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Construction and testing at the same time - New technologies in deep foundations

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ABSTRACT
The oldest method for estimating the capacity or resistance of a pile during construction is used for driven piles. In this method, the pile acts as a large penetrometer, and by counting the impact blows—each theoretically having the same energy—we can qualitatively understand the resistance for a predefined penetration depth of the pile. Over time, several empirical formulas have been developed to estimate the 'capacity' or 'actual resistance' of driven piles.
Modern systems, such as the pile driving analyzer (PDA), now provide accurate information about soil resistance. Additionally, various technologies are available for recording measurements during drilling. While this monitoring equipment provides accurate data on parameters like torque and forces, it does not directly yield pile resistance values. However, with a few load tests, these qualitative measurements can be transformed into quantitative data.
Some technologies have demonstrated cost efficiency in terms of materials, equipment, labor, and completion time, while also ensuring high-quality quality control/quality assurance (QC/QA) and reducing the carbon footprint. In this paper, we present two such technologies: Smart Cells and Expander Bodies, which provide direct resistance values
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1.- INTRODUCTION

The design of deep foundations inherently assumes that the process involves resistance estimation, which is not entirely accurate. This assumption has been widely demonstrated in prediction events, where even highly sophisticated design methods resulted in significant discrepancies compared to load test results. In some cases, the maximum and minimum predicted values differed by as much as 600%.
Given the various uncertainties in estimating a pile's service load—from soil parameters to the estimation methods used—it is crucial to recognize the high value of information recorded during pile construction/installation. This data reflects the actual conditions of the pile/soil system at each pile's precise location. Instrumented driven piles (e.g., using a PDA system) provide accurate resistance values; however, the same accuracy is not yet available for drilled piles.
Over the past 30 years, the use of electronics has increased, monitoring pile installation processes and measuring parameters like torque, tool penetration force, and penetration rate. These advances are beneficial for certain types of piles (e.g., full displacement and CFA piles), where multiple variables are continuously measured and recorded during drilling (i.e., measurement while drilling or MWD) to achieve a fairly accurate resistance estimation or, at least, a qualitative indication of it. When load tests are conducted, the installation data can be correlated within an acceptable range of variation. Qualitative data is then transformed into quantitative data. However, the integration and full acceptance of electronic records in practice are still lagging, even though the electronic data is highly reliable. It's also important to understand that the data obtained pertains to the mechanical drilling process and not a direct measure of the pile (as with driven piles).
The question remains: what can be done for other types of piles where the information retrieved during the installation process cannot directly correlate with pile resistance (e.g., depth, diameter, concrete volume, torque, penetration velocity, and integrity)? The only reliable solution would be to perform a loading test, but it is neither feasible nor cost-effective to perform loading tests on 100% of the piles. So, what can be done to provide insight into at least the toe resistance of every pile shortly after construction? Two technologies are presented that offer a positive solution to this challenge.

2. SMART CELL

2.1. *Introduction*

A Smart Cell (SC) is a closed-type tip post-grouting device that is attached to the bottom of the steel reinforcement cage of drilled shafts (Figure 1 a) and acts as a hydraulic jack to mobilize the end resistance of the drilled shaft irrespective of the type of ground condition. Control of the grout is maintained within the device during grouting and uniform stress is imparted across the entire base area simultaneously. The SC device is equipped with telltales to know the movement of the cell during injection, so a load-movement curve can be developed after finishing the injection. The key objectives of tip post-grouting are to improve the stiffness of the in-situ soil, improve the shaft's nominal axial resistance, better align the load transfer curves, and get geotechnical information about each pile. Tip post-grouting should not be used instead of proper execution and good quality workmanship in the construction of a drilled shaft.) The SC devices are used to enhance performance and reduce uncertainty. Using the measurements of the grouting operation, the premobilization of axial resistance and induced load imparted into the drilled shaft and to the soil beneath the base will be discussed. In addition, the Smart Cell acts as a testing device (Figure 1b).

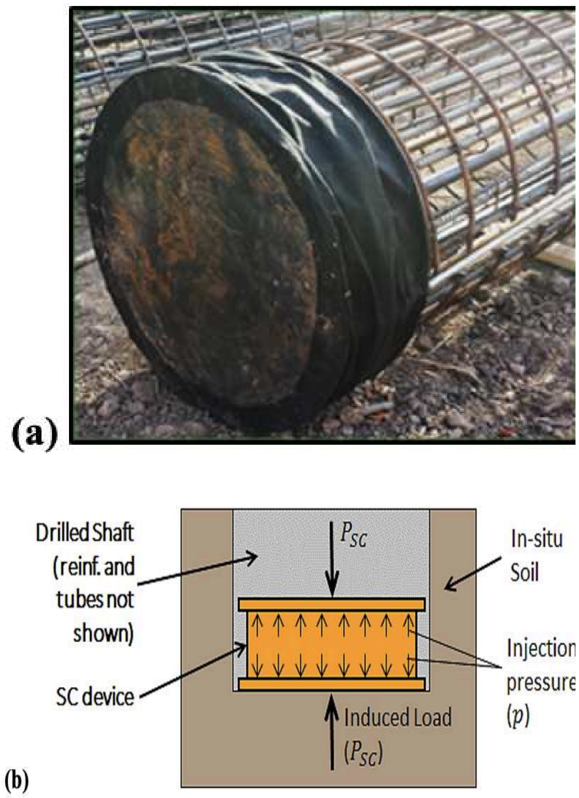


Figure 1. (a) Photograph of a Smart Cell attached to the bottom of a steel reinforcement cage, and (b) graphical depiction of grouting and induced loading (Marinucci et al, 2021)

2.2. *How it works*

The generalized load transfer behaviors of a conventional (i.e., ungrouted) drilled shaft in cohesionless and cohesive soils loaded in axial compression are presented in Figure 2.

The side resistance of a drilled shaft will mobilize its peak strength after a normalized vertical displacement, (i.e., vertical displacement, δ_v, divided by the diameter of the drilled shaft, D_p) of about 0.2% to 0.4%, regardless of soil type. Chen and Kulhawy (2002) presented that, at a normalized displacement of about 0.4%, approximately 50% of the failure threshold axial resistance is mobilized, where about 90% of which is from side resistance and 10% is from end resistance.

The toe or tip resistance does not fully mobilize until a much larger $_{vn}$ have been realized: about 4% to 5% in cohesive soils and about 10% (practical limit) in cohesionless soils.

At $_{vn}$ of about 4%, Chen and Kulhawy (2002) reported that 100% of the failure threshold axial resistance is mobilized (i.e., ultimate state for cohesive soils and serviceability state for cohesionless soils), where about 76% of which is from side resistance and 24% is from toe resistance. $_{vn}$ is defined as

Displacement/Shaft Diameter (%)

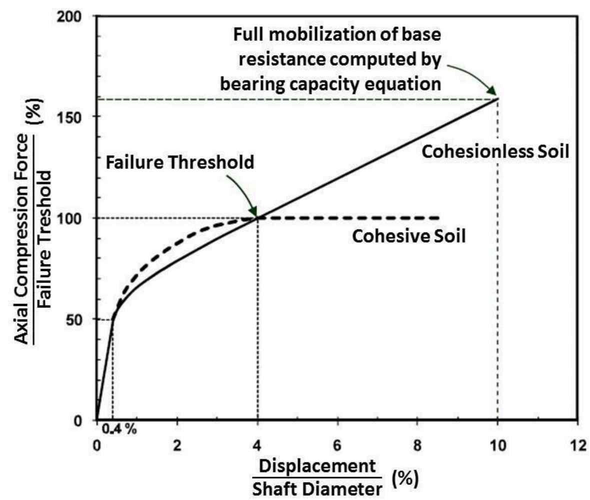


Figure 2. Normalized load-displacement curves of drilled shafts in axial compression in cohesive and cohesionless soils (mod. after Brown et al, 2018)

For cohesive soils, this is the maximum axial resistance that can be achieved. For cohesionless soils, however, the maximum axial resistance is achieved at much larger normalized displacements (governed by bearing capacity), thereby mobilizing about 159% of the failure threshold axial resistance, where about 76% of the axial resistance is from side resistance and 83% is from end resistance. For practical design purposes, the end resistance is typically capped at $_{vn}$ of about 10%. Due to this strain incompatibility in achieving the peak strength, utilizing the full side and end resistance in design is not realistic and designers have typically neglected one component or reduced the relative contributions of side and/or end resistance. Design is clearly and fundamentally essential; the long-term performance of a drilled shaft is mainly governed by the construction technique(s) utilized and the quality of the craftsmanship applied to install the foundation element.

Tip post-grouting is a technique used to pre-mobilize the axial end resistance of the shaft as well as to mitigate against a soft bottom condition and stress relief due to installation. This technique is used to inject a neat cement grout, under pressure, beneath the base of a drilled shaft to improve its performance when subjected to compressive axial loads. It is accomplished using an open- or closed-type grout distribution device that is incorporated into the bottom of the steel reinforcement cage. For open-type systems (i.e., sleeve-port or tube-á-manchette systems), the grout is injected out of the supply tubes and into the surrounding ground around the tip of the shaft; conversely, for closed-type systems (e.g., Smart-Cells), the grout is contained within the expanding device and does not contact the ground directly (Figure 1b). The main differences when comparing a Smart Cell with other closed-type systems include larger displacements allowed by the SC device, continuous records of tip movement (i.e., generation of a load-movement curve), the possibility of evaluation not only of the tip resistance but also the shaft resistance, and the benefit of the information obtained during the injection.

1.3. *The SC as a testing device*

As mentioned, the SC provides direct information about the load-movement transfer of the pile toe, which is essential for QC/QA and for assessing long-term performance. The SC acts as a bi-directional testing device in 100% of the piles where installed, so QC/QA is much better than with traditional methods where testing is only performed on a small number of piles. When the results of a good-quality soil investigation are available, it is possible to define more accurate lengths of piles before starting the work. In addition, when combining the injection data with the soil investigation data, it is possible to confidently adjust the design where the injection pressure (force) and resulting toe movement can be compared to the soil data. Moreover, the stiffness of the pile response can be measured and the expansion of the SC provides a qualitative representation of the type of soil below the SC.

1.4. *Conclusions for SC*

During tip post-grouting the SC device can obtain field data for analysis (i.e., load-settlement behavior at the tip) for each outfitted shaft preload the soil and shaft (i.e., via induced load), pre-mobilize axial tip resistance, and recompact loose soil or debris (i.e., soft bottom condition)
Benefits that can be realized include:
-Optimizing design and improving performance (reliability)
-Stiffening the load-deformation response under working loads thus reducing post-construction settlement of the shaft
-Shortening of the constructed length of drilled shafts with
-Reduction of the overall cost of drilled shafts
-Achieve strain compatibility with the deformation between the shaft and the toe.
-Reduction in carbon footprint by using less resources (steel, concrete, machine time)

2. EXPANDER BODY (Broms et al, Berggren et al, Sellgren et al, Massarsch et al, Fellenius et al, Terceros et al., Eurocode 7 - CEN, Randolph et al.)

2.1. *Introduction*

The Expander Body (EB) consists of a folded steel tube, which can be expanded from 0.12 m to a diameter ranging from 0.3 m to 1.2 m, depending on the model (Figure 3). During expansion, the injection pressure and injected volume of grout are continuously recorded. Because of the electronically controlled expansion process, the horizontal soil stress, soil strength, and stiffness of the soil around the EB can be improved significantly.

2.2. *How it works*

The EB functions as a large-scale, large deformation, pressuremeter, which compacts the surrounding soil and provides information about stress-strain characteristics of the soil adjacent to the pile toe. An injection curve is generated for each EB, during which it is possible to identify different phases (Figure 4). According to cavity expansion theory and pressuremeter testing principles, it is possible to infer the type of soil based on the shape of the expansion curve. This information is used to assess whether the toe-bearing resistance has been achieved and to calculate the actual resistance provided by the EB. During expansion and with increasing diameter, the EB shortens in length and the surrounding soil moves to fill this volume to regain stress equilibrium. After injection, the soil below the EB base can be post-grouted during a second controlled grouting phase to increase the stiffness of the soil and the toe-bearing resistance of the pile (Figure 5). In this way, the resistance of each pile toe can be tested and verified. The innovative combination of the EB system with traditional drilled piles, continuous flight auger (CFA) piles, full displacement piles (FDP), etc. has increased service load, reductions in cost and construction time, improved QA/QC, and safer, economic foundations.

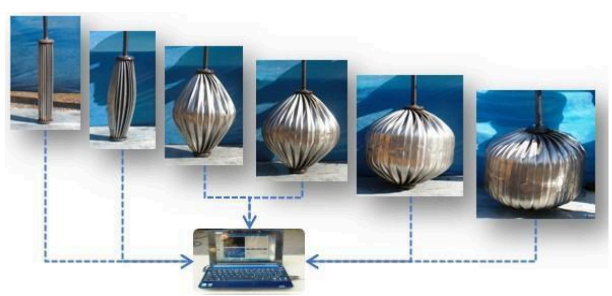


Figure 3. Different stages of the EB expansion (Incotec SA files)

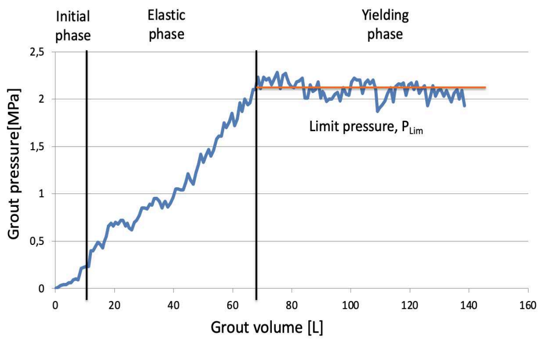


Figure 4 . Injection curve

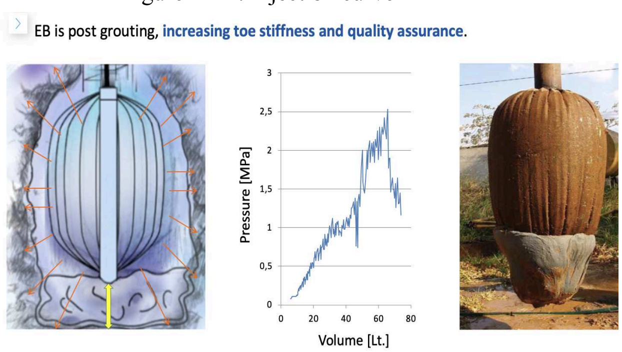


Figure 5 . Post-grouting process

The initial and final values of relative density, friction angle, stiffness, E modulus, G modulus, etc., are typical values obtained to explain the effects of the installation process. With FDP systems, cavity expansion theory has been proven to be a very reliable criterion. The drained expansion of a cylindrical cavity, the most common case with EBs, has solutions that have been proposed by different authors. Vesic (1972) proposed a general solution for soils possessing both cohesion and friction. Hughes et al (1977) assumed that the rate of volume change is constant during cavity expansion and is related to the peak angle of shearing resistance using the concept of stress dilatancy for very dense sands. Robertson and Hughes (1986) extended this work for loose to medium-dense sands. In general, the conclusions of several authors point out that the shear modulus describes a non-linear stiffness curve during expansion. For an EB, those concepts are helpful for the interpretation of the injection curves because, from a practical point of view, the limit pressure is the value used for the calculation of the toe capacity and the friction of the EB. Essentially, the estimate of the ultimate resistance of an EB is based on the pressuremetric method recommended by LCPC-SETRA (1985).

The EB base area used for design is the area of the EB fully expanded. The area used to evaluate the capacity after expansion is the real area based on the actual injected volume and a calibration curve for that EB model (Figure 5). This curve is very important when the full volume is not achieved because it is possible to deduce the real diameter of the EB based on the real injected volume, which allows the calculation of the resistance post-expansion.

2.3. *The EB used as a testing device*

As the initial, pre-expansion diameter is typically around 120 mm, the EB has been used as a soil investigation device for projects in which this technology has been selected. Installing an EB at the expected depth of the project before production works provides the limit pressure at the desired bearing level. With this value, it is possible to re-analyze the original design and adjust the design to match the real conditions. Depending on the size of the project, as a general rule, the recommended number of EB tests ranges between 3 and 6. If possible, static loading tests should also be performed on production piles to adjust the design even further, correlating the values of the injection pressure with the results of the loading tests.

2.4.- *Conclusions for EB*

During expansion, EB can compact the soil surrounding the toe, obtain and visualize data, real-time, about the soil conditions and foundation performance, perform QA/QC on 100% of the installed elements.

Benefits that can be realized when using an EB include:

-Increase in resistance between 50% and 600%, reduction of foundation construction time by 25% to 40%, and savings of 25% or more of the total foundation budget when compared to traditional methods

-Strain compatibility between the shaft and the toe

-Reduction in carbon footprint by using less resources (steel, concrete, machine time)

-Global experience across more than 8 countries and 40,000+ installed EBs.

3. CASE HISTORY

As a part of the 3rd Bolivian International Conference on Deep Foundations, a comprehensive pile testing program was undertaken at the Bolivian Experimental Site for Testing Piles, B.E.S.T. The main objective of the program. was to compare the results of static loading tests on piles constructed using different methods at a site where the geotechnical conditions would be documented by detailed investigations, using state-of-the-art testing and interpretation methods. The geotechnical conditions and the details on the piles, and testing arrangement, is presented in Proceedings Volume 2, Chapter 5. All field investigation records of the static loading tests are available for downloading at http://www.cfpbolivia.com/web/page.aspx?refid=113

The proceedings are also available at http://www.cfpbolivia.com/web/page.aspx?refid=163.

Considering the scope of this paper, Figure 6 and Figure 7 are presented. In both figures is shown the behavior of piles with no enhancement device, compared with similar piles equipped with Expander Body or Smart Cells.

Figure 6 shows the comparison curves of the head-down static loading test of three drilled piles, 620 mm in diameter, 9,5 m long (A piles). A1 is equipped with an

Expander Body, A2 with a Smart Cell, and A3 is a regular pile without any enhancement device.

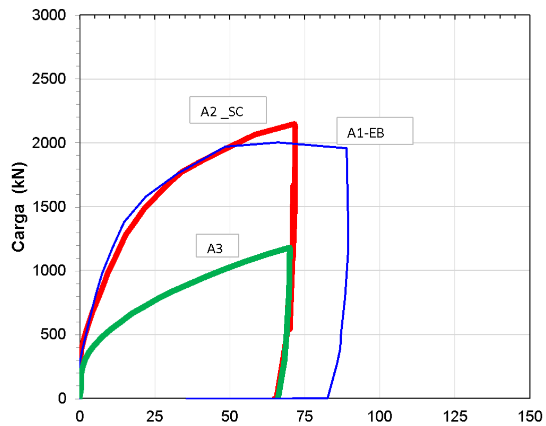


Figure 6 – Drilled piles

Figure 8 presents several behavior predictions and the real behavior of Pile A3 after the loading test. With this figure, we want to emphasize the magnitude of the problem of designing single piles with traditional methods. All the information is available in the links provided.

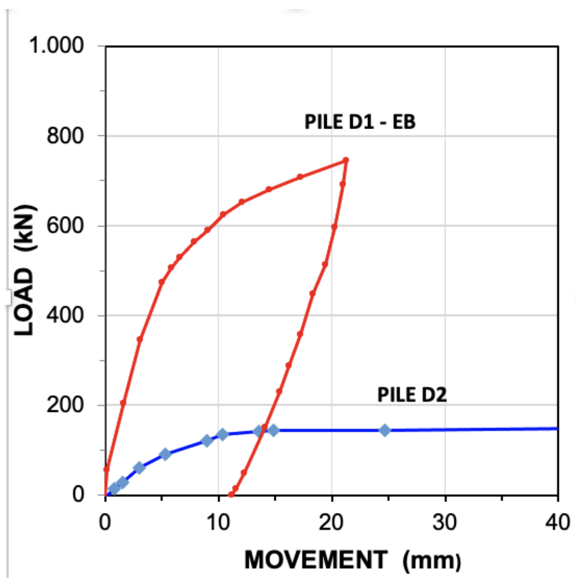
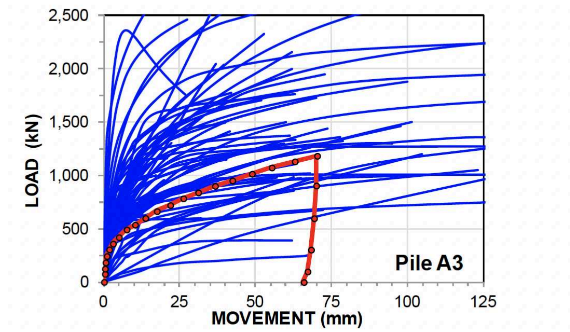


Figure 7



Pile A3. Predicted and actual head-down tests pile-head load-movements.

Figure 8

4. GENERAL CONCLUSIONS

The use of new technologies like the ones presented in this paper, has important benefits (see Fig. 6 and Fig. 7) if compared with traditional systems without them. The information provided is crucial for a more accurate real resistance value.

Nowadays the importance of having data on each installed pile is something out of the question and such systems generate the information on each pile. This is something that was not possible in the common drilled piles, constructed without modern monitoring tools. On the other hand, not using new technologies can result in serious under-designs or overdesigns, as shown in Fig. 8. This difficulty can be reduced by performing loading tests as part of the design. The SC is also a bidirectional cell, so measuring the tip resistance (at least) for 100% of the installed piles is possible.

The paper also shows that these systems generate, besides information, measurable economy, quality, and carbon footprint reduction, their uses are aligned with the necessities of the industry.

Table 4 shows a summary of the advantages of both systems.

Table 4, Summary of advantages

SUMMARY OF ADVANTAGES	
EXPANDER BODY	SMART CELL
Provides an efficient, enlarged-base pile base.	Soft bottom compaction
A high degree of quality control can be achieved, with information of the 100% of the pile toes. High quality information during the construction of the foundation	A high degree of quality control can be achieved, with information of the 100% of the pile toes and shafts. High quality information during the construction of the foundation
The post-grouting below the expanded pile toe increases soil strength and stiffness.	Preload of the pile
EB increases the pile toe resistance in a wide range of soils, from very loose, silty sands to dense sands and stiff clays, and soft rocks	SC increases the pile resistance in a wide range of soils, from very loose, silty sands to dense sands and stiff clays,gravels and rocks
Ccost-effective deep foundation solution	Predeformation of the soil with stiffnes increase
The construction time is reduced	The construction time is reduced
Pile capacity can be increased at least four times compared to conventional bored piles.	Design improvement and control
Allows to identify non detected soft soils	Cost efective deep-foundation solution
Carbon footprint reduction >50%	Carbon footprint reduction >50%
Provides stress information of the surrounding soil	Provides stress information of the surrounding soil

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