

A New Teaching Concept for Axially Loaded Piles

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Abstract. It is a common feature of teaching methodologies to divide the content into modules for lectures or book sections. However, these divisions are often not intrinsic to the real problems. Students, and consequently future professionals, may fail to bridge these artificial gaps, bringing into practice a mind-set organized by educational divisions instead of the functional demands of each problem. An example of this is the division between capacity and deformability of axially loaded piles, which follows the approach of regulatory manuals dividing stability and serviceability calculations. The real underlying mechanism is that pile resistance, both on the toe and along the shaft, is only mobilized through a certain amount of displacements. This is widely recognized and often mentioned in basic literature and general educational sources. However, it still features as a side note and is not directly incorporated in the calculation methodologies. This paper evaluates an instruction methodology to tackle this issue. Pile behavior is presented within a flexible framework that directly incorporates the concept of displacement dependent mobilized capacity. Through a straightforward formulation, based on the load-transfer method, general features, such as pile compressibility, residual loads and negative friction can be explicitly dealt with. Therefore, even though these different aspects may be presented individually, they can all be pulled together for an assessment of their interdependent effects on the pile response to axial loads.

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1. Introduction

Foundation engineering is arguably one of the most traditional branches of geotechnical engineering and a highly sensible feature of most infrastructure projects. As such, it has been a recurrent topic in engineering courses, from undergraduate to postgraduate levels, since the early days of the foundations field. Introductory geotechnics courses used to be limited to the discussion of shallow foundations. However, nowadays there is a clear demand for civil engineers to be knowledgeable about deep foundation systems, which can be applied in a far wider range of conditions than shallow foundations.

The dissemination of deep foundations can be attributed both to the advancements of the construction technology and an increase in demand. The first aspect has expanded the range of applicable soil conditions and the magnitude of the piles, with micro-piles in one end, reaching large diameter caissons and monopiles in the other.

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The construction productivity of these technologies has also been significantly improved by techniques such as continuous flight augers, static pile driving and screw piles. On the other hand, the increase in demand is a direct result of the developments in worldwide urbanization. This requires a complex range of infrastructure projects to be built ever more frequently. In this context, more often than not, the urban developments will reach regions of informal settlements with challenging infrastructure conditions and at the outskirts of the city, which may possess difficult conditions that have been previously averted.

2. State-of-Practice: Design and Education

The scientific profile of foundation design is based on a theoretical structure that is built around simple physical principles. Due to the characteristic repetitiveness of processes in the construction of foundations, an extensive empirical knowledge could be gathered and associated with these simple models, establishing a robust and reliable design process. This empirical association plays an important role in the general assessment of new design methods that cannot make use of the elements that were gathered in the decades of empirical experience. Therefore, although numerical analyses and new theoretical developments are slowly gaining more acceptance, in terms of state-of-practice design and regulatory systems, the traditional empirical methods are still the basis of most projects.

From the perspective of engineering education, deep foundations are an umbrella to a variety of topics. The traditional approach divides the design and the construction aspects of different piling methods. The design instruction starts from a set of common core principles, normally laid out around the example of axially loaded piles, advancing to more specialized branches, as laterally loaded piles, offshore foundations and piled-raft foundations. It should be noted that the design is where most academic sources and research efforts are focused, while the industry holds most of the know-how and developments of the construction techniques. This core-branches layout, where fundamental concepts from the common core are adapted to the more specialized branches, is present both in education and design methods. This stresses the importance of an effective instruction of the basic elements for the development of all topics of deep foundations. As mentioned, it is customary to present the basic concepts around the design of axially loaded piles, and the same will be done throughout this paper. The long-established methodology for teaching this topic follows three sequential points, namely axial capacity assessment, which is eventually divided between cohesive and non-cohesive soils, axial deformation and complementary aspects, such as layered soil profiles, pile compressibility and shaft/toe mobilization displacements.

This division is a common feature of teaching methodologies and it even follows the approach of regulatory manuals that distinguish between stability and serviceability calculations. However, this division is not intrinsic to the real mechanism of axially loaded piles. Students, and consequently future professionals, may fail to bridge these artificial gaps, bringing into practice a mind-set organized by educational divisions instead of the functional demands of each problem. A more verisimilar model is that the pile resistance, both on the toe and along the shaft, is only mobilized through a certain amount of displacements, eventually reaching a failure limit. This is widely recognized and often mentioned in basic literature and general educational sources. However, it still features as a side note and is not directly incorporated in the

calculation methodologies. The same can be said about the artificial chasm between the continuum from serviceability to ultimate limit states.

Therefore, this study presents an instruction methodology to tackle this issue. Pile behavior is presented within a flexible framework that directly incorporates the concept of displacement dependent mobilized capacity. Through a straightforward formulation, based on the load-transfer method, general features, such as pile compressibility, residual loads and negative friction can be explicitly dealt with. Therefore, even though these different aspects may be presented individually, they can all be pulled together for an assessment of their interdependent effects on the pile response to axial loads

3. New Teaching Concept: Groundwork

Before presenting the proposed methodology, it is important to contextualize the ideas behind it, namely the importance of model thinking, the recurrence of scaling factors for soil resistance and the elements' interdependence in the design of a deep foundation system. Engineering theoretical developments are mostly founded on scientific modeling rather than logical reasoning, and empirical evidence is extensively used to validate their conceptual and mathematical models. Consequently, it is essential for the users of these theories to understand the underlying models, their structure and limitations. Considering the objectiveness and pragmatism of engineering education, such abstract epistemological terms can be easily overlooked. To transfer this understanding within this structure, an instructor is better off adopting clear examples of fundamental interpretation models before moving on to scientific modeling.

The popular scheme of scientific methodology does not deal with the limitations of the observation phase. A model based on biased or limited observations will most likely deliver biased results. Examples concerning the limitations of our human senses, as our ability to see light only within the visible spectrum, tend to provoke an empathetic response and reflection from the students. On the other hand there is the hypothesis phase and the issue known as posing the right question. In this phase, engineers tend to possess an instrumentalist bias, focusing on the final result that is needed for design. An attempt to conceive models based on a preconceived set of parameters can inadvertently disregard significant underlying mechanisms. A powerful proverb about this limitation was created by the psychologist Abraham Maslow, who said: *"I suppose it is tempting, if the only tool you have is a hammer, to treat everything as if it were a nail"*.

The second idea behind this study is that most methods to assess the axial capacity of piles are based on a scaled measure of the soil resistance. There are, of course, peculiarities of each method. However, one can certainly see the benefits of discussing and comparing all the different methods under a common light. This also presents an opportunity for a critical analysis of the different methods to assess the soil resistance and why their scaling factors differ among various methods. The toe capacity is defined as the average vertical normal stress to cause confined failure of the soil under the toe area. It can be calculated through the soil undrained shear strength, cone resistance, friction angle and vertical effective in-situ stress through their respective scaling factors, normally called bearing capacity factors. The shaft capacity is defined as the integration along the pile depth and perimeter of the maximum shear stress on pile-soil interface. It can be related, along the pile depth, to the undrained shear strength or cone resistance, but with different scaling factors. For the effective stress analysis, the

scaling factor represents both the interface coefficient of friction and the ratio between the horizontal effective stress at the interface and the in-situ vertical effective stress.

The third basic concept is the interdependence of the design parameters and the design elements, which are recognized as important factors but still don't feature as objective parameters in most design methods. In this study the axial capacity and settlements represent the former and the pile body compressibility, residual loads and negative friction, the latter. The interdependence will be traced hereafter in a conceptual model while the operational and mathematical models will be presented in the methodology section. The point of connection between all these elements is that the mobilized capacity of the pile depends on its relative displacement between the pile and the soil. In this context, negative friction as well as any source of passive soil displacements, are promptly translated into changes on the mobilized pile forces. At the center of this link is the account of pile compressibility, which depends on the stress level at the same time as it induces it through the incremental displacements. Finally, when the stress-displacement relation accounts for permanent displacements, the feature of residual stresses can be modeled. Most importantly, when the continuity of displacements and equilibrium of forces is ensured, all these elements can be constantly interacting.

4. Methodology

The connection between the design methodology and the educational schemes, traced in section 2, is also present in this study. This new teaching concept derives from the new pile analysis framework presented by Dias & Bezuijen [1], which will be summarized hereafter. The framework is based on the load transfer method, so it can be schematically presented by the load transfer models, the equilibrium of forces and the continuity of displacements. The method is based on the division of the pile in segments, where the equations are solved considering a linear variation between the parameters on the top and on the bottom of each segment.

The load transfer models are functions relating the relative soil-pile displacement to the mobilized stresses, both on the toe and along the shaft. The relative displacement can be arbitrarily defined as the difference between the pile settlement and the soil settlement. In this case, a negative relative displacement means that the soil settles more than the pile in that point, which is associated with downward interface shear stress, also called negative friction. A positive relative displacement, on the other hand, means a positive shaft friction and toe reaction.

The shaft model was conceived in a particular way to cope with the fact that the displacement to fully mobilize the shaft friction (≈ 5 mm) is much smaller than the range of pile settlements. The mobilization path is quite straightforward; the friction is fully mobilized, on both directions, when the mobilization displacement is reached. Larger displacements can develop without further changes on the mobilized force. However, upon inverting the direction, the model will respond in regard to the maximum settlement that was previously achieved, reaching the point of null mobilization and full mobilization in the opposite direction, when that turns to be the new maximum mobilization settlement (Figure 1 and Figure 2a).

The toe model is traced on a different basis, as the normal force is only mobilized in compression and the maximum toe force, only fully mobilized at the compressive ultimate bearing capacity, is never exceeded. In the model, that is equivalent of saying

that the maximum toe settlement is never exceeded. However, there is a need to account for the development of permanent settlements before full mobilization is reached. This is done through a rebound factor, that defines the percentage of the maximum achieved settlement that deforms elastically when the toe reaches zero mobilization. A factor of 1 represents a complete rebound of an elastic soil (Figure 2b). With these functions, the system can simulate piles under tension and compression.

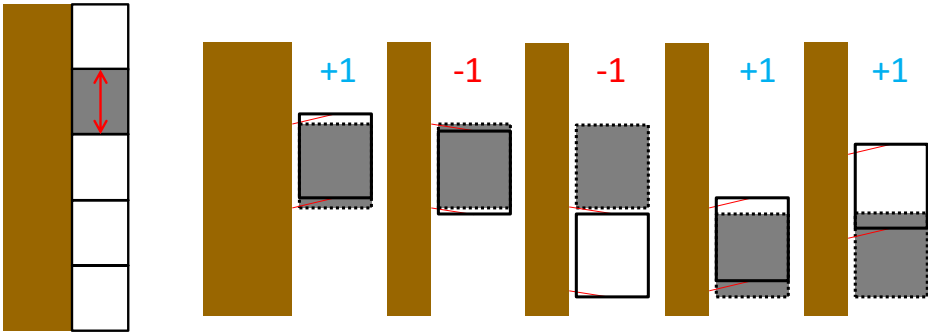


Figure 1. Scheme of shaft friction mobilization

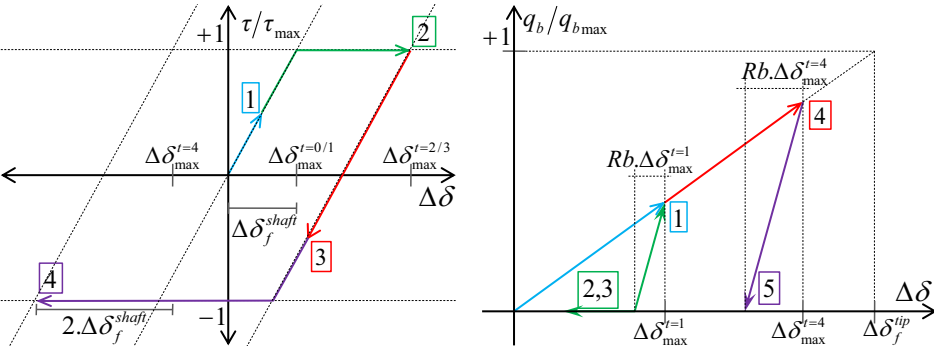


Figure 2. Load transfer models, assuming linear mobilization functions, for the shaft friction (left) and pile toe (right).

The equilibrium of axial forces is calculated (Eq. 1) at the base of each element (i+1) based on the force at the top (i) added with the body weight of the pile and the average shaft friction. Starting with the head load as a boundary condition, the force profile is calculated downwards based on the mobilized friction, which in turn depends on the relative displacements. At the pile toe, the axial force should be the same as the mobilized toe force, so that the system is in equilibrium.

$$\sigma^{i+1} = \sigma^i + \gamma_p . dl + \frac{P_p . dl \left(\tau^i + \tau^{i+1} \right)}{A_p \quad 2}$$

(1)

The continuity of displacements is calculated (Eq. 2) at the top of each element (i) based on the settlement at the bottom (i+1) added with the compression of the pile body due to the average axial stress on the segment. Setting the toe settlement as another boundary condition, the displacement profile is calculated upwards based on the previously calculated axial force profile.

$$\delta_p^i = \delta_p^{i+1} + \frac{\sigma^i + \sigma^{i+1}}{2.E_p} . dl$$

(2)

This interconnectivity forms an implicit system of equations, depending on the toe settlement, that can be solved in common spreadsheet software (Figure 3). In a standard load-transfer formulation, with no account for residual loads, the system forms a bijective function between head load and the toe settlement. The toe displacements are automatically associated with the pile equilibrium and the system is resolved upwards along the nodes. The traditional procedure explores the domain of toe displacements, automatically drawing the domain of head loads and tracing a unique load-settlement curve. However, in the present formulation, the load-displacement equilibrium depends on the previous states which define the limits of toe/shaft mobilization. In this case, each loading step is defined by the head load and the vertical equilibrium has to be solved by searching for the pile toe settlement that results in pile equilibrium. This process can be implemented as a simple root finding scheme, such as the false position method.

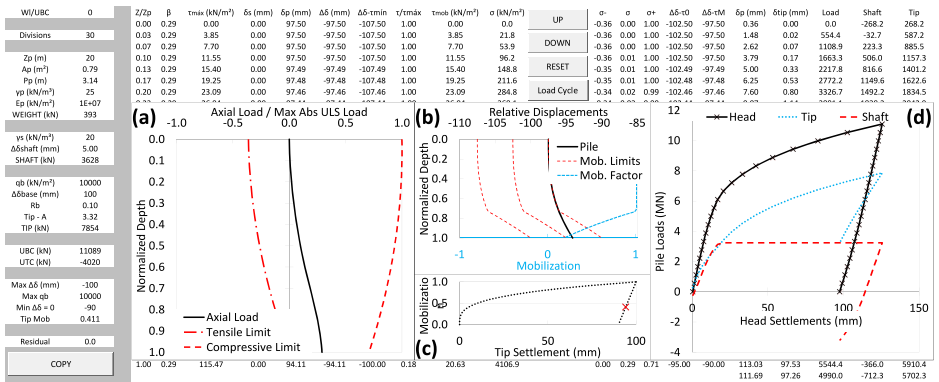


Figure 3. Spreadsheet layout – axial load profile (a), relative displacements profile (b), toe mobilization (c) and load settlement curve (d).

Overall the load transfer method enables the discussion of all the individual conceptual elements that affect the pile behavior and their association in a single interactive framework. The issues of number of pile division, discrete approximation of continuous processes and iterative calculations, also provide an opportunity to discuss some basic concepts of numerical analysis and modeling on a practical application.

5. Discussion

The groundwork on basic concepts of section 3 followed by the methodology of section 4 are supposed to lay out a set of conceptual, operational and mathematical models for the analysis of axially loaded piles. However, as the understanding of the models sets the proficiency, the experimental learning will set the fluency in the method, and they are both equally important for engineering education. In this regard, the fact that the method can be implemented and distributed in common spreadsheet software is a considerable advantage. It is significantly faster than hand calculation methods, allowing diverse experimentation, and it isn't a closed code, allowing a full interaction with the procedures.

A compelling element for analysis is the possibility to define different load transfer models along the pile shaft, modeling different soil layers in terms of their settlements to achieve full mobilization, ultimate resistance and mobilization function. The differences between constant and stress-dependent resistances can also yield interesting comparisons. The three most common bearing capacity methods: α , β and CPT-based, can all be used in this framework as long as their parameters are assessed or interpolated at the points of division along the shaft. Therefore, the methods from the state-of-practice, founded on an extensive empirical base, can be promptly applied in this framework.

The other elements of the model: the displacement to fully mobilize the resistance and the mobilization curves, are not routinely characterized for a pile system. Previous research has established that the displacement necessary to locally mobilize the shaft friction is around 5 mm. Taking this as a first approximation, the other parameters can be easily calibrated from a load-settlement curve. The modeled load-settlement curve can be processed in less than one minute in a regular computer, enabling a rapid validation. This can potentially reach the point where the geotechnical characterization or the empirical know-how would be set around these parameters, and not just the final settlement and ultimate bearing capacity of the system, enabling a more thorough discussion of the mechanisms of axially loaded piles with different soil and piling conditions.

In this sense, a parallel can be traced with the Eurocode 7 national annexes on pile design from Belgium [2] and The Netherlands [3]. In these documents, standard load mobilization curves are presented for the toe and the shaft, for driven, bored and continuous flight auger piles (Figure 4). These curves can be traced with polynomial functions and used within the framework that was presented. Such combination supports a comprehensive visualization of the mechanism and possible interactions with other parameters. Once the model parameters are validated for the circumstances where these curves were created, the framework supports the analysis of different conditions (longer or more rigid piles, a weak soil layer, passive soil displacements, etc) based on the carefully discussed physical principles of the model.

6. Conclusion

This conceptual study discussed the features of engineering education of deep foundations, especially concerning the basic elements of axially loaded piles. The argument that educational divisions may distort the proficiency of students to analyze the mechanism of pile response was thoroughly discussed and the reasons for the present state of practice were explored. It was concluded that the models of analysis are generally robust but tend to be interpreted independently. A framework to combine them for the assessment of the global mechanism is, consequently, of great value for educational and design purposes alike. The proposal of such a framework was presented and discussed, showing great potential for general use.

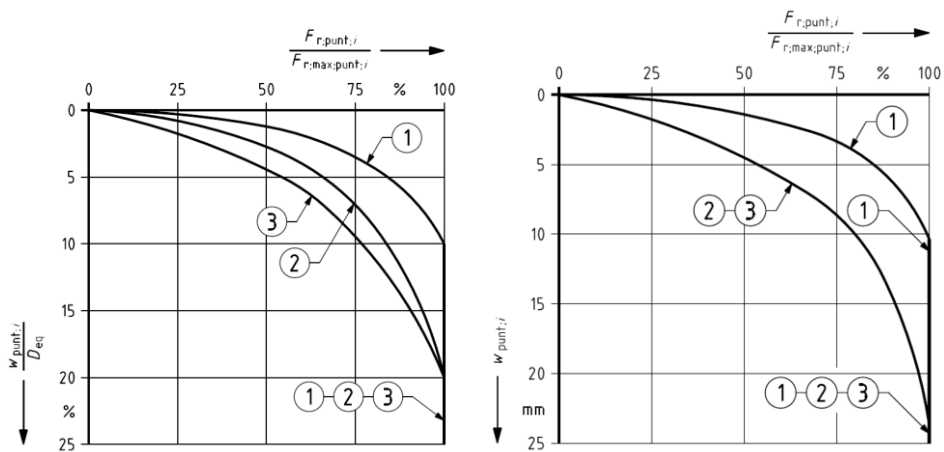


Figure 4. Load mobilization curves for the toe (left) and shaft (right) for driven (1), continuous flight auger (2) and bored (3) piles. The settlements for the toe curves are normalized by the pile diameter.

Acknowledgements

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