A Factor of Safety for Geotechnical Characterisation

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ABSTRACT: Uncertainties are inherent to geotechnical engineering. In order to design safe structures, safety factors are used in most design codes in different formats. Ideally, these safety factors are calibrated such that they ensure sufficient reliability for a wide range of cases. Whilst these concepts are widely implemented for load and material (resistance) properties, an important source of uncertainty, the characterization of the subsoil, is usually neglected; at least, it is not treated explicitly. This paper aims to provide the theoretical background and reasoning for a factor of safety for geotechnical characterization that has been introduced in the Netherlands in the field of river dike design recently. The factor of safety is based on subsoil scenarios and associated probabilities as well as the conditional probabilities of failure per scenario to achieve sufficient reliability. The method is demonstrated by means of an example. The introduction of the safety factor is expected to lead to more comparable and transparent designs, more awareness about design choices, and incentives to increase the quantity and/or quality of soil investigation.

1. INTRODUCTION

In the recent decades, geotechnical design codes have developed considerably. The geotechnical engineering practice has developed from experience-based decisions to rational design criteria. In many aspects, geotechnical design codes have followed developments in structural engineering (e.g., Load and Resistance Factor Design [LRFD]), probably because the problems are similar: uncertainties in load and resistance, limit-state design, or failure mechanism models based on physics. Besides design approaches, also structural reliability theory (i.e., the probabilistic approach) has developed considerably. For instance, the calibration of partial safety factors in both, geotechnical and structural engineering is based on reliability concepts.

Nevertheless, there are fundamental differences between concrete or steel structures and geotechnical structures. Geotechnical engineering deals with a naturally deposited material in contrast to concrete or steel, which are man-made. Whereas in concrete the main uncertainties are in material properties due to the production process, with ground conditions even the composition or layering is usually not known perfectly. It is common practice that geotechnical engineers or engineering geologists make characterisations of ground conditions as best guesses or cautious estimates based on the available data; and whilst safety factors from design codes take care of the material uncertainties within these chosen scenarios or possible truths, the uncertainty in the characterisation process itself is not covered by any safety concept whatsoever.

This paper shows how the revised design recommendations for river dike design in the Netherlands [1] deal with this issue by introducing a safety factor for geotechnical characterization. After explaining the theoretical basis of the concept, which is consistent with safety factors for material properties, the design procedure is explained, followed by a simple example.

2. GEOTECHNICAL CHARACTERISATION

The three main steps in geotechnical characterisation are (a) characterization of the subsoil layering and geometry, (b) assumptions and modelling regarding pore pressures, and (c) the choice of an adequate computational model and its input parameters. Different designers would definitely make different choices in each of these steps, leading to outcomes somewhere between optimistic and very conservative or pessimistic. This implies, that the reliability of the resulting designs varies, because optimistic assumptions do not lead to higher safety factors to be applied or vice versa (Fig. 1). The recently introduced safety factor deals with exactly this issue. The fundamental difference with other current design methods is that not only one characterization is chosen in the beginning of the design process, but several ones.

3. SUBSOIL SCENARIOS AND DESIGN RELIABILITY

3.1 Generating Scenarios from the Basic Information

The first step is generating credible scenarios of the subsoil composition and the geohydrological conditions of the site based on the hard data available. Typically, for river dikes in the Netherlands we just have a few CPTs per kilometre and some pore pressure response measurements at the most.

![Figure 1 Steps and Choices in Geotechnical Characterisation](image1)

![Figure 2 Ambiguous Interpretation of CPT results](image2)
A CPT gives reasonably reliable information on the type of soil (sand, clay, peat) along a vertical line, the space in between is a matter of educated guesses. For example, geological anomalies are missed easily, as Figure 2 demonstrates. This is just one example of many aspects in interpretation of subsurface data that are ambiguous. Therefore the first key aspect in this approach is not to discard any reasonably imaginable ground condition scenario that might significantly influence the design.

Thus, generating scenarios in the presented approach means making a complete set of geometry, soil layers or types, geohydrological properties, just like in classical design, only considering several possible truths that comply with the hard data. Of course, for efficiency the scenarios should be significantly different or not too similar in a sense that they would practically lead to the same results.

3.2 Assigning Probabilities to Scenarios

When it comes to working with probabilities, engineers often unnecessarily think that this implies a high degree of accuracy and that a large amount of data is required to perform statistics. However, the essence of the approach is not in the numbers, it is in the working scheme itself. Therefore, scenario probabilities are only important in orders of magnitude. In fact, [1] suggests working with the (upper bounds of) probability categories, when few information is available (see Table 1).

<table>
<thead>
<tr>
<th>Category</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>likely</td>
<td>&gt; 0.5</td>
</tr>
<tr>
<td>reasonably possible</td>
<td>0.5 - 0.1</td>
</tr>
<tr>
<td>unlikely</td>
<td>0.1 - 0.01</td>
</tr>
<tr>
<td>very unlikely</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>virtually impossible</td>
<td>&lt; 0.001</td>
</tr>
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</table>

Often, (engineering) geologists with local experience can assist in estimating the likelihood of a scenario. In the rare case that sufficient hard data is available, geostatistical or probabilistic approaches are preferable to assess the scenario probabilities directly.

3.3 Determining Probabilities of Failure

The reliability of a design is determined by the scenario probabilities and the probabilities of failure (non-satisfactory performance) conditional on the scenarios:

\[ P_f = \sum_{i=1}^{N} P(Z(X) < 0|S_i) \cdot P(S_i) \]  

(1)

where \( S_i \) is the \( i \)th scenario, \( X \) is the vector of random variables and \( Z() \) is the performance function of the failure mechanism of interest (i.e., \( Z(X) < 0 \) implies failure). The determination of scenario probabilities \( (P(S_i)) \) has been treated in the previous section. The conditional probabilities of failure \( (P(Z(X) < 0|S_i)) \) can be determined with standard structural reliability techniques, for a recent overview is referred to [2].

From equation 1 we can also define significant scenarios as the ones that have a significant contribution \( (P(Z(X) < 0|S_i) \cdot P(S_i)) \), to the total reliability (i.e., the same order of magnitude).

For use in design practice, a relation between the conditional probability of failure can be used. An analysis of a range of typical cases and failure mechanisms in river dike design [3] showed that using the following relation, the probability of failure is approximated reasonably well based on a safety factor (in this case of slope failure, based on mean values of the soil parameters):

\[ P_f = \Phi (-12 \cdot (1 - 0.95/F)) = f(F) \]  

(2)

3.4 Design Requirement

The general requirement for a structural design is that it complies with the desired target reliability (i.e., maximum admissible probability of failure \( P_{f,adm} \)). In design codes, this basic requirement is usually expressed in terms of derived criteria which are more suitable for design practice, but at the same time ensure meeting the reliability target for a wide range of structures.

For the design method presented in this paper, including a safety factor for geotechnical characterisation, the high level requirement is expressed as:

\[ P_f(D, S_i) \left( 1 - \sum_{j=2}^{N} P(S_j) \right) \leq P_{f,adm} - \sum_{j=2}^{N} P_f(D, S_j) P(S_j) \]  

(3)

where \( P_f(D, S_i) \) is the conditional probability of failure, given the chosen design \( (D) \) and given scenario \( S_i \). The requirement says that the contribution of the base scenario \( S_i \), the scenario chosen as basis for design, to the total probability of failure may not exceed \( P_{f,adm} \) minus the contributions of all unfavourable scenarios \( S_j \) \( (j=2...N) \). The left hand side of Eq. (3) represents an upper bound of the contribution of \( S_i \) in the sense that the scenario probability is taken as one minus the sum of the probabilities of the unfavourable scenarios. The advantage of this approach is of practical nature; since only the probabilities of the unfavourable scenarios have to be estimated. For a detailed derivation of the criterion it is referred to [3].

4. WORKING WITH THE SAFETY FACTOR

4.1 General Procedure

The previous sections presented all the ingredients necessary for designing with a factor of safety for geotechnical characterisation. This section presents the way these ingredients are used in the work method proposed in [1]. The steps are the following:

1. Establish the subsoil scenarios based on the available information (see 3.1) and assign the respective probabilities \( P(S_i) \) (see 3.2).
2. Choose a base scenario \( S_i \), the base scenario is usually a "cautious" choice, just like in real design, often in the category "reasonable possible" or even "unlikely".
3. Choose a safety factor for geotechnical characterisation \( \gamma_c \).
4. Make a design for the base scenario (requirement: \( F_D < \gamma_{adm} \gamma_c \)).
5. Identify and list all unfavourable scenarios \( S_j (j=2...N) \) (resulting in less safety than the base scenario, thus requiring a heavier design).
6. Determine the maximum contribution to the probability of failure of the base scenario:

\[ P_f(D, S_i) \left( 1 - \sum_{j=2}^{N} P(S_j) \right) \]
7. Determine the contribution of the probability of failure of the unfavourable scenarios: 
\[ \sum_{j=2}^N P_f(D_j, S_j) P(S_j) \]
8. Check the design requirement (equation (4)). If the requirement is not satisfied or the safety is too high (room for optimization), repeat steps 4 to 8 with an adapted \( \gamma_c \).
9. If even with a high value of the factor of safety for geotechnical characterization the safety requirement cannot be fulfilled, choose a less favourable base scenario.

The working scheme as described above (see also Figure 4) can be adopted in various ways with different levels of analysis complexity, as will be explained in the following sections.

![Diagram](image)

Figure 4 Working scheme for design using a safety factor for geotechnical characterization (\( \gamma_c \))

4.2 Using Fully Probabilistic Calculations

Using fully probabilistic analyses per scenario (see 3.3), the design can be optimized using a target reliability for the base scenario instead of a safety factor for geotechnical characterization (\( \gamma_c \)). Subsequently, the conditional probabilities of failure per unfavourable scenario are determined and the design check (Eq. (3)) is carried out.

4.3 Using Reliability Approximations Based on Safety Factors

For implementation in design codes, if available, approximate relations between safety factors and probabilities of failure can be used such as in Eq. (2). The imperfection of the approximation should be taken into account as model uncertainty in the derivation of the design code requirements. If such relations are given to the designer, the procedure as described in 4.1 is directly applicable. Only the probabilities of failure, given the design and the subsoil scenario (steps 7, 8) have to be obtained using these approximations.

4.4 Using Derived Requirements

The other option for implementation in design codes is formulating the design requirements in terms of required safety factors, both, for the reliability given a scenario (\( \gamma_{radm} \)) and for the geotechnical characterization (\( \gamma_c \)). This was the method chosen for the guidelines for river dike design in the Netherlands [1].

The basic idea for working with safety factors is to set minimum admissible safety factors depending on the category of scenario likelihood (Table 1). The design requirement for the base scenario is that the factor of safety must exceed \( F_D(S_i) = \gamma_{adm} \gamma_c \) (\( \gamma_c \) may range from 1.1 to 1.3). The additional requirements in [1] are:

1. If the safety factor for characterization for the base scenario is chosen as \( \gamma_c = 1.3 \), no further justification or analysis of unfavourable scenarios is required. (A responsible choice of the base scenario is a prerequisite in all design activities regardless of the design procedure.)
2. For \( \gamma_c < 1.3 \), unfavourable scenarios have to be listed and categorized according to the classification as in Table 1.
3. Any unfavourable scenario leading to a safety factor of \( F_D(S_i) < 1.1 \cdot \gamma_{adm} \cdot \gamma_c \) must be at the most very unlikely (probability < 0.01) and any unfavourable scenario with \( F_D(S_i) < 1.0 \cdot \gamma_{adm} \cdot \gamma_c \) must be virtually impossible (probability < 0.001).

The calibration and justification of the chosen values in the rules above was based on relationships between factors of safety and probabilities of failure for slope stability as in Eq. (2) for typical Dutch river dike designs. Discussion of those relationships is beyond the scope of this paper, for details it is referred to [3].

5. SIMPLE EXAMPLE

The design approach is illustrated by means of a short slope stability problem concerning a fictitious river dike.

5.1 Description

![Diagram](image)

Figure 5 Example: River Dike

We contemplate two possible scenarios for the subsoil conditions:

- \( S_1 \): The sand layer under the dike body is not in hydrological contact with the river. For this scenario and the currently existing dike, a safety factor of \( F_D(S_1) = 1.36 \) has been calculated. This is the base scenario.
- \( S_2 \): The sand layer under the dike body is in hydrological contact with the river. Therefore the pore pressure directly under the clay constituting the dike is high, causing considerably lower safety with \( F_D(S_2) = 1.15 \). This scenario is classified as unlikely, therefore a probability of \( P(S_2) = 0.1 \) is assigned to it.

5.2 Current Level of Safety

The required (i.e., unconditional) safety factor is assumed to be \( \gamma_{adm} = 1.28 \), which corresponds with a target reliability of \( P_{adm} = 10^{-3} \). Using the simple rules according to 4.4, the situation would be unacceptable, because, given \( P(S_2) = 0.1 \) (unlikely), the safety factor should at least be \( 1.1 \cdot 1.28 = 1.41 \);
alternatively, the probability of \( S_2 \) would have to be virtually impossible (<0.001).

Therefore, this dike must be strengthened. We will use the presented design approach to determine the degree of strengthening that is required.

5.3 Design Level of Safety

We assume the dike geometry can be adjusted to fulfill any requirement in terms of factor of safety for the base scenario. Furthermore, we assume in first instance that changing the design would keep the difference between the factors of safety
\[
\Delta F = F_D(S_1) - F_D(S_2) = 0.2 \text{ constant for sake of workability (this will have to be checked in the end)}.
\]

First, we consider the design approach using derived requirements, as described in 4.4. Due to the (only) unlikely unfavourable scenario, we would have to present a design with a required design factor of safety of
\[
F_D(S_2) > 1.1 \cdot 1.28 = 1.41, \text{ and for the first scenario of } F_D(S_1) > F_D(S_2) + \Delta F = 1.61,
\]
both based on mean values of soil properties. Thus, in this case, we end up with a scrutinization factor of \( \gamma_c = 1.61/1.28 = 1.26 \). After designing on either of the two scenarios it must be checked, if the assumption of a constant difference \( \Delta F \) was justified, in this case by analysing the design for the other scenario too.

Using the design approach with approximate relations between factors of safety and the probability of failure (4.3), one can design directly on the target reliability \( (P_{r,adm} = 10^{-2}) \). Assuming a constant \( \Delta F \), a combination of \( F_D(S_1) = 1.38 \) and \( F_D(S_2) = 1.18 \) would be sufficient. Again, this assumption is to be checked and, if necessary the design has to be adjusted. For this specific case, the simplified (derived) rules show to be rather conservative.

Notice that an alternative option would be to investigate, if scenario \( S_2 \) is indeed realistic. One possibility would be to monitor the pore pressure response in the sand layer in order to verify the geohydrological contact between the sand layer and the river. That way this scenario might be discarded, at least its probability can be amended. The cost effectiveness of such a measure can be assessed by means of pre-posterior and cost-benefit analysis. This is clearly an advantage of the presented approach compared to current practice. The type and extent of soil investigation can be optimized and justified explicitly. There is an incentive to use soil investigation optimally.

6. CONCLUSION

The aim of the paper was to show that uncertainties in geotechnical design regarding the composition of the subsoil other than uncertainties in the geotechnical properties themselves can be treated explicitly. Working with scenarios and assigning probabilities to these is a workable option. The safety format can range from fully probabilistic to semi-probabilistic depending on the type of problem and the capabilities of the engineers assessing it. For the semi-probabilistic safety format, which is more suitable for design practice, a safety factor for geotechnical characterisation has been defined. The value of such a factor depends on the degree of certainty with which unfavourable ground conditions can be disregarded. The proposed working scheme provides the possibility of an easy way out by using a high factor for situations in which this can easily be achieved, and it provides the option to determine the value of the factor iteratively for cases where optimization is desirable.

Such an approach is consistent with the way material or resistance factors are determined and used in LRFD concepts. Since the proposed iterative working scheme requires executing more design calculations than classical approaches, in practice it will only be applicable to relatively simple design problems, such as the design of a berm for a dike as exemplified in this paper. Nevertheless, the authors are convinced that the application of the approach closes a considerable gap regarding the, up to now non-existent, explicit and consistent treatment of uncertainties implied with choices made by geotechnical designers in the characterization of the ground conditions.

The approach has been introduced in design guidelines for river dikes in the Netherlands. The first tests cases and applications in practice have shown that the approach is workable. The proposed working scheme is expected to lead to more comparable and transparent designs, more awareness about design choices, and incentives to increase the quantity and/or quality of soil investigation. Choices have to be made explicitly; thus, they can be discussed and examined (e.g., second opinions) more easily.

Finally, a word of caution: In this paper, examples of relations between factors of safety for slope failure based on mean values of soil properties and probabilities of failure were given. They only apply to very limited application areas of very similar problems and with similar dominant factors, in this case typical Dutch river dikes in the characteristic Dutch ground conditions. They are not suitable for general application.

7. REFERENCES

