Settlement predictions for coarse grained soils based on SPT results

La prévision des tassements dans les sols granulaires au moyen des résultats du SPT

V. Caputo
Università della Basilicata, Potenza, Italy

ABSTRACT

Burland and Burbidge (1984) collected, presented and back-analysed more than 200 hundred case histories of settlement of full scale structures founded on coarse grained soils and proposed an empirical procedure for settlement prediction.

Berardi and Lancellotta (1991) performed further back-analyses on the data base provided by Burland and Burbidge and developed a different approach for the same purpose.

This paper presents some further analyses, performed on the same data base used by Burland and Burbidge and by Berardi and Lancellotta. The results of these analyses are used to assess the reliability of both procedures and provide simple empirical correlations which can be used for settlement predictions for coarse grained soils with a reliability comparable with the reliability of the procedures proposed by Burland and Burbidge and by Berardi and Lancellotta.

RÉSUMÉ

Plus de 200 cas d'étude de tassements de structures réelles sur sols granulaires ont été publiées et étudiées par Burland et Burbidge (1984), qui ont aussi développé une méthode empirique pour la prévision des tassements.

Les mêmes données fournies par Burland et Burbidge ont été utilisées par Berardi et Lancellotta (1991), qui ont proposé une méthode differente dans le même but.

Cet article présente les résultats d'autres calculs faits sur les mêmes données utilisées par Burland et Burbidge et par Berardi et Lancellotta. Ces résultats sont utilisés pour évaluer la fiabilité des deux méthodes et aussi pour montrer que de simple formules peuvent être appliquées pour la prévision des tassements des sols granulaires avec une fiabilité comparable à celle démontrée par les méthodes de Burland et Burbidge et de Berardi et Lancellotta.

Keywords : settlement prediction; coarse grained soils; SPT results

1 INTRODUCTION

In routine design, procedures for settlement predictions for coarse grained soils are usually based on the results of in situ tests, being undisturbed sampling for these soils extremely difficult.

A relevant contribution to the development of such procedures is due to Burland and Burbidge (1984), who:

- collected a wealth of data concerning the settlements of full scale structures founded on coarse grained soils;
- published all the relevant information of the case histories they had collected in the form of a detailed data base;
- proposed an empirical procedure which in most cases reproduces observed settlements rather satisfactorily.

The broad data base published by Burland and Burbidge is presented in such a detailed fashion to be amenable to additional evaluations. This has been done by Berardi and Lancellotta (1991), who developed an alternative procedure for settlement predictions, based on the assumption of nonlinear elastic behaviour of coarse grained soils.

This paper: (i) briefly reviews the relevant features of the procedures developed by Burland and Burbidge (1984) and Berardi and Lancellotta (1991); (ii) offers some remarks on the accuracy of both procedures; (iii) presents the results of additional evaluations performed on the data published by Burland and Burbidge; (iv) uses these results to suggest alternative approaches for settlement predictions.

2 BURLAND AND BURBIDGE (1984)

Burland and Burbidge collected the results of more than 200 well documented case histories of settlements of full scale structures (buildings, tanks, embankments) founded on coarse grained soils and published them in the form of a detailed data base, which encompassed 20 different items.

The relevant data and information of the case histories were:

- geometry of the foundation (breadth B, length L and depth B);
- thickness H of the compressible soil layer;
- depth H_w of the water table below founding level;
- description of grain size distribution of the soil;
- N_{av}, average SPT blow count over the depth of influence Z, which is subsequently defined;
- q', q'_n gross and net effective bearing pressure;
- total observed settlement s.

From the back-analyses of all the case histories, Burland and Burbidge derived an empirical procedure which in most cases reproduces observed settlements rather satisfactorily and expressed it in the form:

$$s(mm) = C_1 \cdot C_2 \cdot C_3 \cdot \left[\left(q' - \frac{2}{3}\sigma'_{VD} \right) \cdot B^{0.7} \cdot I_c \right] \quad (1)$$

In eq. (1), σ'_{VD} is the maximum previous overburden pressure (expressed in kN/mq, as q'), I_c is a compressibility index defined as:

$$I_c = 1.706 / (N_{av})^{1.4} \quad (2)$$

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The depth Z over which N_{av} is calculated is provided by Burland and Burbidge in a graphical form as a function of breadth B, and is conveniently expressed in tab. 1.

Table. 1 Values of the depth of influence Z.

B (m)	2	3	5	10	30	50	100
Z (m)	1.63	2.19	3.24	5.56	13.0	19.86	34.0

C_1, C_2 and C_3 are dimensionless factors respectively expressed as:

$$C_1 = [1.25(L/B)/(0.25 + L/B)]^2 \tag{3}$$

$$C_2 = (H/Z)\cdot[2-(H/Z)] \tag{4}$$

$$C_3 = 1 + R_3 + R_1 \cdot \log(t/3) \tag{5}$$

where t (> 3 years) is time after construction, R_3 is the ratio of time dependent settlement (that takes place during the first 3 years after construction) over immediate settlement, and R is the creep ratio. Burland and Burbidge suggest conservative values of R_3 and R respectively equal to 0.3 and 0.2 for static loads, and to 0.7 and 0.8 for fluctuating loads.

3 BERARDI AND LANCELLOTTA (1991)

In order to develop an alternative procedure for settlement predictions, Berardi and Lancellotta (1991) back-analysed 125 case histories provided by Burland and Burbidge, namely those where the value N had been actually obtained by means of SPT tests, rather than being derived from a different test.

In this procedure, the subsoil is assumed to be a compressible layer of thickness H equal to the foundation breadth B, overlying a bedrock formation. Soil behaviour is assumed to be nonlinear, with a decay of modulus E with stress/strain level.

The settlement s is expressed by means of eq. (6), which is derived from the theory of elasticity, while the decay of modulus E with stress level is expressed by means of eq. (7), proposed by Janbu (1963):

$$s = \frac{q'_n \cdot B}{E} I_{sh} \tag{6}$$

$$E = K_E \cdot p_a \cdot \left[\frac{\sigma'}{p_a}\right]^n \tag{7}$$

In eq. (6), I_{sh} is a dimensionless settlement factor depending on H/B, L/B and soil Poisson's ratio ν; Berardi and Lancellotta suggest to assume H/B=1 and $\nu = 0.15$. In eq. (7) K_E is a dimensionless modulus number, and may be assumed to vary with strain level, p_a is the reference atmospheric pressure, σ' is the effective stress as resulting from its initial value σ'_{vo} and the stress induced by loading; all stresses are evaluated at a depth equal to half the active zone.

Soil initial stiffness is defined by means of the value of N_{av}, for which two corrections are required, the former accounting for the Energy Rod Ratio ER_r, the latter for stress level, defined through the ratio CN, as reported in eq. (8)

$$N_1 = N_{av} \cdot \frac{ER_r}{60} CN \tag{8}$$

where CN is given by eq. (9),

$$CN = 2/(1+\sigma'_{VO}) \tag{9}$$

Relative density D_R is then evaluated according to Skempton's equation:

$$D_R = \left(\frac{N_1}{60}\right)^{0.5} \cdot 100 \tag{10}$$

An initial value of the modulus number (namely, the value $K_{E(0,1)}$ corresponding to s/B = 0,1 %) is calculated as:

$$K_{E(0.1)} = 90{,}1 + 9{,}15 \cdot D_R \tag{11}$$

An iterative procedure can thus be initiated, calculating the initial values of modulus E and settlement s by means of eq. (7) and eq. (6), which in turn provides a value of dimensionless settlement s/B.

Nonlinearity in stress-strain behaviour is then modelled assuming a decay of modulus number K_E from its initial value with increasing s/B as provided by Berardi and Lancellotta in a graphical form, which can also be expressed by eq. (12):

$$K_E / K_{E0,1} = \alpha_1 \left(\frac{s}{B}\%\right)^{-\alpha_2} \tag{12}$$

where: $\alpha_1 = 0.2$; $\alpha_2 = 0.7$. The iterative procedure requires subsequent updating of the modulus E, the settlement s and the modulus number K_E by means respectively of eqs. (7), (6) and (12), until convergence is achieved.

4 ADDITIONAL EVALUATIONS

The reliability of the procedures previously described has been analysed comparing the values of settlement s_{cal}, obtained by means of both procedures, with the observed values s_{mea} of settlement for 125 case histories provided by Burland and Burbidge, i.e., the case histories used by Berardi and Lancellotta.

For both procedures it was thus possible to calculate, for each case history, the ratio s_{cal}/s_{mea}.

For both procedures, the number of cases corresponding to values of s_{cal}/s_{mea} falling within given ranges are plotted in fig.1. It can be observed that the procedure suggested by Burland and Burbidge is more conservative, since it yields a higher number of cases featuring R > 1.

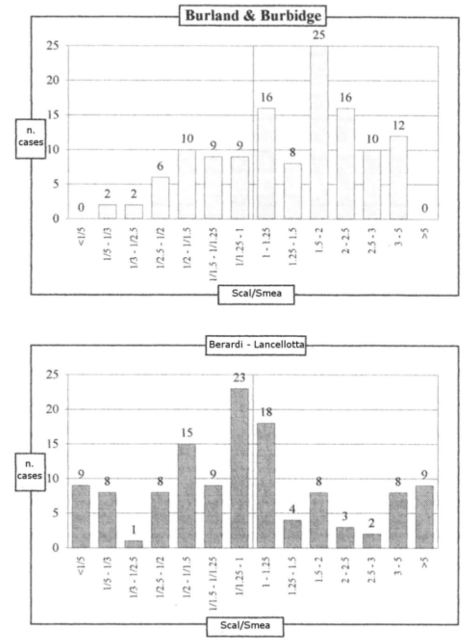

Figure 1. Number of cases corresponding to s_{cal}/s_{mea} within given ranges.

The introduction of the parameters R' and R'', respectively defined as:

$$R' \quad s_{cal}/s_{mea} \quad if \quad s_{cal}/s_{mea} \quad 1 \qquad (13)$$

$$R'' \quad s_{mea}/s_{cal} \quad if \quad s_{cal}/s_{mea} \quad 1$$

allows a different representation, shown in fig. 2, where for each value of R' (R'') the percentage of cases not exceeding R'(R'') is plotted.

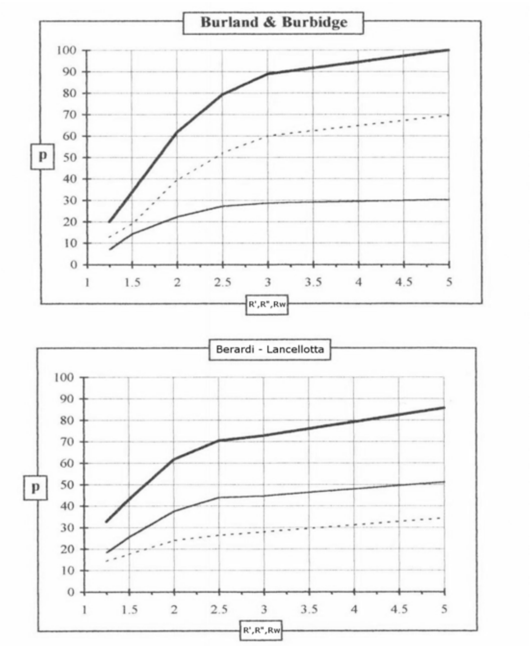

Figure 2. Percentage of cases not exceeding R'/R''/R_w.

In both diagrams the dotted line corresponds to conservative values of R (i.e.: R'), while the thin full line corresponds to R''. The thick full line represents the sum of the percentages corresponding to R_w = R' and R_w = R''.
As it can be seen, the procedure proposed by Burland and Burbidge offers a further advantage since it provides a thick full line consistently higher than the corresponding curve obtained by Berardi and Lancellotta's approach.

Some further simple analyses have been carried out using the same case histories analysed by Berardi and Lancellotta.
These analyses confirmed the validity of eq. (12) and pointed out the influence of the ratio q'_n/σ'_{VO} on the values of parameters α_1 and α_2. In other words, more accurate interpolating curves can be obtained subdividing the data according to 5 different ranges of values of the ratio q'_n/σ'_{VO}; in tab. 2a the values of parameters α_1 and α_2 which define the 5 interpolating curves are reported, while one of these curves is plotted in fig. 3 as an example.

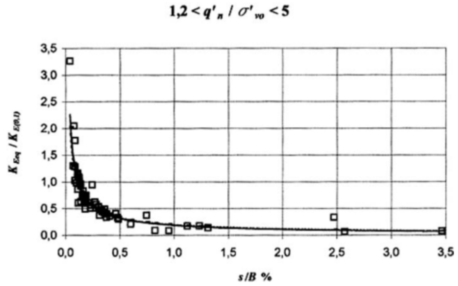

Figure 3. Decay of Modulus Number with dimensionless settlement s/B, for a given value of the ratio q'_n/σ'_{VO}

Table 2. (a) values of parameters α_1, α_2 of eq. (12);
(b) values of parameters α_5, α_6 of eq. (16)

(q'_n/σ'_{vo})	α_1	α_2	N_1	α_5	α_6
0.09- 0.25	0.0425	0.7565	11-15	0.2208	0.7898
0.25-1.20	0.1412	0.6641	16-29	0.0972	0.8004
1.20-5.00	0.1893	0.7705	30-43	0.1044	0.7396
5.00-31.00	0.2068	0.7839	44-57	0.0910	0.3847
			58-80	0.0153	0.9667

Back-analyses also provided two additional useful interpolations. The former is a direct relationship between dimensionless settlement s/B, ratio q'_n/σ'_{VO} and the value N_1 defined in eq. (9), expressed by eq. (14), plotted in fig. 4:

$$\left(\frac{s}{B}\right) \Big/ \left(\frac{q'^n}{\sigma'_{VO}}\right) = \alpha_3 \cdot N_1^{-\alpha 4} \qquad (14)$$

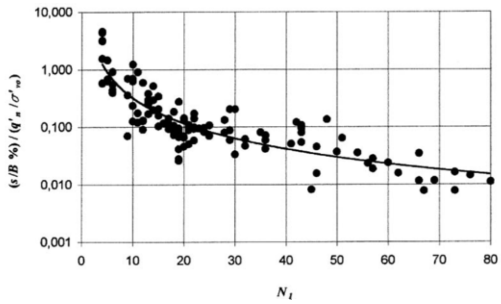

Figure 4. Relationship between s/B, q'_n/σ'_{VO}, and N_1 dimensionless settlement

where α_3 = 9.6635 α_4 =1.4749

As an alternative, the relationship between s/B, q'_n/σ'_{VO} and N_1 can be defined by means of 5 different interpolating curves, expressed by eq. (15):

$$\left(\frac{s}{B}\right) = \alpha_5 \left(\frac{q'^n}{\sigma'_{VO}}\right)^{\alpha_6} \qquad (15)$$

each curve being defined by a different pair of values of parameters α_5 and α_6, corresponding to a different range of values of N_1. In tab. 2b the values of parameters α_5 and α_6 which define the 5 interpolating curves are reported, while one of these curves is plotted in fig. 5 as an example.

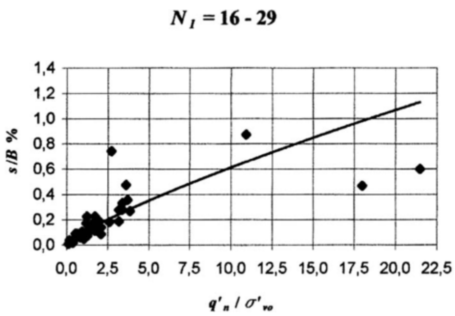

Figure 5. s/B as a function of stress level (q'_n/σ'_{VO}) and N_1

The results of the evaluations previously described can be used for simple settlement predictions, following three different approaches, respectively defined as (A), (B) and (C).

Approach (A) is the simplest, and consists in evaluating settlement using eq. (14), independent of the value of N_1.

Approach (B) makes use of eq. (14) only for N_1 values <11; for N_1>11 eq. (15) is used, adopting the values of α_5 and α_6 reported in tab. 2b.

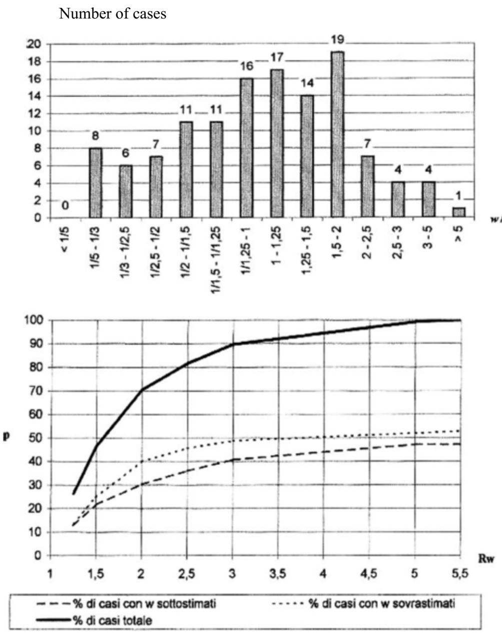

Figure 6. Approach (A) (a) Number of cases corresponding to s_{cal}/s_{mea} within given ranges; (b) Percentage of cases not exceeding R'/R"/R_w.

Approach (C) requires again use of eq. (14) for N_1 < 11, while for N_1 >11 eq. (14) is used only to provide an initial value of settlement. Approach (C) then follows the same path as Berardi and Lancellotta's procedure, the only difference being the use of eq. (12) with values of α_1 and α_2 depending on the ratio q'_n/σ'_{VO} and provided by table 2a.

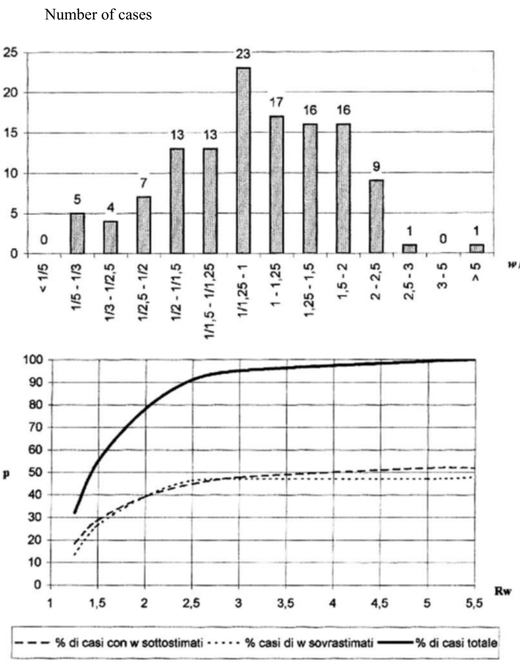

Figure 7. Approach (B) (a) Number of cases corresponding to s_{cal}/s_{mea} within given ranges; (b) Percentage of cases not exceeding R'/R"/R_w.

Approaches (A), (B) and (C) have been used to back-calculate settlements for all the cases examined by Berardi and Lancellotta; the results have been respectively reported in figs. 6, 7 and 8, in the same format used in the previous section for figs. 1 and 2.

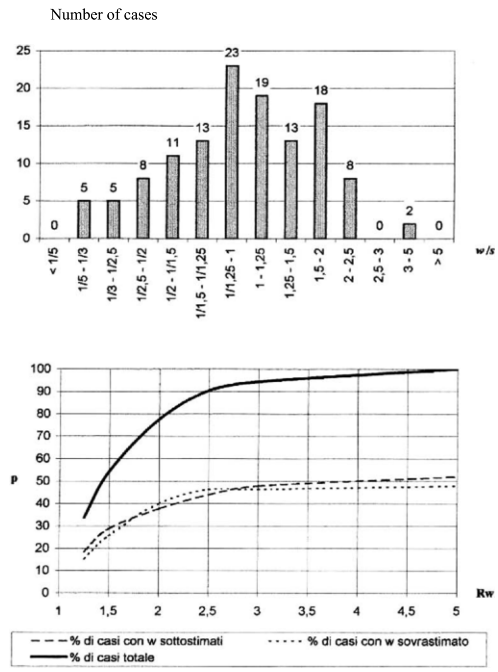

Figure 8. Approach (C) (a) Number of cases corresponding to s_{cal}/s_{mea} within given ranges; (b) Percentage of cases not exceeding R'/R"/R_w.

As it can be observed, the thick full lines provided by the three simple approaches are consistently higher than the corresponding curves obtained by means of Burland and Burbidge's and Berardi and Lancellotta's procedures.

5 CONCLUSIONS

The results of simple back-analyses performed on the data base provided by Burland and Burbidge have been presented.

Such results have been used to assess the reliability of the procedures for settlement predictions proposed by Burland and Burbidge and by Berardi and Lancellotta. It has also been shown that these results can provide a direct means for the evaluation of settlements, with a reliability which compares favourably with the reliability of the above procedures.

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