

Soil Classification Chart based on MWD parameters

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ABSTRACT: Many geotechnical investigations require the drilling of a borehole for sampling or in preparation of the test itself and the analysis of this drilling process has become more popular in recent years, a practice known as Measurement While Drilling (MWD). Various parameters are monitored in the drill rig, such as advance rate, torque and downthrust-pressure, as these parameters can correlate with different soils. However, due to the large amount of variability inherent to the drilling methods, no method of classification has been devised to take advantage of all the data collected. This paper proposes a method of normalizing the measurements of the machine parameters, reducing the influence of the operator's decisions and bringing forward the soil's response to the drilling process. By analyzing the parameters of penetration resistance and shear resistance, the differentiation of the different soil types and their classification becomes possible. A chart is presented, inspired by the one proposed by Robertson et al. (1990), and data from several drillings is used to validate it and establish ranges for the different soil types. Measurements from the pressure in the machine's hydraulic systems, the usual way of monitoring drilling parameters, and also more precise measurements using sensors atop the drill string are used to validate the method.

KEYWORDS: Measurement while drilling, geotechnical engineering, ground investigation, soil classification, in situ testing.

1 INTRODUCTION

The safe and effective design of foundations for any kind of construction project is dependent on a good model of the underlying soil layers. An investigation campaign is then required to gather information about the terrain through a variety of methods that can measure soil characteristics directly in situ or collect samples that will be then tested in a specialized laboratory.

One of the many in situ methods available to the geotechnical team is the Measurement While Drilling (MWD) technique. This rapid method can be employed in a large variety of soils as a complement to other more time-consuming methods and consists of recording the machine parameters of a drill rig as it drills through the terrain, creating a log of the drilling process as a function of depth. The drillings are usually only a few centimeters wide and, especially in France, done in preparation for pressuremeter tests. Typically, the parameters measured are the advance rate, downthrust pressure, holdback pressure, torque, rotation speed. A fluid is commonly used to stabilize the hole during the drilling process, be it simply water or bentonitic mud with or without the addition of polymers, the injection pressure and injection rate is also recorded. This fluid is also responsible for cooling down the drill bit and removing debris (Kreziak and Pioline, 2005; Reiffsteck, 2010).



Figure 1. Geotechnical drill rig

The technique is the only way of recuperating any information about the terrain while destructive drilling, as the drill effectively destroys the terrain through a combination of mechanisms as it advances and samples cannot be collected for laboratory testing. Even if the recorded parameters don't directly measure a characteristic of the soil, they are considered to provide information on the soil's properties. Only the downthrust pressure, rotation speed and injection rate are directly controlled by the driller, meaning that the other parameters will change in response to the terrain's resistance to the drilling process, with larger variations expected during the transition between soil layers. However, all parameters are interdependent, and it can sometimes be difficult to determine if a change in the logs is due to the soil's heterogeneity or to a change in the way the driller piloted his machine.

Multiple researchers have put forward proposals of compound parameters like Somerton's index or the Specific Drilling Energy, calculated from the base parameters and designed to reduce this complexity by eliminating the driller's influence from the logs and aggregating the multiple logs into a single curve. Reiffsteck et al. (2016) proposed a set of compound parameters that would quantify the drilling resistance and friction encountered by the drill bit with normalized values. These parameters were inspired by those created by Robertson (1990) for his soil classification chart based on Cone Penetration Tests (CPT), shown in Figure 2.

This chart, widely used in the geotechnical world, uses the cone resistance q_t , lateral friction f_s and the pore pressure u_2 to calculate the normalized parameters for cone resistance Q_t and friction ratio F_r .

$$Q_t = \frac{(q_t - \sigma_{v0})}{\sigma'_{v0}} \quad (1)$$

$$F_r = \frac{f_s}{(q_t - \sigma_{v0})} \quad (2)$$

Where σ_{v0} is the vertical earth pressure and σ'_{v0} is the effective earth pressure. CPT data differs significantly from MWD data in that the cone penetrates the soil at a steady rate, without rotation and using standardized machinery. Meanwhile, MWD has more variables to contend with by introducing rotation into the process, by allowing the driller to

manually adjust the downthrust and rotation speed used, and by using drill bits designed to mechanically crush or shear soil particles while the cone only pierces the terrain and moves the grains aside. These added variables allow the drill rig to effectively drill through a larger variety of soils and even soft rocks like marls and limestones but also greatly increases the complexity of the subsequent analysis.

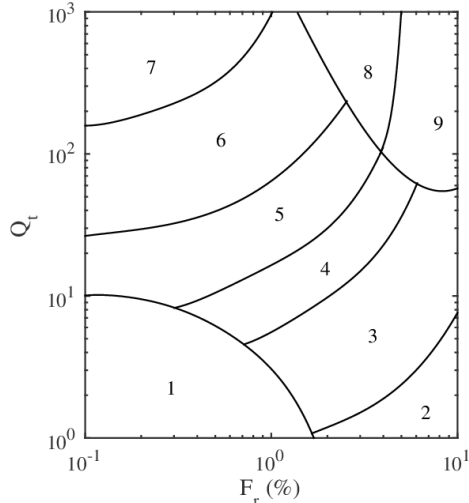


Figure 2. Soil classification chart by Robertson (1990)

Most of the methods of analysis aim to identify the depths of each soil layer encountered by quantifying the energy or work per volume spent during the drilling process (Moussouteguy, 2002; Viana da Fonseca, 2007; Wu et al., 2022; de Oliveira Souza et al., 2024) or simply by visually correlating the drilling logs with other investigation results, while not directly determining the soil type. The proposal by Reiffsteck et al. (2016), however, was to create a chart that could distinguish a soil's granulometry and compacity much like Robertson's chart for the CPT.

This new method needs to account for the larger number of variables present in MWD, as the downthrust can vary and the assembly rotates. The advance rate is thus used to normalize the downthrust and the rotation speed does the same for the torque measurements, even if the resulting parameter isn't dimensionless. With this, the drilling resistance Q_t and friction ratio R_f are calculated by Equations 3 and 4, respectively.

$$Q_{t,MWD} = \frac{(P_E - \sigma_v)/u}{\sigma'_v} = \frac{P_E - \sigma_v}{u \cdot \sigma'_v} \quad (3)$$

$$R_{f,MWD} = \frac{T/N}{(P_E - \sigma_v)/u} = \frac{T \cdot u}{(P_E - \sigma_v)N} \quad (4)$$

Where the effective downthrust P_E and the total vertical stress σ_v are in *kPa*, the advance rate u is in *m/s*, the rotation speed N is measured as the linear velocity in *m/s* at the outer edge of the drill bit and torque T is in *kN.m*.

In this paper, this classification method is tested by analyzing drillings from multiple campaigns throughout Metropolitan France.

2 METHODOLOGY

Various geotechnical investigation campaigns made in France by Groupe Fondasol were used in this analysis. Every point in the drilling logs analyzed was categorized according to the stratigraphy defined by the project's geotechnical lead into

simplified categories by granulometry: clays, silts, sands, gravel or marl.

The data was then filtered with a moving median filter to eliminate any incongruous measurements that may appear during drilling stoppages. For each of the drilling parameters, the median value was calculated for any given depth considering the 10 measurements above and below that point. If this median differed from the actual measurement by more than 30%, the measurement was considered incongruous and replaced by the median value for that interval.

The data compiled in these investigations, apart from the advance rate, was the pressure measured in bars in the hydraulic circuits of the drill rigs. These values had to be converted by taking into account the yield of the various hydraulic components. Consulting the maintenance manuals for each of the machines used in the investigations, simple linear correlations were sometimes given by the manufacturers to estimate the torque and rotation speed from the pressure delivered to the rotation head. No such estimations are given for downthrust, so the pressures measured in bars were directly converted into *kPa* which means a 100% efficient transfer of force had to be assumed for the translation mechanism. Finally, σ_v was estimated based on average unit weights for each type of soil.

The values of drilling resistance and friction ratio were then calculated using Equations 3 and 4. The data point were then plotted in a log – log graph, much like the one presented by Robertson (1990) and then revised by Robertson (2009) separated by their identification. This was done with the intent of determining zones in the graph that characterized a given type of soil, creating then a classification chart.

3 RESULTS AND DISCUSSION

The first campaign analyzed was realized in the north of Paris, in the city of Aubervilliers and had 12 destructive investigations done up to depths of 45m. There, drillers found a superficial layer of gravelly sand between 3 and 5 meters deep, followed by a layer of marl to sandy marl down to 22m in depth and then second sandy layer. The first layer was identified as anthropic in nature, while the following two are part of the Parisian Basin geological formations.

Observing the graph in Figure 3, it can be seen that the points classified as marl sit in between two groups of points labelled as sand. As the two sandy layers were depicted in different colors, it is visible that the all points relative to the infill sandy layer were to one side of the marl points, and the deeper sandy layer was on the other side.

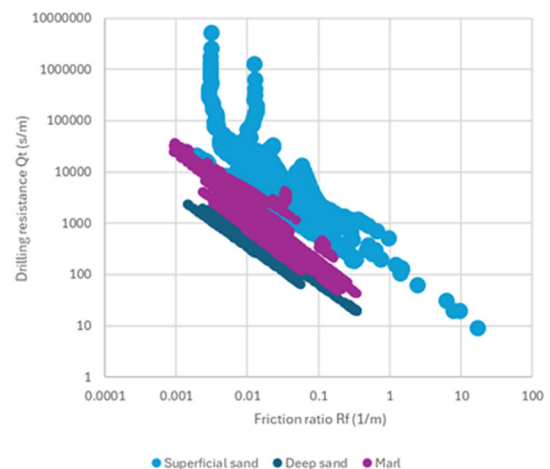


Figure 3. Point clouds representing the different soils in Campaign 1.

This separation might be due to different compacities in between the layers, which should be expected as the equations try to quantify the drilling resistance encountered. However, with the way the marl points are nested in between them, it seems the points were separated by depth. The use of the rotation pressure to estimate both the torque and the rotation speed probably affected these results and caused this distribution. As both variables are derived from a single data point, the hydraulic pressure at the rotation motor of the drill rig, both logs are directly proportional when they should be inversely proportional. From the logs and reports filled after an investigation, the way it is currently done in France, there is no way of knowing which gear the driller selected for the rotation motor and how he adjusted the rotation speed during the process. This creates many unknowns that hamper a more detailed analysis.

The second campaign comes from the city of Mantes-la-Jolie to the west of Paris. There were 4 drillings that found a layer of gravelly sand infill 1 to 2 meters deep, then 9 meters of silty sand (alluvions) followed by limestone. As pressuremeter reports indicated a significant difference in soil strength between the infill and the alluvion layers, they were analyzed separately in the hope of identifying a similar pattern in the normalized drilling parameters.

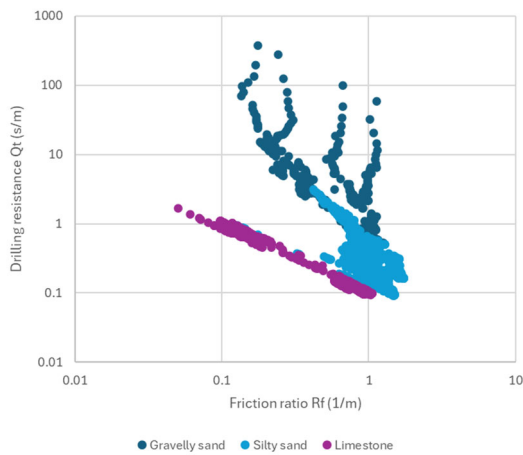


Figure 4. Point clouds representing the different soils in Campaign 2.

Again, the three different layers are seen to occupy different zones of the log-log space on Figure 4, with the silty sand point being particularly concentrated in one area while the gravelly sand and limestone have larger dispersions. However, the points seem to once again be organized according to their depth along an axis from the top-right to the bottom-left corners. In both Figures 3 and 4, the values calculated for Q_t don't seem to correlate with the soil's resistance to drilling, as the superficial layers have higher values than deeper ones.

A third campaign, this time in Biarritz in the southwest of France, was then analyzed. Even though only two drillings were made, this campaign was chosen because a special sensor was equipped on the drill rig that allowed the direct measurement of torque in kN.m, downthrust in kN and rotation speed in rpm. The stratigraphy encountered on site was that of alternating layers of clayey sand and sandy silt on top of marl 25.5 meters deep.

Figure 5 shows a much clearer separation between the soil types encountered in the investigations than Figures 3 and 4. This separation follows expectations, with marl (a soft rock) presenting the highest drilling resistance and the silt (cohesive material) having higher friction. There is some overlap between the sand and silt groups, but this could be due to

erroneous classification at the transitions between the layers or some heterogeneity in the soil like a sand lens inside the sandy silt layer. This enforces the importance of having accurate measurements, as the torque and rotation speed didn't need to be estimated from a single value of hydraulic pressure. As discussed by Peronne et al. (2021) and Caplane et al. (2024), the hydraulic pressures are good indicators of the actual drilling parameters for the type of quick analysis MWD is typically used for, but they are not accurate enough for this type of more involved analysis.

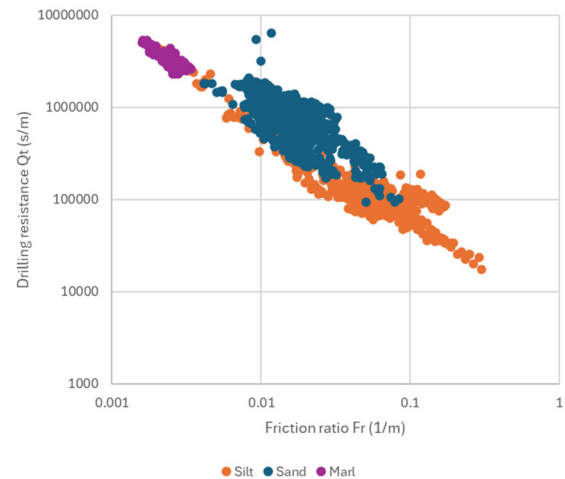


Figure 5. Point clouds representing the different soils in Campaign 3, with measurements from the special sensor.

For comparison, Figure 6 shows the point distributions for the same investigations shown in Figure 5 but this time with the normalized parameters calculated from the measurements of hydraulic pressure. This time, almost all points align in a curve, something that wasn't seen in the other campaigns. It is not clear why this graph doesn't look like the ones in Figures 3 and 4, it may be due to differences in the drill rig architecture or a maladjusted sensor.

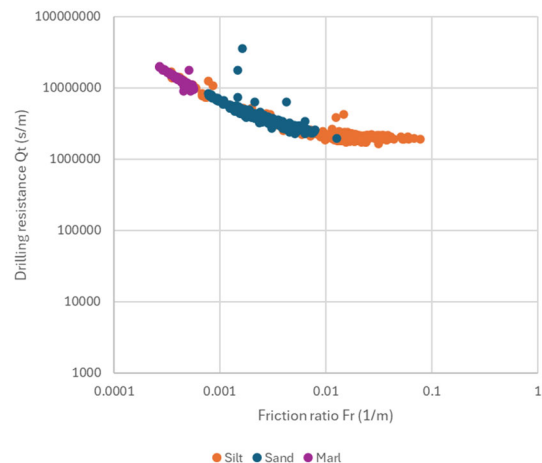


Figure 6. Point clouds representing the different soils in Campaign 3, with conventional measurements

From the results shown in Figure 5, a tentative chart can be drawn indicating the areas related to fine soils, sand and soft rocks. This chart is shown in Figure 7. More drillings on different sites with different geologies are necessary to confirm these divisions and to increase the classification categories. It is also important to note the need for the correct type of measurements.

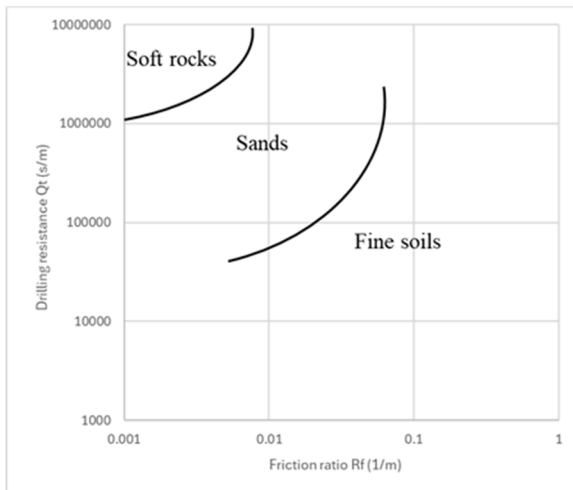


Figure 7. Tentative classification chart based on MWD data collected with a special sensor.

4 CONCLUSION

This paper presented a proposal for a classification chart based on Measurement While Drilling (MWD) data. The chart, modelled after the chart created for CPT investigations by Robertson (1990), uses two normalized parameters called drilling resistance and friction ratio and plots them in logarithmic scale. Two types of MWD data were analyzed with differing results: one used the hydraulic pressures in the rig's mechanisms while the other had used a special sensor to directly measure the torque, rotation speed and downthrust delivered to the drill bit. Results were inconclusive for the first set of data while something much clearer was found during the analysis of the later set, evidencing the need for accurate measurements and that information is lost when only the pressure in the rotation motor is measured, not the rotation speed and torque per se.

A tentative chart was drawn based on these results, separating three areas related to marls or soft rocks in general, sands, and silts or fine soils in general. This would allow for soil classification based on MWD data in campaigns where other types of geotechnical investigations weren't available or have inconclusive results, ultimately leading to a more accurate model of the local geology. More drillings are needed to further expand this categorization, to test it in different geologies and to evaluate the influence of different drill rigs and drill bits on the data collected. Another aspect to be analyzed is the influence of hydraulic percussion on these results, a variable often ignored in the drilling logs and that would change all other parameters.

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