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Evaluation of *p-y* springs for nonlinear static and seismic soil-pile interaction analysis under lateral loading

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ABSTRACT

In the current state of practice, static/seismic soil-pile interaction is included in design calculations by a set of one-dimensional (1D) uncoupled springs. The guidelines of American Petroleum Institute (API) are often adopted to develop backbone curves for the lateral springs. The purpose of the paper is to assess the reliability of this practice. Twenty-seven static field and laboratory tests, and two dynamic centrifuge tests are simulated to evaluate the performance of the springs. More detailed elaboration on the performance of the springs is provided by simulation of one of the static tests and both of the dynamic tests using also three-dimensional (3D) continuum approach. The evaluation results indicate that API springs do not capture the major mechanisms involved in soil-pile interaction, and this results in erroneous estimation of pile deflections and bending moments. It is shown that the observed errors stem not only from the insufficient characterization of the spring properties (API backbone curves), but also from the inadequate simulation method in which three-dimensional continuum configuration of the supporting soil is represented by a 1D uncoupled spring.

1. Introduction

A key element in the design of pile foundations is the appropriate prediction of load-deformation responses at the soil-pile interface. The engineering practice utilizes the concept of beam on a nonlinear Winkler foundation (BNWF), called "spring method" hereafter, in order to approximate the load-deformation responses. In this approach the pile is simulated as a beam supported on a series of discrete nonlinear springs, so-called *p-y* springs. Although simple and practical, characterization of nonlinear springs is difficult and challenging. The American Petroleum Institute (API) [1] provides some simple procedures to develop nonlinear backbone curves for piles embedded in both clays and sands. The guidelines of API [1] were originally developed for the design of offshore piles based on the measurements of limited number of field tests performed on free-head steel pipe piles with the diameter of around 40 cm subjected to static and slow cyclic loadings. The slow cyclic load tests were supposed to replicate wave loading condition not seismic. Despite this limited database, practitioners use the API curves for the analysis of any type of pile, such as large diameter piles under static or even seismic loads. Other design guidelines such as FEMA 451 [2], AASHTO [3] and Canadian Foundation Engineering Manual [4] refer to API guidelines for characterization of *p-y* springs. This is in spite of the findings of several researchers who have argued against the reliability of these curves and reported significant levels of error primarily in estimation of the static response of pile foundations.

Murchison and O'Neill [5] and Gazioglu and O'Neill [6] can be considered as the first researchers studying the range of applicability of the API curves. Murchison and O'Neill [5] studied 24 full-scale tests on piles in cohesionless soils; 14 static tests and 10 slow cyclic tests on single piles. They concluded that the API curves are not adequate for the analysis of static or slow cyclic loading tests. Gazioglu and O'Neill [6] performed similar studies on 30 full-scale tests in clayey soils; 21 static and 9 slow cyclic tests. They reported that deflections and bending moments are poorly estimated when the API curves are used in their numerical analyses. In addition, Zhang et al. [7] showed that API recommendations for calculating ultimate resistance of cohesionless soils underestimate the actual ultimate lateral resistance at shallow depth but overestimate the actual ultimate lateral resistance at deeper depths. McGann et al. [8] also reported that the initial stiffness and ultimate soil resistance are both significantly overestimated if the recommendations of API are employed for static analysis of a single pile embedded in cohesionless soils. Kim and Jeong [9] concluded that for piles embedded in clayey soil, using the API curves results in significant overestimation of pile lateral displacement and bending moment profiles. Based on the results of some dynamic centrifuge tests, Choi et al.

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[10] reported that the API curves are significantly different from the experimental ones; the ultimate soil resistance is underestimated, while the sub-grade reaction modulus is overestimated at the small deflections of piles. A number of studies have been conducted to find alternative approaches for determination of the interaction backbone curves for static loading. One of these was the Strain Wedge Model (SWM) approach that was originally proposed by Norris [11], and modified later by Ashour et al. [12]. This approach was shown to have better performance than the API *p-y* springs in static loading. In addition to the static loading, this paper aims to also investigate how the still very popular *p-y* curves perform in the context of seismic loading of piles. This was considered as an important component of the validation of *p-y* curves because unlike the case of static or slow cyclic loading, very few validation studies have been conducted on seismic loading of piles based on such curves.

With the advances in continuum modeling methods, the reliability of the spring method began to be questioned. Finn [13] used both methods for dynamic analysis of soil-pile interaction, and he concluded that the API springs are very unreliable in predicting the seismic response of piles. The study showed that the spring model of the soil-pile system poorly estimates the kinematic and inertial interactions. Rahmani et al. [14] investigated the seismic force-deflection responses at the soil-pile interface using both their validated continuum model and the API spring model. Their results indicated that by the use of one-dimensional springs the initial slope, the ultimate resistance, and hysteretic loops are all poorly predicted.

The authors of this paper believe that there are two fundamental issues with the *p-y* spring method: (i) determination of spring stiffness is inevitably associated with significant levels of uncertainty, and (ii) idealization of a soil continuum configuration which is highly nonlinear and anisotropic with a simple one-dimensional uncoupled spring seems to be inappropriate and questionable. This study collects the results of all previous studies and comprehensively examines the reliability of the spring method in analysis of laterally-loaded piles. The goal of the study is to inform the pile designers of the reliability of their analysis results when the spring method is used. To this end, the data from twenty-seven static tests and two dynamic centrifuge tests, are used. In addition to the *p-y* spring method, three-dimensional (3D) continuum modeling method is used for simulating these problems. With the aid of continuum method, the advantages or disadvantages of the spring method are elaborated in more details.

2. Static soil-pile interaction analysis

2.1. Baseline data

Table 1 presents a brief description of the selected twenty-seven experimental tests. The test results are collected from different sources, which are referenced in Table 1. In all tests, piles are subjected to static lateral load at the free head of the pile. The pile diameters range from 5 to 240 cm. The first 10 tests were conducted in dry and saturated sands, and the remaining tests were conducted in soft and stiff clays. All tests except Tests No. 7, 8, and 9, were field tests conducted on full-scale piles. Tests No. 7, 8, and 9 were conducted on small-scale piles in centrifuge tests where a monotonic load was applied at the pile head while the container was spinning. All tests, except tests No. 3, 4, 18, and 24, were performed on steel pipe piles. The piles were H-shape in tests No. 3 and 4. Drilled shaft piles were tested in tests No. 18 and 24.

2.2. Analysis procedure

All tests are simulated using the spring method in which API *p-y* springs represent the static soil-pile interaction. Schematics of the spring model is shown in Fig. 1. Following the state of practice, the computer program LPILE v.6 (ENSOFT Inc.) [35] is used to develop the backbone curves for the springs and perform the static analyses. The

Table 1
Description of the selected twenty-seven experimental tests.

Test	Test type[a]	Pile diameter (cm)	Pile type	Soil type	Ref.
1	field	41.0	steel pipe	saturated sand	[15]
2	field	5.0	steel pipe	saturated sand	[16]
3	field	–	steel H-shape (16WF26)	dry sand	[17]
4	field	–	steel H-shape (14H17)	dry and saturated sand	[18]
5	field	61.0	steel pipe	saturated sand	[19]
6	field	27.0	steel pipe	dry sand	[20]
7	static centrifuge	122.0	steel pipe	dry sand	[21]
8	static centrifuge	43.0	steel pipe	dry sand	[22]
9	static centrifuge	72.0	steel pipe	dry sand	[23]
10	field	51.0	steel pipe	dry and saturated sand	[18]
11	field	32.0	steel pipe	soft clay	[24]
12	field	32.0	steel pipe	soft clay	[25]
13	field	11.5	steel pipe	soft clay	[26]
14	field	22.0	steel pipe	soft clay	[26]
15	field	32.5	steel pipe	soft clay	[26]
16	field	41.0	steel pipe	soft clay	[26]
17	field	102.0	steel pipe	soft clay	[27]
18	field	240.0	drilled shaft	soft clay	[28]
19	field	64.0	steel pipe	saturated stiff clay	[29]
20	field	11.5	steel pipe	saturated stiff clay	[30]
21	field	22.0	steel pipe	saturated stiff clay	[30]
22	field	32.5	steel pipe	saturated stiff clay	[30]
23	field	41.0	steel pipe	saturated stiff clay	[30]
24	field	90.0	drilled shaft	saturated stiff clay	[31]
25	field	41.0	steel pipe	dry stiff clay	[32]
26	field	85.0	steel pipe	dry stiff clay	[33]
27	field	76.0	steel pipe	dry stiff clay	[34]

[a] In all tests, load is monotonically applied at the pile head of a free-head single pile.

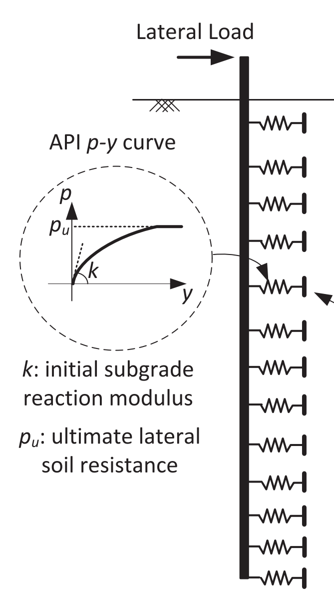

Fig. 1. Schematic of the spring method used in practice for static analysis of laterally loaded single piles.