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Scaling of lateral pile *p-y* response in clay from laboratory stress-strain curves

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This paper deals with the static lateral load-displacement response (*p-y* spring) of a pile slice in soil. The response is governed by a localised flow-around soil failure mechanism. A model is proposed that allows for construction of site-specific *p-y* springs by directly scaling the soil stress-strain response measured in laboratory tests. This model is based on an extensive parametric finite element study and can explicitly account for the effect of pile-soil interface roughness factor on both the strength and shape of the *p-y* spring. The model demonstrates excellent agreement with the *p-y* responses calculated numerically. An example application illustrates the capability of the model to predict the overall pile response by comparison with full three dimensional finite element analysis. The proposed model is compared with existing models in the literature, where similarities and differences are discussed and highlighted. The model provides practising engineers with a simple yet powerful approach to use site-specific *p-y* curves in design based on element soil behaviour measured in laboratory, without the need for advanced numerical analyses.

1. Introduction

Piles, especially offshore piles, often have to be designed to resist lateral loading. The load-transfer approach is usually adopted for pile design, in which soil resistance is represented by lateral load (p, defined as force per unit pile length) versus displacement (y) springs along the pile and the overall pile response is solved by a beam-column approach. It is well known that for a laterally loaded slender pile in clay, two soil failure mechanisms may exist. In the upper part, soil fails in a conical wedge that extends to the soil surface. A gap may also form along the interface between the pile and the soil on the active side if the suction between the pile and the soil is lost. At a certain depth, however, the soil failure mechanism transits into a localised plane flow-around mechanism, as the soil resistance encountered in this mechanism becomes less than failure in conical wedge. Randolph and Houlsby [1] studied the limiting lateral bearing pressure (i.e. peak of the *p-y* spring) for a circular cylinder failing the soil in a plane strain flow-around mechanism based on plasticity theory. The *p-y* spring that leads up to the peak for the same mechanism is subject of this study. The *p-y* springs appropriate for shallow wedge failure, gapping, and the local behaviour at the tip are beyond the scope of this paper.

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1.1. Literature review

In the offshore industry, the API guideline, latest version as [2], is conventionally used to design the pile foundations. The static *p-y* spring model in clay recommended in API originates from the field pile tests performed at Sabine River in the 1950s and reported in Matlock [3]. The static *p-y* model relates the mobilised lateral resistance to the normalised lateral displacement in a power law relation:

$$\frac{p}{p_u} = 0.5\left(\frac{y}{y_c}\right)^{0.33} \leq 1 \tag{1}$$

where p_u = the ultimate lateral resistance (force) per unit pile length; y = lateral displacement; $y_c = 2.5 \cdot \varepsilon_{50} \cdot D$, with ε_{50} defined as axial strain at which 50% of maximum deviator stress is mobilised in an undrained compression test (the API document is not specific on the type of tests. In practice, this is often chosen from unconsolidated undrained (UU) compression tests). D = pile diameter.

Full mobilisation of the API *p-y* spring is achieved (i.e. $p/p_u = 1$) at $y = 8y_c$. It must be recognised that the Matlock *p-y* model has been developed and calibrated mainly against the field tests performed lightly over-consolidated clays at the Sabine River. The applicability of the empirical model to other soil conditions should therefore be checked.

Based on centrifuge tests detailed in Jeanjean [4] and finite element analyses detailed in Templeton [5], the following expression, denoted as Jeanjean *p-y* model in this paper, is proposed in Jeanjean [4]:

$$\frac{p}{p_u} = \tanh\left(\frac{G_{max}}{100 s_u}\left(\frac{y}{D}\right)^{0.5}\right) \tag{2}$$

where G_{max}/s_u = initial shear modulus (G_{max}) over shear strength (s_u) ratio;

The remaining parameters are as defined previously.

Eq. (2) includes the influence of the G_{max}/s_u ratio on the shape of the *p-y* spring. However, it is reasonable to anticipate that not only the initial stiffness of the soil, but also the stress-strain response beyond the initial phase will influence the *p-y* response of the pile. It should be noted that the Jeanjean *p-y* model is calibrated against testing/finite element analyses in Kaolin soil with a specific stress-strain behaviour. This perhaps explains why only G_{max}/s_u is formulated in the model. Furthermore, the proposed impact of G_{max}/s_u on the pile p-y response is not verified through either model tests or numerical analyses, but is rather based on postulation.

It should be further noted that Eq. (1) and Eq. (2) imply infinite stiffness at $y = 0$. In practice, a limitation of $(p/p_u)/(y/D) \leq x \cdot (G_{max}/s_u)$ is applied, with x typically taken in the range 0.35–0.5. This ensures an initial stiffness that is consistent with elastic solutions.

Bransby [6] reported a finite element study of a plane strain pile slice in nonlinear elastic soils with power law stress-strain relation expressed as $\tau = a\gamma^b$ where a and b are material constants. It is demonstrated that the resulting *p-y* curve from the finite element analysis can be scaled from the stress-strain curve by a scaling coefficient that varies with the power law factor b. The significance of the work is that it illustrates the self-similarity between the soil stress-strain response and the resulting *p-y* response of a translating pile slice.

Osman and Bolton [7] demonstrated that it is possible to scale the soil stress-strain response to the load-settlement response of a circular foundation vertically loaded on undrained clay through the so-called moblisable strength design (MSD) concept. Similar concepts are applied to study the lateral load transfer response of a pile slice deforming in plane strain mode by Klar [8], Klar and Osman [9] and recently by Yu et al. [10]. Load transfer (*p-y*) curves can be derived by solving energy dissipation equations over a pre-defined pattern function (failure mechanism). The method is shown to provide comparable *p-y* curves to those calculated by finite element analyses. Klar and Randolph [11] also applied the MSD concept to study the pile head load displacement response.

1.2. Motivation of this study

The work by Bransby [6], Klar [8], Klar and Osman [9] and Yu et al. [10] demonstrates from the numerical and theoretical perspectives that it is possible and rationale to link the pile *p-y* curves to the soil stress-strain response. Erbrich et al. [12] present a procedure that calculates site-specific envelope *p-y* curves by means of finite element/finite difference analyses using the stress-strain responses measured in laboratory tests and subsequently uses them in assessment of pile response under cyclic loading. With computation power of modern computers and availability of advanced soil model that can follow the soil non-linear stress-strain response, finite element parametric analyses of *p-y* response of a pile slice can be easily performed, with sufficient discretisation accuracy. The soil flow mechanism is automatically calculated in a finite element analysis and the *p-y* curve is a direct analysis output. In this study, a large parametric study of a pile slice *p-y* response over a wide range of soil stress-strain behaviour and pile-soil interface roughness are performed. The motivation of the analyses is to come up with a simple *p-y* model that allows for construction of site-specific *p-y* curves from fundamental soil stress-strain response measured in the laboratory, without the need of advanced numerical analyses.