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p-y curves from in-situ ROBOCONE tests: a similarity approach for laterally loaded piles in clay

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The design of offshore piles requires assessment of the lateral load-displacement response, achieved using lateral nonlinear springs (*p-y* curves) distributed along the pile [1]. Specifically, a *p-y* curve describes the horizontal displacement, *y*, resulting from a distributed lateral load, *p*, at the pile-soil interface. Numerous methods are available to obtain *p-y* curves, either relating them to soil properties [2,3,4], or using empirical relationships with cone penetration test (CPT) data [5]. An advantage of the latter method is that the *p-y* curves are obtained from in-situ testing, which offers undisturbed, continuous measurements and does not require additional laboratory test data. However, the CPT approach relies heavily on empirical correlations and the loading applied to the soil by the CPT is notably different to that of a laterally loaded pile. An alternative solution is being pursued within the EPSRC-SFI funded ROBOCONE project, which involves the development of a horizontal loading module that can be included in a standard cone penetrometer [6]. The aim of this proposed module is to directly obtain lateral load-displacement curves, referred to herein as a ROBOCONE P_R-y_R curve, by moving part of the module horizontally, perpendicular to the long axis of the cone penetrometer (Figure 1(a)), closely replicating the soil loading in the pile problem under consideration.

The soil resistance from the horizontal loading of the ROBOCONE module, P_R, is achieved by applying a constant displacement, y_R, over a short length of pile, H_R, at a specific depth; while for a pile *p-y* curve, the displacement varies with depth and is applied over a much greater portion ("active length") of the pile, which is closer to a plane-strain "horizontal soil slice" problem. Therefore, while the horizontal loading applied to the soil by the ROBOCONE module is similar to that applied by a pile under lateral load, the ROBOCONE P_R-y_R curve may not be directly substituted for a *p-y* curve for any soil-pile configuration. Instead, a correction factor in some form must be employed to transform between the two curves, without the intermediate stage of recovering soil properties from the ROBOCONE data and then evaluating the resulting *p-y* curve.

A simple analytical method to obtain a correction factor for piles in clay is the similarity approach, which takes the form of a linear-transformation of axes. This method was first introduced by Skempton [7] who suggested that a stress-strain curve of
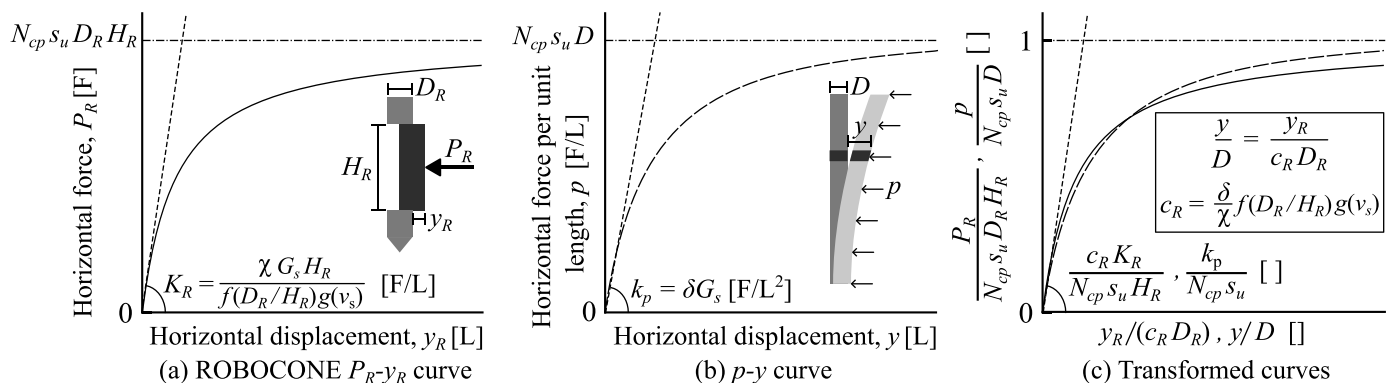

Figure 1: Illustration of the similarity concept applied to relate a ROBOCONE P_R-y_R curve to a *p-y* curve in clay.

a representative clay soil sample can be considered similar in shape to a load-settlement curve of a vertically loaded foundation. It has since been employed to relate a stress-strain curve from an element test with a *p-y* curve [1,2] or a *t-z* curve (describing the vertical pile displacement as a result of a distributed axial force) [8], the former of which is still used in current design codes [3]. Additionally, the similarity approach has not only been used to obtain curves transformed from element test results, but also to obtain an *m-θ* curve (describing the pile rotation as a result of a distributed moment) directly from a *t-z* curve [9,10].

To employ the similarity approach to this scenario, it must be assumed that a ROBOCONE P_R-y_R curve can be considered similar in shape to a *p-y* curve. Following this assumption, two steps are required to obtain a *p-y* curve, illustrated in Figure 1. Firstly, the *y*-axis of each curve is normalised by a bearing capacity factor, N_{cp}, the soil undrained shear strength, s_u, and their respective dimensions, which naturally bound the ordinates of the two curves between 0 and 1. Secondly, the *x*-axis of each curve is normalised by a characteristic length, the pile diameter D, and a factored ROBOCONE diameter, $c_R D_R$, respectively; where c_R is a linear-transformation factor intended to collapse the two curves into a single curve.

To employ this method, a value of c_R is needed. In the original work, Skempton [7] determined this factor by matching the dimensionless initial stiffnesses of the two curves he considered; this approach is followed here with the ROBOCONE P_R-y_R and *p-y* curves (see Figure 1). Firstly, from dimensional arguments, the initial stiffness of the ROBOCONE P_R-y_R curve, K_R, is a function of the soil shear modulus and Poisson's ratio, G_s and v_s, and the dimensions D_R and H_R, multiplied by a constant χ. K_R can be estimated from elastic solutions for rectangular footings or embedded or buried cylinders (e.g. [11]). Secondly, the initial stiffness of the *p-y* curve is the Winkler spring stiffness, $k_p = \delta G_s$, for which many solutions are available (see a recent summary [12]). The resulting expression for c_R is shown in Figure 1(c), which can be used to directly relate a ROBOCONE P_R-y_R curve with a pile *p-y* curve in practice. By taking K_R as double the stiffness of a rigid rectangular footing on an elastic half-space [11] and $\delta \approx 3$ for a fixed-head slender pile [12], $c_R \approx 0.5$ to 0.6 was obtained. This suggests that (1) the ROBOCONE P_R-y_R curve should be "stretched" to obtain a *p-y* curve, (2) the multiplier c_R is independent of s_u and N_{cp}, (3) c_R tends to increase with increasing δ (e.g. free-head over fixed-head pile [12]) and ROBOCONE slenderness H_R/D_R. This initial result indicates the magnitude of the scaling factor for approximating the *p-y* curve. However, this method requires numerical verification and/or field or physical modelling observations to be undertaken prior to application in design practice. This will be undertaken as part of the ROBOCONE project.

Contributor statement

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References

[1] Reese, L. C., & Van Impe, W. F. (2011). *Single piles and pile grounds under lateral loading* (2nd Edition). CRC Press.
[2] Matlock, H. (1970). Correlations for design of laterally loaded piles in soft clay. *Proc. 2nd Offshore Technology Conf.*, 557–588.
[3] ANSI & API. (2011). *Geotechnical and Foundation Design Considerations: ANSI/API Recommended Practice 2GEO.* API Publ. Serv.
[4] Jeanjean, P. et al. (2017). A Framework for Monotonic P-Y Curves in Clays. *OSIG 8th International Conference Proceeding*, 108–141.
[5] Truong, P. & Lehane, B. (2014). Numerically derived CPT-based p-y curves for a soil clay modelled as an elastic perfectly plastic material. *Proceedings of 3rd International Symposium on Cone Penetration Testing*, 975-982.
[6] Diambra, A., Creasey, J., Leonet, J., Conn, A., Ibraim, E., et al. (2022). Concept design of a new CPT module for direct in situ measurement of P-Y soil responses. *Cone Penetration Testing 2022*, Bologna, Italy, 900–906. https://doi.org/10.1201/9781003308829-134
[7] Skempton, A. W. (1951). The bearing capacity of clays. *Building Research Congress*, 1, 180–189.
[8] Bateman, A. H., Crispin, J. J., & Mylonakis, G. (2022). A simplified analytical model for developing "t-z" curves for axially loaded piles. *20th International Conference on Soil Mechanics and Geotechnical Engineering*, 3211–3216.
[9] Fu, D., Zhang, Y., Aamodt, K. K., & Yan, Y. (2020). A multi-spring model for monopile analysis in soft clays. *Marine Struct.*, 72, 102768.
[10] Bateman, A.H., Mylonakis, G. & Crispin, J.J. (2023) Simplified analytical "m-θ" curves for predicting the nonlinear response of piles under lateral loads. (Submitted)
[11] Guha I., Randolph, M.F. & White D.J. (2016). Evaluation of elastic stiffness parameters for pipeline-soil interaction. *Journal of Geotechnical and Geoenvironmental Engineering*, *ASCE*. 142(6): 04016009 https://doi.org/10.1061/(ASCE)GT.1943-5606.0001466
[12] Mylonakis, G., & Crispin, J. J. (2021). Simplified models for lateral static and dynamic analysis of pile foundations. In Kaynia A. M. (Ed.), *Analysis of pile foundations subject to static and dynamic loading*, 185–245. CRC Press. https://doi.org/10.1201/9780429354281-6