choice between the use of peak or residual shear strength parameters may be made.

Different people evaluating the same raw test results may derive different values of soil parameters, introducing significant subjectivity even prior to the estimation of a characteristic value. However, efforts to remove the subjectivity of characteristic value estimation should not remove engineering judgment from the estimation process. Disregarding previous experience and limitations of applied testing methods can lead to the use of inappropriate parameters. For example, deriving effective strength parameters for fibrous peat, based on triaxial results, may be incorrect without consideration given to the specificity of the material [66].

Further distinction can be made when selecting values of parameters guiding different types of limit states. For assessing the reliability of a geotechnical structure, in the case of ULS, a selection of a lower estimate of strength parameters is important; cautious estimate can be between mean and lower bound values. However, when significant post-peak strain-softening behavior can occur, this value can be as low as a residual value. On the other hand, for SLS, the most probable (mean) value should generally be used; especially for parameters guiding deformation behavior, as excessively low or high values can lead to incorrect results and prediction of the most probable behavior of the structure may not be possible.

Finally, parameters estimated based on a back analysis can be used directly as characteristic values for a given problem, as they account for averaging over the area of an influence (active) zone of that specific limit state.

The abovementioned characteristics of parameter selection process distinguish geotechnical from structural engineering. Without standardized parameter values, which cannot be used in geotechnics with sufficient reliability, it is often not clear who is to take the ‘moral’ responsibility for the choice of these parameters. This matter is further complicated by varying practice concerning professional liability in different countries.

3.7. Ground model and geotechnical design model. In geotechnical practice, site investigation is used as a basis for definition of a ground model; it is an idealized representation of real geotechnical conditions, simplified and described in geometrical and parametrical manner. In comparison, geotechnical design model is defined as developed for a particular design situation and limit state (Fig. 5). In LSD framework, site variability is taken into account by specifying different soil layers and through the choice of characteristic values of soil parameters.

Establishing a ground model requires the combination of the content (i.e. data gathered during the ground investigation) as well as the context (i.e. previous local experience, subjective judgement). This context factor, in some cases, may result in two opposing points of view and definitions of ground model, even based on the same data [23].

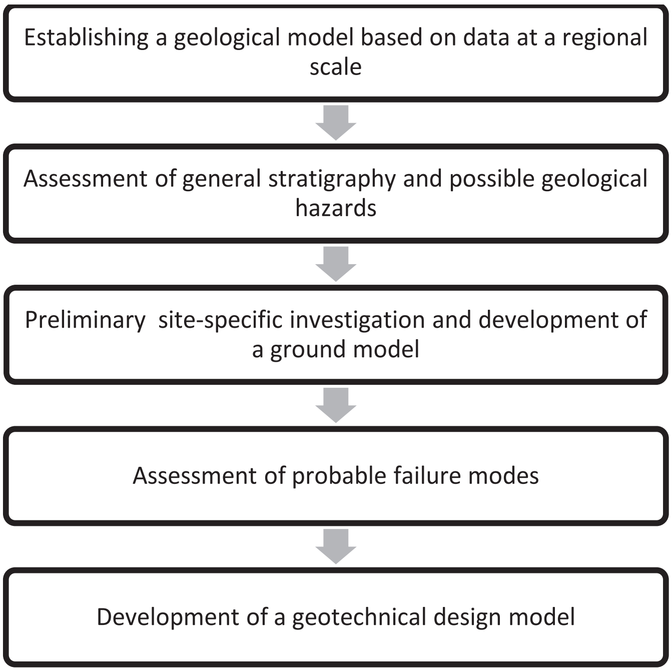

Fig. 5. A design procedure flow chart for risk assessment evaluation in a LSD framework

A ground model used for analysis is only an interpretation based on very limited number of data. As the selection of parameters can be supported by the use of statistical models, the assumption of the ground stratification does not have to be the exact representation of reality. The inherent uncertainties resulting from simplifications should be included in the model [67], as well as should be any uncertainty caused by insufficient investigation. Knowing the geological history of the area where a given project is located is important for preliminary assessment of potential uncertainty sources and for the definition of a ground model.

Geometrical aspects of a ground model, for purposes of defining a geotechnical design model, may be presented in various forms, i.e. as:

- a soil profile (1D);
- a geotechnical cross-section of the subsoil (2D);
- a spatial representation of ground conditions (3D).

The extent, complexity and accuracy of such definition is generally dependent on the failure mode or limit state under consideration and the corresponding extent of active zone within the soil that may be expected. For example, a settlement of a footing involves averaging soil properties within its zone of influence [68]. In result, the type, scope, and quality of a ground investigation should be affected by the considered failure modes, as well. However, a common problem exists that site investigators concentrate their effort on the soil layers based on the simplicity of conducting tests and taking samples for laboratory tests, while offering only qualitative assessment for layers which may actually guide the design. The most important soil layers are not always the ones that are investigated the most extensively. Usually, geotechnical investigators tend to characterize dominating soil strata rather than those that may guide the design or occurrence of specific limit states. This often results in a scope of investigation limited in number of test locations and their maximum depth, as much as possible to fulfil minimum requirements of existing standards or recommendations. Usually, increasing the scope of investigation, thus decreasing the uncertainty, is of great benefit when design optimization is considered. Nevertheless, Jaksa et al. [68] simulated a shallow footing on a randomly generated soil model, extracting data equivalent to soil test profiles. With an increasing number of boreholes included in the analysis, the design solution converges asymptotically to the optimal one. This proves that with the increasing number of tests used in the analysis, the accuracy of the prediction increases, up to some extent. At some point, dependent on the complexity of soil conditions, a benefit of increased knowledge is marginal and a cost of additional tests is no longer justified as it will provide only redundant information without significant reduction of uncertainty. Balancing the uncertainty and cost-optimization highlights the need for risk-driven geotechnical investigation as the basis for design. Ideally, the presence of uncertainty should motivate to seek information, i.e. by performing additional soil tests. Then, a ground model should be verified and refined during all stages of the project.

Depending on the scale of the analysis and the extent of active zone, different levels of detail can be used when establishing ground model. These differences may exist, for example, between conducting the analysis of a single diaphragm wall panel in plane strain conditions and the whole structure in 3D, or between a foundation slab and a footing. Multi-scale models involve trade-offs between the details required for accuracy and simplifications needed for practical purposes and computational efficiency [43].

3.8. Calculation models. For design based on calculations, three main types of calculation models can be distinguished:

- Analytical;
- Empirical;
- Numerical.

Empirical or analytical models evolved after establishing a scientifically-supported framework for a given problem. Then, with the increase in complexity of design problems and advances in computational power, numerical models were developed. With the advancement of understanding of soil behavior and soil-structure interaction, as well as significant technological advancements in soil testing and numerical modeling, new opportunities have arisen.

Nowadays, however, the existence of wide variety of calculation methods is one of the main inhibiting factors of harmonizing design practice and procedures between countries. It is difficult to obtain targeted safety level when a calculation model is used with a set of code-given partial factors, without consideration of the degree of conservatism and variability of different models [28]. Fenton et al. [21] pointed out to model understanding as subjective confidence of a designer in a predictive tool used to estimate geotechnical resistance. Moreover, Vardanega & Bolton [29] stated that existing behavioral models are a poor fit with reality due to system uncertainty, which results from necessary simplifications.

Usually, distinctive components are affecting the behavior of a foundation. They can be described by mathematical functions, often of non-linear nature. Their performance is dependent on basic design parameters. For example, even a simple analytical equation for calculation of bearing capacity of a shallow foundation in drained conditions involves three different contributing factors, which are multiplied by up to five correction factors, each to account for shape, eccentricity, load inclination, depth, base tilt, and ground surface inclination [11]. Model uncertainty is connected to the idealization of real physical behavior caused by mathematical approximations and simplifications.

Lacasse & Nadim [54] defined the model uncertainty as the ratio of the actual quantity to the quantity predicted by a model. In probabilistic framework, it can be represented by a function with normal distribution. This uncertainty may be included in the design by factoring [54]: each variable, a specific component, or a safety factor in LSD.

As the scale of the analysis affects the detailed description of the geotechnical model, it also introduces simplifications to the representation of a structure. Simplifications may lead to unnecessary conservatism, while the required number of parameters and factors, which have to be taken into account for advanced methods, may make those methods not fit for practical applications. As the number of required parameters increases for a given calculation model, usually, the number or extent of tests used for their estimation decreases. Lambe [69] highlighted the interrelationship of methods of prediction and the necessary data. In practice, using advanced models which parameters are based on unrepresentative number of soil tests may be even less reliable than using simplified models for which the amount of data is sufficient.

Seldom is the consideration of a calculation model based on in-depth analysis and rational decision process. From practical point of view, the choice of the most appropriate calculation model is important in the design process. The appropriate model can be described as one providing the most favorable balance between the reliability of prediction and the necessary data for its application, i.e. the type and the number of input parameters. For evaluation of regression models in statistical analysis, Honjo [70] used the Akaike Information Criterion (AIC) [71], which may be used to balance the accuracy of the model with its complexity and the number of required parameters. However, when considering the choice of a calculation model, designers often have to base their decision on the availability of different tools and data provided for them. According to Vardanega & Bolton [29], it is important to use models with limited number of parameters, and to have access to a database allowing to ascertain the variability of these parameters. Their use in conjunction with robust and simple calculation models representing deformation mechanisms should be calibrated against observed performance. For example, such calibration for pile foundations has been performed by Burlon et al. [72], and for deep excavation some interesting analysis by Mitew-Czajewska [73].

The most appropriate calculation models are often not the best available ones. Time and budget constraints, often imposed by investors during design stage, inhibit the use of the state-of-the-art methods. Generally, the scientific drive for better representation of reality does not go hand-in-hand with the practical applications [3], as most designers have limited amount of data at their disposal and the introduction of novel methods is often further impaired by their conservatism. Even decades ago, Lambe [69] argued that we need to prepare simple prediction techniques for practicing engineers.

Alternative failure modes are often not taken into account by designers, i.e. when foundation is located in a stronger layer overlying weaker stratum, reduction of bearing resistance or even a change to punch-through failure mode is possible. Consideration has to be given to the limitations of calculation models and the range of their applicability. Most models can be used in the range of applications for which they were calibrated, i.e. specific ground conditions or soil types, foundation dimensions, etc. Extrapolating these methods outside this range can only be possible with full understanding of such model and with additional care (i.e. by applying the observation method). Furthermore, it should be considered only when no other calculation model seems applicable, as well.

Advanced calculation methods are often not practical for the use by engineers in the industry when less complex models are available. There are significant advantages when using simper calculation models:

- faster analysis;
- significantly lower number of input parameters;
- availability of calculation tools – cheaper software;
- increased robustness;
- properly calibrated model allows to err on the side of safety – additional margin of safety;

Therefore, the use of more advanced calculation methods often have to be justified by:

- the necessity – where simpler models are not applicable;
- advantages – possible cost savings or more reliable prediction (proof of increased safety level).

Existing calculation methods were mostly established on limited number of data points or analysis without sufficiently extensive validation. As every calculation model is just a simplified representation of reality, uncertainty exists in regard to its reliability of prediction. Generally, with the increased sophistication of the model, it should be expected that the reliability of prediction increases as well (Fig. 6).

Model uncertainty is difficult to assess, but can be defined as a mean (bias) and coefficient of variation, based on a comparison of deterministic solutions with results of model tests [25]. They both can be integrated into single model factor accounting for the reliability of prediction of a calculation model. According to Bauduin [28], the model factor is an objective way to compare different calculation rules.

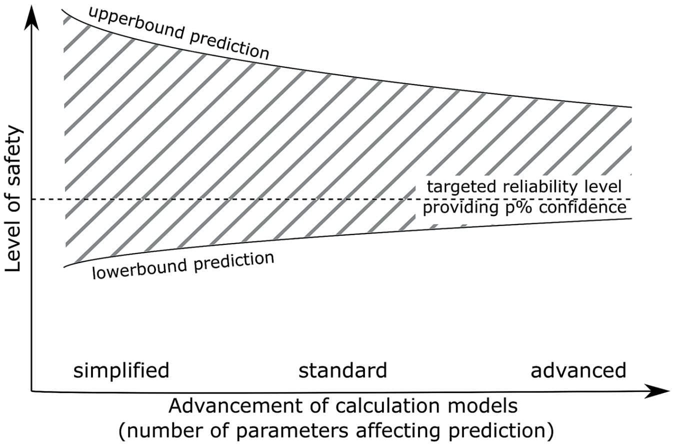

Fig. 6. Conceptual representation of the calculation model reliability evolution in regard to its sophistication [74]

The bias and variability of a calculation model can be ascertained based on the comparison of results of direct load testing with the value calculated using particular model [28] (Fig. 7). Well documented full-scale case studies are preferred for establishing a model factor, but their available number is often limited [75]. Kulhawy & Phoon [24] stated that insufficient data are available to perform statistical assessment of model bias inherent in many calculation models. When measurement of a resistance is not directly possible, a comparison with the results of more advanced calculation method can be made, assuming its bias is negligible and reliability confirmed by successful track-record. In the simplest form, model bias can be defined as [76]:

$$\mu = \frac{X_{meas}}{X_{cal}} \tag{5}$$

However, model factor depends on the bias as well as the COV of the model uncertainty. When the model factor is used

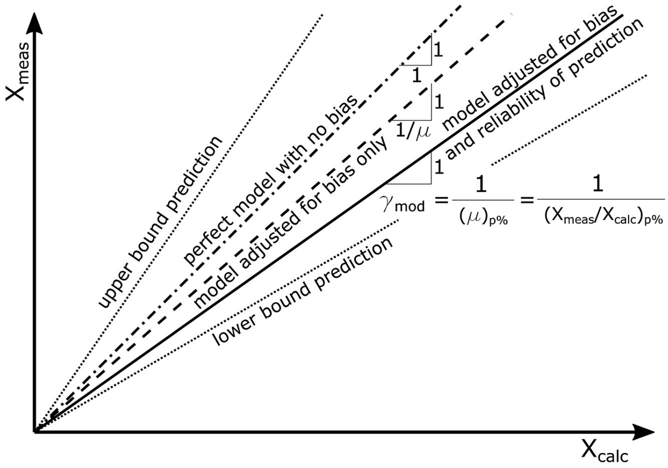

Fig. 7. Representation of linear model factor in geotechnical design [76]

to shift the probability density function of a model uncertainty, to allow only a p% probability of the real resistance value being lower than predicted one, following relationship can be used [28]:

$$\gamma_{\text{mod}} = \frac{1}{\left(\frac{R_{measured}}{R_{calc}}\right)_{p\%}}. \tag{6}$$

With increasing number of test results, calibration of an existing calculation model can be conducted. Also, the implementation of new methods require a proven track record and validation.

3.9. Other uncertainties in geotechnical practice. The design process in geotechnical engineering, implicitly expected by Eurocode 7 [13], requires that the scope of geotechnical investigation should be appropriate for particular type of the structure and the design solution. Conducted investigation should provide information necessary for a calculation model, including geotechnical ground model. However, actual design process is often reversed; the ground and calculation models are chosen appropriately to the provided soil data gathered during geotechnical investigation. Such difference between the expectations of code-drafters and the actual practice of the industry in Poland is a major source of problems and further uncertainties.

In Poland, seldom are the geotechnical investigation and design conducted by the same stakeholder, i.e. one responsible for design of a foundation. Geotechnical investigator is often contracted by the investor, either at the feasibility study or preliminary design stage, while geotechnical designer may be involved as late as at the detailed design stage, which may be parallel to construction stage.

On general, a geotechnical investigator and a designer tend to be over-conservative in selection of ground parameters and design solutions, as to err on the side of safety. Although it is often assumed that the other party has conducted their work correctly, a lack of trust often persists in the design process, which results in over-conservatism; both sides are trying to compensate potential problems with the other side by increasing safety on their own. When selecting a geotechnical investigator, clients often assume the quality of provided results as a given and base their choice on the lowest price only [23]. However, without a geotechnical background and specific reference documents, they do not know what level of quality they should expect. At the same time, many contractors offer low-priced but substandard services, just to meet the minimum requirements imposed on them by the client, standards, or regulations; often, no consideration is given to the actual problem at hand.

In most geotechnical investigation reports (GIR), boreholes are preferred to establish the basic geological model based on stratigraphy of the site; all too often, no follow-up tests are conducted for areas or layers for which clear uncertainty is present (i.e. to assess continuity of a layer of low permeability).

Christian [11] highlighted four main strategies to deal with uncertainties in geotechnical engineering:

- Ignoring it – which is a widespread approach, often used willingly by many practitioners;
- Being conservative – providing robust design, able to resist identified uncertainties; however, at a price of increased cost and time expenditures;
- Using the observational method;
- Quantifying uncertainty – by implementing reliability-based approach.

Unfortunately, the most popular approaches in practice are to either ignore the uncertainties or to provide design solutions with high margins of safety.

4. Alternative existing design approaches

Although design by calculations is the most common approach in geotechnical engineering, over the years, a number of alternative approaches were established. The most common of them were adopted into the current version of Eurocode 7 [13], mostly to accommodate the actual practices in some fields of geotechnical engineering.

4.1. Observational method. The principles of the Observational Method (OM) were defined by Peck [2] in 1969, while the method itself has been implemented even earlier outside any clearly defined framework. However, this term has gained increased popularity after its explicit implementation in Eurocode 7 [13]. The basic idea behind the OM is to balance reliability with economy by allowing design modifications at the construction phase, where design is done for expected conditions but steps are taken to safe-guard against the occurrence of less favorable ones. The most important aspect distinguishing the OM from just "learn-as-you-go" approach, often confused by engineers, is the preparation of fallback scenarios for every predicted unfavorable situation considered, beforehand. These scenarios should be realistic and possible to implement without delay, and all possible modes of failure should be accounted for. Furthermore, Peck [2] stressed the importance of making right observations in regard to measuring phenomena actually governing the behavior of the project; measuring the wrong quantities may cause significant problems.

The use of the OM may be especially beneficial for projects that cannot be quantitatively assessed beforehand with sufficient reliability. Careful analysis of the results of the observations may provide invaluable guidance, especially for major geotechnical projects. A Żelazny Most tailing dam is one of such examples, as reported in [77].

The issue noticed by Peck [2] in 1969 still rings true now that often less effort goes to the significance of data obtained from monitoring than the preparation of formal reports and documents based on them.

Observations should be analyzed as soon as possible, and proper action taken immediately; however, in situations where progressive failure might be possible, and any reaction taken when problems are disclosed, this approach may not be sufficient. Moreover, lack of preparation for all foreseeable scenarios is the main danger for the success of the OM. However, the occurrence of unforeseeable scenario, or one without a solution to counter it, may be the worst case scenario.

The application of the OM has a risk of slowing down the construction works. As most often geotechnical works are on the critical path of the project, this may be not acceptable by either the investor or the contractor and more conservative but costly design assumptions might be preferable, anyway. The same might occur when the most unfavorable conditions have a high probability of occurrence.

Another downside of the OM is the necessity of having access to decision makers in the project management [11], with preference of decisive say being possessed by a single person. Unfortunately, the OM cannot be applied if no modification of the design is allowed at the execution stage. This is often connected with the issue of contractual complications associated with the application of the OM has been noticed almost half a century ago [2]. Unfortunately, till this day it is often the problem of more concern than technical issues alone. Main differences between standard design procedure and the application of the OM are presented in Fig. 8.

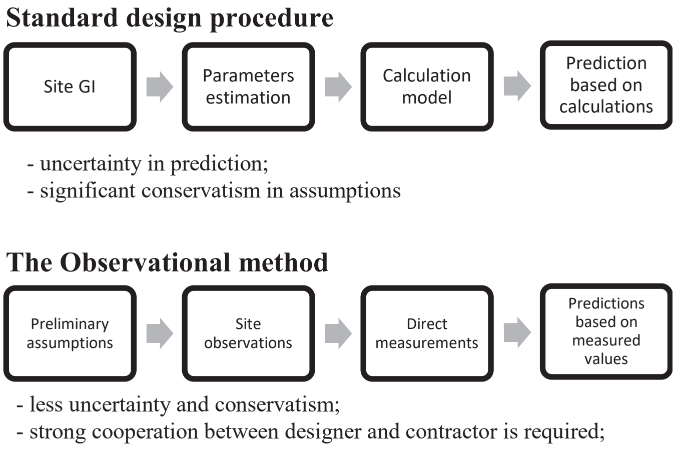

Fig. 8. General difference between standard design approach and application of the observational method

4.2. Comparable experience. Comparable experience is defined by Eurocode 7 [13] as documented or clearly established information, involving the same types of soil for which similar geotechnical behavior is expected, while it involves similar structures. Although all design results should be checked against comparable experience, in simple cases, it may be sufficient to select a design solution based solely on the previous experience.

4.3. Design by prescriptive measures. When calculation models are not available or not necessary, exceeding limit states may be avoided by the use of prescriptive measures that involve conventional and generally conservative rules in the design [13]; it requires comparable experience to be established.

Prescriptive rules may reference to specification and control of materials, workmanship, protection and maintenance procedures. For example, when considering the design of low voltage power lines, it is generally considered that: "self-supporting wood poles shall be erected using direct embedment in the ground. The depth shall be at least 1/7 of the pole length and not less than 1,5 m. The excavation shall be filled with gravel and stones, which shall be carefully compressed to ensure the lateral rigidity of the embedment" [78]. Such simple but practical specification allows to design a foundation without the need for detailed calculations.

Finally, prescriptive measures are especially useful for consideration of durability, e.g. against frost action, and other factors for which direct calculations are not generally appropriate.

4.4. Performance based design. One of the major flaws of the design codes used in most countries is the lack or insufficient consideration of the serviceability criteria and the soil-structure interaction problem of the whole system. Focusing on SLS analysis should often be more important in design as in practice its occurrence often precedes a geotechnical ULS or may potentially be the cause of a structural ULS; thus, guiding the actual design of the foundation. Vardanega & Bolton [29] stated that verification of deformations have not been treated with as much scrutiny as the possibility of collapse. Additionally, they argued against rigid distinction between SLS and ULS failures in LSD framework while applying risk-based concepts. Generally, a strong interdependence exists between ULS and SLS in the case of many geotechnical structures. Although in LSD framework, these states are analyzed separately, physical behaviors affecting SLS may lead to ULS. Even when the behavioral mechanisms, idealized by respective calculation models, are different (e.g. for settlement and bearing capacity of a spread foundation), there is no clear boundary between them in terms of displacements.

Currently, one of the disadvantages of the SLS analysis is the choice of limiting values for specific limit states. Excessive displacements, strains, or vibrations may affect different requirements of the design, defined by standards, investors, and equipment restrictions. In that case, the most unfavorable values guide the design.

While no specific values have been defined by the stakeholders or general provisions provided in the regulations or standards, the choice of limiting value is not always straightforward. Existing standards usually state minimum required safety levels, and they seldom offer guidance on matters of performance. Most standards, including Eurocode 7 [13], offer only arbitrary guidance on selecting specific values. Additionally, the issue of responsibility on specifying such values is in question. Structural engineers expect geotechnical limits (e.g. allowable settlement) to be provided by geotechnical professionals. However, in most cases, the susceptibility of the structure to the foundation deformations is the actual factor guiding the choice of these parameters and serviceability criteria should be decided in cooperation between geotechnical and structural engineers. The problem of limiting criteria has been a subject of many studies over the years [79–83].

Distinction should be made between the verification of SLS, which is governed by limiting values to provide certain reliability in the prediction, and the prediction of most probable value that may be expected to occur during the construction. Contrary to parameters guiding the occurrence of ULS, SLS performance can be measured directly for comparison with predicted values.

The increase in importance of SLS considerations may lead to further development and adoption of Performance-based design (PBD). It is already being considered as a basis for seismic design [84]. The main idea behing this concept is to target specific performance criteria as a way of design optimization.

As an alternative to the complex analysis of the serviceability of the geotechnical structure, often requiring an advanced numerical analysis, a Mobilizable Strength Design (MSD) approach has been proposed [85]-[88] as a link between serviceability and ultimate limit states. For some failure modes, limiting the strength mobilization may safe-guard against occurrence of a SLS.

Finally, an accurate estimation of displacements based on calculations is often difficult, and values measured later are often different. When accurate prediction may not be possible or may not be sufficiently reliable, providing a range of possible values (i.e. based on a parametric analysis) would be beneficial to assess the behavior of the structure in comparison to the design assumptions.

5. Discussion and conclusion

Current geotechnical practice has been strongly influenced by basic rules guiding structural engineering. The main idea behind preparation of Eurocode 7 [13] was to harmonize foundation design rules these guiding structural design, in order to provide a unified framework for civil engineers. This has been accomplished by introducing the concept of reliability through semi-probabilistic application of partial factors of safety and leaving behind the global safety factors used in many countries beforehand. This approach has been based on more rational consideration of uncertainties underlying the geotechnical practice. However, as most European countries based their targeted safety levels on the previous practice, further possibilities may lie in assessment of partial factors tailor-made for specific structures and applications. Another possibility exists in the use of Reliability Based Design, as it allows to directly account for various uncertainties. These approaches, together with reliability discrimination and coordination concepts, may ultimately lead to more rational and optimal design, balancing the safety with economy in more efficient way.

Even though the understanding of the concept of reliability increases among stakeholders, accepting that some probability of failure always will exist, the awareness of underlying uncertainties is still needed. A vast majority of engineers, not specialized in the field of geotechnics, lacking the understanding of underlying soil behavior principles, relate them to known materials, i.e. concrete, steel, etc. This often results in the use of simple, and often not appropriate, correlations and calculation models. Furthermore, results of laboratory and in-situ tests, as well as results of any calculations, often are taken at face value, as their reliability is always affected, to some extent, by: natural variability of the soil, applied testing methods, parameter selection procedure, assumptions concerning a ground model, as well as the choice of calculation method. Additionally, some level of subjectivity may also play an important role.

In relation to the selection of calculation methods, a quote popularized by John Maynard Keynes, from almost a century ago, still rings true that: “it is better to be vaguely right than exactly wrong.” [89]. The same principle applies in geotechnical engineering. Often the use of advanced calculation methods and models offers illusory certainty in the accuracy of prediction that is nothing more than a subjective belief of a designer that may provide a false sense of security. When justified and possible, verification of obtained results should be conducted with the use of simpler and often more robust methods of calculation.

Furthermore, Vardanega & Bolton [29] stated that engineering judgment is essential even for purely technical aspects of the design, to evaluate reasonableness of results, prevents mistakes, detect errors and flaws, etc. It has been argued that codes of practice cannot replace judgment even with the use of exhaustive computations. This philosophy is in line with consideration of engineering judgement already observed in structural engineering [90]. Not only the advancements in design methods, but also well documented histories of failures and performance case studies add value to good engineering practice.

In some of the situations it might not be necessary or possible to conduct detailed design calculations. Then, one of alternative design approaches, which distinguish geotechnical from structural design, can be implemented, namely: the observational method, comparable experience, or prescriptive measures.

It seems that the understanding of technical issues underlying many problems faced by geotechnical engineers is sufficient. Right now, the main problems lie with legal, contractual, social, and psychological factors.

One of the most difficult uncertainties to quantify, but often the source of most geotechnical problems, is associated with the decision process of stakeholders, possibility of human error, or their negligence. It is often a basic assumption of a design code (i.e. Eurocodes [12]) that the design and execution are conducted by sufficiently qualified personnel. In order to safeguard against human error, provisions regarding quality assurance and control, as well as the possibility of verification, are implemented. In a LSD framework, possibility of human error is covered to some extent by implemented partial factors, even though it may not be their intended purpose. They often cannot, however, protect the structure against major errors or combination of unfavorable conditions and gross human negligence. On the other hand, even when over-conservatism in design is repeatedly exhibited and very high, seldom designers and investors look to improve design solutions towards still reliable, yet more cost-efficient ones. Such approach is mostly pursued by geotechnical contractors specializing in some foundation types, in order to improve their competitiveness in construction industry. Especially, since regulations and contractual requirements are inhibiting the use of alternative design procedures, instead of fostering it.

In conclusion, the current state of geotechnical engineering still offers many possibilities for improvement as well as to open new roads for innovation; in that regard, it stands out from others fields of civil engineering practice. However, due to significant uncertainties involved in geotechnical design, some risk factors will always be present and the role of risk management will only increase. Addressing these challenges will require extending the research beyond purely technical matters, as many of the problems stem from regulations, contracting practices, and self-interests of stakeholders. Promoting risk management and resolving the most pressing issue will require engineers to open to wider, more humanistic view on civil engineering.

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