Selecting the appropriate geotechnical parameter

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ABSTRACT: Accurately defining geotechnical parameters is crucial in a design as over conservatism and under conservatism will impact the downstream engineering, from an increase in total cost of the structure or to a higher probability of failure, if not addressed. Geotechnical parameters are defined during the geotechnical investigation, using values from literature, in situ testing and laboratory testing. Lastly it is to the engineer to define the appropriate design value, including the risk of the project, experience and client requirements. This paper aims to illustrate the process for selecting the appropriate design parameter for geotechnical structures highlighting the importance of engineering judgement when dataset is scattered. Attention will be drawn to selecting the appropriate geotechnical investigation methodology relying on desktop study and laboratory testing, which in totality will create a matrix of confidence where the design value will emerge. It is up to the geotechnical engineer to define the value based on the risk associated to the structure, spatial variability and results variability.

1 INTRODUCTION

Any design action requires a value, be it stabilising or destabilising design actions, which is generally a deterministic number. In many fields of engineering, the design value has a high level of accuracy as it is derived from physical properties with a low coefficient of variation (CoV), such as concrete and steel, or actions on the structure based on loading, which can be derived from self-weight, wind load, or dynamic forces.

In geotechnical engineering, the above becomes somewhat less straightforward. In order to achieve a deterministic value, the designer needs to assign a value to a highly variable material in space and time and affected by external factors such as its stress history, chemical composition, and water content and stress. However, in the end, the objective is the same across all engineering disciplines: develop a design characterised by a certain resiliency against failure, often represented by a factor or margin of safety.

To achieve all the above, the procedure for selecting design parameters starts very early in a project, and it is often the last one to be confirmed. It involves multiple phases of fieldwork and laboratory testing and a strong professional team, including geologists, geophysicists, technicians, and engineers to agree on design parameters, with a certain degree of confidence.

2 GEOTECHNICAL INVESTIGATION

A geotechnical investigation is required in the early stages in the project. Depending on the size of the work and the client's project program, a geotechnical investigation is developed between the pre-feasibility and feasibility study levels, as once the project moves to detailed design study level, all design values should be known.

2.1 *Fieldwork*

If the project is relatively simple and the geology is known, then a single phased fieldwork programme is usually enough. However, for complex geology or high-risk projects, a multiphase approach is often adopted, informing the next phase from the previous results and refining where required.

Especially in South Africa, the Site Investigation Code of Practice (SAICE, 2010) provides guidelines for the type and number of data points depending on the type of structure and project phase. These guidelines should be used as a starting point and not as a prescriptive guideline. The aim of the fieldwork is to define the in-situ conditions at the site level down to a structure specific investigation, such as for bridge piles and heavily loaded platforms.

Test pitting and rotary core drilling are the most commonly used techniques to gather information, as well as to retrieve samples for laboratory testing. Understanding the geology and full profile is paramount as problematic soils are usually encountered at shallow depths, seen by test pitting, in some cases, critical layers could be deep seated below overlying more competent strata. To ensure such layers are not overlooked, geophysics is a great tool, such as Electrical Resistivity Tomography (ERT) and Multichannel Analysis of Surface Waves (MASW) reaching depths of up to 100m, identifying horizons to be targeted during the investigation.

A layout and cross-sections are often the preferred method to illustrate the local geological variations following the investigation, highlighting layers, geological and structural features and boundaries. In more advanced investigations, a 3D model is developed for the site with software (i.e. Leapfrog) which can interpolate the stratigraphy using multiple sources of information and include statistical distribution of the boundaries, which can be regenerated when more information provided. The models can be presented using spatial viewers as in Figure 1.

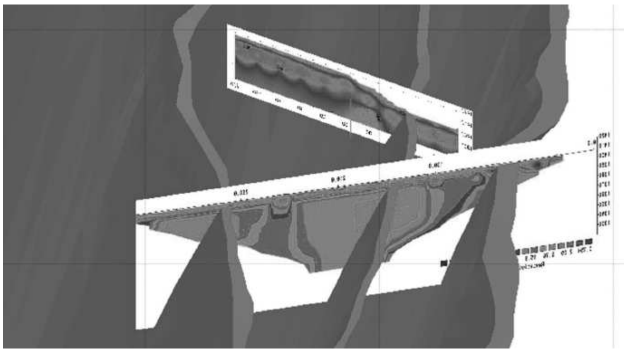

Figure 1. 3D Model of a projected dyke intrusion using geophysics

2.2 *Sampling*

Sampling by means of block sampling if in test pitting, or Shelby sampling in core drilling and more advanced sampling techniques are used to retrieve a representative "undisturbed" soil sample for laboratory testing.

Whilst cohesive soil sampling is easier than in non-plastic soils, the use of the word undisturbed is sometimes abused as the simple act of pushing a sampler into the soil causes pore pressures to develop and could affect the in-stress state of the soil (McDonald 2023). Similar stress changes can affect block samples as for instance transport from site to the laboratory; which at best is a car trip and worst a few planes with careless handling, even with the outmost care in packaging by the site team.

The latest trends in sampling techniques considers the use of thin wall sampling through to freezing techniques to keep the sample intact and reduce disturbance.

2.3 *In situ testing*

In situ testing allows the design parameters to be derived through relationships developed by interpolation using controlled tests where the results are known.

Certain in situ testing methods do not allow the retrieval of the material unless sampling is performed afterwards at a targeted depth.

From common Standard Penetration Tests (SPT) to derive strength parameters for foundations, to more advanced testing such as cone penetration testing with pore pressure, seismic and resistivity measurements (RSCPT-u) allow to measure a various range of parameters from saturation, strength parameters (both drained and undrained) as well as stress history, in a near-continuous recording every 10mm to 20mm as illustrated in Figure 2.

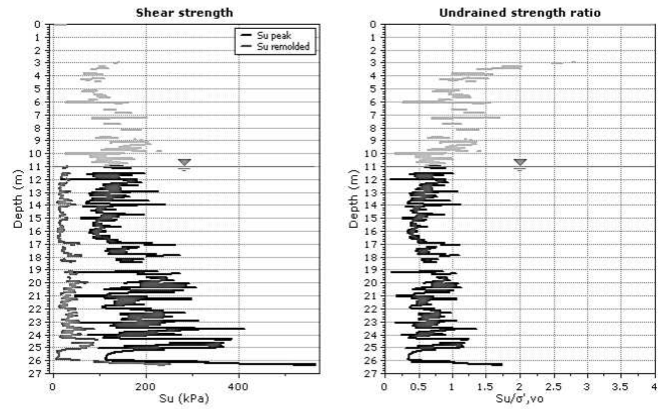

Figure 2. Several parameters derived from CPT probing with depth

The understanding of the range of applicability of the relationship between in-situ measurement and the geotechnical value is function of the soil type (generally cohesive vs non-cohesive) as well as a minimum and a maximum value. An example is the derivation of the undrained peak strength of the soil using CPT, which is simply linked to the tip resistance by a factor (N_{kt}) generally adopted as 15, but varies from 10 to 22 (Mayne 2018) which could lead to higher values than drained values.

Therefore, it is always recommended to perform more than one test to understand the range of applicability. Figure 3 illustrates the undrained strength of a material calculated using CPT and shear vane testing, where the shear vane was used to infer the N_{kt} value characterising the soil layer.

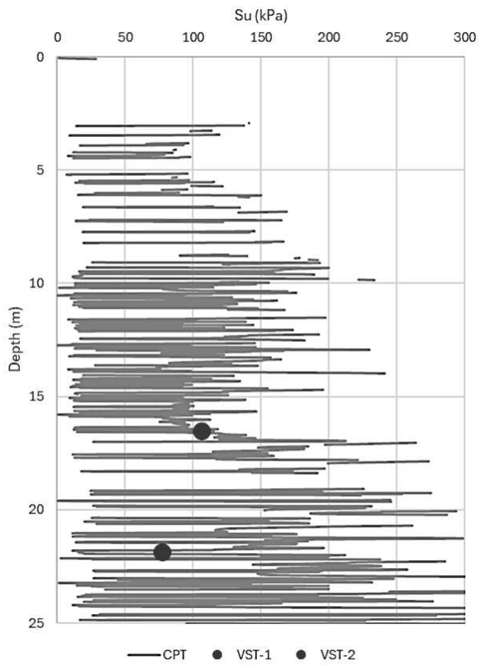

Figure 3. Su calculated from CPT by calibrating N_{kt} (set at 15) from shear vane testing

2.4 *Laboratory testing*

Once the fieldwork is completed, a schedule of testing is generally discussed and agreed upon between the geologist and the engineer. Usually, the geologist was on site with knowledge of the samples taken, their representativity and condition of sample and the engineer concerned with the design value. Ideally, the engineer should spend some time on site to get a feeling for the material. Unfortunately, tight deadlines and budgets often allow for only essential people to be on site. The same goes for the geologist when advanced testing is performed, which is specified by the engineer, and he/she is no longer involved in the project; creating silos within the same process and it should be avoided as much as possible.

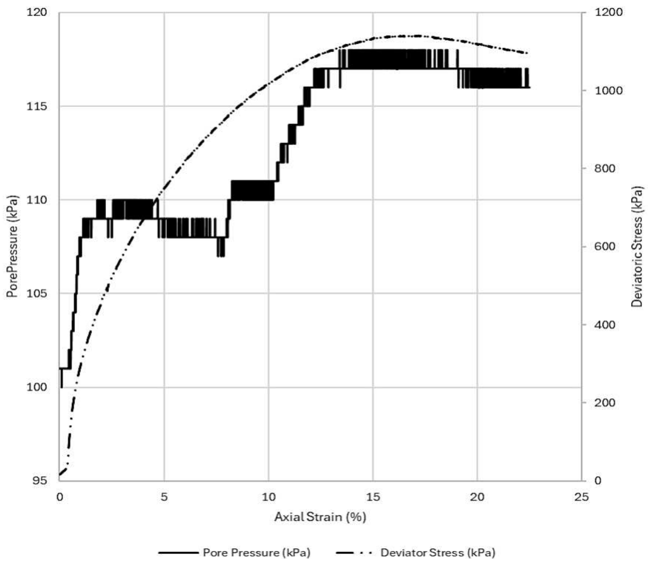

Figure 4. Development of pore pressure during a drained triaxial test

It is of utmost importance to partner with a reliable and trusted testing laboratory. Figure 4 illustrates a triaxial testing under drained conditions, where during shearing the sample was affected by pore water pressure build up, contradicting the requirement for a drained test, where pore pressure shall dissipate during shearing. This impact the interpretation of the shear strength as the calculation of effective friction angle and cohesion will be incorrect.

It is also important to understand which tests are adequate as, for instance, testing a cohesive material in a direct shear box at a high strain rate (base on a cost driven decision and not technical) will generate high resistance at low confining pressure, resulting in a high cohesion and low friction angle due to pore pressures developed and viscous effects. Table 1 summarises results of a clay with low plasticity in shear box at different speeds and both triaxial drained and undrained consolidated tests.

Table 1. Shear strength parameters from shear box and triaxial testing

	Cohesion (kPa)	Friction Angle (˚)
Shear Box	42	30
Triaxial CD / CU	30	20

The soil matrix is an important consideration as, for instance, when testing coarse material, the maximum particle size for a triaxial test is 1/5 the diameter of the sample (BS 2022); therefore, the result might not be representative of the entire soil matrix. Even basic testing such as foundation indicators (Grading analysis and Atterberg limits) can produce different results as presented by SAICE Geotechnical Division in 2024, where a proficiency test between six laboratories produced particle size distribution of the same material with scatter from less than 5% to 20% passing the 0.1mm sieve and 40% to 80% for the 425 microns sieve (SAICE 2024). In a recent workshop conducted by SAICE Geotechnical Division, there was a consensus to close the gap between engineers and the laboratories by increasing the level of engagement to understand the quality of the samples and what tests would be most appropriate, as once the sample is open, a visual analysis could change the testing programme to be more representative of the sample conditions (i.e. Remoulded rather than undisturbed for instance).

3 CHALLENGES

3.1 *Literature*

A comprehensive geotechnical investigation for a major facility such as a highway, bridge, water or tailings dam generally span six months to a year, with some exceptions.

Generally following the fieldwork and receipt of the first set of laboratory testing (often only foundation indicators), recommendations are provided based on relevant literature, which generally provides a range of values, as illustrated in Table 2 for fine-grained residual soils, which classifies as a CL based on the USCS soil classification (ASTM 2017). The triaxial testing performed on an undisturbed sample fell within the expected effective friction angle range, but lower effective cohesion than literature derived values. It is also important to give more weight to well established and reliable local references rather than international ones as the dataset is more representative of the local soils.

Table 2. Material strength for fine-grained residual soil (CL)

	Cohesion kPa	Friction Angle °
Byrne, G. & Berry, A. D. (2008)(1)	10-12	19-31
Heymann, G. (2016)(1)	10-12	28-31
Look, B. (2007) (2)	20-50	20-30
Triaxial CU Tests	0 -11	25 - 31

(1) South Africa, (2) International

3.2 *Spatial variability*

It goes by saying that in the scientific community to "honour the data" and combine with an "as the number of trials or experiments approaches infinity, the sample mean (or observed value) will converge to the true mean (or expected value)". Unfortunately, this is not always true in geotechnical engineering as the dataset might not be homogeneous and representative.

For instance, a CPT campaign in a tailing dam usually provides 50 data points per meter. Assuming four probes were done on a 30m high section, the dataset generated for the section is about 4 500 points. From this, a CPTu provides tip resistance, sleeve friction, and dynamic pore pressure, which is 13 500 data points.

Figure 5 shows the tip resistance (q_c) is plotted over depth and along the section. This graphical representation shows that the slope has some sort of layering, and therefore, using all the data points to have a homogeneous layer might not represent reality.

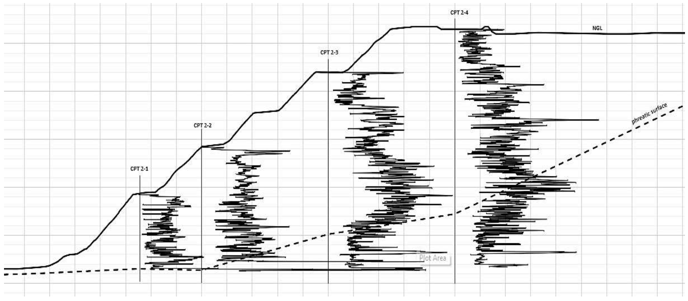

Figure 5. q_c variability over a tailing dam slope

As mentioned in the introduction for in situ soils, even for man-made structures, it is important to know how the soil was deposited and in this case illustrated in Figure 5, it was easily depicted how the layering was defined which reduced the coefficient of variability as illustrated in Table 3, where the CoV reduces for the majority of the values and is closer to the expected value for the undrained residual value using a layering approach.

Table 3. Material strength variability based on layering

	No layering		With layering	
	Value	CoV	Value	CoV
Friction angle (˚)	17	67%	27	22%
Peak Undrained shear strength ratio (-)	0.84	218%	0.43	57%
Peak Undrained shear strength ratio (-)	0.39	60%	0.21	62%

3.3 *Combining in-situ tests and laboratory tests*

In critical projects, multiple in situ tests and laboratory tests are performed on the same materials to increase the robustness of the dataset. Figure 6 illustrates the calculated friction angle using CPT and Dilatometer Marchetti Test (DMT) compared to triaxial testing. The relationship used to infer those values has been developed on similar materials (tailings) therefore, there is high reliability in the correlations between in-situ testing and laboratory testing.

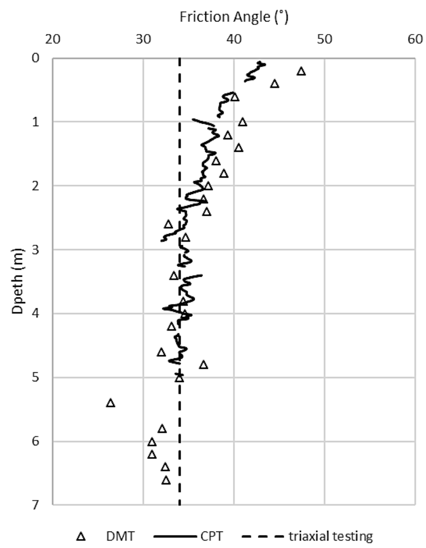

Figure 6. Friction angle calculated from CPT, DMT and triaxial testing

However, the inverse can happen as illustrated in Figure 7 where undrained peak ratios were calculated from CPT, triaxial testing and shear vane testing on a tailings sample where the design value is not clear as the CPT plots higher than drained strength and the triaxial testing provides a much lower value than the vane shear testing in this case more testing is often required and reference to literature and other studies in similar materials would assist in selecting the appropriate value.

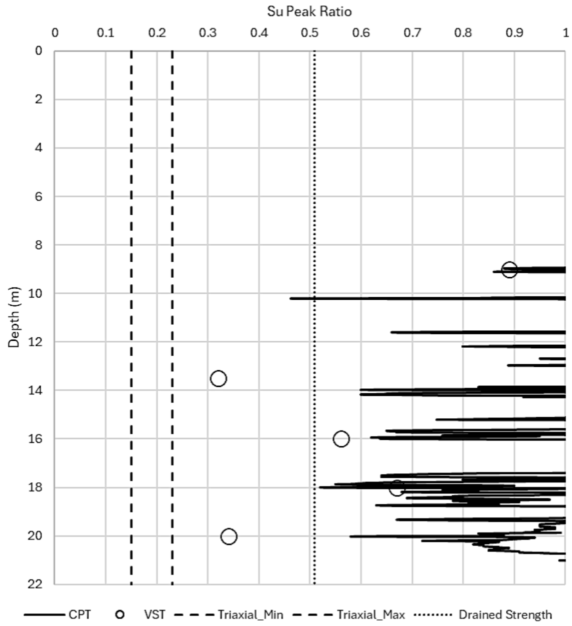

Figure 7. Undrained peak calculated from different tests

3.4 *Engineering Judgement*

According to Eurocode 7, the characteristic value is defined as the value for which 5% of all results are expected to occur (EN 1990). However, when geotechnical parameters are introduced, the characteristics value definition changes to a “cautious estimate…”. Bond & Harris (2008) describe it as “approximate judgement that is careful to avoid problems or dangers”. The reasoning behind this is the high variation in material strength values in soils (even in simple materials such as non-plastic silts).

In practice design values become subjective, and it is known that no geotechnical engineer will pick the same design value as another based on experience, technical background and risk level.

4 RECOMMENDATIONS

The above paragraphs have presented how through the geotechnical investigation soil parameter interpretation could vary from the reasonable value. An approach to define a geotechnical parameter is to start simple and then increase the level of complexity of the test, which often is linked to time and cost. Therefore, it is important to ensure the correct test is performed on representative sample and under the right specifications.

4.1 *Soil Classification*

Some of the first data retrieved from a geotechnical investigation is the soil classification as per USCS based on soil grading and Atterberg limits. This can be coupled with the geologist's field description to provide additional information. If the laboratory and the geologist are trusted, this already gives a qualitative idea of the soil behaviour, cohesive or not, and strength indices (undrained strength for cohesive and density for granular materials).

4.2 *In Situ testing*

From SPT to more advanced such as RSCPT-u and DMT, the key is to select the test with the highest reliability in correlating the required design parameter with the soil type. For instance, SPT does not work well in loose sands or very soft clays, as it is difficult to measure the blow count and retrieve samples. On the other hand, CPT has a robust relationship in terms of clays and silts, requiring an understanding of the formulas (often curve fitting) and the implication of using one input parameter rather than another.

Nowadays, it is expected to have near-continuous readings every centimetre. However, it is paramount to ensure the equipment is in good working condition, such as ensuring the calibration certificate is loaded correctly on the computer and the machine has been set to zero.

Having a larger quantity of values is always a benefit, including manual shear vane testing where a test pit block sample was taken will confirm that the soil is similar. It is suggested to perform between 5 and 10 shear vanes on the floor of the block sample position and compare results with the undrained strength results from the triaxial tests.

4.3 *Sampling*

Where possible, block samples should be taken. However, just cutting a sample could be challenging, and transport to the laboratory intact is even more challenging. If the conditions are challenging, sometimes testing a poor quality block sample will cause more doubt than using it as a bulk remoulded.

There is no true undisturbed sample. Even when the laboratory can reach the site (University of Pretoria, 2023), other factors, such as the calibration of the machines, which are sensitive to vibration (including transport vibration) may give inaccurate results.

4.4 *Laboratory testing*

When the samples arrive at the laboratory, they are thoroughly checked by all the technical team members, such as the geologist who has taken the sample, the laboratory technician prepare the sample for testing, and the engineer who will use this result.

Particle size distribution and Atterberg limits are essential; however, misinterpretations arise by not quartering the bulk sample or correcting the hydrometer portion using specific gravity.

The more advanced testing, such as triaxial and direct simple shear tests, requires a considerable list of references which can be used to compare the results with, as those tests are often expensive and can take months (for low permeability soils).

It is not advisable to test at different laboratories as the assumption is to have two perfect samples, and if it falls away, then the test will not give the same results. Rather, engage with the laboratory and visit during sample preparation and during the test. These checks usually will provide a level of confidence for the results.

4.5 *Present the data*

All the data shall be reported. If a test is considered failed, it needs to be reported with an explanation and included in the report. As mentioned earlier, the dataset for complex geotechnical structures or high-risk developments is considerable in size and needs to be presented in a way that another competent engineer can understand.

Table 4 provides a typical example of how data should be reported, including layer names, which should be derived with the geology in mind (i.e. residual norite rather than soft clay) as it provides a reference to the material, with soil classification, followed by all the design parameters used (strength, permeability, etc.).

Table 4. Material properties summary

Layer	USCS	Effective friction angle	Shearing behaviour	Su peak / Su res	Ref.
Hill-wash	CL	30	Contractive	0.16 / 0.07	CPT
Re-worked residual norite	CH	16	Dilative	0.20 / 0.13	TxCU
Fine Tailings	ML	30	Contractive	0.35 / 0.13	TxCU / CPT

4.6 *Which value?*

At the end of this journey, a dataset is compiled of values for the soil parameters. Again, Bond and Harris (2008) and Parrock (2014) in our South African environment provide a coefficient of variation between 20% and 80% depending on the parameter. Therefore, a good geotechnical investigation with robust laboratory testing should provide you with a probability of failure between 10% and 20%, therefore, a reliability index around 1 and 2 (US Army Corps of Engineers 1997).

This is the reasons why for geotechnical applications the general factor of safety is between 1.5 and goes up to 3 if deformations could be a failure mechanism.

If the dataset allows, statistical analysis can be considered (requires more than 20 data points). In a CPT investigation, it is common to use the 20th percentile for the soil layer, as illustrated in Figure 8, for an undrained peak ratio for a tailings material.

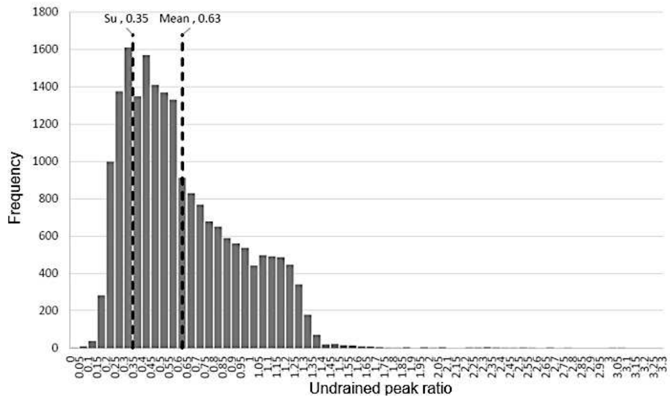

Figure 8. Histogram of undrained peak values for a selected layer

As part of selecting the design value, the failure mechanism should be part of the process. For instance, in a slope, a global failure which affects the entire slope, there could be merit in considering the average value as there will likely be stronger and weaker values, and if the failure mechanism crosses all of them, the result is the average (failure 1 in Fig. 9). However, when a distinctive layer governs the stability, for instance, a weak foundation below a slope or the end bearing capacity for a pile, then the lowest value could be considered as the spatial variability is low, and the failure plane will run along the layer (failure 2 in Figure 9).

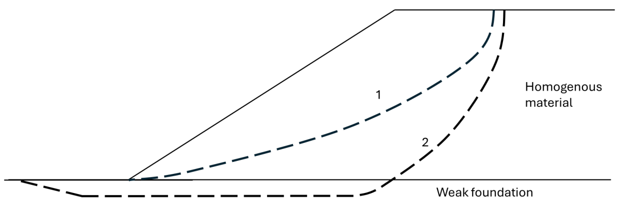

Figure 9. Failure mechanism and parameter selection for a slope stability

5 CONCLUSIONS

Soil in nature varies, depending on the formation, moisture content, relative density and stress history. Until a test pit is open, that soil has never seen the light before (in the past few million years), the geotechnical investigation aims to define a design value to a highly variable material. Generally, two engineers will not assign the same parameter to a given soil as background, experience and risk appetite will affect their selection. The value at the end is meaningless if it not supported by a well thought process detailing how the design value has been derived as there are many different paths to derive it, starting from in-situ testing, laboratory testing and lastly interpretation, keeping in mind the failure mechanism and risk associate to the structure which for the same dataset could provide different values as the perception of the engineer is included in this process.

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