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Effect of the scatter between CPTU measured parameters in soil classification

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ABSTRACT: Using piezocones from different manufacturers may yield different results even if the equipment complies with international standards. This causes problems when soil investigation contractors, using different cones, operate in the same area, and especially on the same project. Studies done in soft clay, sand, silt, and quick clays from different Norwegian sites show that repeatability for the cone resistance measurements and penetration pore pressure is good and that it has improved from one cone type to another. However, the scatter in the measured sleeve friction, and hence the friction ratio, is still very significant. Here, an attempt is made to qualitatively describe the impact of the scatter in the soil classification based on CPTU parameters. The most common soil classification charts are used to illustrate this scatter.

1 INTRODUCTION

Performing piezocone tests (CPTU) with cone penetrometers from different manufacturers may give different results even though the equipment is aligned with international standards. Previous studies (Lunne et al. 1986, Gauer et al. 2002, Powell & Lunne 2005, Tigglemann & Beukema 2008, Lunne 2010, Cabal & Robertson 2014 Lunne et al. 2018) have shown that all three measured parameters, cone resistance q_c, friction sleeve f_s and pore pressures u_2, could vary significantly, and in particular for f_s, depending on the equipment used.

Recent advances in electronics and cone design have been incorporated in the design of the new cones and motivated further field testing. The establishment of the Norwegian GeoTest Sites (NGTS) (L'Heureux & Lunne 2019) has given the opportunity to different companies to do testing at the silt (Paniagua et al. 2021), sand (NGI 2020), quick clay (Lindgård et al. 2019) and soft clay (Lunne et al. 2018) sites. In general, after these tests, it was observed that the measured u_2 and q_c (or corrected cone resistance, q_t) showed little variation between different cone types, while the f_s measurement gave relatively large scatter between different cone types. Then, the question that arises is how much this scatter in the CPTU parameters influence further treatment of the data like for example soil classification based on CPTU.

The present article investigates the impact of varying CPTU equipment and its scatter on the most common CPTU soil behaviour charts. The paper focuses on the effect of the scatter between different types of piezocones. Further analyses regarding the statistical distribution of scatter with depth and between piezocones for each site is done in Lindgård et al. (2018), Lunne et al. (2018), Paniagua et al. (2020) and NGI (2020).

2 METHODOLOGY

Two relevant CPTU data sets selected at the NGTS study sites in Norway have been chosen for this study. The data sets selected correspond to the ones giving the largest scatter between them, i.e., the maximum (data in red in the figures) and minimum (data in blue in the figures) values. In other words, the selected data sets come from the cones which provide extreme profile results. The difference between the two data sets presented here are measured in terms of its CPTU parameters q_t, u_2 and f_s, and then the data was plotted in terms of the classification systems presented in this paper.

The data sets are then plotted in the soil classification charts proposed by Robertson (1990), Schneider et al. (2008) and Senneset et al. (1989). The data plotted in the soil classification charts has been filtered to represent just the layer where the main soil material for the site is to be found.

It should be clarified that the discussion about the validity of the soil classification charts mentioned above for Norwegian soil conditions is out of the scope of this study. Therefore, it is assumed that the soil classification charts may represent fairly well the soil types studied in the present paper.

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The observations presented here assume that the requirements and recommendations given in ISO 22476-1:2012 (Geotechnical investigation and testing - Field testing - Part 1: Electrical cone and piezocone testing) and Norwegian Geotechnical Society (NGF) Guideline No. 5 (2010) are followed. Some of these are:

– Zero readings to be taken before and after each test with the cone penetrometer at a temperature as close as possible to ground temperature.
– It is important to wait until the readings have stabilized before taking zero readings.
– The thrust machine shall push the rods so that the axis of the pushing force is as close to vertical as possible.
– The pore pressure measurement system shall be saturated to give good pore pressure response during penetration.
– For deep CPTUs, it is important to correct the penetration length for inclination effects.
– Recommended minimum distance between a CPT and adjacent boreholes is 2 m.

2.1 *Test sites*

The NGTS sites selected for the present study are well portrayed in the following publications and are shortly described as follows:

– *Tiller-Flotten quick clay* (L'Heureux et al. 2019): The site consists of thick marine clay deposit of a low to medium sensitivity (1-7,5 m) deposit over a high sensitivity (quick) clay (7,5-20 m depth).
– *Onsøy soft clay* (Gundersen et al. 2019): The site consists of a high plasticity marine clay (1--8 m depth), a medium plasticity clay (8--13 m depth) and a high plasticity clay (13-20m).
– *Halden silt* (Blaker et al. 2019): The silt layer varies between 5-15 m and consists of a uniform marine natural silt.
– *Øysand sand* (Quinteros et al. 2019): The site consists of fluvial and deltaic gravelly-sandy-silt sediments with a gravelly sand layer from 0-14 m, a silt layer from 14-17,5 m depth and a sand layer down to 20 m depth.

2.2 *Derived CPTU parameters studied*

The soil classification charts are a combined representation of the in-situ behaviour characteristics of the soil under a CPTU. The CPTU might be able to measure up to seven independent parameters like cone resistance, q_c, friction sleeve, f_s, pore pressure, u_2, shear wave velocity, V_s, and when performing dissipation tests, the time for 50% consolidation, t_{50}, in situ pore pressure, u_o, and hydraulic gradient, i.

Usually the most common parameters (i.e., q_c, f_s and u_2) are normalized to be represented in soil classification charts. Before normalization, the parameter q_c is corrected for unequal pore pressure effects by the formula $q_t = q_c + a\ (1\text{-}u_2)$, where the parameter a relates the cross-sectional area of the shaft and projected area of the cone.

Robertson (1990) relates the normalized parameters Q_t, B_q and F_r, noted as normalized cone resistance, pore pressure parameter and normalized friction ratio, respectively.

Schneider et al. (2008) and Senneset et al. (1989) make use of some of the normalized parameters (i.e., Q_t and B_q) and relate them to either $\Delta u/\sigma_{vo}$' for Schneider et al (2008) or q_t for Senneset et al. (1989).

3 RESULTS

The main observations for all sites are given and discussed below. However, due to space limitation focus will mainly be given to the results obtained at the Halden and Onsøy sites, and some specific observations for Tiller-Flotten and Øysand. The complete figures for Tiller-Flotten and Øysand can be sent to the interested readers upon request to priscilla.paniagua@ngi.no.

3.1 *Tiller-Flotten quick clay site*

The testing of eight different cones from five CPTU manufacturers) showed less variability for the u_2 parameter. The q_t value showed a larger variability than u_2 but lower than f_s (Lindgård et al. 2018). In fact, there are more uncertainties associated to the f_s value since some of the cone types gave good repeatability for f_s readings, while some show relatively large variation.

The following observations were made at Tiller-Flotten:

– For the Robertson (1990) Q_t-B_q plot, the data sets with largest variability all fall in the same soil behaviour type "clay-sensitive" clays. This observation is valid no matter where the largest scatter is in the CPTU parameters.
– For Robertson (1990) Q_t-F_r plot, when the variability focuses in f_s, the data plots in two neighbouring areas (sensitive clay and the limit sensitive clay-clay). When the variability appears in the q_t or u_2 value, then the data plots in the same soil type, however, with a tendency to cover opposite areas in the same or neighbouring soil types.
– For Schneider et al. (2008) (Q_t-$\Delta u/\sigma_{vo}$') chart and Senneset et al. (1989) (q_t-B_q) chart, no clear difference is observed between the data sets showing largest scatter, for q_t and u_2 parameters. The quick clay is classified as sensitive clay (1c) in Q_t-$\Delta u/\sigma_{vo}$' plot and over the soft to very soft clay area in the q_t-B_q plot. However, the variation in f_s for Senneset et al. (1989) shows that the soil can be classified as stiff clay-silt.

3.2 *Onsøy soft clay site*

Seven different cone penetrometers from five manufacturers were used in the comparative testing program and it was concluded that u_2 was the parameter that showed better repeatability, followed by q_t which generally varies somewhat more (Lunne et al. 2018). Some of the cone types give good repeatability for f_s readings, while some show relatively large variation.

When looking at the derived CPTU parameters in the soil classification charts, the following aspects are observed (see Figure 1):

- In Q_t-B_q and Q_t-F_r charts from Robertson (1990), the soil type is classified in soil types 1 and 3 (sensitive clay-clay) independently of the scatter in any of the CPTU parameters. However, for Q_t-F_r chart, when the scatter is in the u_2 and f_s parameter, the data moves also towards a soil type 2 (organic soils).
- Regarding the charts of Schneider et al. (2008) (Q_t -$\Delta u/\sigma_{vo}$') and Senneset et al. (1989) (q_t-B_q), no difference is observed between the data sets showing largest scatter, for q_t and u_2 parameters. The clay is classified as clay (1b)-sensitive clay (1c) in Q_t -$\Delta u/\sigma_{vo}$' plot and soft-very soft clay in q_t-B_q plot. However, the variation in f_s for Senneset et al. (1989) shows that the soil can be classified as fine silt-medium clay.

3.3 *Halden silt site*

After testing five different cone penetrometers on this site, it was concluded that u_2 and q_t showed good repeatability between the measurements, while f_s gave the largest variation (Paniagua et al. 2020).

Figure 2 presents the CPTU data sets that give the largest scatter for each of the CPTU parameters in the soil classification charts. Observations made are as follow:

- In the chart Q_t-B_q from Robertson (1990), the soil type is classified in soil types 3 and 4 (silty clay-silt mixtures) independently of the scatter in any of the measured CPTU parameters. However, for Q_t-F_r chart, when the scatter is in the f_s parameter, the data mainly plots in two different soil types (either type 3 or 4). A similar observation applies when the scatter is in the q_t parameter but does not apply when the scatter is in the u_2 parameter.
- For the other charts relating Q_t-$\Delta u/\sigma_{vo}$' (Schneider et al. 2008) and q_t-B_q (Senneset et al. 1989), no difference is observed (i.e., both CPTU data sets plot on top of each other in roughly the same soil types: silts (1a)-transitional soils (3) and silt-fine silt, respectively. An exception is observed when the scatter is in u_2 for the Schneider et al. (1998) plot, where the data sets tend to move to neighbouring soil types (one to soil type 3 and the other one to soil type 1a).

3.4 *Øysand sand site*

The CPTU parameters from nine cone penetrometers types tested showed results more dependent on the varying soil conditions for the site. Quinteros et al. (2019) explained this as consequence of the depositional history of the site and the influence of the deltaic foresee beds dipping at an angle of 20-25 degrees. By adjusting the CPTU results in depth, the sand layers appeared to be more homogenous. The relative variation in q_t and u_2 was small and for all practical purposes negligible. However, sleeve friction results showed a large scatter between the different cone types. The variation in sleeve friction also seemed to increase with depth.

Comparison of CPTU data from Øysand on the soil classification charts leads to the following observations:

- In Q_t-B_q and Q_t-F_r charts from Robertson (1990), the soil type is mainly classified from soil types 4 to 7 (silt mixtures to gravelly sand) independently of the scatter in any of the measured CPTU parameters.
- A similar observation applies for the charts of Schneider et al. (2008) (Q_t-$\Delta u/\sigma_{vo}$') and Senneset et al. (1989) (q_t-B_q), where no difference is observed between the data sets showing largest scatter. The deposit is classified as transitional soils (type 3)-sands (type 2) in Q_t-$\Delta u/\sigma_{vo}$' plot and from silt to sand/hard stiff soil in the q_t-B_q plot.

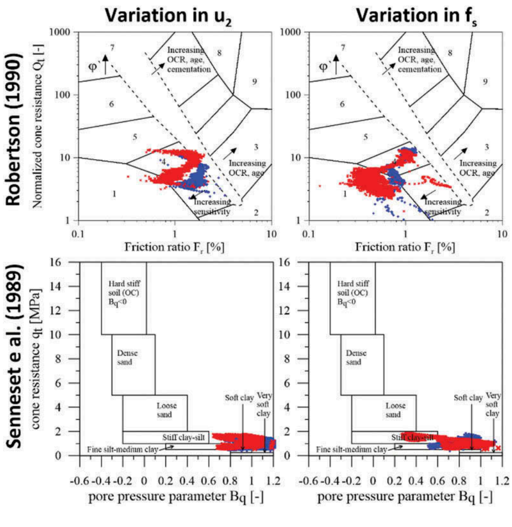

Figure 1. Two CPTU data sets from Tiller-Flotten plotted in two classification charts for two CPTU parameters showing extreme values (min-blue and max-red).

4 DISCUSSION AND CONCLUSION

Generally, previous research om NGTS sites has shown that the measured u_2 shows less variation for one cone type to another while, while q_t shows somewhat larger variation and f_s the largest variation. F_r shows much larger variation compared to B_q.

Therefore, this study has investigated the impact of using CPTU data from different cone types or manufacturers and its influence on the interpretation

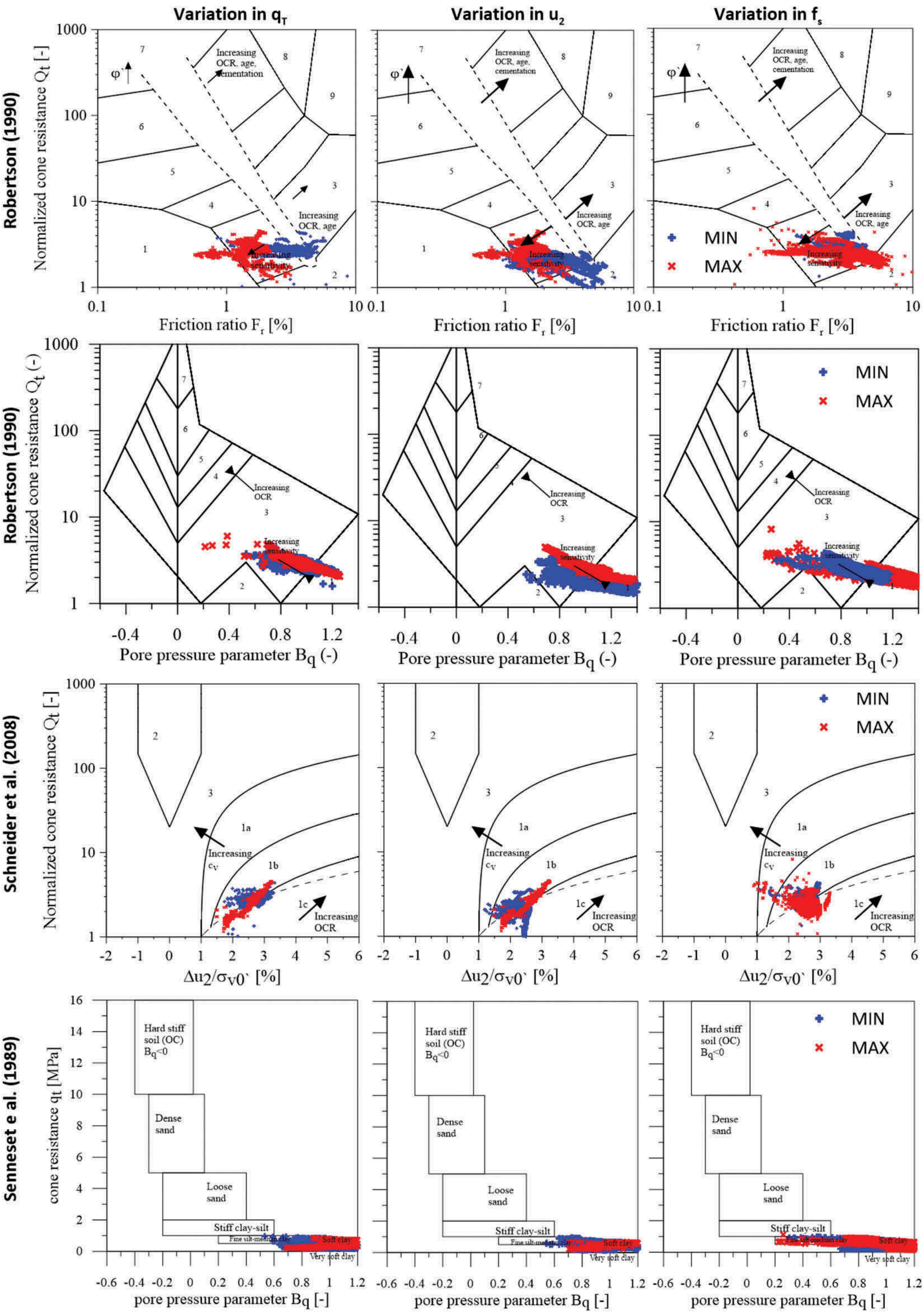

Figure 2. Two CPTU data sets from Onsøy plotted in the different classification charts for each of the CPTU parameters showing extreme values (min and max).

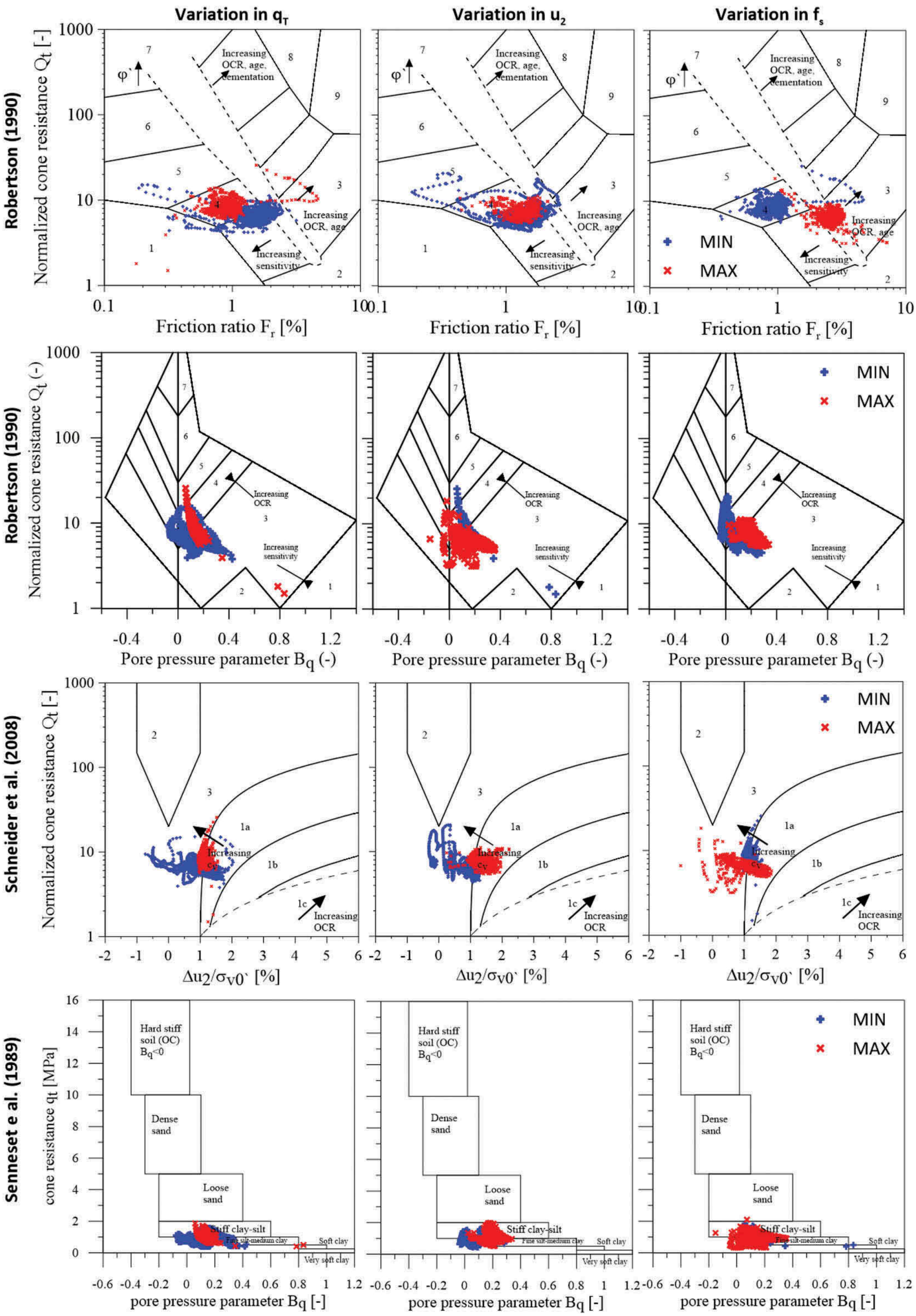

Figure 3. Two CPTU data sets from Halden plotted in the different classification charts for each of the CPTU parameters showing extreme values (min and max).

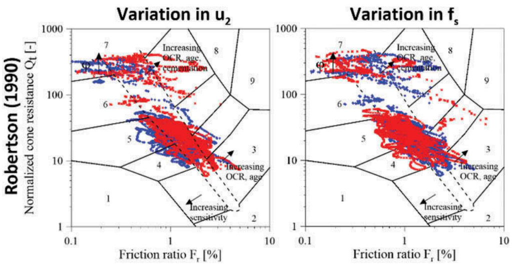

Figure 4. Two CPTU data sets from Øysand plotted in two classification charts for two CPTU parameters showing extreme values (min-blue and max-red).

of soil behavior. The most common soil classification charts have been used in four different soil types.

In general, soil behavior charts using pore pressure measurement and/or derived parameters involving u_2 seem to show less variability in soil classification between the different charts and all soil types. A similar trend is also observed for the cone resistance. In other words, the variation of u_2 and q_t between data sets for a defined soil type do not seem to give a different soil classification in the charts studied here.

The previous observation does not apply when using charts based on sleeve friction measurements. This was highlighted for the Halden silt when the classification chart involved a parameter derived from f_s. It seems that the variation in f_s for Tiller-Flotten clay and Onsøy clay does not have such a strong impact in the classification of the material using the different charts. This seems to also apply for Øysand sand, however, the observations for this site could be influenced by the natural variability of the deposit and therefore it is difficult to conclude.

Finally, due to the large uncertainties with the f_s readings, once should be careful using this parameter, and F_r, when interpreting soil parameters for design. Since the measured u_2 appear to frequently be the most reliable parameters it should be used in addition to q_t for deriving soil parameters.

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