Long term settlement assessment of shallow foundation and extended duration of load step during pressuremeter test

Évaluation du tassement à long terme d'une fondation superficielle et palier longue durée lors d'un essai pressiométrique

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ABSTRACT

This paper compares the results of extended pressuremeter tests with the results of shallow foundation loading tests. These results are discussed in the light of the predictions of the formula for estimating settlement of shallow foundations. This formula, based on the results of the pressuremeter test developed by Louis Ménard, incorporates a time factor through the B/B_0 scale ratio. Other formulae, such as the elastic and Nonveiler formulae, are discussed to show possible adaptations of the Ménard formula. More recent developments proposed by Briaud with his Load Settlement Curve Method and Lehane on the creep factor are also covered in this research. This paper compares the prediction results and their extrapolation with the results of expansion tests carried out with 1, 5 minutes and 1 hour increments. For the tests carried out by the former French Public Works Laboratories (RST) and other authors on experimental sites or real projects, different soils were tested over periods of up to 3 years.

RESUME

Ce papier présente une comparaison des résultats d'essais pressiométriques longue durée avec des résultats d'essais de chargement de fondation superficielles. Ces résultats sont discutés à la lumière des prédictions de la formule d'estimation des tassementes des fondations superficielles. Cette formule basée sur les résultats de l'essai pressiométrique développée par Louis Ménard intègre un facteur temps par le rapport d'échelle B/B_0. Ce papier compare les résultats de prédiction et leur extrapolation à des résultats d'essais d'expansion réalisés avec des paliers de 1, 5 minutes et 1 heure. Différents sols ont pu être testés sur des périodes pouvant aller jusqu'à 3 ans pour les essais réalisés par les laboratoires du RST.

Keywords: footing, settlement, prediction, creep

1. Introduction

All methods developed to evaluate the settlement s of a foundation of any shape, infinitely rigid (uniform settlement) or flexible (uniform stress), placed on a semi-infinite elastic linear isotropic mass, are based on a general relationship linking the load f_1 increase to the scaled parameters characterizing the foundation geometry and soil compressibility f_2 :

$$S_e(mm) = f_1(q).f_2\left(\frac{1}{\mathrm{E}'}\right).f_3(\mathrm{B}).f_4\left(\frac{\mathrm{L}}{\mathrm{B}}\right).f_5\left(\frac{\mathrm{d}}{\mathrm{B}}\right).f_6\left(\frac{\mathrm{d_w}}{\mathrm{B}}\right).f_7\left(\frac{\mathrm{H}}{\mathrm{B}}\right).f_8(\mathrm{t}) \quad (1)$$

where:
q: vertical stress applied by the foundation,
E': ground modulus of elasticity,
L: length,
B: width,
d: embedment of foundation,
d_w: water table depth,
H: thickness of geotechnical unit under the footing,
t: time duration considered in the study.

Settlement calculation methods published vary in the selection and representation of functions f_1 to f_8. SPT method developed by Burland and Burbidge (1984) proposed a complex relationship from a statistical regression analysis of data from more than 200 cases. Their settlement equation is:

$$s_c = f_l \cdot f_s \cdot f_t \cdot (q - 0.67 \cdot \sigma'_p) \cdot B^{0.7} \cdot I_c \quad (2)$$

where:
N: average N-value over depth of influence z_I,
q: vertical stress applied by the foundation,
I_c: compressibility index,
f_l: correction factor for thickness of sand or gravel layer,
f_s: shape factor,
f_t: time factor which is used if t ≥ 3 years,
More precisely

$$f_t = \left(1 + R_{3years} + R_t \cdot log\frac{t}{3}\right)$$

This relationship is based on a proposition first made by Nonveiler (1963). The author has observed the effect of creep (secondary compression or viscous flow) on Rijeka grain silo settlement. Indeed, the publication of Nonveiler's paper in 1963 provided a simple and effective approach for moving from 1-day test results to 10-years values and thus providing a relationship for f_t. First, we need to know the settlement at a given time, e.g. 1 day for a loading test result (noted as s_{1d}), then the settlement s_t of the foundation at time t can be written as:

$$s_t = s_{1d} \cdot \left(1 + \beta \cdot log \frac{t}{t_{1d}}\right) \quad (3)$$

Significant creep settlement (s_c) occurred, even at relatively low stress levels, during the maintained load phases. Lehane et al. (2024) also noted that s_c increased in value as the natural logarithm of elapsed time t since load application, and also with the natural logarithm of creep rate. The following equation was proposed to model the creep response.

$$\frac{s_c}{B} = m \cdot ln\left(\frac{t}{t_{ref}}\right) \quad (4)$$

where m is a creep coefficient and t_{ref} is a reference time corresponding to the onset of creep settlement.

$$m \cong c \cdot \left(\frac{q}{q_{ult}}\right)^2 = c \cdot \left(\frac{p}{p_{lim}}\right)^2 \quad (5)$$

Lehane et al. (2018) derived values for the creep coefficient c from measurements of the one-dimensional creep settlement response of footings, and shear-induced creep measured in pressuremeter tests, over a range of various stress levels (q/q_{ult}) at the Shenton Park sandy site, where q_{ult} was obtained by extrapolating measured load settlement curves. Values between 0.02 and 0.003 were observed for c coefficient.

However, among all the existing methods, the direct method developped for the pressuremeter is the only one that didn't explicitely integrate a time parameter. This pressuremeter method was originally proposed by Ménard and Rousseau in 1962. It was included in the French Bridge Foundation Code FOND72 as soon as 1972, then in Fascicule 62tV in 1992 and its successor standard NF P94-261. It involves calculating the 10-year settlement of an embedded foundation of width B:

$$s_{10\ years} = s_c + s_d \quad (6)$$

In equation 6, the first term s_c represents settlement due to volumetric deformation whereas the second term s_d represents settlement due to shear deformation.

$$s_c = \frac{\alpha}{9 \cdot E_c} \cdot (q - \gamma \cdot D) \cdot \lambda_c \cdot B \quad (7)$$

$$s_d = \frac{2}{9 \cdot E_d} \cdot (q - \gamma \cdot D) \cdot \left(\lambda_d \cdot \frac{B}{B_0}\right)^{\alpha} \cdot B_0 \quad (8)$$

where :

γ: weight by volume of soil,

D: embedment of foundation in soil,

α: rheological coefficient, depending on soil type and soil consolidation,

λ_c and λ_d : shape factors,

B: foundation width or diameter,

B_0: reference dimension equal to 0.6 m,

E_c: pressure modulus of the volumetric zone located in the first layer under the foundation of thickness B/2,

E_d: equivalent pressure modulus of soil in which shear strains are prevailing.

Originally, Ménard, assumed (as is now usual) $E_c = E_M/\alpha$, with α a rheological coefficient dependent on material structure and time factor (varying from 1 to 1/3), total settlement can be written for homogeneous soil (based on Josselin de Jong, 1957):

$$s = \left(\frac{1+\nu}{3 \cdot E_M} + \frac{\alpha}{4{,}5 \cdot E'_M}\right) \cdot p \cdot R \quad (9)$$

with E'_M the spheric modulus.

Three notions were then introduced:

- the notion of form,
- the notion of dimension/time,
- the notion of homogeneity.

For a large circular foundation, Ménard proposes replacing R by $R_0 \cdot \left(\frac{R}{R_0}\right)^{\alpha}$ with R_0 a standard dimension of 30 cm for the pressuremeter. It is assumed that two foundations of different radii (R_0 and R) reach the same stage of evolution at homologous times (T_0=1 day and T=10 years), thus:

$$s_{(10\ years)} = \left(\frac{1+\nu}{3 \cdot E_M}\right) \cdot p \cdot R_0 \cdot \left(\frac{R}{R_0}\right)^{\alpha} + \frac{\alpha}{4{,}5 \cdot E'_M} \cdot p \cdot R \quad (10)$$

It is therefore here, that the parameter α derived from dimensional analysis, defines long-term settlement, fixed from 1967 onwards from the first set given in 1962 in the initial article (Ménard and Rousseau, 1962).

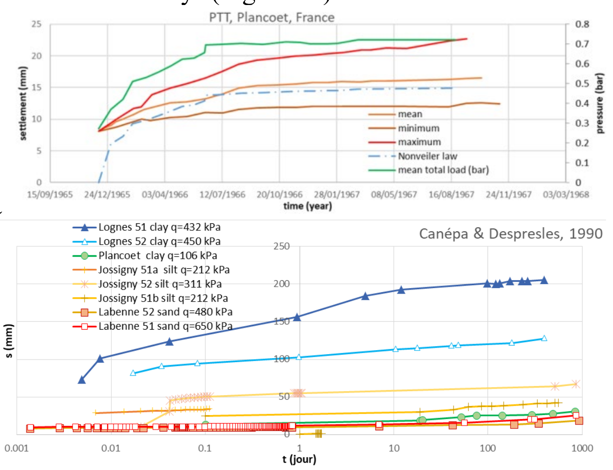
2. Experimental evidences

As early as the 1970s, engineers at the Ponts et Chaussées laboratories began to study the long-term settlement of surface foundations (Figure 1a). The aim was to predict the 10-year settlement of foundations.

From 1973 to 1978, they collected cases of real projects with foundation settlement monitoring (Bru et al., 1972; Amar, 1977). A total of 26 sites and 45 points were collected.

Given that the conditions under which the work was carried out were subject to the spatial variability of the site (excavations were reworked) and the soil conditions were often complex, it was decided to carry out long-term monitoring of foundations under controlled conditions. At six sites, around one hundred points were obtained, albeit with some uncertainties due to the surface crust.

To supplement these data, which did not include pressuremeter measurements, the Ponts et Chaussées laboratories continued their test campaign with long-term tests. At four experimental sites long-term loading tests on metric-size foundations were carried out over a period of 800 to 900 days (Figure 1b).



a

b

Figure 1. Long-term settlement measurements on various structures (Canépa and Despresles, 1990).

Amar et al. (1994) conclude that settlements trends are of the "creep" rather than "consolidation" type, and deferred settlement can be significant, even for sands, but at this stage no alternative equation was proposed for predicting the creep behaviour of foundation.

Observation of deferred settlement of heavy buildings has also shown the difficulty of obtaining a good prediction of long-term settlement from laboratory or the pressuremeter tests alone, accounting that a 60s test hardly catch soil creep parameter (Leidwanger et al., 1994).

3. Fitting of equation on experimental results

From previous statements, two approaches coexist for accounting this effect of time:

- for the pressuremeter method with a direct method (taking into account a scaling factor);
- for the Lehane (and also Schmertmann) penetrometric method, the Burland and Burbidge SPT method with a so-called Nonveiler coefficient.

Figure 2a shows the evolution of volume during 1h pressure steps in Jossigny silt for pressuremeter tests located in the zone of influence of the footing. As shown on figure 2b representing evolution of Ménard modulus at a time t (E_{Mt}) normalised by the conventional Ménard one minute modulus (E_M) versus logarithm of time, β value obtained when fitting a Nonveiler law is equal to -0.055 and -0.07. The same value is observed for Plancoet soft silt.

a

b

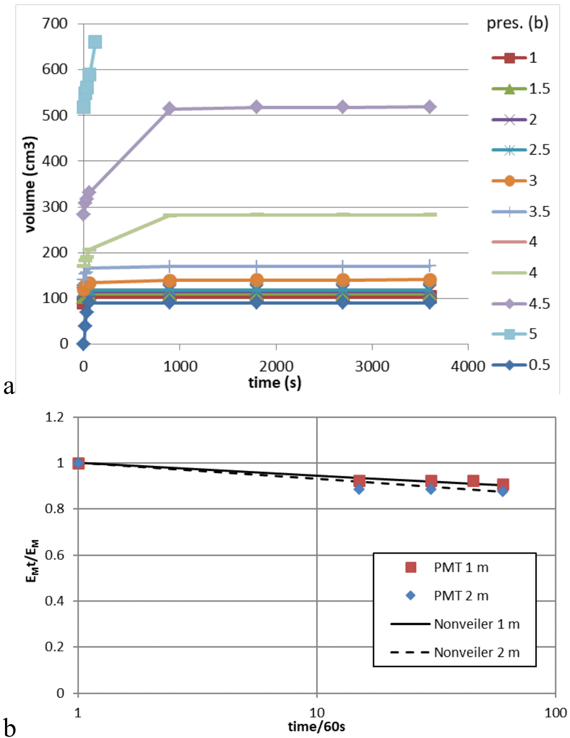


Figure 2. Ménard modulus evolution with extended test duration (Jossigny site).

Figure 3 shows the evolution of normalized settlement versus normalized time taken from Figure 1b for Jossigny site. The fitting of Nonveiler law gives a β between 0.05 and 0.07. It should be noted here, that logically an opposite value is obtained for settlement and modulus. Here, for a 1x1 m footing, we don't find the ratio of 2 mentioned by Briaud between the creep coefficient observed on the foundations and the pressuremeter tests (Briaud et Jeanjean, 1994). To match experimental results, a *c* coefficient of 0.5 seems more appropriate than the 0.02 proposed by Lehane. It seems that in a simple way, a creep factor may be substituted in equation 8 to have:

$$s_d = \frac{2}{9\cdot E_d}\cdot (q-\gamma\cdot D)\cdot \lambda_d \cdot B \cdot \left(1+\beta\cdot log\frac{t}{t_{1d}}\right) \quad (11)$$

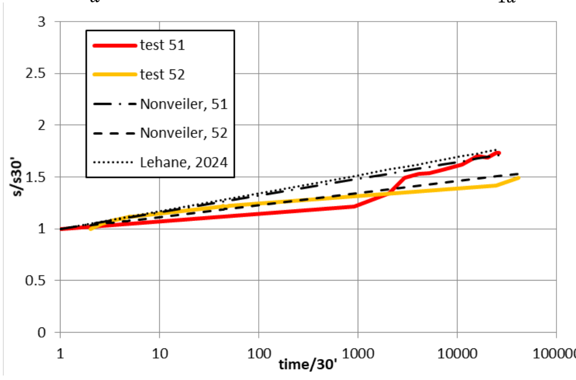


Figure 3. Normalized settlement evolution with creep test (Jossigny site).

Figure 4 shows that using this equation 11, the predictions by equation 6 are much lower than those observed. But as may be seen on Figure 1b, for Lognes experiments performed during a rainy period and on which a load very close to ultimate bearing pressure have been applied, important elastic settlements have been observed (Amar et al., 1994).

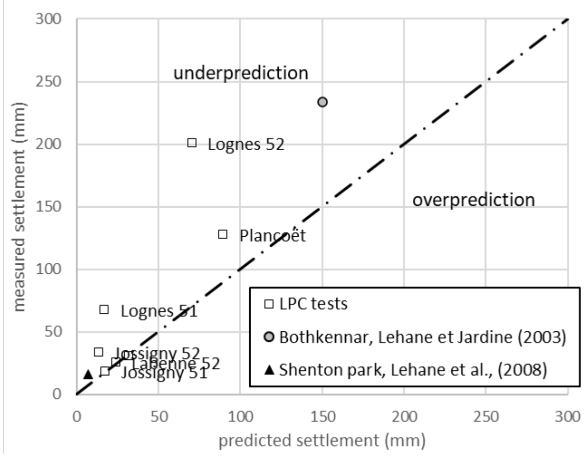


Figure 4. Comparison of prediction of long-term settlement and measure.

It should be noted that Burland and Burbidge (1994) like Schmertmann (1970) proposed a β value of 0.2 and mention that for Shenton Park, Lehane used 10min long increment to fit Equation 5, c coefficient.

Thus, taking this value into account in equation 11, the predicted settlement for the 164 plate loading tests gathered in the Gustave Eiffel university (previously Ponts et Chaussées central laboratory) database, seems to be increased by a factor 2 compare to Ménard and Rousseau formula, and more for more soft soils (Figure 5).

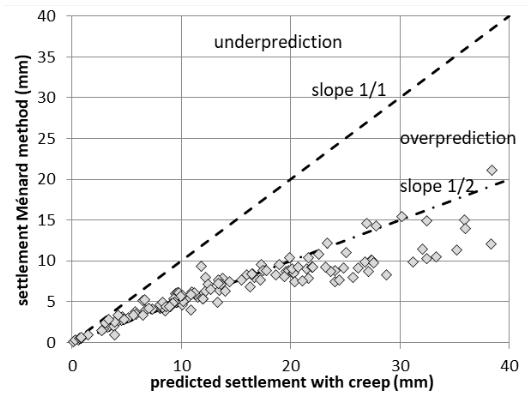


Figure 5. Comparison of prediction of long-term settlement and Ménard and Rousseau equation (1962) on all cases gathered in UGE shallow foundation database.

For heavy building design, EdF realised pressuremeter with 45' pressure steps and developed the Diflupress L.D., a device for in situ measurement of deferred soil behavior under constant loading (Leidwanger et al., 1994). This equipment and its long-term specific procedure have been implemented on several construction sites.

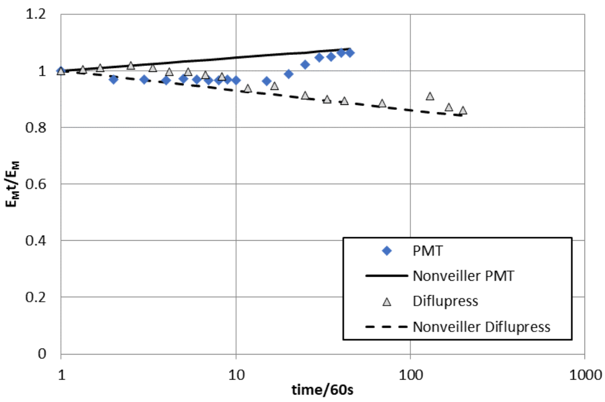


Figure 6. Ménard modulus evolution with extended test duration and Diflupress LD at 16 m depth (withheld name site).

For this equipment test durations have been extended up to 48 days. Figure 6 shows that during the first ten minutes, the trends are similar between the two experiments, but diverge after 10 min. The Ménard modulus has been computed in the same range of pressure for both tests.

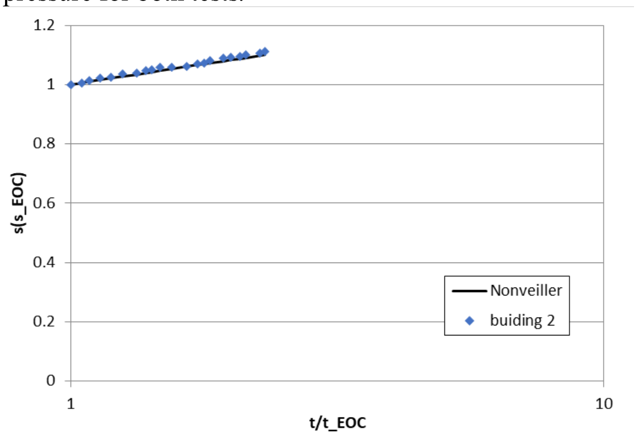


Figure 7. Normalized settlement evolution versus normalized time with reference to End of Construction (withheld name site).

The fitting of Nonveiler law on these curves, gives a β close to 0.02 for PMT and -0.02 for Diflupress L.D. For the settlement of heavy building 2 shown on Figure 7, a β value close to 0.12 is observed.

Therefore, using this β value for heavy building own by EdF and cited by Hoang et al., 2020, the evaluation of long-term settlement by equation 11 give a correct prediction of the observed settlement of large building with an average diameter of 40 m and a mean pressure of 475 kPa (Figure 8).

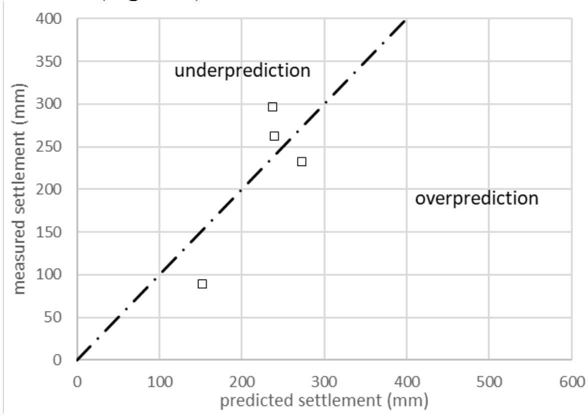


Figure 8. Normalized settlement evolution with creep test.

4. Conclusions

In its actual practice, the pressuremeter mainly use to design pile foundation is well defined in EN ISO 22476-4 standard. However, the versatility of this equipment allows a lot of application now allowed by EN ISO 22476-5 (Karagiannopoulos et al., 2022; Reiffsteck et al., 2022; Savatier et al., 2024).

A specific creep procedure proposed in EN ISO 22476-5 standard may be used to define creep parameter to propose an alternative prediction to the one proposed by Ménard and Rousseau (1962).

This paper has shown that a modification of Ménard and Rousseau formula to include Nonveiller coefficient may be more pertinent to predict long term settlement of structure even heavy loaded.

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