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Analysis and design of piles under lateral loads

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ABSTRACT: A finite element method, based on 'p-y' curves, is suggested for the design of laterally loaded piles. The pile is treated as an Euler-Bernoulli beam embedded in the soil, while the soil medium is replaced by a system of continuous springs placed along the length. The potential of this simple empirical approach for the accurate analysis of laterally loaded single piles, regardless of whether the soil is homogeneous, nonhomogeneous, linear, nonlinear or layered and whether the pile has an uniform or nonuniform cross-section is exemplified from a prediction of observed lateral behaviour of the foundation piles of a portuguese bridge recently constructed.

1 INTRODUCTION

The problem of laterally loaded piles has received considerable attention to date to its frequent occurrence in practice. Several distinct approaches for the analysis of the problem are readily identified from literature. In the so-called Winkler model and its variants, the pile is treated as an Euler-Bernoulli beam embedded in the soil, while the soil medium is replaced by a system of discrete springs placed along the length of the pile. The stiffness of the springs can be varied with depth to simulate linear but nonhomogeneous soil behaviour, or replaced by nonlinear 'p-y' curves to represent pile-soil inelastic interaction. The major drawback of these approaches is that, in the absence of coupling between the springs, only normal stresses are admissible at the pile soil interface. Moreover, the spring model precludes the extension of the method to pile groups analyses because interaction between neighbouring piles may not be taken into account (Nath, 1989).

However, one must draw attention to the enormous potential of this simple empirical approach for the accurate analysis of laterally loaded single piles, regardless of whether the soil is homogeneous, nonhomogeneous, linear, nonlinear or layered and whether the pile has an uniform or nonuniform cross-section.

2 STATEMENT OF PROBLEM

The differential equation for a beam is

$$\frac{d^2}{dx^2}\left[EI\frac{d^2y}{dx^2}\right]+p=0 \qquad (1)$$

in which y is the lateral deflection of pile, x is the depth, EI is the flexural stiffness of the pile and p is the soil-pile interaction force due to pile deflection.

The force-deformation characteristics of the soil can be described by a set of predicted 'p-y' curves (Matlock, 1970; Reese *et al.*, 1974) in which:

$$p=-k(x,y)\cdot y \qquad (2)$$

where k is a reaction modulus [FL^{-2}]. This modulus is not a unique soil property, and it must be understood as only as a computer aid (Matlock and Reese, 1961). Moreover it varies with both depth and pile deflection.

Combining equations (1) and (2), the general differential equation for the laterally loaded single pile is

$$\frac{d^2}{dx^2}\left[EI\frac{d^2y}{dx^2}\right]-k(x,y)\,y=0 \qquad (3)$$

3 COMPUTER CODE DEVELOPED

The finite element method offers a convenient means of solving the problem stated previously (2). A computer code has been developed in Fortran language for microcomputers. The piles are divided into beam elements with two nodal points and external connections can be modelled as rigid or elastic. The 'p-y' function (2) can be assumed as continuous or discrete over the pile length. The program LALOPI (LAterally LOaded PIles) provides the following principal features:

1. Inherent benefits of finite element procedures such as the possibilities to introduce step-changes in flexural stiffness at any depths and various combinations of boundary conditions at top and bottom of pile.
2. The soil is assumed to be layered in any admissible combination. In each strata the 'p-y' data may be introduced in several ways, (Table 1), including a simple numerical tabulation to define a set of individual 'p-y' curves of any form and of any variation with depth. This last feature allows the use of 'p-y' data curves obtained from load test interpretation results in a direct and simple way.

Table 1. Automatic generation of p-y curves for computer code LALOPI.

Code	Curve Type	Description
1	$p=-k_{ht}\ y$	Linear OC clays
2	$p=-n_h\ x\ y$	Linear sands
3	$p=-n_h\ x^2\ y$	Nonlinear sands
4	Hyperbolic	Nonlinear
5	Sands	Simplified procedure (Reese *et al.*, 1974)
6	Soft clays	Simplified procedure (Matlock, 1970)
7	Clays	Simplified procedure (Matlock, 1970)
8	Stiff clays	Simplified procedure (Reese & Welch, 1975)
9	Input file	Load tests results

3. By successive iterations, based on repeated reference to the soil 'p-y' data, the value of the reaction modulus k which represents the proper compatibility and equilibrium conditions for the soil and the pile is computed. A numerical integration procedure over the domain is used.

The output of the program is: lateral deflection (y), slope (θ), bending moment (M) and shear force (V) at nodal points and soil reaction (p) along depth. Moment and shear computations are performed by means of a numerical integration over p. Besides the numerical tabulation scheme LALOPI creates a graphical presentation of computed results.

4 ALCACER DO SAL BRIDGE CASE

In order to illustrate LALOPI potential for the accurate prediction of lateral response of single piles, behaviour analysis of piles tested in Alcácer do Sal Bridge (LNEC, 1991) is now presented.

A brief description of the structural solution selected for Alcácer do Sal Bridge is presented. The geological an geotechnical characteristics of alluvial foundations material are described and the geometric and mechanical properties of tested piles are pointed out.

4.1 General description

The bridge over Sado river at Alcácer do Sal includes two 400 m long approach viaducts with 30 m long spans and a continuous slab deck. The main bridge is a 3 spans 55-85-55 m long structure. The deck structure consists of a box-girder. The viaducts and the bridge are supported on tubular section prestressed concrete piers (Reis *et al.*, 1989).

4.2 Geotechnical characteristics

The valley is filled by alluvial material, which in some places reach a thickness of 40 m, lying on rock of a calcareous formation. The geotechnical characteristics of the alluvial material were determined by in situ tests (SPT, CPT and vane tests) and also laboratory tests (index properties and triaxial compression). Most relevant geotechnical characteristics of alluvial material at tested piles location are summarized in Table 2 (in which c_U denotes undrained strength, ϕ' denotes internal friction angle and γ denotes total unit weight).

Table 2. Principal geotechnical characteristics of alluvial material at tested piles location.

Strata type	Depth limits (m)	SPT (N)	CPT (MPa)	c_U (kPa)	'p-y' code	Input parameters
Silty mud	0-3.5	2	-	20	6	c_U =20 kPa γ=16 kN/m^3
Sand	3.5-8.5	8-14	2-6	-	5	ϕ' =30° γ=19 kN/m^3
Muddy complex	8.5-23	2-6	-	32	6	c_U =32 kPa γ=16 kN/m^3
Sandy complex	23-40	5-20	2-8	-	5	ϕ' =35° γ=19 kN/m^3

4.3 Instrumentation and pile characteristics

Details concerning instrumentation purposes, test program and type of measurement devices selected to perform the horizontal free cap load tests on Alcácer do Sal Bridge can be found elsewhere (LNEC, 1991).

The test piles were cast-in-place underwater concrete filled. Table 3 summarizes the principal characteristics of the piles.

Table 3. Summary of the principal characteristics of the tested piles.

Pile	Length (m)	Diameter (m)	E (GPa)	I (m^4)
1	24	1.00	29.0	0.08
2	40	1.20	31.5	0.19
3	40	1.20	30.5	0.20

During horizontal load tests the following measurements were taken: (1) lateral deflections of pile heads; (2) rotation of pile heads; (3) lateral deflection distribution and (4) strain distribution along the shaft of the piles. Based on strain records the distribution of bending moments, shear forces, slopes and lateral deflection of the shafts and soil reactions were computed (LNEC, 1991).

4.4 Behaviour analysis of tested piles

In order to predict the observed lateral behaviour of the Alcácer do Sal tested piles a set of 'p-y' curves for layered soil conditions had to be selected. Criteria for constructing 'p-y' curves have been presented by Matlock (1970) for soft and medium clays and Reese *et al.* (1974) for sands. These recommendations were based on the results of lateral load tests in homogeneous soils, coupled with earth pressure theory (Reese *et al.*, 1981).

Later on Reese *et al.* (1981) performed a series of tests to investigate the behaviour of piles under lateral loading in layered soil conditions. Experimental results were compared with results from analyses, and fair to good agreement was obtained with the assumption that the behaviour of the individual layers was the same as if all of the soil mass was uniform in characteristics (Reese *et al.*, 1981).

In spite of the limited amount of available experience, using 'p-y' curves on the assumption of homogeneous conditions appears to be a reasonable means to deal with layered soils.

In the Alcácer do Sal case, predictions were made by use of the computer code LALOPI with this kind of assumption. That is, the 'p-y' criteria for soft clays (Matlock, 1970) was used for the muddy materials (Table 2) while that for sands (Reese *et al.*, 1974) was assumed for the sandy soils. These 'p-y' curves were derived for each layer as if the entire soil profile had the properties of that layer.

Layer thicknesses and soil properties adopted for calculations are shown in Table 2. Pile characteristics are presented in Table 3. Some results from the testing are shown in Figs. 1 to 3. Figures 1 and 2 show the pile-head deflection and the maximum bending moment for the first load cycles of piles 1 and 2. Figure 3 shows the entire set of LALOPI results for a 300 kN load on top of pile 3 (Portugal, 1992).

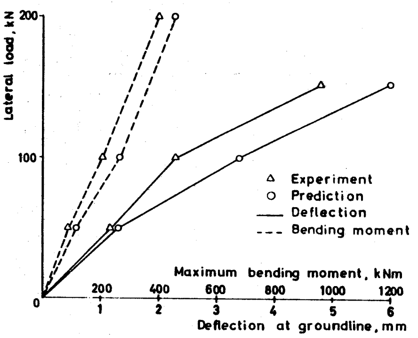

Fig. 1 Results for pile 1, first load cycle

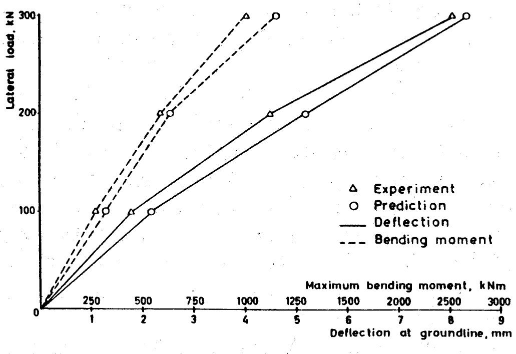

Fig. 2 Results for pile 2, first load cycle

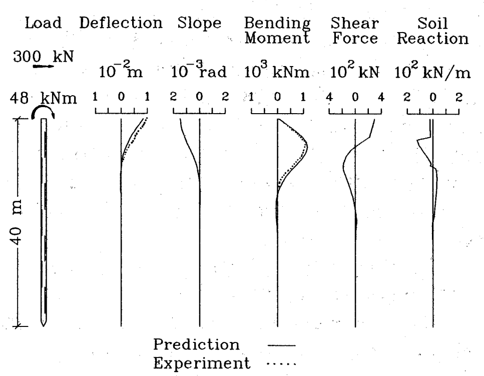

Fig. 3 Results for pile 3, 300 kN on top

5 CONCLUSIONS

A finite element code, based on 'p-y' concept, was presented. Relatively good agreement was obtained between measured and computed values of maximum bending moment and deflections for horizontally tested concrete piles.

These results tend to support the reasonableness of analyses of laterally loaded piles using 'p-y' curves on the assumption of homogeneous conditions, as proposed by Reese *et al.* (1981).

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