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Treatment of uncertainties in site characterization in second-generation Eurocode 7

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ABSTRACT

The purpose of this paper is to introduce the geotechnical engineering community to the treatment of uncertainties in site characterization within the framework of the second-generation Eurocodes. To do so, the main uncertainties related to the Ground Model, the ground properties and the groundwater levels are described before discussion of the statistical and modelling involved. This paper also explains the determination of "representative values" of ground properties within the framework of the Second-Generation Eurocode 7, either selecting the value based on engineering judgment and comparable experience, being in this case termed a "nominal value"; or evaluating the value by statistical methods, being in this case termed a "characteristic value". Additionally, since 2nd-Gen Eurocode 7 allows using reliability-based methods for the verification of limit states, the paper gives some guidance for choosing probability distribution types, and for assessment their parameters like the mean and standard deviation. Finally, two examples are provided to show how to deal with the new elements involved with uncertainty treatment in terms of statistical analysis and probabilistic modelling.

Keywords: uncertainties; Eurocode; statistical analysis; probabilistic modelling; ground properties, ground model.

1. Introduction

1.1. Second-Generation Eurocodes

The Second-Generation Eurocodes will be published during the period 2023 to 2027 and will fully replace the current codes by 2028, when the first-generation Eurocodes will be withdrawn. In the 2nd-Gen Eurocodes, the design of geotechnical structures is spread across four standards: EN 1990 for the *basis* of geotechnical design and three parts of EN 1997 for specific aspects of geotechnical design, as shown in Figure 1.

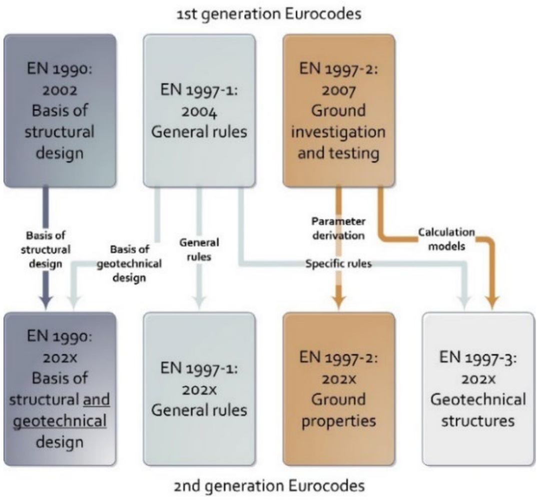


Figure 1. Distribution of contents between First- and Second-generation Eurocodes

The scope of the 2nd-Gen EN 1990 (already published in 2023) has been extended to include geotechnics (as reflected in its revised title *Basis of structural and geotechnical design*), which necessitated generalization of the core principles of EN 1990, particularly with respect to the verification of ultimate limit states and the treatment of uncertainties (Bond et al., 2019).

The 2nd-Gen EN 1997 has been split into three parts, with general principles and rules in *Eurocode 7 – Geotechnical design* – Part 1: *General rules*; provisions for determining ground properties from ground investigation in Part 2: *Ground properties*; and specific rules for design and verification of common geotechnical structures in Part 3: *Geotechnical structures*, such as slopes, cuttings and embankments; spread and piled foundations; retaining, reinforced filled and reinforced ground structures; and ground improvement and groundwater control measures.

1.2. Relevant Guidelines (TG-C) –Objective & Scope

The committee responsible for Eurocode 7 (TC250/SC7) decided in 2020 to establish four "Task Groups" (TGs) to draft four guideline documents to help designers in the understanding, implementation, and use of 2nd-Gen EN1997 in geotechnical designs, three of which with scopes and objectives that are very related to this paper. The titles and objectives of those guidelines, which will be published by the Joint Research Centre of the European Commission (JRC) probably in 2024, are:

- "Determination of representative values from derived values for verification of limit states with

EN1997" (JRC 2024a), whose main objective is to give practical procedures for the designers to determine the representative and design values to be used in limit state verifications, fulfilling the requirement of being a cautious estimate for the limit state considered.
- "Assembling the Ground Model and the derived values" (JRC 2024b), whose main objective is to establish guidelines for assembling a Ground Model for different types of ground (including soil, rock with its discontinuities and groundwater) considering that the aim of the Ground Model is to develop a Geotechnical Design Model.
- "Reliability-based verification of limit states for geotechnical design and assessment" (JRC 2024c), whose main objective is to provide guidance for (full probabilistic) reliability-based verification of limit states for geotechnical structures within the safety concepts of the Eurocodes by giving recommendations for target reliability values and for treatment of the uncertainties of the ground modelling and properties, involved with geotechnical analysis.

1.3. Purpose and outline

The purpose of this paper is to introduce the geotechnical engineering community to the treatment of uncertainties in site characterization as addressed in the guidelines listed above. To do so, the main uncertainties related to the ground model, the ground properties, the groundwater levels are described before discussion of the statistical and modelling involved.

2. Uncertainties in geotechnical design and assessment

The main categories of uncertainties to characterize and handle in geotechnical design and assessment are the following:

1. **Ground Model:** Uncertainties arising from characterizing the ground model based on site investigation and other available information in terms of stratification (layering), geometry of layer boundaries (geotechnical units) and, presence of geological or man-made anomalies.
2. **Ground properties:** Uncertainties in the determination of strength, stiffness and other relevant ground properties arising from spatial variability, measurement error, transformation error (i.e. in "correlation models") and statistical error.
3. **Groundwater:** Uncertainties in groundwater levels and pore water pressures as a result of limit information (e.g. monitoring data).
4. **Models:** Uncertainty in calculation models related to imperfections and idealizations made in applied engineering models for predicting resistances and loads.
5. **Actions:** Uncertainty in actions arising from natural variability (e.g. wind or snow) and limited information (e.g. self-weight).

Below we discuss items 1-3 in more detail since these are related to site characterization.

2.1. Ground Model

The characterization of the Ground Model (i.e. identification of geotechnical units) is essentially a mapping problem involving the following assessments (Baker and Calle 2006):

1. the main pattern of (statistically) homogeneous ground layers, the so-called "geotechnical units"
2. potential presence of smaller ground units or other local phenomena such as discontinuities, and
3. classification of each geotechnical unit (i.e. determination of the type of soil or rock).

If uncertainties in this assessment, such as the boundaries of ground layers or other discontinuities, have significant effect on the performance of geotechnical structure at hand, these uncertainties need to be addressed in the Ground Model, and are to be considered explicitly in a reliability analysis. The accuracy by which a geotechnical unit can be defined, depends on the prior knowledge of the ground conditions, and the extent and quality of the ground investigation. Defining geotechnical units is also affected by the variability in ground properties. The process usually involves considerable engineering judgement. Since the focus of this paper is on ground properties, we refer the reader to JRC (2024b) for details.

2.2. Ground properties

Uncertainties in ground properties derive from the following causes or components:

- **Inherent variability** (natural or intrinsic variability) is the natural randomness of a quantity, such as the natural (spatial) variability of soil strength within a ground layer (or geotechnical unit).
- **Measurement error** is uncertainty caused by imperfect measurement tools and/or sample disturbance effects.
- **Transformation (model) uncertainty** is due to imperfection and simplifications inherent to model formulations (often called "correlations") used to obtain a geotechnical parameter from measurements (e.g. undrained shear strength from CPT through an Nkt factor).
- **Statistical uncertainty** is due to limited information, such as a limited number of observations of a certain quantity (e.g. undrained shear strength). For instance, statistical uncertainty is present when the population mean is estimated using a limited number of samples.

All the above uncertainties are to be accounted for in the determination of characteristic values (as defined in 3.2.3) and in defining probability distributions for random variables used for reliability analysis.

2.3. Groundwater

Groundwater levels, piezometric levels and pore pressures are subject to fluctuations (i.e. time-variability) and potentially measurement errors. In the 2nd-Gen EN 1990-1 and 1997-1, the uncertainty in groundwater actions is treated in terms of probability of exceedance and the corresponding return period, as summarized in Table 1.

Table 1: Specification of water actions according to EN 1990:2023

Variable or accidental water action	Symbol	Probability of exceedance
Characteristic	Q_{wk}	2% per annum (return period 50 years)
Combination	$Q_{w,comb}$	10% per annum (return period 10 years)
Frequent	$Q_{w,freq}$	Fraction of time exceeded = 1%
Quasi-permanent	$Q_{w,qper}$	Fraction of time exceeded = 50%
Accidental	$A_{w,rep}$	0.1% per annum (return period 1000 years)

That means that groundwater actions are amenable to statistical analysis (see e.g. Schweckendiek et al., 2024), whenever appropriate data are available, and, in any case, the treatment of groundwater levels follows the same principles in the degree of conservatism for water actions as is common for other variable actions.

Of course, where little or no appropriate data are available, a judgement-based (nominal) value should be applied.

2.4. Geometrical properties

From a geotechnical point of view, as stated in EN 1997-1/4.3.3 (2), the following items must be regarded as geometrical properties: ground surface, surface water level, groundwater levels, boundaries between geotechnical units and dimensions of geotechnical structures, all of them very related with the development of the Ground Model, previously mentioned.

In this respect, the key role of discontinuities in rock engineering design should be noted. For this specific issue, according to EN 1997-1/4.3.3 (3), "*the geometrical properties of discontinuities in the ground shall include information on location, orientation, spacing, extent, voids or openings, and surface roughness*". Furthermore, geometrical properties of discontinuities within a geotechnical unit may be considered either as properties of discretely defined discontinuities within the unit or as equivalent ground properties of the unit when modelled as a continuum.

On other hand, according to EN 1990-1/8.3.7 (2), "*when the design of the structure is not significantly sensitive to deviations in a geometrical property, the design value of a geometrical parameter a_d may be calculated*" as the nominal value. However, when the design of the structure is sensitive to deviations in a geometrical property, the design value of the geometrical property, a_d should be calculated as the sum of the nominal value (a_{nom}) and the deviation (Δa) in the geometrical property.

It is worth noting that, according to EN 1990-1/6.3.(3), "*when there is sufficient data, the characteristic value of a geometrical property may be determined from its statistical distribution and used instead of a nominal value*". Besides that, according to EN 1997, 4.3.3.(6) "*the nominal value of geometrical properties for ground discontinuities may be determined by sensitivity analysis using a probabilistic approach*".

3. Statistical analysis of ground properties and probabilistic modelling

3.1. Ground property value affecting the limit state

The geotechnical parameter of interest is the ground property value affecting the occurrence of the limit state. Therefore, averaging over an affected volume or a failure surface is typically involved, leading to variance reduction. The degree of averaging is governed by the relationship between the averaging dimensions (i.e. affected volume), and the scale of fluctuation of the ground property.

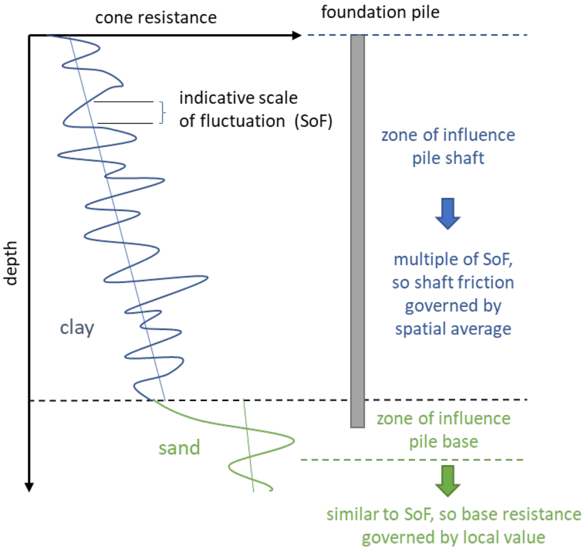


Figure 2. Illustration of spatial averaging depending on the ground volume affected compared to the scale of fluctuation (SoF)

The core of the matter is that when the variability in a ground property as found from site investigations occurs on a very small spatial scale compared to the volume or surface relevant for failure, the designer should be rather interested in the average over that volume or surface, and for design or assessment purposes a cautious estimate thereof. The value of a ground property at a point is only interesting, when the affected volume or surface is small, and roughly of the same order of magnitude as the scale of fluctuation of the ground property of interest. Figure 2 illustrates this point for the example of a foundation pile. Suppose use a pile resistance model based on CPT cone resistance, then for the pile shaft we would certainly be interested in the average (or trend) along the pile shaft, while for the pile base the local value is governing because the affected volume is relatively small.

In many geotechnical problems significant volumes or surfaces are involved with the mechanism of failure or the limit state, for example instability of (large) slopes, global instability of retaining walls or active earth pressures on these, bearing capacity of (large) shallow foundations etc. In some problems, the affected volumes are small, and assuming local values instead of averages is more appropriate, for example most internal erosion problems or bottom heave of an excavation.

The effect of spatial averaging is already dealt with in various approaches to the determination of characteristic values (Länsivaara et al, 2021; Calle et al, 2021), which will be further detailed in the 2nd GEN-EN 1997-1 as well as in the upcoming guideline JRC (2024a) (see section 3.2). Equivalently, probability distributions which are input to reliability-based assessments need to deal with spatial averaging or homogenization (Phoon et al., 2024), as addressed further in section 3.3.

3.2. Determination of representative values

3.2.1. Introduction

In the design process, the determination of representative values of ground properties is performed before the verification of any Limit State, when the designer analyses the derived values presented in the Ground Investigation Report.

There is a set of interrelated concepts relative to different values of the ground properties that are adopted throughout the design process depending on the design stage. These values are: "Measured values", "Derived values, "Nominal value", "Characteristic value", "Representative values" and "Design value". Figure 3 shows the path that a ground property value must travel from when it is obtained during the ground investigation stage to when it is used in a calculation model at the design stage to verify a limit state, either an ultimate limit state (ULS) or serviceability limit state (SLS)

3.2.2. Ground Investigation and "measured and derived values"

The purpose of a ground investigation is to determine the ground properties for design. Part 2 of the 2nd-Gen Eurocode 7 gives the requirements for ground investigation, which involve the following tasks: Desk study, Site inspection, Performance of field and laboratory tests and Geotechnical monitoring. The upper part of Figure 3 shows the different types of values that can be obtained during these tasks, which are: historical values, assessed values, measured values and monitored values. The only value referred to explicitly in the 2nd-Gen Eurocode 7 is the measured value, which is defined as "*the value of a ground property recorded during a test*", while the others appear for the sake of explanation.

The values obtained during the ground investigation (historical values, assessed values, measured values and monitored values) are transformed into derived values, by applying theory, correlation or empiricism, as shown in Figure 3. Derived values are used to establish the Ground Model that, "*shall reference the derived values of ground properties for encountered geotechnical units*". In this respect, a geotechnical unit is "*the volume of ground that is defined as a single material*".

3.2.3. Representative value

The 2nd-Gen EC7 states that "*Representative values of ground properties to be used in ultimate and serviceability limit state verifications shall be determined from derived values presented in the Ground Investigation Report".* Consequently, *"the representative value refers to a particular ground property of a single geotechnical unit*".

From that, the representative value (X_{rep}) can be determined from the set of derived values, as:

- A characteristic value (X_k) when the designer considers that the available data is sufficient to perform a statistical determination of the value of a ground property.
- A nominal value (X_{nom}), when the available data are insufficient to establish the characteristic value of a ground property.

The designer needs to decide whether to determine the representative value as a characteristic or a nominal value, based on their understanding of the sufficiency of the available data, i.e. a) its quantity and quality, b) its spatial distribution, c) the extent of the zone of influence, and d) the need to avail of and take into account pre-existing knowledge in the form of comparable experience. These four aspects need to be considered when determining a representative value as extensively explained JRC (2024a).

While the use of statistics is not extensive in current geotechnical design practice in Europe, it is anticipated that, in the future, as ground investigation methods develop and more data become available, there will be a tendency for an increased use of statistics and of characteristic values. Nationally determined practices may also influence whether the representative value is determined as a characteristic or a nominal value.

On the other hand, according to 4.3.2.1(3), "*The representative value of a ground property shall be determined for each limit state, according to its sensitivity to spatial variability of the ground property in the volume of ground involved*". In 4.3.2.1(4) it is stated that "*If the limit state is insensitive to spatial variability of the ground, the representative value of the ground property shall be determined as an average value*", while in 4.3.2.1(5) it is stated that "*If the limit state is sensitive to spatial variability of the ground, the representative value of the ground property shall be determined as an inferior or superior value*".

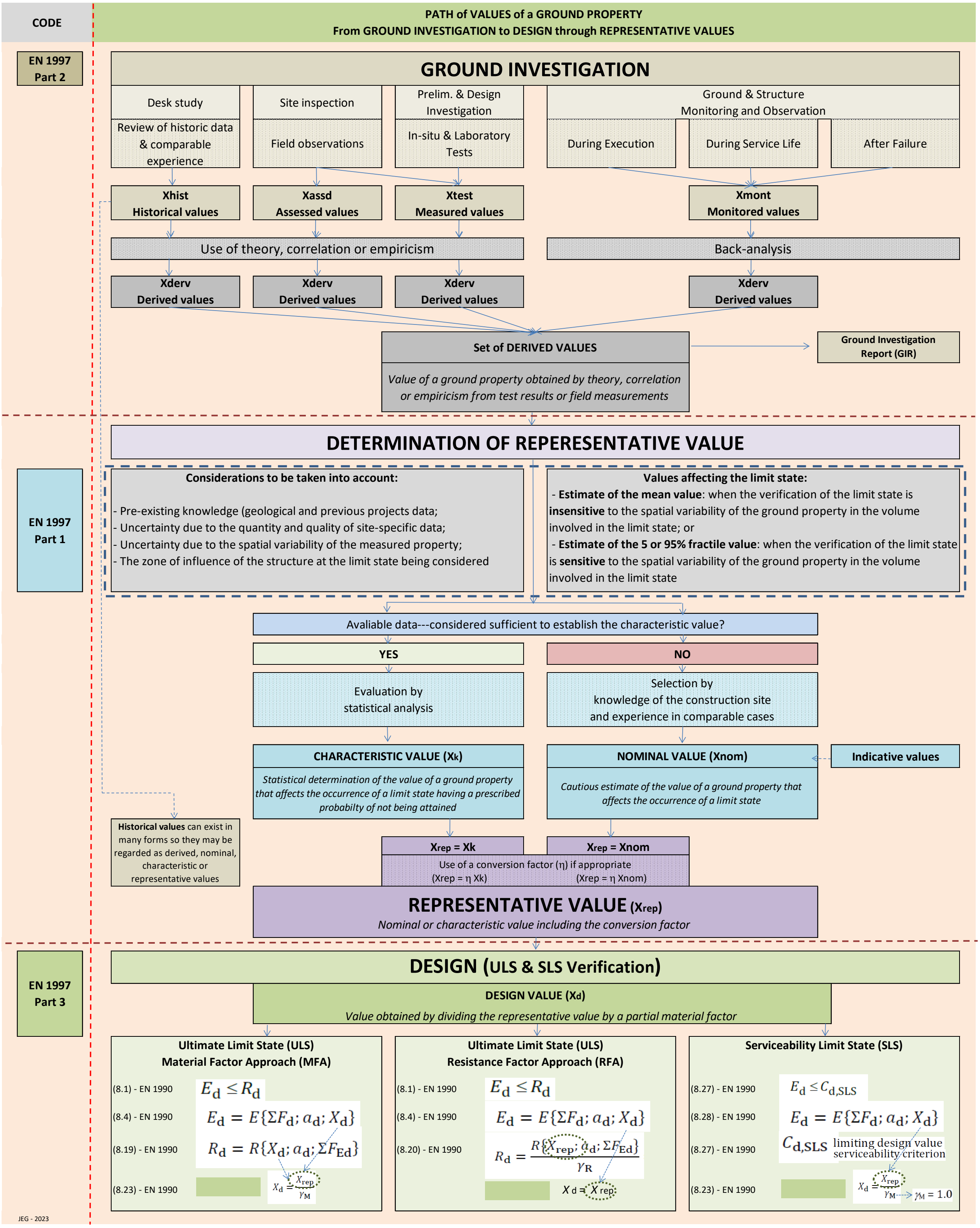
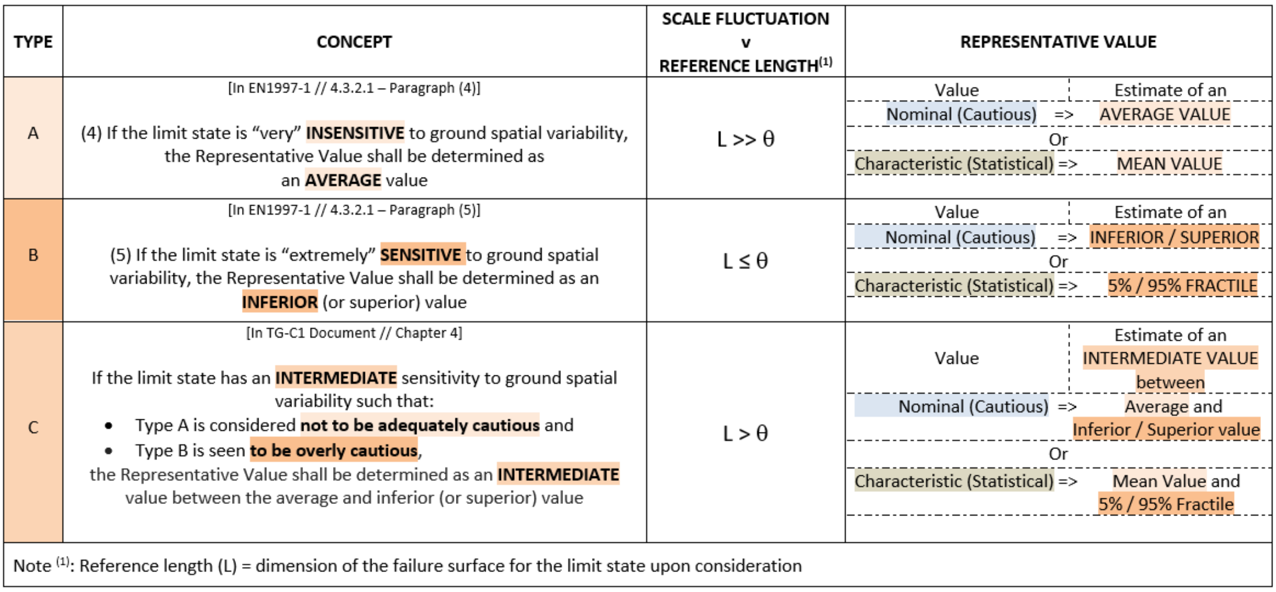


Figure 3. Overview of derived, representative, characteristic and design values in the context of EN1997-1

The significance of the sensitivity of the limit state to the spatial variability of the ground leads to the three "Types of estimates" of the representative value shown in Figure 4. Selecting the appropriate representative value corresponding to Type A, B or C is a function of the designer's understanding of the extent of limit state that mobilises the ground property and the magnitude of the ground spatial variability, represented by the extent of the volume of ground involved in the limit state (L) compared to the magnitude of the scale of fluctuation of the ground property (θ), as addressed before in section 3.1. Note Type C is introduced in the JRC(a) document (JRC, 2024) and is not in EN 1997-1.



TYPE	**CONCEPT**	**SCALE FLUCTUATION v REFERENCE LENGTH$^{(1)}$**	**REPRESENTATIVE VALUE**
A	[In EN1997-1 // 4.3.2.1 – Paragraph (4)] (4) If the limit state is "very" **INSENSITIVE** to ground spatial variability, the Representative Value shall be determined as an **AVERAGE** value	L >> θ	Value ⁞ Estimate of an Nominal (Cautious) => AVERAGE VALUE Or Characteristic (Statistical) => MEAN VALUE
B	[In EN1997-1 // 4.3.2.1 – Paragraph (5)] (5) If the limit state is "extremely" **SENSITIVE** to ground spatial variability, the Representative Value shall be determined as an **INFERIOR** (or superior) value	L ≤ θ	Value ⁞ Estimate of an Nominal (Cautious) => INFERIOR / SUPERIOR Or Characteristic (Statistical) => 5% / 95% FRACTILE
C	[In TG-C1 Document // Chapter 4] If the limit state has an **INTERMEDIATE** sensitivity to ground spatial variability such that: • Type A is considered **not to be adequately cautious** and • Type B is seen **to be overly cautious**, the Representative Value shall be determined as an **INTERMEDIATE** value between the average and inferior (or superior) value	L > θ	Value ⁞ Estimate of an INTERMEDIATE VALUE between Nominal (Cautious) => Average and Inferior / Superior value Or Characteristic (Statistical) => Mean Value and 5% / 95% Fractile
Note $^{(1)}$: Reference length (L) = dimension of the failure surface for the limit state upon consideration			

Figure 4. Types of estimates of the representative values

3.2.4. Characteristic value

The definition of the characteristic value of a ground property given in EN 1997-1/3.1.3.4 is the "*statistical determination of the value of a ground property that affects the occurrence of a limit state having a prescribed probability of not being attained*".

According to EN 1997-1/4.3.2.2(4), the characteristic value should be determined statistically from Formula 1, when a normal distribution is assumed and taking account of the number (n) of derived values:

$$X_k = X_{mean}[1 \mp k_n V_X] \qquad (1)$$

where X_{mean} is the mean value of the ground property X from a number n of derived values; k_n is a coefficient that depends on the number of derived values used to calculate X_{mean}, the level of knowledge regarding V_X, and the type of characteristic value being determined; V_X is the coefficient of variation of the ground property while $\mp$ denotes that $k_n V_X$ should be subtracted or added depending on whether a lower or upper value of X_k is required.

Formulae for k_n for different V_X cases and types of estimates (A, B or C) are given in Figure 5 (inspired by EN1997- 1/Table A.3), while EN1997- 1/Table A.2 gives indicative values of V_X for various ground properties.

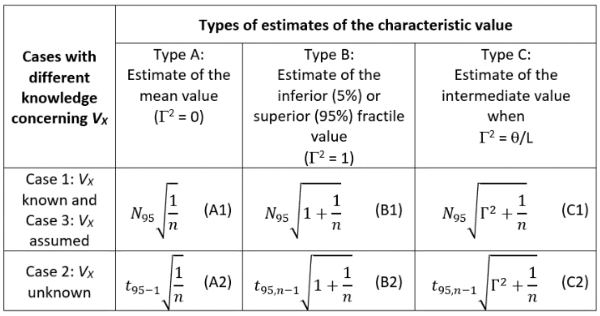
The Type C formulae includes the sensitivity index (Γ^2), defined by Formula 3, that can only take values between 0 and 1:

$$\Gamma^2 = \theta / L \qquad (2)$$

where θ is the scale of fluctuation, i.e., magnitude of the ground property variability, and L is the extent of the volume of ground involved in the limit state.

Indicative values of the horizontal and vertical scales of fluctuation (θ_h and θ_v) can be found in the literature (e.g. Cami et al, 2020). These indicative values show that the θ_h values are much greater than the θ_v values. In addition, examination of these numbers shows that, for normal design situations, θ_v values range mainly from 1 to 1,5 m while θ_h values range from 15 to 50 m.

However, it is necessary to decide on the bounds for Type A and B and when the X_k/X_{mean} values should be considered Type C rather than Type A or B. Some proposal on this issue is given in Figure 6.



Cases with different knowledge concerning V_X	**Types of estimates of the characteristic value**		
	Type A: Estimate of the mean value ($\Gamma^2 = 0$)	Type B: Estimate of the inferior (5%) or superior (95%) fractile value ($\Gamma^2 = 1$)	Type C: Estimate of the intermediate value when $\Gamma^2 = \theta/L$
Case 1: V_X known and Case 3: V_X assumed	$N_{95}\sqrt{\frac{1}{n}}$ (A1)	$N_{95}\sqrt{1+\frac{1}{n}}$ (B1)	$N_{95}\sqrt{\Gamma^2+\frac{1}{n}}$ (C1)
Case 2: V_X unknown	$t_{95-1}\sqrt{\frac{1}{n}}$ (A2)	$t_{95,n-1}\sqrt{1+\frac{1}{n}}$ (B2)	$t_{95,n-1}\sqrt{\Gamma^2+\frac{1}{n}}$ (C2)

Figure 5. Formulae for k_n for different combinations of types of estimates and V_x cases

On other hand, three different cases are identified regarding the knowledge of V_X. According to EN 1997-1/Annex A.4 Case 1 - V_X *known* - "*should be used when the coefficient of variation of the ground property is known from prior knowledge*"; Case 2 - V_X unknown – "*should be applied when the coefficient of variation of the ground property being determined is unknown ab initio*" and Case 3 - V_X assumed – "*should be applied when indicative values are used for ground properties, or for test parameters*".

In addition, EN 1997-1/Annex A provides formulae to determine the characteristic values for lognormally distributed data.

Lastly, the JRC(a) document (JRC, 2024) proposes the following "rule of thumb" on the bounds for the different types of estimate that can be applied to all design situations and types of ground, when there is no further information on the value of the scale of fluctuation:

- Type A bound when L ≥ 25m
- Type B bound when L ≤ 2m
- Type C when 2m > L < 25m

Figure 6 shows these bounds and the corresponding ratio of the characteristic property value to the mean value in percent obtained for the design situation when Vx = 0.3 and "n" = 10. For other values of V_x and n formula of Type C in Figure 5 should be used.

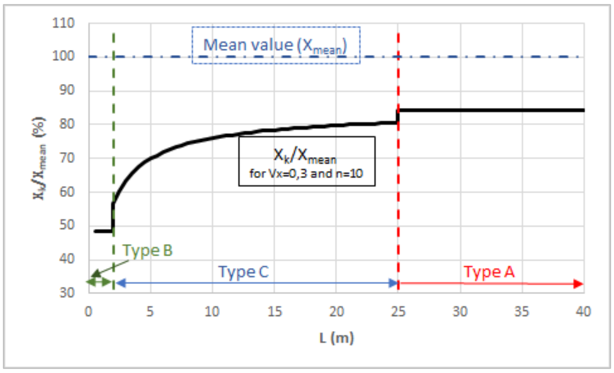


Figure 6. Characteristic values and "rule of thumb" for Type bounds

3.2.5. Nominal value

The nominal value of a ground property (X_{nom}) is defined in EN 1990-1/3.1.2.29 as the "*value fixed on a non-statistical basis; for instance, on acquired experience or on physical conditions*". EN 1997-1/ 4.3.2.3(1) elaborates this by stating that "*the nominal value of a ground property (X_{nom}) shall be selected as a cautious estimate of the (average, inferior or superior) value affecting the occurrence of the limit state (based on the knowledge of the construction site and comparable experience)*".

The nominal value is selected by the designer based on derived values, knowledge of the construction site, consideration of the design situation and limit state, and comparable experience. It is a cautious estimate of the property value chosen to represent the behaviour of the volume of ground involved in the limit state being considered.

The selection of the nominal values also follows the three types of estimates, shown in Figure 4: Type A as a cautious estimate of an average value; Type B as a cautious estimate of an inferior or superior value and Type C as an estimate of an intermediate value between the Type A and B values.

3.3. Probability distributions for reliability-based verification

When using reliability-based methods for the verification of limit states, the uncertainty in ground (and other) properties are captured in probability distributions. To that end, we have several types of probability distributions at our disposal, such as the Normal (Gaussian), Lognormal, Truncated Normal or Triangular distribution, to name a few which are frequently used for ground properties, as shown in Figure 7. JRC (2024c) provides guidance for choosing distribution types, and for assessment the parameters like the mean and standard deviation.

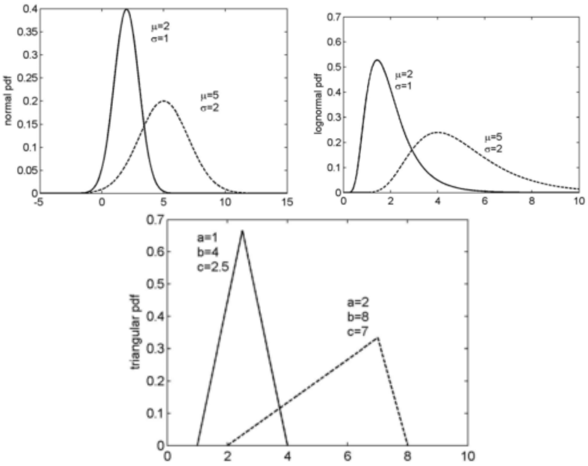


Figure 7. Normal (Gaussian), Lognormal and Triangular distributions

As discussed in section 2.2, there are several sources of uncertainty in the assessment of ground properties. All relevant sources of uncertainty need to be involved in assessing the total uncertainty in a ground property. Of course, not all uncertainties are relevant in all cases; for example, transformation uncertainty is only relevant when transformations (i.e. 'correlations') are used, such as for estimating undrained shear strength based on CPT cone resistance.

Generally speaking, the sources of uncertainty add up to the total uncertainty, as expressed in:

$$V_{X,tot} = \sqrt{V_{X,inh}^2 \Gamma^2 + V_{X,trans}^2 + V_{X,meas}^2 + V_{X,stat}^2}$$

where $V_{X,inh}$, $V_{X,meas}$, $V_{X,trans}$ and $V_{X,stat}$ are coefficients of variation for inherent variability, measurement error, transformation uncertainty, and statistical uncertainty, respectively. Γ^2 is variance reduction factor that accounts for spatial averaging effects, as discussed in section 3.1 and as used also in the equations for characteristic values.

This general equation reduces to specific versions for different situations, depending on whether the data are site-specific or regional, whether the measurements were direct or indirect (through 'correlations'), and other factors (see JRC, 2024c).

Hence, the task in uncertainty characterization for reliability analysis is mostly assessing site- or problem specific mean values and coefficients of variation, besides choosing an appropriate type of distribution. For some properties of interest, sufficient data will be available for a rigorous statistical analysis, but in geotechnical engineering more often than not we rely on combining site-specific data with experience and judgement or recommended values from standards, guidelines or literature. JRC (2024c) provides guidance on how to approach this task, recommended values and pointers to the relevant literature.

Example 4.2 provides an illustration of how to determine a probability distribution of undrained shear strength from shear vane data.

4. Examples

4.1. Determination of representative values for an overall stability ULS of a natural slope

4.1.1. Description of the geotechnical structure

This example from the upcoming JRC (2024a) illustrates the determination of representative values of a ground property of a geotechnical unit is developed. The geotechnical structure under analysis is a natural slope for which the overall stability ULS for a persistent design situation must be verified. For this purpose, it is necessary to perform some calculation of slope stability, so the strength characteristics of the geotechnical units must be determined.

Figure 8 shows the Ground Model of the slope that showed signs of instability. The red line represents the ground surface prior to the last landslide whose origin is the scour of the footing due to the circulating water in the river. From top to bottom, the following geotechnical units are distinguished: Unit 1- sands with gravels (in yellow); Unit 2- clayey marls (in brown with stripes) and Unit 3- silty clayey sands (in red). For this example, only the characteristic and representative values of Unit 3 will be determined.

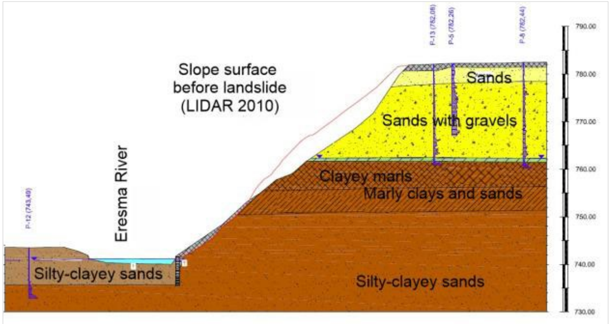


Figure 8. Ground Model of the natural slope

4.1.2. Determination of representative values of strength properties

To determine the strength characteristics of Unit 3 formed by silty-clayey sands, six direct shear tests were performed, whose horizontal displacement-shear stress curves can be considered as the "measured values". The normal stresses used in these tests ranged from 120 to 960 kPa while the shear strengths obtained ranged from 100 to 550 kPa. The interpretation of the "measured values" obtained in the six direct shear tests (shown in Figure 9), using the Mohr-Coulomb model, allowed obtaining the derived values for effective cohesion (c´) and friction angle (φ´), considered as independent properties, as collected in Figure 10.

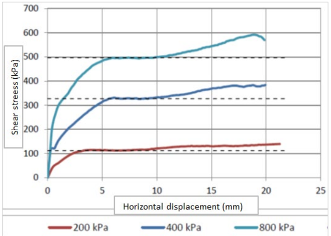


Figure 9. One example of "measured values"

Measured values (kPa)		Derived values		
Normal stress	Shear strength	c´ (kPa)	Tan φ´	φ´(°)
200 400 800	112 327 496	27	0,61	32,40
200 400 800	139 346 535	45	0,63	32,36
226 480 960	140 294 492	47	0,47	25,21
214 430 860	162 287 520	46	0,55	28,95
204 404 837	115 199 432	4,5	0,51	26,86
121 242 363	83 119 212	9,5	0,53	27,98

Figure 10. Table with the "derived values"

According to the ULS under verification, the representative values must correspond to the mean value of the material property in the volume affected by the limit state, so the calculations must be made using Type A "Estimate of the mean value ", defined in Figure 5, with the two alternatives referring to Case 3 "Vx Assumed" and Case 2 "Vx Unknown".

Table 2 and Figure 11 show the values of the statistical parameters used in the calculations and the characteristic values obtained. Between the two representative values obtained for Cases A2 and A3, the designer must choose which one to use in the calculations, although such choice is beyond the scope of this article.

Table 2: Statistical values for the determination of characteristic values of effective cohesion and friction angle

Parameter	Effective cohesion (kPa)		Effective friction angle (°)[1]	
Number of data (n)	6		6	
X_{mean}	29,81		28,79	
Standard Deviation	19,20		2,71	
Case	*Case A3 Vx,assumed*[2]	*Case A2 Vx,unknown*	*Case A3 Vx,assumed*[2]	*Case A2 Vx,unknown*
N_{95} - $t_{95,\, \mathrm{n-1}}$	1,645	2,02	1,645	2,02
Vx	0,40	0,64	0,10	0,09
k_n	0,67	0,82	0,67	0,82
X_k	21,82	14,01	26,86	26,56

Note (1): Determination done in terms of coefficient of friction angle (tan φ´)

Note (2): Values of Vx,assumed taken from Table A1 in EN1997-1, Annex A

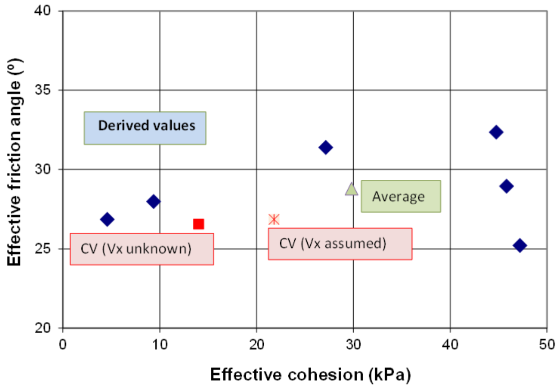


Figure 11. Derived and characteristic values

4.2. Determination of a probability distribution of undrained shear strength from shear vane data

This example from the upcoming JRC (2024c) illustrates how we can assess the probability distribution of undrained shear strength for a fictitious geotechnical design problem from a data set of shear vane tests.

4.2.1. Shear vane data

Consider a soft clay layer (depth z = 0.78-4.32 m) with n = 22 measurements combined from three field vane shear strength $s_{u,FV}$ profiles (data from Lehtonen et al. 2015). The soft clay layer was identified by means of both $s_{u,FV}$ and classification tests. The 22 observations (shown in Figure 12) are assumed independent (uncorrelated).

z[m]	$s_{u,FV}$ [kPa]	z[m]	$s_{u,FV}$ [kPa]
0,78	9,3	2,78	11,3
1,19	12,2	2,82	12,8
1,28	10,2	3,19	10,7
1,32	13,6	3,28	11,6
1,69	9,3	3,32	14,8
1,78	11,3	3,69	12,8
1,82	12,5	3,78	9,9
2,19	9,9	3,82	15,4
2,28	6,4	4,19	11,3
2,32	16	4,28	11,6
2,69	10,4	4,32	16,8

Figure 12. Field vane shear strength observations

4.2.2. Assessment of observed variability

As a first step, we assess the observed variability in the data (a) assuming a constant mean value, and (b) assuming a linear depth-trend.

Option (a) mean $s_{u,FV}$ constant with depth

The sample mean is m_x = 11.8 kPa. The sample standard deviation is:

$$s_x = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - m_x)^2} = 2.45 \text{ kPa}$$

The resulting coefficient of variation is $V_{x,obs} = 0.207$.

Option (b) mean $s_{u,FV}$ as linear trend with depth

The mean can be obtained using linear regression as:

$$\hat{t} = t(z) = a_0 + a_1 z = 9.41 + 0.78z$$

The de-trended standard deviation becomes:

$$s_{x,detrended} = \sqrt{\tfrac{1}{n-2}\textstyle\sum_{i=1}^{n}(x_i - \hat{t_i})^2} = 2.35\ kPa$$

The corresponding $V_{x,obs}$, calculated using the trend value $\hat{t}$ at the middle of the soft clay layer (11.7 kPa), is $V_{x,obs} = 0.201$.

In principle, we would opt for the model with lower coefficient of variation, because it explains the variability better. However, in this example, the mean can be assumed constant with depth for simplicity, as the difference in the results is very small (see Figure 13).

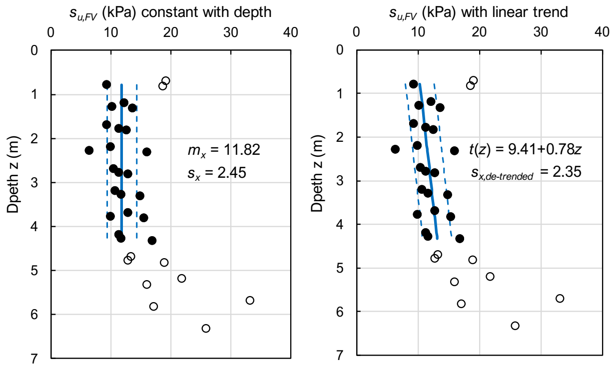


Figure 13. Estimates of mean and standard deviation for field vane shear strength for soft clay.

4.2.3. Assessment of total uncertainty

In this example, we assume the measurement error to be small compared to the inherent variability of the undrained shear strength. Therefore, we equate the inherent variability with the observed variability, i.e. $V_{X,inh} = V_{X,obs} = 0.207$.

When s_u is estimated from $s_{u,FV}$ measurements, a correction factor is needed to consider strain-rate and anisotropy effects. The transformation uncertainty related to field vane testing of soft clays is estimated to be in the range of $V_{X,trans}$ = 0.075–0.15 (Phoon and Kulhawy 1999b). A mid-range value is chosen to account for the transformation uncertainty, i.e. $V_{X,trans} = 0.11$.

The variance reduction factor Γ^2 is estimated assuming that the averaging length is the thickness of the soft clay layer, L = 3.54 m. For the vertical scale of fluctuation, δ_v = 1 m is chosen based on the upper bound of the likely value range of clays. Vanmarcke's approximation gives $\Gamma^2 = \delta_v / L \approx 0.282$.

Three field vane test profiles were used to calculate the average field vane shear strength, and hence, we have three independent observations (n = 3).

The total uncertainty of the spatial average s_u can then be evaluated from (see Eq. 5-21 in JRC (2024c)):

$$V_{X,tot}^2 = V_{X,inh}^2\left(\Gamma^2 + \frac{1}{n}\right) + V_{X,trans}^2$$
$$= 0.207^2\left(0.282 + \tfrac{1}{3}\right) + 0.11^2 = 0.196$$

Now that the total uncertainty has been assessed, the probability density function can be constructed, as shown in Figure 13. A lognormal distribution is assumed, which is a common assumption for undrained shear strength to acknowledge non-negativity. The (arithmetic) mean is the average $s_{u,FV}$ (11.8 kPa) multiplied by the corresponding correction factor: μ_{su} = 0.94×11.8 kPa =11.11 kPa. The standard deviation corresponding to the total uncertainty is given by: $\sigma_{su} = \mu_{su} \times V_{X,tot}$ = 11.11 kPa ×0.196=2.18 kPa

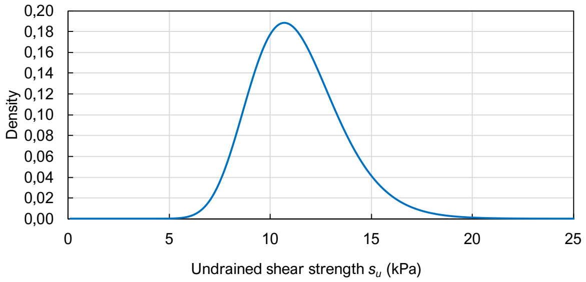


Figure 14. PDF of undrained shear strength

5. Conclusions

Geotechnical engineering deals with large uncertainties as a consequence of spatial and natural variability, and more importantly of limited information (e.g. from site investigation). Consequently, the Second-Generation Eurocodes will contain more elements of explicit treatment of uncertainties compared to the first generation. The 2^{nd}-Gen EN 1997 will also allow for reliability-based methods for the verification of limit states, which requires probabilistic modelling of uncertain quantities.

In this paper, we have given an overview of the elements involved with uncertainty treatment in terms of statistical analysis and probabilistic modelling, focusing on ground properties. More detailed information and instructions can be found in the soon to be published guidelines accompanying the Second-Generation Eurocodes (see 1.2). We expect that these new or extended elements will improve geotechnical engineering practice by providing a more systematic approach and a consistent basis for uncertainty treatment in all sorts of design and assessment situations.

It is important to realize that geotechnical engineers have dealt with uncertainties since the beginning of the profession, starting with global factors of safety. The partial factor method was introduced to allocate safety as a function of where uncertainties were relatively the greatest. Combinations of representative (or characteristic) values and partial factors are closely tied to the reliability targets we must achieve for our geotechnical structures. Against this background, the introduction of more explicit elements of treating uncertainties is a logical next step in making our decisions more consistent, transparent, and objective.

At the same time, we should also acknowledge that it will cost the professional community some time and effort to go through the learning curve and adopt these new elements. The soon to be published guidelines hopefully aid in speeding up the process, and should be combined with adequate computational tools, educational offer and sharing or publication of successful examples.

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