Evaluation of construction phases through drilling rig data

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Background
Special foundation industry is characterized by the use of highly sophisticated machinery for the realization of geotechnical systems such as piled rafts, retaining walls and slabs for excavation pits, cut-off walls for levees and embankments or ground improvement solutions. Rigs can vary in size, weight, and power and can be provided with several drilling tools to cope with the different soil conditions (e.g. clay, sand, rock) and the different geometries of the elements to be built at the site (e.g. micro-piles, large-diameter bored piles, diaphragm walls, anchors). Due to the challenging construction procedures, various types of sensors have started to be mounted on the equipment in the last decades to monitor the behavior of some important machine parameters and to inform rig operators about the on-going process and the status of their devices. Information such as depth, start and end installation times, crowd force, hydraulic pressure, temperature and many other details are available nowadays for most of the existing special foundation techniques. Furthermore, the importance of data logging is also confirmed by norms, which for some methods define the reaching of a certain threshold level for a predefined set of parameters as a standard criterion to assess the success of the works or to identify hindrances or obstacles.

Production and machine data are typically transferred to a server of the manufacturer by a modem directly placed in the cabin and additionally saved as text files on the on-board computer. A file is initially generated after the rig operator introduces some essential features related to the next element to be created (e.g. name of the jobsite and of the element) and presses a start-recording button on the main control touch-screen display. The logging ends once the element is finalized and another stop-recording button is pressed. The records can be subsequently retrieved with a USB-stick/CF-card or downloaded from the server of the manufacturer.
Despite the regular collection of this type of documentation at the jobsite for contractual purposes, not much interpretation is carried out on the monitored values, which are usually visualized in profiles plotted over time and/or over depth. For example, the investigation of gross and net performances along with quantity and quality analyses are normally not included in routine practice, but, on the other hand, they become strategically valuable when claims or discussions with other stakeholders arise.

It is worth noticing that circumstances exist where reviewing and examining the recorded data turns into an extremely time-consuming activity, which requires unexpected efforts due to the complexity of the installation sequence. The creation of bored piles is one of these cases, the continuous alternating of several actions/movements of the rig being the most difficult aspect to be distinguished from a first look at the behavior of the production parameters. Most of Züblin Ground Engineering projects actually involve piling works and, for this reason, a research focused on the possible use and interpretation of data collected from piling rigs has recently started and has already contributed to a deeper understanding of this construction procedure from several points of view.

Project description
The project selected for this study is the Kombilösung project in Karlsruhe implemented by building owner “Karlsruher Schieneninfrastruktur-Gesellschaft” (KASiG). This is an active jobsite intended to further develop the public transportation network of the city by 2021. In this context, a new cut-and-cover tunnel for motor vehicles with a length of approximately 1850 m is currently under construction by Züblin Spezialtiefbau GmbH. The tunnel is conceived as a watertight rectangular frame composed of several concrete blocks located within an excavation pit supported by impermeable diaphragm walls and secant pile walls retained by 3 to 4 layers of tie-back anchors. The bottom of the excavation pit is sealed by means of a slab obtained by deep injections of soft gel with a deepest treated level of 21 m below ground level. During site operations, the groundwater-table is deepened by means of wells.
situated along the perimeter of the tunnel, which are then converted into dewatering wells once the bottom of the excavation is reached.

Figure 2: Liebherr LB36 operating in the Kombilösung project (Karlsruhe)

The secant pile wall is produced in accordance with the pilgrim step system by using two Liebherr LB36 drilling rigs. The piles have a diameter of 1.2 m and a depth comprised between 15.0 and 23.0 m with a center-to-center distance of 0.90 m. Due to the granular nature of the soil, the support of the wall is guaranteed by casings for the whole length of the drilled hole. Water is used as drilling fluid. In order to avoid possible filtration effects at the pile toe, the fluid level inside the casings is always maintained higher than the outside groundwater level. A double-cut rock drilling bucket is mainly adopted to achieve a high performance in the dense sandy and gravelly soil layers encountered in the area.

Production data have been collected from one of the two Liebherr rigs employed in Karlsruhe. Both were equipped with the Liebherr proprietary software PDE (Prozessdatenerfassung), which allows the logging of several parameters on a text file during the installation of bored piles. The recording frequency was set to 1 Hz. Among the different information that can be stored in the log-files, particular consideration has been given to:

- depth (from a predefined zero-level – in m);
- drilling pressure (oil pressure of the hydraulic engine at the rotary drive – in bar);
- crowd force (force applied by the crowd winch to the sledge where the rotary drive is placed – in kN);
- torque (torque applied by the rotary drive – in kNm);
- rotation speed (rotation speed of the rotary drive – in rpm).

It is worth mentioning that a time representation of the measured values generally provides an unbiased and more meaningful understanding of the working activities than that obtained from depth profiles. Moreover, misinterpretations or false assumptions are less likely to occur.

Figure 3: a) identification of construction operations based on video recorded at the site; b) recognition of construction operations based on depth profile and data analysis. Yellow: C1; Green C2; Blue: C3; Grey: C4, and Red: C5.
Time diagrams gave the opportunity to study in detail (second per second) the status of the rig throughout the construction process and to automatically deduce the corresponding phases based on the behavior of several properties within a predetermined time interval. This kind of interpretation is directly linked to performance issues and, in particular, to the overall dependences of performance from soil conditions, excavation tools, rig operators, and other external factors.

Furthermore, by combining the above-mentioned parameters, it was also possible to compute the specific energy necessary to drill with a selected tool 1 m³ of a certain type of soil and to refer it to the results of in-situ geotechnical investigations like cone penetration tests (CPT) or standard penetration tests (SPT).

Discussion and Results
At present, criteria have been pinpointed to distinguish predefined phases during the installation of fully cased bored piles at the KASIG project in Karlsruhe.

The operations were classified in five groups as follows:

C1. movement of the drilling rig (positioning, swinging, fast movement of Kelly bar, emptying of drilling bucket etc.);

C2. handling of casing (introduction or extraction of casing in/from the soil, connection/disconnection of casing pieces etc.);

C3. drilling (penetration of drilling tool into the soil);

C4. other activities related to the rig or tools (refueling, increase of level of drilling fluid inside the casing, cleaning of tools, standstill);

C5. other activities unrelated to the rig or tools (introduction of reinforcement in the hole and concreting).

Figure 4: combination of production parameters for the definition of the criteria necessary to automate the recognition of drilling operations.
The criteria were based on the simultaneous and combined interpretation of the behavior of several production parameters considered in time intervals where the operations were effectively conducted. To clarify dubious situations, the phases were further compared with a video filmed at the jobsite.

The rules primarily took into consideration depth as main parameter, accounting for other details only when doubts about the nature of the activities arose. A clear example shown in the diagrams over time is given by the last portion of each drilling step, which was frequently described by a steady reduction of rotational speed and simultaneous increase in torque.

Machine data were also used to calculate the specific energy ($E_s$) required to drill 1 m³ of soil. The formula adopted is that proposed by Teale (1964):

$$E_s = \frac{F}{A} + \frac{2\pi NT}{AV}$$

where $F$ is the crowd force (in kN), $A$ the drilling section (in m²), $N$ is the rotation speed (in rps), $T$ is the torque (in kNm), and $V$ is the penetration rate (in m/s). Start and end times along with start and end depths were obtained for each drilling step in order to determine the corresponding penetration rates. Values of crowd force, rotational speed and torque were averaged over the duration taken by every stage of advancement into the soil. The resulting specific drilling energy varied between 400 MJ/m³ and 1300 MJ/m³.

The definition of a relationship between the computed specific drilling energy and the type of soil was attempted based on the SPT results available from the preliminary investigation campaign. It is important to note that a correlation between specific drilling energy and strength parameters of the soil would be presumably affected by a higher level of unreliability since mechanical properties of granular materials (e.g. density state, peak friction angle) are often derived from the outcomes of in-situ geotechnical tests and the application of additional empirical equations found in the international literature.

In this study, the number of blows from SPT tests ($N_{SPT}$) was first corrected for field procedure (hammer efficiency, bore-hole diameter, rod length and type of sampler) according to ASTM D1586-99 and then normalized to account for the overburden pressure with the formula of Liao and Withman (1986).

Figure 5: empirical correlation between specific drilling energy and corrected SPT-values derived from the data collected in Karlsruhe.
The regression algorithm implemented on the experimental data resulted in a linear function approximately passing through the origin of the axes (no energy required to drill in materials with \( N_{SPT} = 0 \)) and characterized by a relatively high coefficient of determination (\( R^2 = 0.75 \)). This correlation represents a first tool to relate the results of in-situ geotechnical investigations to the specific energy necessary to drill in granular soils of medium to high density under saturated conditions by means of a double-cut drilling bucket.

Complementary studies are clearly required to confirm the validity of the relationship and to calibrate the equation depending on other construction procedures, drilling tools and types of soils.

**Conclusion and way forward**

Production and rig data collected during the works represent an essential information for a more comprehensive understanding of drilling processes. These details can be used to automate the recognition of the sequence of rig activities carried out at the jobsite. The automatic recognition of such phases is expected to support engineers to get a quick overview about net and gross performance by defining the duration of standstill periods and to analyze production rates associated to different piles constructed with the same/different equipment or by the same/different crews.

Data can also be utilized to determine correlations between in-situ test measurements obtained from initial geotechnical investigations and the specific energy required to drill 1 m³ of soil. When combined with performance, consumptions and wear & tear, relationships between specific drilling energy and soil type can be applied by tender engineers to prepare more accurate and reliable cost estimations of incoming projects. Additionally, by comparing curves referring to different tools in similar ground conditions, the most efficient drilling tool to be used in particular soils can be reasonably identified.

Specific drilling energy is foreseen to be used in the future as a direct sounding parameter in the course of the execution of bored piles to confirm the accuracy and trustworthiness of geotechnical reports and, ideally, to update the types and levels of soils at the building site. This indirect measurement of the actual stratigraphy is supposed to represent a valuable negotiation instrument for contract managers in the resolution of disputes or claims with other involved parties.

The research conducted so far has taken into consideration only one construction project where fully cased piles were installed into medium to high dense granular soils. However, the promising results observed until now encourage further extensive implementation of methods of analysis on production parameters.

Future developments will also try to combine rig data with different sources of information like that collected manually at the site by means of digital forms. This has the purpose of explaining, for instance, the reason why standstills occurred or why the advancement in a specific soil layer was slower than assumed.