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# Soil Modulus for Laterally Loaded Bored Piles in Pozzolana

## Module de Réaction Latérale de Pieux Forés in "Pozzolana"

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**SYNOPSIS** The results of a number of horizontal load tests on piles of different diameter and with different boundary conditions at the top are reported. All the tested piles have been bored through cohesionless volcanic soils ("pozzolana") in the Naples area; the soils have been characterized by means of static cone penetration tests, sand SPT. The program included load tests on two pairs of piles with head rotation restrained by a rigid cap, and on four free-head single piles; the diameter of the piles is of 0,5 or 0,6 m. In some cases the displacement of the shaft has been measured by means of inclinometers, in other only displacement and rotation of the pile head. Back-analysis of the results obtained for the inclinometer instrumented piles allows the determination of soil modulus distribution with depth and stress level. It has been found that the expression  $E_s = K_0 + K_1 z^n$  fits satisfactorily experimental results;  $K_0$ ;  $K_1$  and  $n$  values depend on relative density of soil and on stress level.

### 1. INTRODUCTION

The results of horizontal load tests on eight piles are presented in this paper. All the piles are drilled in the pyroclastic soils of Naples area; five of them are instrumented with inclinometer tubes.

The analysis of experimental results allows some useful indications to be drawn, regarding the selection of design parameters for piles subjected to horizontal loads. Such indications apply to the soils found in the above mentioned area, whose general characteristics are, by now, sufficiently known (Croce, Pellegrino, 1967; Pellegrino, 1967) and can be regarded as homogeneous from a geotechnical viewpoint. Furthermore, the analysis sheds light on some aspects of the pile-soil interaction, pointing out once more the limitations of the usual calculation model.

### 2. OUTLINE OF THE SOILS IN THE NAPLES AREA

The Neapolitan area is a "region" whose subsoil has, essentially, such geotechnical characteristics to allow an even collection of significant and homogeneous experience. In particular, the subsoil is made of "pozzolanas", "pumices", "lapilli" and "tuffs" coming from the volcanic eruptions of the Campi Flegrei. We remind, on this subject, that the term "pozzolanas" is given to the volcanic ashes - vitreous

substance, with a more or less spongy texture and a pore size ranging between silts and sands - which form the most common and widespread soil in the considered area. Pozzolanas are often mixed to bigger particles (2-3 cm) which are called "pumices" and "lapilli".

From a mechanical point of view, "pozzolanas" be have as cohesionless soils (friction angle ranging between  $30^\circ$  and  $40^\circ$ ) and exhibit, as a rule, a small but not negligible cohesion (Pellegrino, 1967). This feature is due to a certain degree of cementation and/or capillarity effects; it allows the stability of remarkably high vertical cuts. Furthermore, in such a soil, provided there is no water table, it is possible to drill uncased piles.

Volcanic tuff is a weak rock ( $G_R = 2 \cdot 10 \text{ MPa}$ ) and derives from autometamorphism processes of "pozzolanas" (Scherillo, 1955; Sersale, 1958).

### 3. SOIL PROPERTIES AND PILES CHARACTERISTICS

The test piles were entirely drilled through pozzolanas whose geotechnical characteristics have been found out through S.P.T. and static cone penetration tests.

Figures 1 and 2 show some typical profiles at the test sites.

Dry rotary drilling with uncased hole, using a bucket, has been adopted for the piles at sites

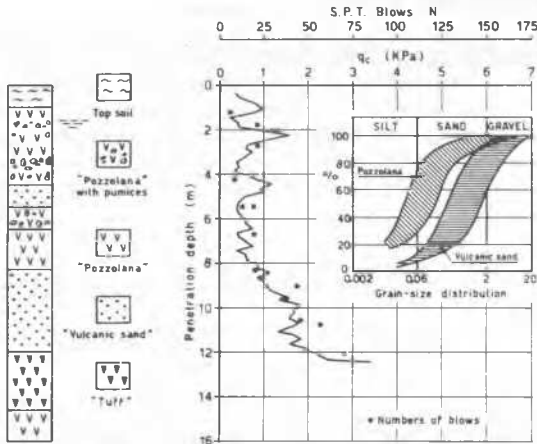


Fig. 1 Zone A - Soil profile

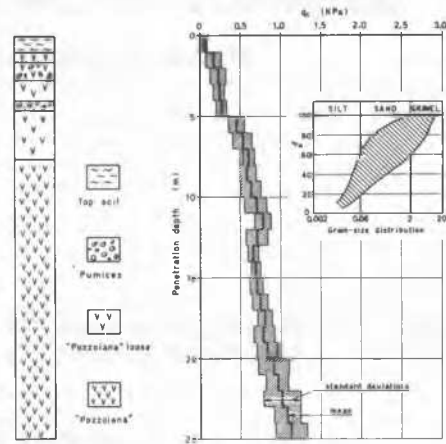


Fig. 2 Zone B - Soil profile

B, C and D; at site A, due to the occurrence of the water table, percussion drilling and steel casing have been selected. In table 1 are reported some data on the piles geometry and the values of the relative density,  $D_r$ , of the soils in the five meters. Figure 3 reports the scheme of a load test carried out on instrumented piles.

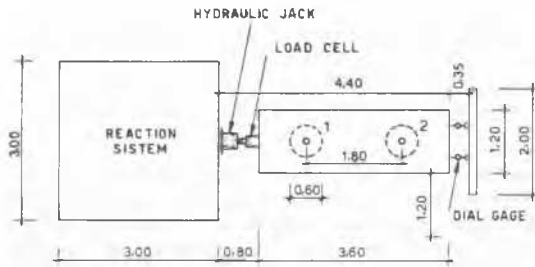


Fig. 3 Scheme of load test

4. MEASUREMENTS AND RESULTS

Figure 4 shows, as an example, the sequence of applied load steps, while in figures 5, 6, 7 and 8 the load-displacement diagrams obtained in several load tests are reported. In figures 9 to 11 the results of some inclinometric measurements are reported.

5. ANALYSIS OF THE RESULTS

A first analysis of the results has been done by considering the horizontal soil modulus  $E_s(z)$  as linearly increasing with depth. In this hypothesis, a series of values of the soil reaction coefficient  $K_1$  have been determined by fitting calculated and observed displacements at some load level.

TABLE 1

ZONE	PILE	d (cm)	l (m)	e (cm)	$A_f$ (cm <sup>2</sup> )	Inclinom.	$D_r$	Water table	$H_{max}$ (KN)	$Y_{max}$ (mm)
A	*1A	60	14	35	37,7	yes	70-80	yes	500	50
B	1B	50	15	50	31,4	yes	40-50	no	300	13
	*2B	50	15	50	31,4	yes	40-50	no	630	50
C	1C	50	15	50	31,4	no	70-80	no	45	1
D	1D	50	16	50	34,5	no	50-60	no	45	2
	2D	50	15	50	43,9	no	50-60	no	35,7	1,55

- \* test on a piles footing
- d = diameter
- l = length
- e = load eccentricity
- $Y_{max}$  = maximum horizontal displacement at the pile top
- $H_{max}$  = maximum test load
- $A_f$  = reinforcement area.

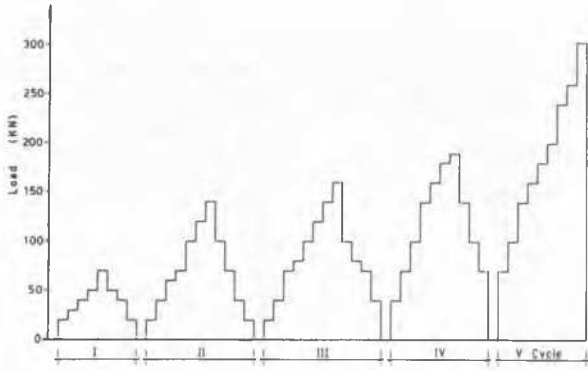


Fig. 4 Sequence of load steps applied in horizontal load tests

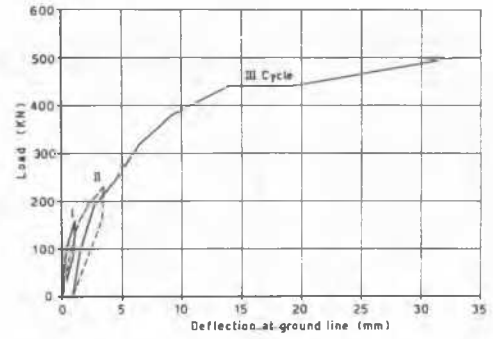


Fig. 5 Pile 1A - Load-settlement curve

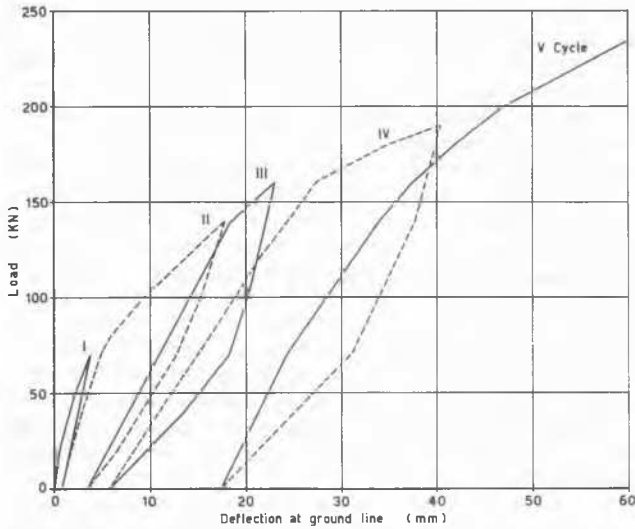


Fig. 6 Pile 1B - Load-settlement curve

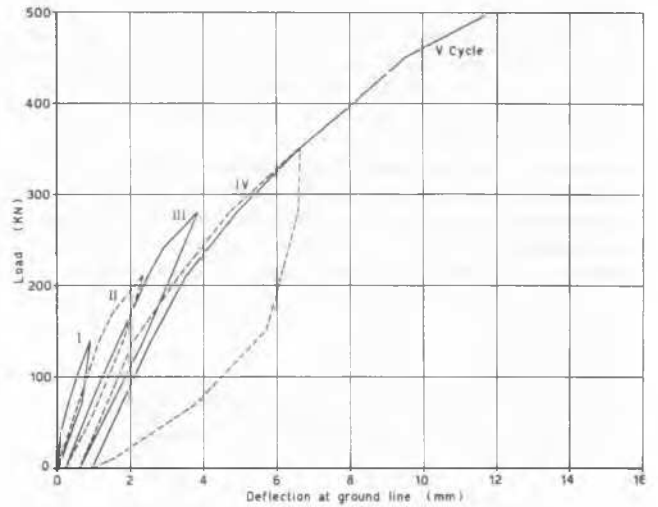


Fig. 7 Pile 2B - Load-settlement curve

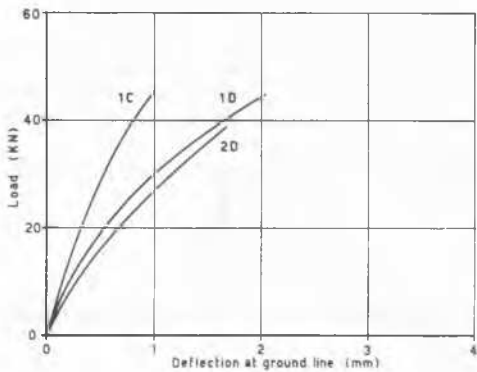


Fig. 8 Piles 1C, 1D, 2D - Load-settlement curve

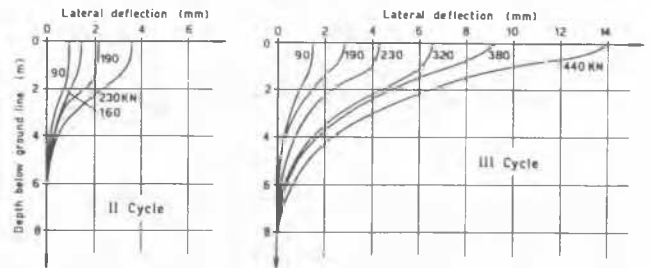


Fig. 9 Pile 1A - Results of some inclinometric measurements

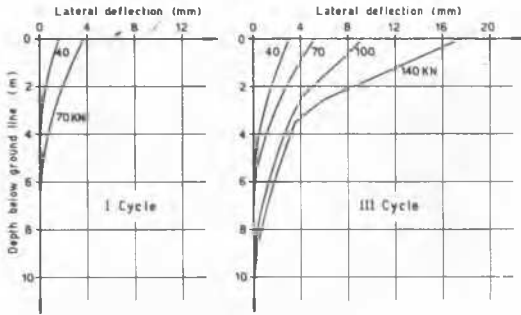


Fig. 10 Pile 1B

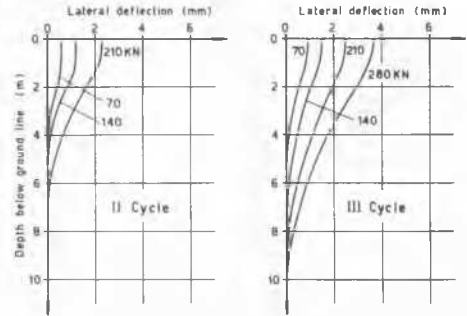


Fig. 11 Pile 2B

Furthermore, since the coefficient  $K_1$  depends on the load level, it has been possible to obtain, from the load-settlement curves, the different working loads (evaluated as 1/3 of the ultimate bearing capacity) and determine the  $K_1$  values at this load level.

In figure 12 are reported the  $K_1$  values of each load test calculated as above (vertical segments); curve 4 interpolates the  $K_1$  values corresponding to the working loads. Curves 1, 2 and 3 in the same figure report

the values of  $K_1$  respectively suggested by Reese and others (1974) for submerged sands, and by Terzaghi (1955) for dry sands (curve 2) and submerged sands (curve 3).

It may be observed that curve 4 is well below curve 2 by Terzaghi.

This is essentially due to the construction methods used to make the piles, that undoubtedly disturb the soil strata nearer to the surface. Nevertheless such methods have been shown to be particularly effective for piles under axial stresses (Sapio, 1967; Galateri and Picarelli, 1976; Evangelista and others, 1977). Actually, as it is known, the disturbance affects more the soil deformability (working condition) rather than the strength (ultimate condition). Finally in figure 12 the initial tangent values of  $K$ , obtained from the curves  $K_1(H)$ , are reported.

By using the inclinometric measurements and referring to the well known equation of the elastic curve :

$$EI \frac{d^4 y}{dz^4} + p(z) = 0 \quad (1)$$

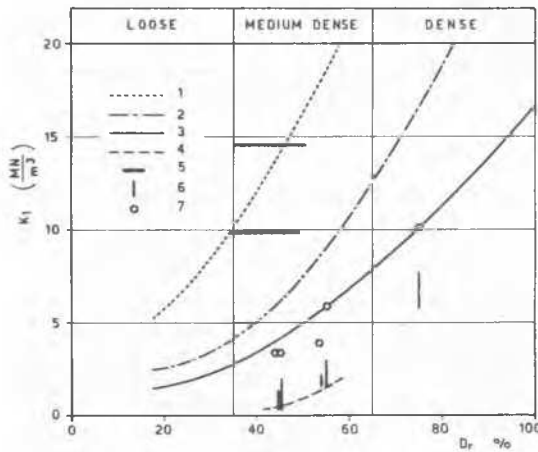
it is possible to determine the horizontal soil modulus  $E_s(z)$  through the ratio  $\frac{p(z)}{y(z)}$ . In particular, having recorded the rotations  $\psi(z)$  of the pile axis for each load step, they have been fitted with a polynomial by means of the least square method.

With further derivations the function  $p(z)$  is obtained

$$p(z) = EI \cdot \frac{d^3 \bar{\psi}(z)}{dz^3}$$

and, by integration, the displacement function  $y(z)$

$$y(z) = \int_{z=0}^{z=1} \bar{\psi}(z) dz$$



- 1 - Reese et Al. (1974) - Submerged sands
- 2 - Terzaghi (1955) - Submerged sands
- 3 - " " - Dry sands
- 4 - Present investigation; values of  $K_1$ , at working load
- 5 - Garassino et Al. (1975) - Submerged sands
- 6 - Present investigation; range of  $K_1$  at varying load levels
- 7 - Initial tangent values of  $K$

The integration constant is given by the displacement measured at the top. Once the modulus  $E_s(z)$  is defined as above, it is possible to determine the experimental curves of  $E_s$  with depth. In figure 13, as an example, the experimental curves  $E_s(z)$  for the pile 1B at different load levels are reported.

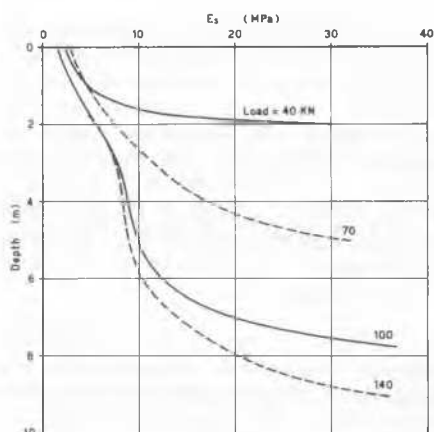


Fig. 13 Curves  $E_s(z)$  for different load levels

The figure shows how the depth of the mobilized soil increases with increasing load. Meanwhile, the  $E_s$  values at a given depth decrease. The curves we are examining can be expressed, with good approximation, with a law of the type :

$$E_s(z) = k_o + k_1 \cdot z$$

In table 2 are reported some laws corresponding to different load levels, being  $E_s$  and  $K_o$  expressed in 0,1 MPa and  $z$  in cm.

TABLE 2

PILE	CYCLE	LOAD (KN)	$K_o$	$K_1$	n
1A*	II	90	174	0,54	1,1
		190	95	0,14	1,3
		230	65	0,05	1,5
	III	90	95	0,29	1,2
		190	50	0,038	1,5
		230	40	0,002	2,0
1B	I	40	24	0,5	2,9
		70	22	0,5	2,1
	II	40	22	0,5	2,3
		70	20	0,085	2,5
		100	16	0,020	2,8
		140	16	0,005	3,1

\* Croce-Galateri (1978).

It is easily noticeable from the table that, at the ground level, the soil modulus is not null. This can be due to a certain degree of cementation existing in the upper strata of zone A; while for zone B it can be due to the slight cohesion of pozzolanas.

It is also noticeable that the  $K_o$  value rapidly decreases by uncreasing the load and the number of load-cycles and that the soil modulus increases linearly with depth. This can be due to the different displacement of the soil at different levels and to the non-linearity to the stress-strain relationship.

Figure 14 reports the trend of the soil modulus, at different depts, as a function of the horizontal displacement. The figure shows that  $E_s$  depends markedly on the displacement up to values lower than 2÷3 mm; over such a limit  $E_s$  keeps practically constant with increasing displacement.

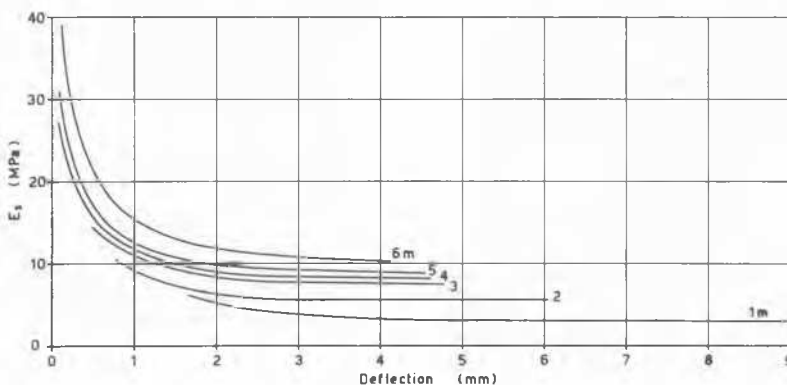


Fig. 14 Soil modulus versus horizontal displacement, at different depts

The inadequacy of a linear Winkler model to reproduce such a behaviour is evident.

## 6. CONCLUSIONS

The reported experimental findings suggest the following remarks, applying strictly to drilled piles in pozzolanas :

- full scale observations on the interaction between the soil and horizontally loaded piles by means of high accuracy inclinometers are feasible and useful, notwithstanding the unavoidable inaccuracies involved in the threefold numerical derivation required to calculate  $E_s$ ;
- in the hypothesis of linear variation of  $E_s$  with depth, the experimental values of the gradient of  $E_s$  have been found to be smaller than those suggested by Terzaghi. This is believed to be due to construction methods influence;
- the value of the reaction coefficient at the surface,  $K_0$ , is not nil; this is probably due to the slight cohesion of pozzolanas;
- the non-linearity of the soil modulus with displacement is further confirmed; the variation of the modulus with depth is very nearly linear.

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