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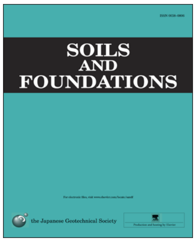

A method to compute the non-linear behaviour of piles under horizontal loading

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Abstract

The empirical evidence for vertical piles under horizontal or lateral loading is firstly reviewed. The load–deflection relationship is nonlinear from the early stages of loading, while the load–moment relationship is nearly linear. Moving from the available experimental evidence, typical design issues are addressed and a validation of the widespread Broms' method is then carried out. To predict the pile–soil interaction, a computer code, NAPHOL, based on a hybrid BEM approach, is fully presented and discussed. A limiting pressure profile, coupled with a cut-off procedure, allows the method to cope with the nonlinear behaviour. Simple guidelines and equations, to calibrate the model parameters, are derived on the basis of the back-analysis of a significant number of case histories. The program is finally used to throw light on the mechanism of the pile–soil interaction under horizontal loading.

Keywords: Analysis; Computer code; Horizontal load; Piles; BEM

1. Introduction

The behaviour of piles under horizontal loading is different from that under vertical loading. When axially loaded, the structural section of the piles does not have a large influence on the pile–soil interaction, as the compression stress is generally very low compared to the strength of the pile material (wood, steel or concrete). With an increasing load, failure may occur, if at all, at the interface between the pile and the soil where the limiting values of the available shaft friction are attained. Under horizontal loading, on the contrary, the piles are primarily subjected to bending moment and shear, and their structural section has a large influence on the pile response both at the serviceability limit state (SLS) and at the ultimate limit state (ULS).

Furthermore, the behaviour of a vertical axially loaded pile depends essentially on the properties of the soil immediately adjacent to the shaft and below the base, which are the zones largely affected by the pile installation process. Accordingly, the behaviour of a vertically loaded pile, particularly its bearing capacity, is markedly affected by the installation process and the technology adopted (Poulos et al., 2001; Mandolini et al., 2005). Under horizontal loading, the pile–soil interaction is confined to a volume of soil which has a different shape and location (Ng et al., 2001; Rollins et al., 2005). Such a volume is typically confined to the upper part of the pile shaft, close to the ground surface, and it develops at a larger distance from the pile shaft. For this reason, a major part of this volume of soil is not affected by the pile installation. However, the available full-scale experimental evidence on piles tested under horizontal loading is less exhaustive than for vertical loading. Furthermore, most of the available horizontal loading tests have been conducted on piles whose heads were free to rotate even though pile heads in actual

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foundations are usually fixed. In the next section, some data from horizontal loading tests on piles are firstly reviewed to figure out the main features of the experimental behaviour. The paper proceeds with a short section dedicated to the validation of the widespread Broms' method for the calculation of the ultimate capacity of piles under horizontal loading and to the assessment of the limiting pile–soil interaction pressure. Next, sections are presented in which the computer code, NAPHOL, is described and successfully applied to the back-analysis of well-documented case histories. Some peculiar features of the soil–pile interaction for piles under horizontal loading are highlighted and discussed.

2. Pile behaviour under horizontal loading: experimental evidence

A small number of full-scale horizontal loading tests on piles at the same site, but with different installation techniques, have been reported in the literature. As an example, Fig. 1 shows the results of four loading tests on prefabricated piles carried out in the framework of the Arkansas River Project (Alizadeh and Davisson, 1970).

The subsoil at the site consists mainly of dense sand, and the groundwater table is located very close to the ground level. Piles E7 and F7 were installed by jetting to 8 m and then driving to 15 m; Piles E3 and F3 were driven from the ground surface to the final depth of 15 m. The different installation techniques do not appear to affect the results, while the position of each test pile within the group does seem to have a large influence on the load–displacement curves.

The load–displacement curves obtained by Mori (2003), who tested two different piles in the same sandy gravel subsoil, are compared in Fig. 2. The *Tsubasa* pile is a kind of displacement screw pile; the other pile is an ordinary open-end steel pile driven by vibrations for which the inside soil has been removed. In this case, the installation procedure seems to affect the observed behaviour, namely, the stiffness of the *Tsubasa* pile is higher than that of the open-end steel pile (*Vibration* pile).

According to the above findings and to other available data (Reese and Van Impe, 2001), it can be stated that the influence of the installation technique has sometimes been observed, but that the available data are somewhat contradictory. The influence of both the technology and the installation procedure on the load–displacement curves of the piles under horizontal loading is surely less marked in comparison to the case of piles under vertical loading.

Close scrutiny of the available empirical evidence allows for insight into another feature of the behaviour of piles under horizontal loading.

Ruesta and Townsend (1997), for instance, reported the results of horizontal loading tests on a reinforced concrete prefabricated pile, 16 m in length with a 0.76 m^2 square section, driven into a sandy subsoil (Fig. 3). During the tests, a displacement as high as 15% of the pile width was attained; the test load exceeded the value corresponding to the fissuring of concrete and approached the horizontal bearing capacity, corresponding to the complete yield of the structural section. The pile was instrumented with 8 levels of strain gages which allowed for the accurate determination of the bending moment profile along the shaft at each head load level. These measurements were also supported by a standard inclinometer pipe which was explored by a manual torpedo during the load tests. The load–displacement curve is markedly nonlinear from the very beginning; on the contrary, the load–maximum bending moment curve is nearly linear. Similar results have been obtained by Brown et al. (1987) for tubular piles driven in finely grained soils. In Fig. 4, the load–displacement curve and the head load–maximum bending moment curve are plotted as solid lines together with dashed lines representing the initial tangent of the two curves. This was done to allow for the easy appreciation of the different contributions of nonlinearity to the two experimental curves. In this case, however, the difference between the trends of

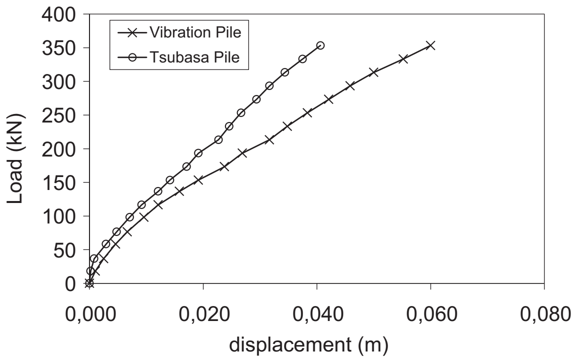

Fig. 2. Horizontal loading tests on displacement screw pile (*Tsubasa*) and an open end tubular vibro-driven pile in the same subsoil (after Mori (2003)).

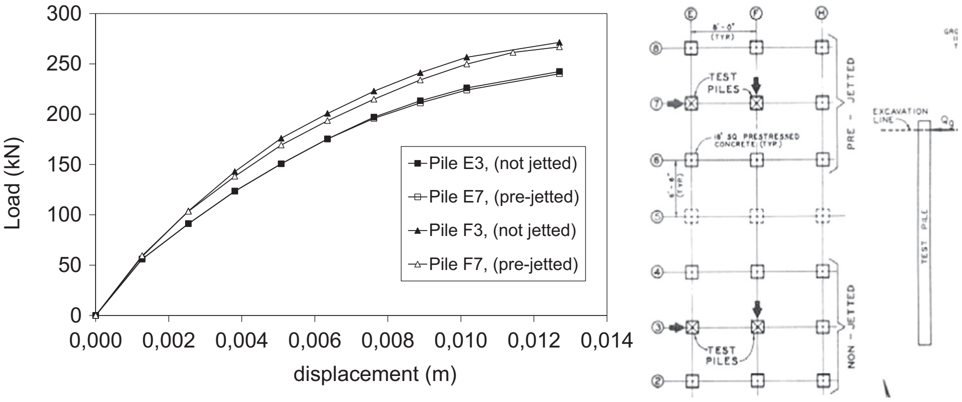

Fig. 1. Horizontal loading tests on four different piles in the same subsoil (after Alizadeh & Davisson, 1970).

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