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Modern guidelines for classification of fine soils

Lignes directrices modernes pour la classification des sols fins

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ABSTRACT: Existing guidelines are illogical and inconsistent for classification of fine soils, however the basics of the Casagrande chart is useful. New guidelines is proposed in this article. The local composition of clay minerals in natural clay sediments determines the location relatively to the A-line in the chart because some minerals like organic matter and diatomite's can hold water in a way in which it is ineffective in producing plasticity. Accordingly, plasticity index and not liquid limit shall be used to classify plasticity. Soils who plot below the A-line shall be classified according to the clay mineral or the material which causes the position to shift below the A-line and named accordingly. The slope of the A-line shall be increased when liquid limit exceeds 120 %. Only plasticity index shall be used to distinguish clay from silt.

RÉSUMÉ: Les directives existantes sont illogiques et incohérentes pour la classification des sols fins, mais les principes de base du diagramme de Casagrande sont utiles. De nouvelles directives sont proposées dans cet article. La composition locale des minéraux argileux dans les sédiments argileux naturels détermine l'emplacement par rapport à la ligne A du graphique, car certains minéraux comme la matière organique et la diatomite peuvent retenir l'eau de manière à rendre la production de plasticité inefficace. Par conséquent, l'indice de plasticité et non la limite de liquidité doit être utilisé pour classifier la plasticité. Les sols qui se situent sous la ligne A doivent être classés en fonction du minéral argileux ou du matériau qui provoque le déplacement de la position en dessous de la ligne A et nommés en conséquence. La pente de la ligne A doit être augmentée lorsque la limite de liquidité dépasse 120 %. Seul l'indice de plasticité doit être utilisé pour distinguer l'argile du limon.

Keywords: Soil classification; Fine soil; Organic soil; Diatomite soil; Plasticity.

1 INTRODUCTION

A precise soil description and classification with indication of deposition environment and geological age is a prerequisite for incorporating prior knowledge when deriving the geotechnical properties.

A large number of classification systems exists for soil classifications. Each of them is developed to fulfill a specific need and purpose. As a result, each of them has some strengths and some limitations. The latter becomes particularly pronounced when used outside their intended purpose.

Many (Tanaka et al 1995), (Huang et al 2009) and (Hind 2017) have, over time, pointed out that existing systems in some context are illogical, inconsistent and misleading for geotechnical purposes and it is very much needed that they are adjusted so that they can deliver a more precise and useful classification.

For geotechnical purposes it is very important, that the classification system addresses the geotechnical soil properties, which is not always the case with the present systems as demonstrated in the following. This article proposes adjusted guidelines for classification of fine-grained soils, which are more logical, clear and consistent than the existing and adaptable to local geological conditions.

2 CLAY SOILS

Some clay minerals plots above the A-line in a Casagrande plasticity chart and some below cf. Figure 1.

This is because some clay minerals can hold water in a way in which it is ineffective in producing plasticity e.g. Halloysite nanotubes and Allophane spherules (Dumbleton, 1966). This property affects the consistency limits in a way that the location in the plasticity chart is displaced below the A-line. This defuse placement of pure clay minerals in the plasticity sheet complicates the use of the chart for classification.

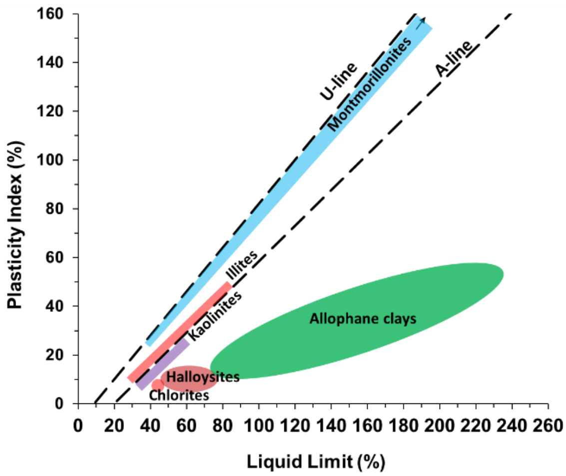

Figure 1. Location of clay minerals in a Casagrande Chart.

Natural clays always contain a mixture of different clay minerals, which composition reflects local geology. Samples of the same geological origin normally fall on a line parallel or slightly angled with the A-line cf. the trendlines in figure 3. The local composition of the clay minerals determines the location of the line. This means, that the plasticity chart has to be customized to local geological conditions in order for it to be used for a consistent classification.

Natural fine-grained soils comprise of varying proportions of fines and coarser material. Arthur Casagrande argued that plasticity is the most important characteristic of fine-grained soils in order to describe the engineering behavior and that plasticity, rather than grain size, should be the basis of a classification system (Dumbleton, 1966).

3 PLASTICITY CHART

Many classification systems use consistency limits and the plasticity chart to distinguish clay from silt and clay form organic soils. According to most systems, clastic clays generally plot above the A-line, whereas gyttja and silt generally plot below it. Notable exceptions are presented in Figure 1. According to many conventional classification systems such exceptions are classified as silt. However, they do not display the characteristics normally associated with silt. At the same time they are not as plastic (clayish) as the liquid limit indicate.

Silts have by definition none or very limited degree of plasticity, but anyway many conventional classification systems allows for high plasticity silts. This makes a consistent and accurate classification of fine-grained soils difficult and at the same time such a classification is ambiguous for geotechnical purposes.

To sum up, soils plot below the A-line for two reasons which obviously complicates a clear classification significantly:

- The soil is dominated by a clay mineral, which contains "inactive" water and therefore plots below the A-line cf. Figure 1.
- The soil is dominated by another material, which contains "inactive" water e.g. organic matter or diatomites.

It is strongly advised to use the A-line in the plasticity chart to distinguish clays which can hold ineffective water from those clays which cannot and to use plasticity to distinguish clays from silts.

For geotechnical purposes it is very important that the classification indicates if the soil plots below the A-line and why. Thus, the name of the primary fraction should change when the A-line is crossed e.g. from *clay* to *Allophane-clay* or from *clay* to *gyttja*.

4 NATURAL CLAY DEPOSITS

Plasticity depends on both clay fraction and clay mineralogy. This means that clay samples with a wide variety of clay fraction can have the same plasticity. For this reason, the clay fraction is an insufficient measure of plasticity and therefore also an insufficient criterion for when a soil should be classified as clay.

The plasticity of natural clay soils is highly dependent on the composition of clay minerals. In many countries - including Denmark - the most common groups of clay minerals in natural clay soils are kaolinite, illite and smectite (Deyu 1987), (Trankjær 2012) and (Grønbech 2015). The distribution varies greatly, but the overall trend is that smectite dominates the Paleogene clays and most of the glacial and lateglacial deposits - especially in the western parts of Denmark.

In connection with geotechnical investigations for 12 new highway stages around Denmark, large bag samples representing a wide range of the Danish quaternary geology were retrieved in boreholes carried out for approx. every 100 m road by the dry rotary drilling technique using temporary casings for borehole wall support.

Most of the samples were extracted in glacial and lateglacial deposits, tills and ice-lake deposits. In the laboratory a grading curve as well as Atterberg Limits were determined for selected samples. No tests were performed to determine the organic content, but on the basis of a knowledge of the cold depositional environment and the color of the samples, it can be determined with great certainty that the organic content is insignificant - if any.

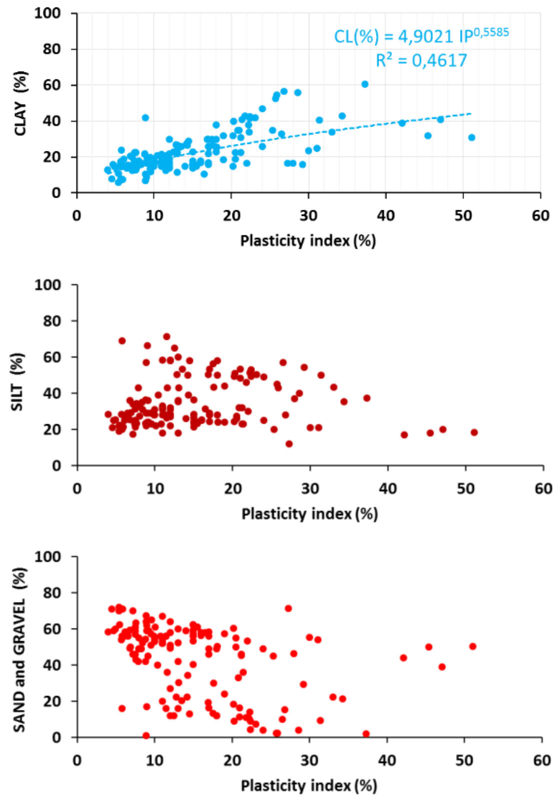

Figure 2. Clay-, silt- and sand/gravel-proportion of weight in typical inorganic glacial and lateglacial Danish clay deposits (90 samples in total).

The clay, silt and sand/gravel content read by the grading curves for 90 bag samples representing a wide range of the Danish quaternary geology throughout the country are presented in Figure 2 for the clay deposits. From this, it appears that the clay fraction in Danish lateglacial and glacial clay deposits is between 7 and 60 % and is only slightly correlated (increasing) with the plasticity index. This means that clay mineralogy plays a decisive role in clay plasticity.

The silt fraction is typically between 20 and 60 % and the sand/gravel fraction between 0 and 70 % and neither of these fractions seems to correlate with the plasticity index. The clay fraction in typical Danish glacial and late glacial clay deposits is thus quite subordinate to the fractions of non-plastic material, silt, sand and gravel.

Figure 3 presents trendlines for the glacial and lateglacial clays from the Highway projects (90 samples) and of typical Danish Paleogene clays (68 samples with I_p between 55 % and 200 %) in a plasticity chart. The Paleogene clays are very fine-grained with a clay fraction between 70 % and 95 % and without sand and gravel content (Grønbech 2015). According to figure 3 all clays plot well above the A-line indicating that they really are without organic content.

5 PLASTICITY

As plasticity is the most important characteristic of fine-grained soils in order to describe the engineering behavior, classification of plasticity should be appropriately differentiated and include all naturally occurring clays in the world and thus also extremely plastic clays found in e.g. Denmark.

Table 1. Classification of plasticity

Term	**I_P (%)**
Extremely high plasticity	>150
Very high plasticity	50-150
High plasticity	25-50
Medium plasticity	10-25
Low plasticity	7-10
Very low plasticity	4-7
Non-plastic	<4

In conventional classification systems CV (Very High Plasticity Clay) covers only a fraction of the natural range because the range of validity of the Casagrande Chart terminates at w_L = 120 % ($I_P \approx$ 80 %). Due to this limitation the author propose to introduce a new category CE (Extremely High Plasticity Clay) extending existing classification system to cover clays with w_L up to 350 % ($I_P \approx$ 300 %).

6 SILT

It is important to note that the classification terms *clay* and *silt* refer to the clay-like and silt-like characteristics of a soil rather than grain size. The clays that (Casagrande 1948) used to define the empirical A-line were naturally occurring soils that had a substantial, and at times a majority of non-clay fraction. Therefore a majority of clay content is not a prerequisite for a soil to plot above the A-line.

Many classification systems require a certain amount of fines in order to be classified as a clay. USCS (ASTM D2487) defines fine-grained soils as having a physical dominance of fines (>50 %, <0.075mm), whereas NZGS guidelines (2005) requires only a 35 % fines content (<0.060mm) for a soil to be classified as fine-grained (Hind, 2017). In DK only soil with plasticity index less than (4 to) 7 % is classified as coarse-grained. The lack of a fines content threshold in DK (Larsen 1995) is an acknowledgment that some soils exhibit the fine-grained characteristics even though coarse-grained material is physically more abundant.

According to ISO 14688-2 the classification of fine soils for geotechnical purposes should be made in accordance with their plasticity (w_L and w_P) which shall be determined by laboratory testing in accordance with ISO 17892-12. According to this definition as little as approx. 10 % clay may be sufficient to insure plastic behavior according to figure 2. However, it should be borne in mind that the Atterberg Limits tests are carried out only after removing soil particles greather than 0.4 mm by sieving beforehand according to the test standard.

According to ISO 14688-2 silt is non-plastic or of very low plasticity. Newertheless, this standard as well as many others classification systems allows for high plasticity silt according to the plasticity charts presented in the standards.

All data in Figure 2 plots between the A-line and the U-line regardless the silt fraction (10 – 70 %). Therefore, it can be concluded, that it is not the size of the silt fraction which causes a soil to plot below the A-line and it is therefore wrong and misleading to classify soils which plots below the A-line as *silt*.

On this background it is strongly advised to use plasticity index and not plasticity chart, to distinguish *silt* (I_P < 4-7 %) from *clay* (I_P > 4-7 %).

7 ORGANIC SOIL

The presence of organic matter has great influence on the mechanical behavior of soils, particularly the compressibility. As a consequence Casagrande (1948) originally used the plasticity chart to characterize a fine soil's potential for compressibility (w_L<120%).

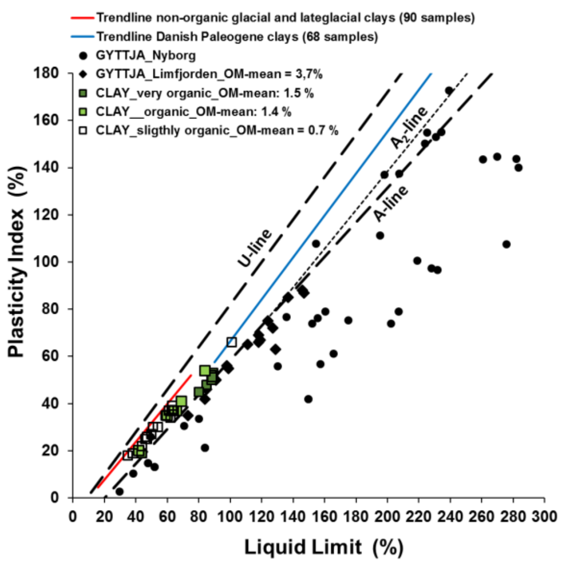

Figure 3. Example of where clay with varying organic content and gyttja plots in the plasticity chart. The mean of the computed organic content defined as OM = LOI – SWL is stated in the legend.

When fine soils are dominated by organic matter, they are capable of containing large amounts of "inactive" water with the result that such soils plots below the A-line c.f. Figure 4. However some organic soils plots above the A-line for high w_L values c.f. Figure 3. Therefore an A_2-line almost parellel with the Paleogene trend line is proposed introduced for fine soils when w_L is out of range of the Casagrande Chart and exceeds 120% as shown in Figure 3:

$$I_P = 0.82(w_L - 31) \quad (1)$$

Different classification systems introduce very different definitions of organic soil. Some systems refer e.g. to different organic content % of dry mass, while others refer to the ratio between the liquid limit determined on dried material and the liquid limit on non-dried material. For the same reason, no agreement can be reached on where organic soil plots in the plasticity chart, and when organic content dominates to a degree so it must be reflected in the naming of the soil. In this regard, it should be noted that the location in the plasticity chart also depends on where the natural inorganic clays are plotted in comparison to the A-line under the given geological conditions. It is thus obvious that classification of organic soil must be customized to local geological conditions and the chosen classification practice. In geological areas where inorganic clays normally plots well above the A-lines, fine soils shall be defined as an organic soil when the organic content is so large that it causes the soils to plot below the A-line. Otherwise the organic content is considered subordinate and the classification of the organic content shall be made using the terms given in table 2.

In many classification systems Loss on Ignition (LOI) is used to derive the organic matter content (OM) of a soil sample regardless of the content being overestimated due to the influence of structual water and sulfides (e.g. iron sulfide).

In Denmark soil samples are dried in an oven at 105°C and the moisture content estimated as the weight loss. Thereafter the samples are burnt at 550°C in six hours and the organic matter estimated as the weight loss.

It is chosen to ignite at 550°C to avoid decomposition of carbonate (inorganic carbon) which mainly decompose above 700°C (Dinesen 1985).

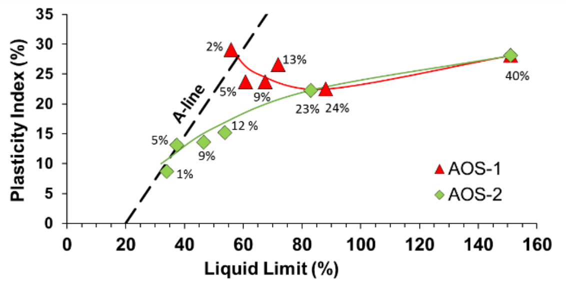

Figure 4. Movement in the plasticity chart when the content of organic matter is increased in natural clay soils by mixing in a natural peat soil with OM = 40 % (Huang et al, 2009). The tags indicates the organic matter content, which were measured using dry LECO analysis.

However when clay is heated to 550°C, the crystal structure of the clay minerals is disintegrated, and the water of crystallization and combined OH-groups is liberated (Grønbech 2010) resulting in an error (Clay content-dependent correction factors for structural water loss, SWL). The size of SWL depends on clay-content as well of clay mineralogy, which means that SWL normally is under the influence of local geological conditions.

(Stockmarr 2008) suggest that the plasticity index up to an I_P of 60 % is proportionally to LOI for natural inorganic Danish clay soils. This means that for fine soils who plot above the A-lines $SWL_{550°C}$ can be estimated as (2a):

$$SWL_{550°C}(\%) = (I_P(\%) + 9)/12.5 \qquad (2a)$$
$$SWL_{440°C}(\%) = 0.0496 I_P(\%) + 0.58 \qquad (2b)$$

From the data of (Stockmarr 2008) it is possible to estimate $SWL_{440°C}$ as well c.f. equation 2b.

According to equation 2a the SWL value is rather high for inorganic high plasticity fine soils ($SWL_{550°C}$ = 5,5 % when I_P > 60 %)), which makes it uncertain to derive OM from LOI. For that reason it is recommended not to ignite fine soils at temperatures higher than 440 degrees.

According to figure 5, fine soils passes the A-lines when the OM content exceeds 2-3 % and if so they shall be named *gyttja* or *peat* while soils with lower OM shall be named *clay*. The large scatter is due to the fact that OM is a computed value and some of the LOI tests have not be performed on the same subsample as the corresponding Atterberg index. On the basis of the trends of this figure the classification system for organic soils in Table 2 is proposed.

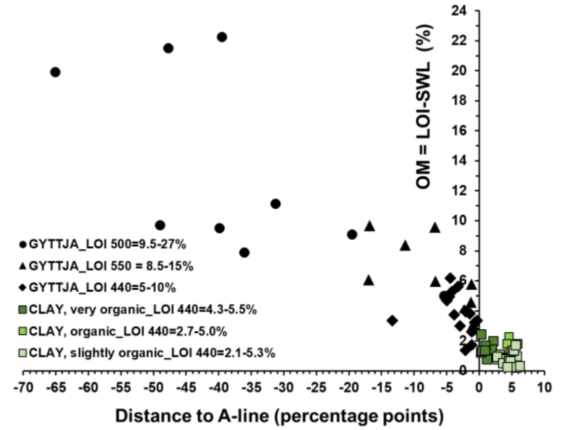

Figure 5. Computed organic matter content (OM = LOI – SWL) as function of the distance to the A-line. When the soil plot above the A-line distance to A-line is positive.

Clays with subordinate organic content normally plot between the inorganic clay-lines and the A-line cf. the examples of soft postglacial organic soils presented in Figure 4.

Table 2. Classification of organic soil

Term	**OM (%)**
CLAY, inorganic/sligthly organic	<1
CLAY organic	1 - 2
GYTTJA*	2 - 15
GYTTJA*, very organic	15 - 30
PEAT** and GYTTJA*, extreemly org.	> 30

* allochthonous. ** autochthonous.

Based on the Danish experience it is strongly advised to use the plasticity chart to distinguish clays from organic soils and to use *gyttja* as main soil type when the organic content dominate the consistency limits to a degree that the soil plots below the A-line.

8 DIATOMITE SOILS

(Tanaka 1999) conducted a series of consistency tests (w_L and w_P) on controlled mixtures of almost pure diatomite and pure Kaolin cf. Figure 6.

Adding non-plastic diatomites to Kaolin increased both plastic and liquid limits, whereas the plastic limit decrease slightly when diatomite exceeds 50 %. Diatomites itself is non-plastic, therefore no measurement could be made for the pure 100 % diatomite mixture.

The presence of a significant amount of microfossils can significantly influence the mechanical behavior of soils, particularly the compressibility.

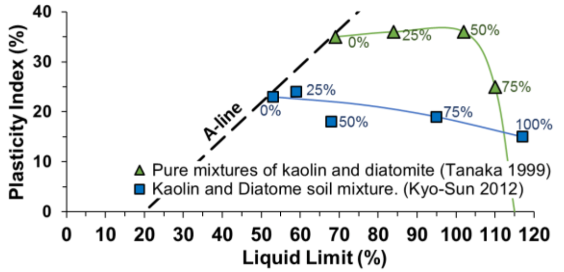

Figure 6. Movement in the plasticity chart when the diatome content is increased in Kaolin and in a Diatom soil mixture.

(Tanaka 1999) recommend that fossiliferous sediments are recognized as a stand-alone class of soil, just as in the case of organic and inorganic soils.

(Sun-Kyu 2012) performed a corresponding series of consistency tests on controlled mixtures of natural diatomite soil and pure Kaolin cf. Figure 6 with virtually the same result only with the deviation that the plasticity index in this case does not converge against zero for 100% diatomite soil, since the natural soil does not consist of pure diatomite, but also contains clay minerals.

Figure 7 illustrates how natural diatomite sediments from DK plot in a plasticity chart.

These are interglacial Cromerian deposits (860.000 - 478.000 BP) from a site nearby the city of Herning, where widespread organic and clayey diatomite deposits were found in connection with a highway construction.

The deposit contains varying amounts of diatomite, clay and organic matter which explains the scatter in the chart. The diatomite content is not analyzed, but is expected to vary dramatically, and probably only the non-plastic samples consist of almost pure diatomite.

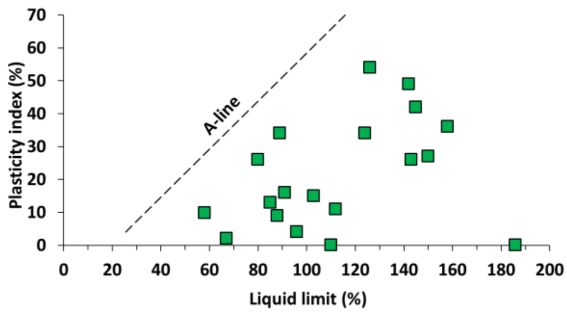

Figure 7. Danish Diatom soils with varying content of clay and organic matter.

It is strongly advised to use diatomite as main soil type when the diatomite content dominates the consistency limits to a degree that the soil plots below the A-line. For diatomite with a substantial content of clastic clay or organic soil, the terms *Diatomite-gyttja* or *Diatomite-clay* are suggested.

9 CONCLUSION

It is strongly advised to introduce more consistent classification of fine soils. Present conventional guidelines are in some context illogical, ambiguous, inconsistent and misleading for geotechnical purposes.

However the author consider the basics of the Casagrande chart (A-line) to be very useful, but the guidelines should be amended as follows when soil is classified for geotechnical purposes:

- Plasticity index and not liquid limit should be used to define and classify plasticity.
- It is not the size of the silt fraction which causes a soil to plot below the A-line and it is therefore wrong and misleading to classify soils who plots below the A-line as *silts*.

- Only plasticity index shall be used to distinguish *clays* (I_P > 7 %) from *silts* (I_P < 4 %).
- When a soil plots below the A-line it should be classified according to the clay mineral or material which causes this position and named accordingly e.g. *diatomite, gyttja* or *Halloysite clay*.
- Some organic soils plots above the A-line for high w_L values out of range of Casagrandes original chart. Accordingly, an A_2-line with steeper slope is proposed when w_L exceeds 120%.
- The distance from the A-lines to a point below it are proportional to the content of "inactive" water and thus to the content of e.g. organic matter and diatomites.
- The plasticity chart is recommended to distinguish *clay* from *organic soil* in geological areas where natural clay soils plots above the A-line and to use *gyttja* as main soil type when the organic content dominates the consistency limits to a degree that the soil plots below the A-line.
- In geological areas were inorganic fine soils plot well above the A-line fine soils normally passes the A-line when OM excess approx. 2 %.
- It is strongly advised always to describe plasticity for all fine grained soils when the description is done for geotechnical purposes.
- It is strongly advised to use the terms diatomite, diatomite-clay and diatomite-gyttja as main soil type when the diatomite content dominates the consistency limits to a degree that the soil plots below the A-line in geological areas where natural clay soils plots above the A-line.

Finally, a call for geotechnical engineers to give geology and soil classification more attention. It is important to dare to move into this border field if we are to ensure a competent basis for design by optimizing the use of prior knowledge when deriving the geotechnical properties.

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