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WHY FAILURES IN GEOTECHNICS ARE LESS FREQUENT THAN PREDICTED?

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Abstract: One of the most important unresolved problems in geotechnical risk assessment is that "Why are failures less frequent than our reliability studies predict?" In order to answer this question the safety requirements of Eurocode 7 have been investigated. It has been concluded that the safety of soil mechanics parameters, defined by probability requirements, does not included in the calculated Overall Factor of Safety, which represents the overall reliability of a geotechnical design. Method, how to convert the probability requirements to factor of safety is proposed. Incorporating the probabilistic safety of soil mechanics parameters into the Overall Factor of Safety results in a reliable estimation for the failure of geotechnical structures.

Keywords: *Factor of safety, Overall Factor of Safety, EUROCODE 7, probabilistic safety requirements*

1. INTRODUCTION

John T. Christian and Gregory B. Baecher (2011) list the ten most important unresolved problems in geotechnical risk and reliability. The number one question in this list is "Why are failures less frequent than our reliability studies predict?". In order to answer this question the safety requirements of Eurocode 7 (EC7) are investigated.

The EC7 employs the limit state design criteria (Harris and Bond, 2012). The limit states are defined as "state beyond which the structure no longer fulfills the relevant design criteria". There are two limit states in EC7, the Ultimate Limit State (ULS) and Serviceability Limit State (SLS). The Ultimate Limit State is associated with the collapse or with other similar form of structural failure, like the failing of a foundation due to insufficient bearing resistance. The Serviceability Limit State corresponds to specific service requirements of the structure, which must be satisfied. One example could be - limiting the excessive non-uniform settlement. The aim of the design is to make sure these limit states are not exceeded (Gulvanessian et al., 2002). The safety of a geotechnical design is described by the Overall Factor of Safety (OFS), which is defined as the ratio of the characteristic values of the resistance and the actions (Frank et al. 2013). In geotechnics, the uncertainties affecting the structures arouse from the soil layering, soil properties, actions, and resistances. In order to avoid both ULS and SLS failing, the allowed uncertainties in geotechnical designs are regulated. The uncertainties of the deferent contributing factors are limited by imposing factor of safety, probabilistic, or risk analysis requirements. These methods are summarized.

2. METHODS ENSURING SAFETY REQUIREMENTS

2.1. Factor of safety

This is the classical engineering method used for estimating the chance of failing. The method modifies the expected value relating to collapse by adding/deducting a constant or by multiplying/dividing with a factor.

Constant value for safety is used when the uncertainty is independent from the value of the risk component. An example could be the design value of Ground Water Level (GWL_d). The uncertainty in the estimation of the GWL is independent of its elevation. Thus the safety (F_s) is a constant and added to the characteristic value, when the design value is calculated.

$$GWL_d = GWL_c + F_s \tag{1}$$

If the uncertainty is proportional to the size of the investigated risk component, then the factor of safety is a multiplier of the base or the characteristic value. An example might be the relationship between the load and deformation or settlement (Atkinson, 2007). The load relating to collapse (q_c) gives the Ultimate Limit State with and excessive settlement. This can be avoided through the introduction of the factor of safety (f_s), which reduces the load to an allowable or safe load (q_s) (Fig. 1.) as:

$$q_s = \frac{1}{f_s} q_c \tag{2}$$

The factor of safety can be taken into consideration by using a lump value, which combines all the contributions of uncertainties, or through the introduction of partial factors representing the different sources of the uncertainties separately. The EC7 divides the uncertainties and uses partial factors to take into consideration the safety of the actions and the resistances.

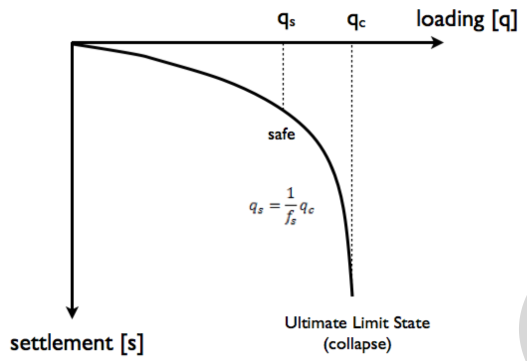

Figure 1

The essentials of Ultimate Limit State and the factor of safety are shown, where q_c is the load relating to failure or collapse and q_s is the safe load allowed by the standard. The factor of safety is $f_s = q_c/q_s$.

2.2. Probabilistic method

Probabilistic method requires that failure should not occur more often than a giving probability. For soil parameters EC7 requires 95 % confidence level for geotechnical designs. Thus 5 percent of the given parameters can have lower or higher value, which ever is safer, than the characteristic value of the parameter used for the design (Fig. 2).

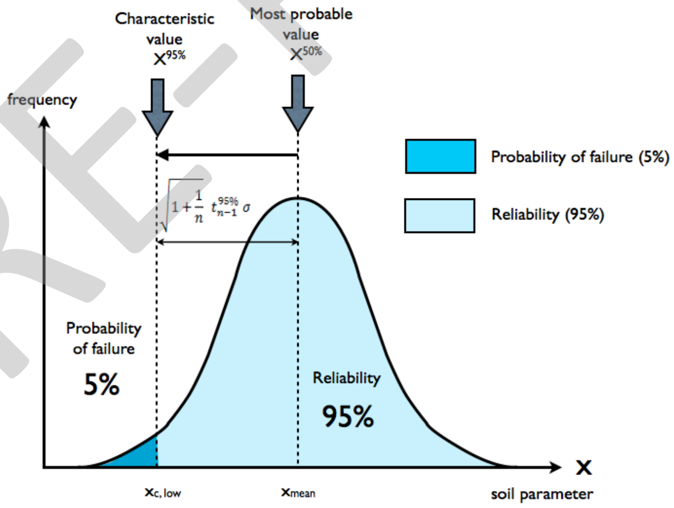

Figure 2

Probabilistic approach defines the characteristic values of soil parameters. The safety is introduced by reducing the most probable value of the parameter, $X_{mean} = X^{50\%}$, to the characteristic value of the parameter relating to 95% confidence level

In most of the cases it can be assumed that the probability distribution is normal and that student or t distribution can describe the convergence to this distribution. The calculation of the characteristic value then requires 2 statistical parameters, the arithmetic mean, and the standard deviation, which sometimes called variance, or the coefficient of variation (Schneider & Schneider, 2013). The characteristic value of a soil parameter (X_c) can be calculated then as:

$$X_c = X_{mean} \pm \sqrt{1+\frac{1}{n}}\, t_{n-1}^{95\%} \sigma \tag{3}$$

or

$$X_c = X_{mean}\left(1 \pm \sqrt{1+\frac{1}{n}}\, t_{n-1}^{95\%}\, c_v\right) \tag{4}$$

where n is the number of data, and X_{mean} is the value of the mean, which can be calculated as:

$$X_{mean} = \frac{\sum_{i=1}^{n} X_i}{n} \tag{5}$$

σ is the standard deviation, calculated as:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(X_i - X_{mean})^2}{n-1}} \tag{6}$$

c_v is the coefficient of variance, calculated as:

$$c_v = \frac{\sigma}{X_{mean}} \tag{7}$$

and $t_{n-1}^{95\%}$ is the student distribution parameter for n-1 freedom at 95% confidence level.
The characteristic value of the mean at 95% confidence level can be calculated as:

$$X_{c,mean} = X_{mean} + \sqrt{\frac{1}{n}}\, t_{n-1}^{95\%}\, \sigma \tag{8}$$

Despite the different forms, equations (3) and (4) are identical. The characteristic values for known distributions can be calculated by using the t value of $t_{\infty}^{95\%} = 1.646$.

2.3. Probability risk analysis

The Hazard (H), the Vulnerability (V), and the Element at Risk (E) are estimated. The product of these three factors defines the Risk (R) (Cetina & Uzielli, 2012) as:

$$R = H \times V \times E \tag{9}$$

where H is the probability of particular threat occurring within a particular set of time (P×time^{-1}), where P is the probability of the occurrence of the event. Vulnerability is the degree of loss to an element or a set of elements within the area affected by the hazardous event. It is expressed in the scale of 0 (no loss), and 1 (total loss). E is the value of the caused damage by the disaster; including repair and maintenance cost of the vulnerable assets. It can be expressed in monetary value, life etc. The risk is the probability of an adverse event multiplied with the consequences if the event occurs. The unit of risk is: probability ×value×time^{-1}

3. THE UNCERTAINTIES REGULATED BY EC7

If the design is carried out by calculation method, then the uncertainties in civil engineering are emerging from three sources, actions, materials and resistance. In geotechnical engineering there is an additional source of uncertainty, which arises from the uncertainty of the spatial extent of the soil layering. The EC7 treats these four uncertainties separately and uses different methods in order to ensure the required safety standard/s.

● The uncertainties arising from the actions and the resistant are taken into consideration by the application of standardized partial safety factors.

● The uncertainties of the material represented by the soil parameters in geotechnics. Using probabilistic method, the safety is insured by changing the value of the soil parameter from the most probable value relating to 50% confidence to 95 % confidence level. The value of the parameter at 95% confidence level defined as the characteristic value of the soil parameter. Depending on the design, either the characteristic value of the mean or the weak value can be used (Fig. 3.).

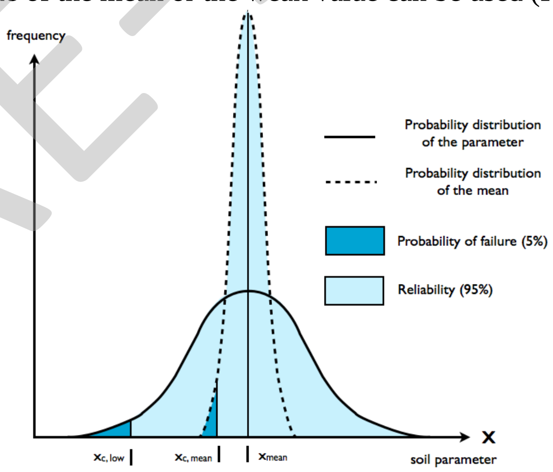

Figure 3

Probability distribution of the soil parameter and the probability distribution of the mean are shown. The characteristic values for the mean and the low or weak values are shown

If the overall stability is investigated, where the resistance can be averaged out, then the characteristic value of the mean should be used (Eq. 8), like calculating the weight from the unit weight or cohesion and internal friction in shaft resistance. On the other hand investigating a local equilibrium, like bearing capacity, where the weak value (Eqs. 3, 4) of the parameters should be used **(**Fig. 4.**)**. The characteristic low values of the soil parameters many times would result in a very conservative (non-economical) design. In such cases it might be advisable and economical to intensify the ground investigations and determine the local mean soil parameters of these locations.

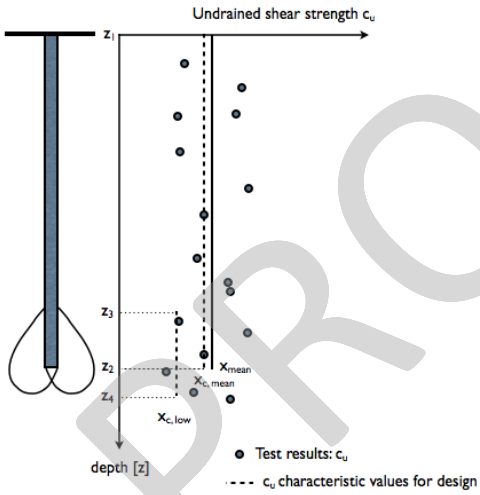

Figure 4

Investigating the overall stability of a structure, where the resistance can be average out, like the shaft resistance of the pile, the characteristic value of the mean should be used. For local equilibrium, where the resistance cannot be averaged out, like the bearing capacity of the pile, the low or weak value of the characteristic parameter should be used. Characteristic values of undrained shear strength for the design of pile shaft (z_1-z_2) and base resistance (z_3-z_4) are shown (Frank et al., 2013)

● The uncertainty in the spatial extent of the soil layering is taken into consideration by employing probability risk analysis. The design works are classified into categories, based on the complexity of the structure, the ground conditions, the loading, and the level of risk that is acceptable for the purposes of the structure. For each category recommendations are given to the required extent of site investigation and to the amount of effort in the checking of the design. The regulation does not quantify the risk but gives recommendation/s for the extent of the exploration, which is proportionate with the accepted level of risk.

● The Overall Factor of Safety (OFS), which represents the overall reliability of a geotechnical structure, is defined as the ratio of the characteristic values of the resistance and the actions. The problem with this representation of the total safety of a geotechnical design is that the calculated OFS does not include the safety of the soil mechanic parameters introduced by probabilistic requirements (Fig. 5).

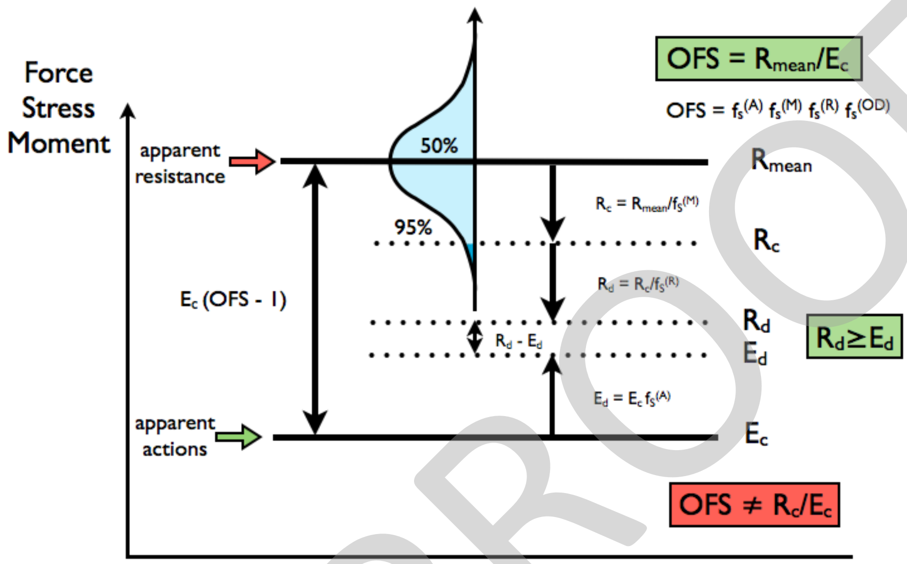

Figure 5

It is shown that the current recommendation of EC7 calculating the OFS as the ratio of R_c and E_c is incorrect. The uncertainty of soil parameters should be incorporated into the overall factor of safety as: $OFS = \frac{R_{mean}}{E_c}$.

The characteristic value of the soil mechanics parameters, which is used to calculate the resistance, represents the 95% confidence levels of the parameters. The increase of the confidence level from 50 to 95 induces safety in the values of the soil mechanics parameters. The current recommendations of EC7 do not incorporate this safety into the OFS. Neglecting the safety built into the soil mechanics parameters makes the geotechnical risk analysis unreliable (Ivandić et al. 2022). In order to incorporate the safety of soil parameters into the OFS, the safety induced by probabilistic requirements must be converted into factor of safety and vice versa (Fig. 5). EC7 does not give recommendations, how the safeties introduced by probabilistic method and factor of safety can be converted into each other.

4. CONVERTING PROBABILITY REQUIREMENTS TO FACTOR OF SAFETY

The safety introduced by changing the value of the soil parameter from 50 to 95 percent confidence level might be described as the ratio of the two confidence levels. Based on EC7 this value would be 1.9 for geotechnical designs. However, this

"probability safety" is not equivalent with the conventional factor of safety used in engineering. Thus the safety calculated by probability method cannot be directly incorporated into the calculation of OFS.
In order to comply with the traditional factor of safety approach, which is used for the actions and resistance, the safety of the soil parameters should be considered as the ratio of the resistances calculated by using the soil parameters at 50% and 95% confidence levels. Thus the partial factor of safety for the soil parameters (f_s^{soil}) should be defined as:

$$f_s^{soil} \equiv \frac{R_{mean}}{R_c} \tag{10}$$

where R_c is the characteristic value of the resistance calculated from the 95% confidence level soil parameters, and R_{mean} is the most probable resistance calculated from the mean value of the soil parameters, which relates to 50% confidence level.

5. OVERALL FACTOR OF SAFETY

Converting the safety, introduced by probabilistic method, to factor of safety allows incorporating this safety, representing the uncertainty of the material or soil parameters, into the OFS. It is suggested that the Overall Factor of Safety should be defined (Fig. 5.) as:

$$OFS \equiv \frac{R_{mean}}{E_c} \tag{11}$$

The partial factor of safeties (f_s) representing the different source of uncertainties, actions (A), soil/material (M), and resistance (R) can also be calculated separately.

- The partial factor of safety for the action ($f_s^{(A)}$) can be calculated as:

$$f_s^{(A)} = \frac{E_d}{E_c} \tag{12}$$

where E_d is the design and E_c is the characteristic values of the effects of all actions. EC7 defines the characteristic value of the actions as:

$$E_c = \sum_{j\geq 1} G_{c,j} + P + Q_{c,1} + \sum_{i>1} \Psi_{0,i} \times Q_{c,i} \tag{13}$$

where $G_{c,j}$ are the permanent actions, P is the prestress, $Q_{c,1}$ is the leading variable action, $Q_{c,i}$ is the accompanying variable actions, and $\Psi_{0,i}$ is the combinations factor of the variable actions.

- The partial factor of safety for the resistance ($f_s^{(R)}$) is:

$$f_s^{(R)} = \frac{R_c}{R_d} \tag{14}$$

where R_c and R_d are the characteristic and the design values of the effects of all resistance respectively. The defined partial factor $f_s^{(R)} \geq \gamma_R$, where γ_R is the partial factor for resistance in EC7

● The partial factor for the material ($f_s^{(M)}$) or soil in geotechnics should be calculated as given in Equation (10) as:

$$f_s^{(M)} = f_s^{soil} = \frac{R_{mean}}{R_c} \tag{15}$$

If $R_d = E_d$, most economical design, then the OFS is the product of the partial safety factors, contributing to the safety of the structure.

$$OFS = f_s^{(A)} \times f_s^{(M)} \times f_s^{(R)} \tag{16}$$

If $R_d > E_d$, then an additional factor of safety ($f_s^{(OD)}$), representing the factor of over design, which is introduced as the ratio of R_d and E_d:

$$f_s^{(OD)} \equiv \frac{R_d}{E_d} \tag{17}$$

The OFS in general case can be defined then as:

$$OFS \equiv f_s^{(A)} \times f_s^{(M)} \times f_s^{(R)} \times f_s^{(OD)} \tag{18}$$

Falling or the collapse or damage of the structure occurs when the value of the Overall Factor of Safety falls below one. Thus it is possible partial factor/s of safety fall below one without resulting in the failing of the structure as long as the OFS > 1 condition is satisfied.

Please note that the safety relating to the uncertainty of the spatial extant of the soil layers has no contribution to the OFS. The uncertainty of the soil layers is taken into account by regulations, which defines the extent and detail of the explorations in accordance to the risk assessment. The safety has been achieved by more detailed exploration and not by making the structure stronger. The safety required for the soil layering is not quantified.

6. CONCLUSIONS

The current version of EC7 defines the allowed uncertainties, emerging from different sources, by recommending different methods for the requirements of safety. No recommendation is given how the required safety of the different methods can be converted into each other. In order to overcome on this problem, a method, transferring the probabilistic safety requirements to factor of safety is proposed. Converting the probabilistic values of soil parameters into a partial factor of safety allows incorporating this uncertainty in the Overall Factor of Safety. Incorporating the probabilistic safety of the soil parameters into OFS increases its value approximately from 2 to 3. Thus, the proposed definition of the Overall Factor of Safety gives a reliable description of the safety of geotechnical designs and explains, "Why failures in geotechnics are less frequent than predicted" when the current recommendations of EC7 are used.

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