# Panel discussion: Some comments on the analysis of piled rafts

## Débat de spécialistes: Quelques remarques sur l'étude des radiers sur pieux

C.Viggiani – *University of Napoli Federico II, Italy*

### 1. INTRODUCTION

In the design of piled rafts, if the traditional capacity based approach is adopted, only the calculation of the bearing capacity of the pile is required. The contribution of the raft is neglected, and all the design load is assumed to act on piles. As a consequence of such conservative assumptions, the total and differential settlement of the large majority of piled foundation are usually rather small and are not considered a major problem.

There are a number of compelling arguments for moving towards a settlement based design methodology for pile foundations, and in recent years a number of interesting developments have occurred in this direction. Nevertheless, the capacity based design is still dominant, as it is evident for instance in current revision of national and regional design codes.

Such a situation may be partially attributed to a widespread belief that predicting settlements is more difficult and less reliable than predicting bearing capacity. On the contrary, a variety of analytical and numerical techniques for the analysis of piled foundations and suitable experimental procedures for the determination of the relevant stiffness have been developed in recent years.

The most widespread technique is provided by the BEM; non linearity may be simulated by a stepwise linear incremental procedure. In practice the computational resources required become excessive for all but the simplest foundation systems; it is therefore necessary to introduce simplification.

### 2. SETTLEMENT ANALYSIS

The procedure developed at the University of Napoli Federico II for the prediction of settlement of piled rafts is implemented in the program GRUPPALO (Mandolini, 1994). It is based on BEM, and makes use of the following simplifications:

- raft clear of the soil. It has been shown that the contact between the raft and the soil does not significantly affect the settlement of the group, even if the load taken by the raft is as high as 50% of the total applied load;
- raft either rigid or fully flexible (in which case the load acting on each pile is known), thus avoiding the difficult task of evaluating the combined stiffness of the raft and superstructure;
- use of interaction factors to represent the influence of a complete pile on the displacement of another pile;
- finite influence radius (Randolph & Wroth, 1978);
- non linearity concentrated at the pile-soil interface, while the interaction between other elements is assumed linear (Caputo & Viggiani, 1981). This suggestion is equivalent to that formulated by Randolph (1994) to estimate the group response on the basis of initial small strain elastic stiffness and then add the plastic displacement due to the slip at the pile-soil interface.

These simplifications substantially reduce the computational resources required to analyse even largest groups. The accuracy of the numerical procedure in the linear range has been checked against known benchmark solutions.

For the analysis of real cases, the results of all the available site and laboratory investigations are first used to develop a model of the subsoil in which the geometry is adapted to a scheme of horizontal layering and the ratios between the stiffnesses of the different layers are evaluated. The absolute values of the stiffnesses are then established by fitting the computations to the results of loading tests on single piles.

Three approaches are possible:

- a linear elastic (LE) solution based on the elastic properties backfigured from the initial stiffness of the load test;
- an equivalent linear elastic (ELE) solution, based on the secant stiffness at the average working load of the pile in the group;
- a stepwise linear incremental analysis (NL).

Mandolini & Viggiani (1997) back analysed 19 well documented case histories including bored, driven and auger piles in cohesionless soils and stiff and soft cohesive soils. The large majority of these foundations were designed according to the conventional capacity based approach, and hence with a rather high safety factor; a simple linear analysis may be expected to be adequate for engineering purposes.

In fact a LE analysis based on low strain moduli, as backfigured by the initial stiffness of the load test on single piles, gives a satisfactory agreement with the observed values in all but two cases (fig. 1a). One of these refers to a small pile group close to failure load, in which case non linearity plays a major role.

In four cases, where site measurements of the shear wave velocity were available, there is a substantial agreement between the values of the moduli deduced by the initial stiffness of pile load tests and by the shear wave velocity.

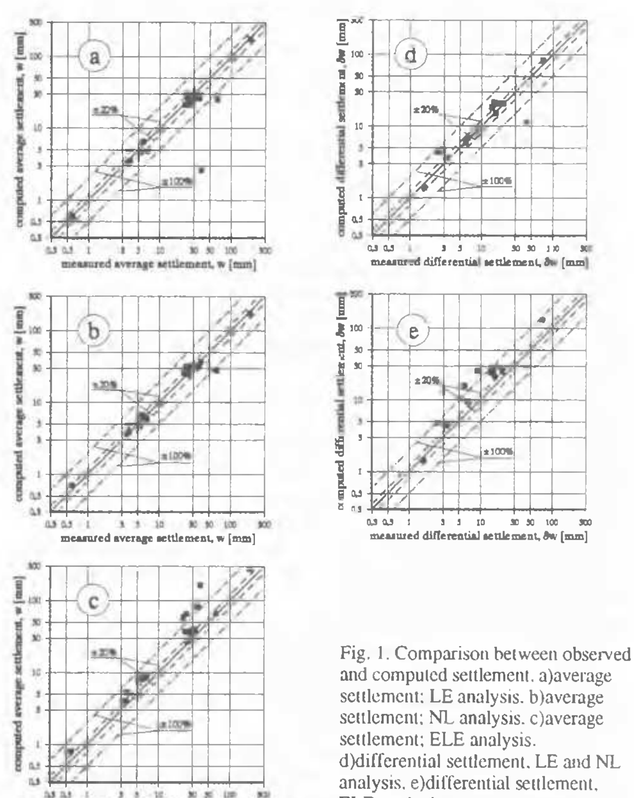


Fig. 1. Comparison between observed and computed settlement. a)average settlement; LE analysis. b)average settlement; NL analysis. c)average settlement; ELE analysis. d)differential settlement. LE and NL analysis. e)differential settlement. ELE analysis

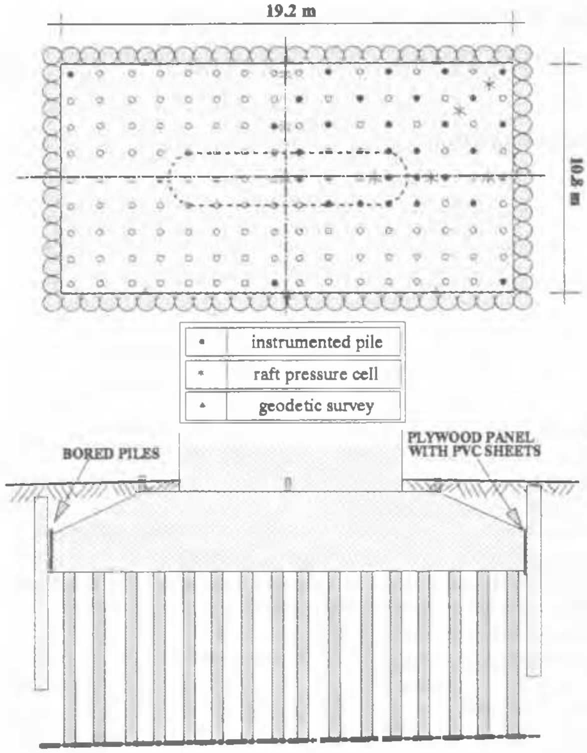


Fig. 2. Plan view and longitudinal section of the foundation of pier n. 7 of the bridge over the Garigliano, showing the location of installed instrumentation

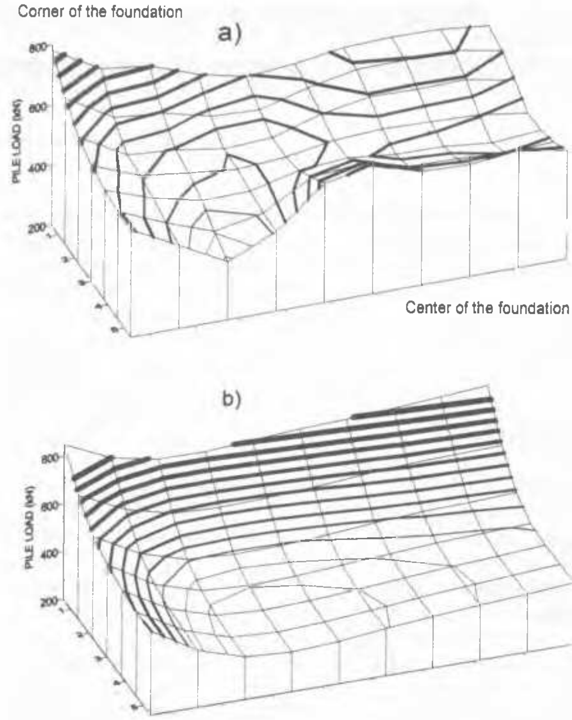


Fig. 3. Load distribution among the piles. a) observed values; b) values predicted by NAPRA

The NL analysis (fig. 1b), which essentially consists in adding the non linear component of the settlement of the single pile to the settlement of the group obtained by LE analysis, slightly improves the predictions in all the cases where the LE analysis was already satisfactory. In the case where non linearity plays a significant role, NL analysis substantially improves the prediction.

The ELE analysis (fig. 1c), which amplifies both the linear and non linear components of the settlement, substantially overpredicts the observed settlements.

The same comments apply to the prediction of the maximum differential settlement, evaluated assuming a fully flexible foundation (fig. 1d, 1e). The available data, however, are more scanty and scattered than those on average settlement.

## 3. INTERACTION ANALYSIS

The program NAPRA (Russo, 1995) is an extension of GRUPPALO to account for raft-soil interaction. In the linear range it compares satisfactorily with complete BEM solutions and other simplified approaches (Russo & Viggiani, 1997).

A well documented case history is that of the central pier of a new cable stayed bridge in Southern Italy (Mandolini & Viggiani, 1992), founded on 144 tubular steel piles driven through a soft clay deposit to a sand substratum at the depth of 48 m. The load sharing between piles and raft and the load distribution among the piles has been monitored by load cells at the top of 35 piles and by 8 pressure cells at the interface between raft and soil. The foundation with installed instrumentation is represented in fig. 2.

A detailed report of the resultswill be presented elsewhere. It may be reported that 83% of the total applied load less the buoyancy is taken by the piles. The load increment due to the construction of the bridge deck, accounting for 80 % of the total load, is completely taken by the piles.

The load distribution among the piles is shown in fig. 3. The effect of raft stiffness (larger loads on peripheral piles) and of applied load (larger loads on piles directly below the pier shaft) is evident. A prediction by NAPRA is also reported; it appears satisfactory from an engineering point of view.

Fig. 3 refers to the load distribution at the end of construction. Five years later the distribution has significantly smoothed. This phenomenon deserves further attention, since it could dramatically affect the design approach.

## 4. CONCLUDING REMARKS

There is both a scientific and a practical interest in a more rational use of piled rafts. So far, the following tentative conclusions may be drawn:

- for conventional capacity based design and large number of piles, a linearly elastic analysis is perfectly suited. There is some evidence that it can be based on small strain moduli;
- for low safety factors and small number of piles (settlement based design), a non linear analysis is needed;
- the equivalent linear elastic analysis based on secant moduli, though widespread, is conceptually misleading;
- a conservative prediction of differential settlement may be obtained by assuming fully flexible foundation and superstructure;
- available simplified methods of analysis are satisfactory for engineering purposes, provided they are applied properly (subsoil model, maximum interaction spacing, type of analysis);
- further experimental evidence of full scale behaviour, including load distribution, is essential to further developments.

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