Pile behavior from static load test and CPTU data

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ABSTRACT: The aim of this paper is to show that the static load curve normalized by the bearing capacity in the force axis is characteristic for a given type of deep foundations within a range of the geometry and soil conditions. The mean, normalized static load curve determined here – called design chart – can be used to estimate the entire load curve by multiplying the load coordinate with the CPTu limit load, and the constant for the given method.

For this aim, static load test curves of CFA piles were normalized by load capacity values determined by different CPTu prediction methods: DIN 4014 and its modified version, EUROCODE 7-3, FTV method and some modified versions of these. Good quality static load test data and nearby CPTu data were used. The mean static load test curves were suggested as design chart for the entire load curve of CFA piles. Some constant multipliers were determined for the various methods (DIN method, EUROCODE 7-3 method, FTV method) applied in Hungarian soil conditions.

The coefficient of variation of the load curve at the d/10 load is about the same for every CPTu prediction method, the normalized d/10 loads differ in constnts. Comparing two groups of piles (18 and 11 CFA piles), the statistical tests showed that the results of the two groups did not differ significantly, validating the charts. In the discussion, the CFA pile results are compared with earlier bored and Franki pile data. The mean curves normalized by the shaft yield load indicates that the effectiveness of the bored and CFA piles are about the same, but the Franki piles are about “7 times” more effective.

Keywords: CPTu pile prediction, loading test, confidence interval, CFA piles, bored piles, Franki piles

1. Introduction

The goal of the research is to propose a new design tool for the prediction of the entire loading curve on the basis of new CPTu data, including various CPTu prediction methods. The suggested design charts were elaborated on the basis of the evaluation of static load test data at the Hungarian soils conditions for various pile types, incorporating some pile prediction methods.

In this paper the validation of the method is presented on the example of CFA piles and the results are compared with the result of a similar analysis made on Bored pile and Franki pile data. The piles were installed at various soil conditions in Hungary.

Two groups of CFA data (the static load curves and CPTu tests data) were used for the validation, a part of each data set was more reliable than the remainder part. The first group comprised 18 CFA piles, the second group 11 CFA piles.

The data were “more reliable” if the pile was fully loaded and “less reliable” if the CPTU side friction measurement was made with a prototype CPT. The more reliable data were treated separately within each group and were unified into a third data set which finally gave the constants related to the various methods.

The mean normalized load test curves of the two groups did not differ significantly and gave the statistically same constants for the Hungarian soil conditions, verifying the method. The confidenc intervals was smaller for more reliable data and vice versa; and were about the same for all the tested methods if reliable data were used.

2. Methods

2.1. Pile capacity prediction methods

The pile prediction methods can be categorized on the basis of three aspects.

a) may or may not include the measured local side friction data fs for the shaft resistance prediction,

b) may or may not include other load values than the bearing capacity,

c) the pile type may or may not be used during the computation (the “pile type” free methods can be used to compare the “effectiveness” of the different pile types).

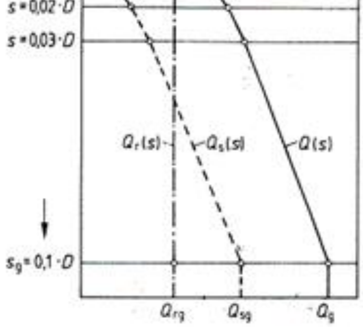

Figure 1. The DIN method

The following methods were incorporated into design charts: (i) the DIN 4014 for bored piles predictingboth the bearing capacity and the whole loading curve (DIN); (ii) the EUROCODE 7-3 for bored piles which predicts the bearing capacity (EU), (iii) the FTV method (see App) which uses local side friction data and predicts shaft yield (R1), bearing capacity (R4) and two other points.

The DIN method and the FTV methods are similar estimating four points of the grading curve. In the modified version of the DIN and the FTV methods the tip resistance was replaced by the EUROCODE 7-3 value.

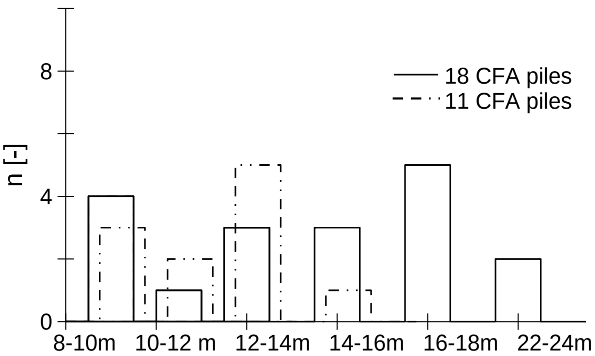

Figure 2a. Geometry: Tested CFA pile length data a, b, 18+11

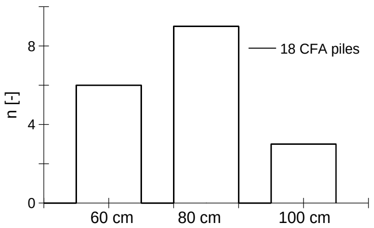

Figure 2b. Geometry: Tested CFA pile diameter data

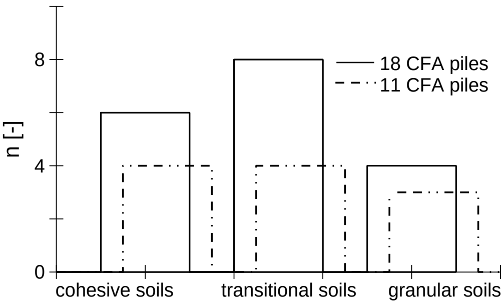

Figure 3. Soil condition Tested CFA pile data a. b. 18, 11

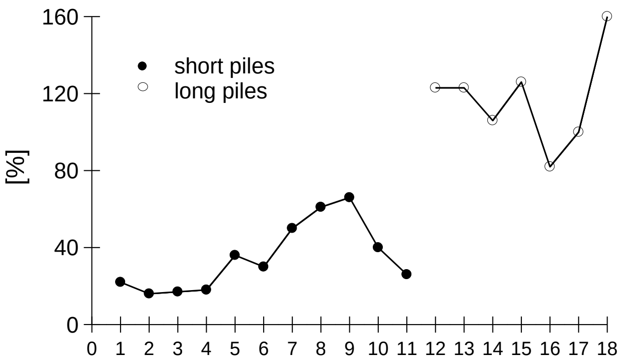

Figure 4a. The ratio of the maximum settlement and the d/10 settlement achieved by the pile load test Group 1.

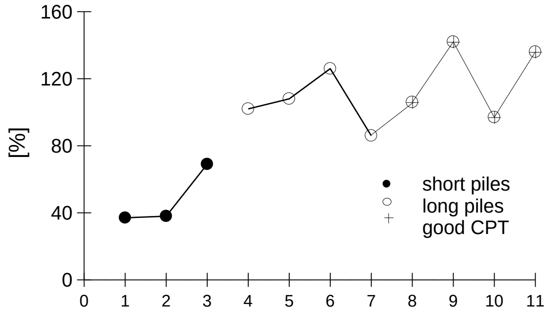

Figure 4b. The ratio of the maximum settlement and the d/10 settlement achieved by the pile load test Group 2.

2.2. Measured data

The first group comprises 18 CFA piles, seven piles were statically fully loaded. In the second group 11 CFA piles are available, the data of nine/four is more "reliable" (fully loaded/with reliable CPTU).

Figures 1 to 4 show that in the first (second) group the length of the piles ranged from 8.00 m to 22.90 m (8.00 m to 16 m). The diameter ranged from 0.60 m to 1.00 m for group 1 and was 0.8 m for group 2. Only seven piles (piles 12-18 in Fig 4a) were fully load-ed during the static load test in group 1 and 7-8 out of group 2 (out of the latter 4 tests were with reliable CPT, Fig 4b).

The CPTU measurement was made with two kinds of equipment. Besides a BORRO, a prototype CPT was used. The two systems differed basically in the measured local side friction data (no comparison is available). It is very probable that in the case of the prototype CPT the shaft stresses were not measured properly.

2.3. Static load test inter- and extrapolation

Six models (the side friction curve with two hyperbolae and the tip resistance curve with three different functions) were fitted on the measured load curves using non-linear Least Squares model-fitting method. Three models of them:

$$F= (F_k \cdot s / c+s) + R_{cs} \cdot s \quad (1)$$

$$F= (F_k \cdot s / c+s) + R_{cs} \cdot \sqrt{s} \quad (2)$$

$$F= (F_k \cdot s / c+s) + R_{cs} \cdot \log(s) \quad (3)$$

where F is load, s is settlement, and F_k , c, R_{cs} are parameters.

The loads of the static loading curve related to the following settlements were then determined with the best-fit closed form function: 0.5 mm, 0.7 mm, 1 mm, 1.5 mm, 2 mm, 4 mm, 6 mm, 8 mm, 10 mm, 20 mm (Szabó & Imre, 2004).

2.4. Mean normalized loading curves

The closed form static loading curves were normalized by limit load values computed from CPTU data with the following pile bearing capacity prediction methods: the DIN 4014 method and its modified version, the EUROCODE 7-3 method, the FTV method and some modified forms.

Then the mean normalized static loading curves with 75 % confidence intervals (design charts) were computed pointwise for each group and CPTu prediction method, related to the settlements, 0.7 mm, 1 mm, 1.5 mm, 2 mm, 4 mm, 6 mm, 8 mm, 10 mm, 20 mm.

Two data sets were used first. Then the more reliable data (where no extrapolation was needed) were treated separately within each group and were unified into a third data set. For the third – reliable – data set, the diameter was 0.8 m, the 80 mm load was the d/10 load which was considered as a limit load.

2.5. Validation with statistical tests

The normalized loading curves were statistically evaluated for each prediction method separately. The mean and the 75% confidence interval of the load ratio – settlement curves were computed. The 75% confidence interval was determined with the Tschebiseff inequality:

$$P[|x - p_i| \ge a] \le \frac{SD^2}{a^2}, a > 0 \quad (4)$$

where p_i is the actual value, x is the expected value and, SD is the standard deviation.

Statistical tests were used to compare the results of the two groups assuming that the standard deviation of the groups is the same.

$$t' = |x_1 - x_2| \sqrt{\frac{n_1 n_2 (n_1 + n_2 - 2)}{(n_1 + n_2)(n_1 s_1^2 + n_2 s_2^2)}} \quad (5)$$

where x_1 and x_2 is the mean, where n_1 and n_2 is the sample number, s_1 and s_2 is standard deviation for group 1 and 2, respectively, t' is with Student distribution. The difference of the mean was tested on 0,9; 0,8; 0,3; 0,01 and 0,001 probability levels.

3. Results

3.1. Static load test inter- and extrapolation

The best closed-form function fitted on the measured load-settlement curves was the one related to Equation (2). All load curves were evaluated with the Mazurkiewicz method. The load curves were normalized by the so determined bearing capacity value and with the measured d/10 load, the results are shown in Figure 5 a and b resp.

Comparing these figures, it can be seen that the Mazurkiewicz method is approximate, the d/10 load is underestimated by 15% in case of fully loaded piles. The d/10 load was considered as the bearing capacity which was determined by the Mazurkiewicz method for the “short” loading tests, which is safe.

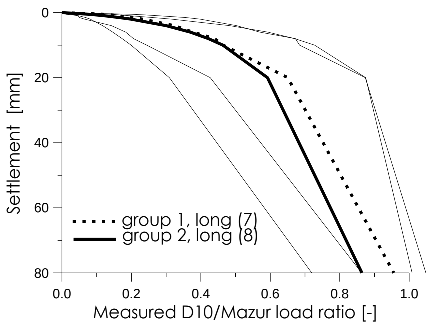

Figure 5a. The ratio of the measured load normalized with the Mazur load with the indication of the 75% normalized confidence intervals

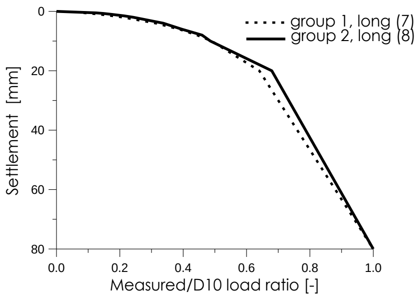

Figure 5b. The loasing curve normalized with the *d*/10 load. Fig. 5a indicates the standard deviation due to the various soil types and proves that the Mazurkiewicz limit load is safe, underestimates the limit load.

3.2. Mean normalized loading curves

Figure 6 and Table 1 compile the reliable data information. According to the main result with the most reliable data, the d/10 load (i.e. bearing capacity value) divided by the CPTu prediction methods was not equal to 1 for any method, and the difference was the smallest for the DIN, it was not negligible for the EUROCODE 7-3 (the mean was 0.78 instead of 1). Therefore, some constant multiplier differing from 1 is suggested for all methods.

Using reliable data, the coefficient of variation at the d/10 load is about the same for every method (the smallest is for the R4 which uses local side friction data fs, too).

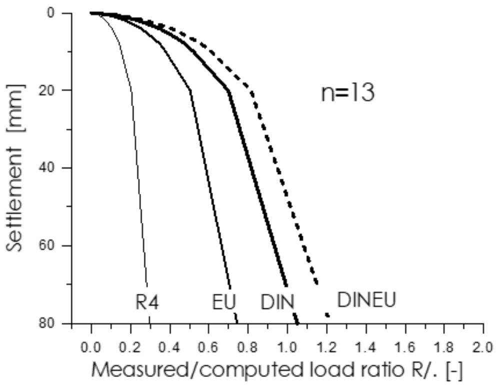

Figure 6a. Unified data set. a. The mean load ratio settlement curves for the various methodS (The diameter was 0.8 m, 80 mm load is the d/10 load).

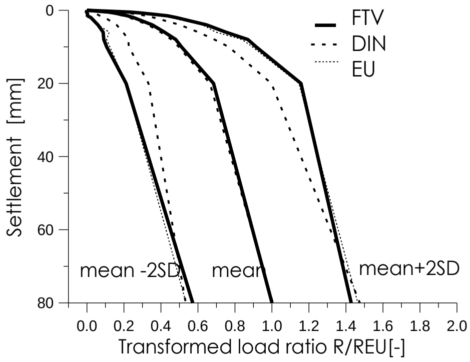

Figure 6b. Unified data set. b. The 75% normalized confidence intervals for the various methods.

The mean static loading curves with 75 % confidence interval normalized with the computed CPTU loads ("design charts") are shown separately for group1 and group 2 data in the Appendix 2.

The thin lines indicate all data, thick lines reliable data (i.e. the "fully loaded" tests and the piles with "good" CPTU). Using reliable data, the 75 % confidence interval decreases. Figure B6 shows the effect of "non-precise" CPTU using group 2 data with R4/R4EU normalization.

The results of the prototype shaft CPT measurements are indicated with thick lines. It can be seen that the 75 % confidence interval is not decreasing rather increasing in this case.

Results of the statistical tests are shown in Tables 1 to 3. According to the results the statistical tests (Tables 1

to 3), the difference between the two groups is never significant on a 0,001 level. The agreement is better for the 3 basic methods: DIN, EU, R4 than for the modified methods DINEU, R4EU.

In general, if the data were more reliable ("fully loaded tests") then the standard deviation of the data were less. When the data were less reliable then the standard deviation of the data were larger. The DIN method was robust in any change between all data and reliable data.

4. Discussion

4.1. Dissipation type CPT test results

The cone penetrometer tests can be made in continuous and in rheological testing modes. In the u-dissipation test, the pore water pressure is recorded ([5 to 11]). In the "simple rheological test" ([8-9]) the time variation of the local side friction and the cone resistance are measured, the rod is clamped. In these tests, after an immediate stress drop (possibly due to the change of the dynamic loading to static one), the cone resistance generally decreases, the shaft resistance decreases or increases in the first minutes. The inclusion of the rheological tests into the pile design method is present in the FTV data base.

4.2. FTV data base

Earlier research analyses were made by the FTV Company (unpublished internal research reports) on comparing static load test data with computed load values using continuous and dissipation type Sz832 CPT data with larger shaft element.

The area of the shaft element of the static probe Sz832 is 350 cm2, as opposed to the usual 250 cm2, this allows more accurate measurement. This is due not only to the larger surface area, but also to the fact that it measures at a higher altitude, where the conditions are indeed one-dimensional. It was found in a parallel research that the use of larger shaft element (within the size limits recommended by Tokyo conference recommendation) gives theoretically acceptable data ([8-9]).

4.3. Bored pile and Franki pile data re-evaluation from FTV data base

The re-evaluation of 17 bored and Benoto piles were made from the FTV data base. Concerning the load tests of the 17 Bored and Benoto piles, 12 test loads were less than half the D / 10 settlement value (Figure 7).

Some evaluation results are shown in Figure 8 indicating that the Mazurkiewicz method was safe to predict the limit load and the closed form formulae gave more reliable results if the final settlement of the static load curve was closer to d/10.

The results with bored piles analyses indicated that the bearing capacity can be estimated more precisely from dissipation type cone resistance and local side friction data than from continuous CPT data.

In addition, the data of 21 FRANKI piles were re-evaluated, which can be divided into 2 groups (17 piles, 3 piles), each calculation was performed separately, taking into account corrected and uncorrected peak resistance. The load-bearing estimations based on the two sets were characterized by almost the variance.

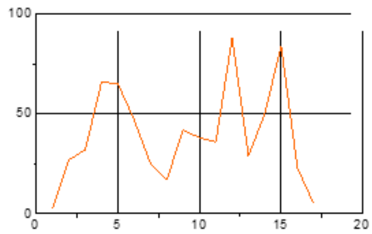

Figure 7a. The ratio of the maximum settlement and the d/10 settlement achieved by the bored pile load tests.

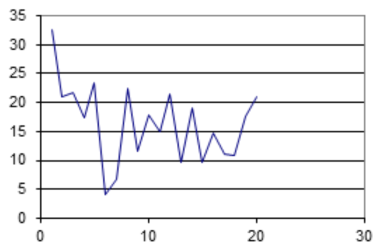

Figure 7b. The ratio of the maximum settlement and the d/10 settlement achieved by the Franki pile load tests.

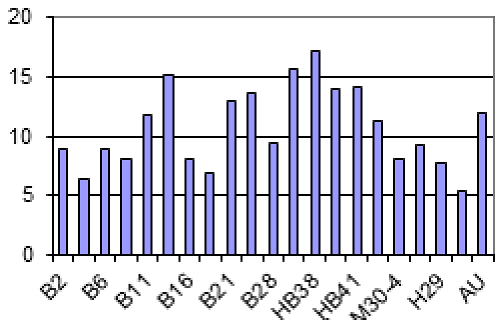

Figure 8 Geometry of tested Franki piles

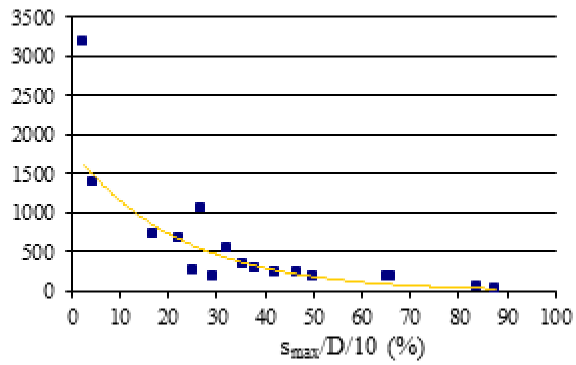

Figure 9a. The maximum difference of the various closed form functional estimations of the d/10 load decreases as the maximum settlement during the static load test divided by d/10 increases, as the closed form functional extrapolation becomes more reliable.

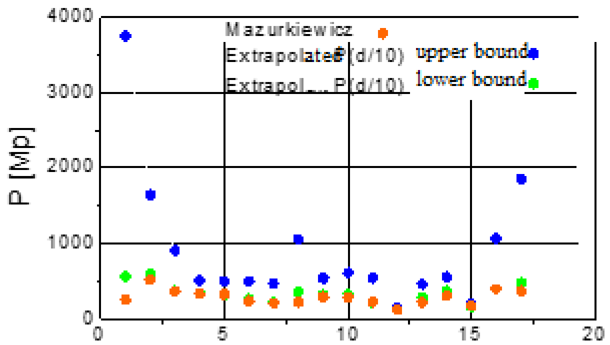

Figure 9b. Comparing the closed form estimation of the d/10 load from static load test data and the Mazurkiewicz load from static load test data, the latter seems to be a safe estimation of the limit load.

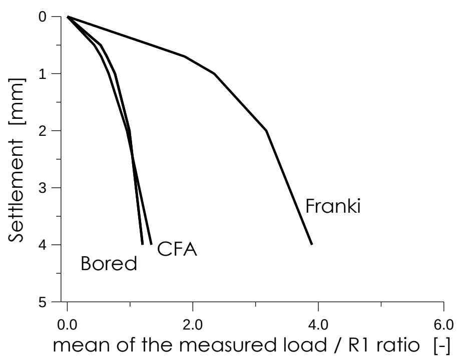

Figure 10. The mean load ratio (measured load/ computed R1 value) - ettlement curve for various pile types

Figure 10 compares the "effectiveness" of the different pile types on the basis of the data of some previ-ous diploma works.

5. Conclusions

The main result of this study indicates that the static loading curve normalized by the pile bearing capacity value is similar for a given pile type for a range of the geometry and soil conditions. It follows that the mean static load curves determined here can be used as preliminary design charts for the entire load curve. Multiplying by the limit load value computed from CPTu data and the constant of the methods, the "actual" static loading curves can be estimated in a new site. This results are resulted from the following research work.

1. The static load test data were described by some closed form functions and were extrapolated with the Mazurkiewicz method if it was necessary. The best closed form function was selected by model discrimination and was used in the research.

This method was verified as follows. The d/10 load was determined with the Mazurkiewicz method for the long tests, where the d/10 load was available. Comparing these data, it was found that the Mazurkiewicz method is approximate, the d/10 load is underestimated by 15% in case of fully loaded piles. It is very probable that the bearing capacity determined by the Mazurkiewicz method for the "short" loading tests, is a safe estimation.

It was also shown that the closed form functions gives larger d/10 load values than the Mazurkiewicz method.

2. The mean, normalized static load curve points and their standard deviation were determined pointwise at settlements 0.7 mm, 1 mm, 1.5 mm, 2 mm, 4 mm, 6 mm, 8 mm, 10 mm, 20 mm. Then further normalization was made with a load values computed from CPTu data by a pile load prediction method. The methods were the FTV method or its modified form, the DIN 4014 method or its modified version, the EUROCODE 7-3 method.

3. To verify the mean load curves, the data were divided into two groups comprising the data of 18+11 CFA piles in various soil conditions (static load tests and CPTU tests). The number of fully loaded tests was 7 and 8, respectively. In the second group only 4 among the fully loaded tests were with reliable CPT (for the remainder a prototype CPT was used).

The statistical tests showed that the results of the two groups did not differ significantly. The agreement seemed to be better for the 3 basic methods: DIN, EU, R4 than for the modified methods DINEU, R4 EU. It was found that the quality of data significantly influenced the scatter. Using reliable data, the coefficient of variation at the d/10 load was about the same for every method.

4. According to the results with the reliable data, the mean of the normalised d/10 load (i.e. bearing capacity value) was not equal to the limit load for any method, and the difference was the smallest for the DIN and was not negligible for the EUROCODE 7-3 (0.78 instead of 1).

It follows that some constant multiplier differing from 1 is suggested for all CPTu bearing capacity methods in case of Hungarian soils and CFA piles.

5. Using the FTV data base, the CFA normalized static load test curves were compared with Franki and bored pile data. The “effectiveness” of the different pile types was tested using the “4 mm settlement load” divided by the shaft yield load R1 of the FTV method.

The mean curve results indicated that the effectiveness of the bored and CFA piles are about the same, the Franki piles are about “7 times” more effective.

6. In the FTV data base, dissipation type local side friction and the cone resistance CPT data were also collected. These were used in the case of the bored piles and Franki piles. In the case of the Sz832 CPT, the friction sleeve has surface area of A=350 cm^2 for the presently used equipments it is A=250 cm^2 but both are within the suggested range. The general geometry of the penetrometer tip and of the cone would be in accordance with the recommendations (ICSMFE, 1977).

7. Further research is suggested on the possible enlargement of the sleeve element and the local side friction reliability in this case. It is also suggested the use of a short dissipation type testing model to minimize the dynamic effect of the continuous CPTu.

8. Further research is suggested on the dissipation testing mode not only for the local side friction and the cone resistance but also for the last load value determined by the static load test. At the end of the static load test, a dissipation type soil response can be determined (clamped sysem, determining the load release).

Table 1

	DIN	EU	R4	R4	Mazur
n_1	7	7	7	18	7
n_2	11	11	4	11	11
x_1	1,03	0,78	0,28	0,45	0,96
x_2	1,04	0,79	0,33	0,43	0,86
s_1	0,22	0,19	0,06	0,34	0,05
s_2	0,22	0,22	0,04	0,23	0,06
t'	-0,09	-0,09	-1,35	0,17	3,46

Table 2

	DINEU	R4EU	R4EU	R1(d/10)	R1(4mm)
n_1	7	7	18	6	6
n_2	11	4	11	4	4
x_1	1,06	0,42	0,52	3,20	1,73
x_2	1,27	0,63	0,94	4,78	1,51
s_1	0,18	0,06	0,25	1,73	0,62
s_2	0,31	0,07	0,44	1,02	0,63
t'	-1,53	-4,75	-3,16	-1,47	0,49

Table 3

n	11+7-2	4+7-2	4+62	11+18-2	13+4-2
p					
0,90	0,13	0,13	0,13	0,13	0,128
0,80	0,26	0,26	0,26	0,26	0,258
0,30	1,07	1,09	1,11	1,06	1,074
0,01	2,921	3,25	3,36	2,771	1,753
0,001	4,015	4,781	5,04	3,69	4,073

Table 4 Coefficient of variation for reliable data set, d/10 load

	DIN	EU	R4	DINEU	R4EU
s / x	0,235	0,232	0,214	0,202	0,256

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6. Appendix A – FTV methods

In the FTV method four points of the static load-settlement curve are related to some yield or bearing capacity phenomena (Table 5) are predicted on the basis of fs (measured local side friction) and qc (measured point resistance) data as follows:

$$R_k = \int_l^0 U f_{sk}(x)dx + Fq_{ck} \qquad k = 1,2,3,4 \tag{6}$$

where: $f_{sk}(z)$ is the local side friction in depth z for the k-th point; q_{ck} is the point resistance at the k-th point; l=pile length, U=perimeter, F=cross section.At the shaft yield point the local side friction f_{s1} (z) is computed as:

$$f_{s1}(z) = \min_{l+4D \geq x \geq z} f_s(x) \quad (7)$$

which is the minimum measured local side friction f_s between depths of z and of l+4D.

Equation (7) expresses that the unit side resistance cannot be greater at any given depth than the smallest unit side resistance value under this point up to the depth of interest. This suggestion was supported by the FTV data base, by the bored pile and Franki pile result mentioned here and by other deep foundation data (see eg. in [1 to 2]).

The shaft bearing capacity is estimated in such a way that f_{s3} (z)=f_{s1} (z) is used. At the tip yield load point the tip resistance q_{c2}:

$$q_{c2} = \min_{x=l+3D}^{x=l} q_c(x) \quad (8)$$

is the minimum measured point resistance q_c between depths of l and of l+4D. At the tip bearing capacity point the tip resistance q_{c4}:

$$q_{c4} = \operatorname{mean}_{x=l+3D}^{x=l} q_c(x) \quad (9)$$

is the mean measured point resistance q_c below the pile tip between depths of l and of l+4D.

Table 5 The estimated points for the FTV method

	Assumption for		Notation for total load
Point	Shaft load	Point load	
1	Yield		R1
2	Limit		R2
3	Limit	Yield	R3
4	Limit	Limit	R4

The computation of the R1 and R2 data was made on the bases of the smaller value out of the stabilized (dissipation) test value and the continuous test value mwasured by the Sz 832 CPT.

The settlements within the load limits R1 and R4 grow monotonously: s1<s2 < s3< s4, the last one can be approximated by d/10. The values s1<s2 < s3 can be determined by by plotting time-dependent settlements of the static load test data (Figure A1) on condition that there are proper number of stage load values and the consolidation of the soils is included in the load test.

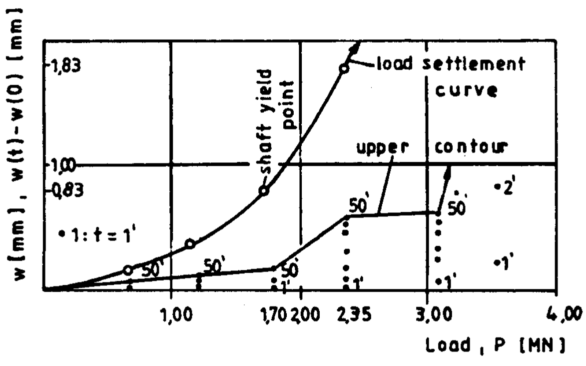

Figure A11 Construction of the shaft yield point, point yield point from staged load test data

7. Appendix B – Design charts

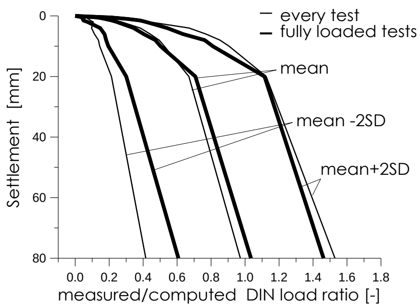

Figure B1a. The load - settlement curves normalized with the DIN bearing capacity, Group 1.

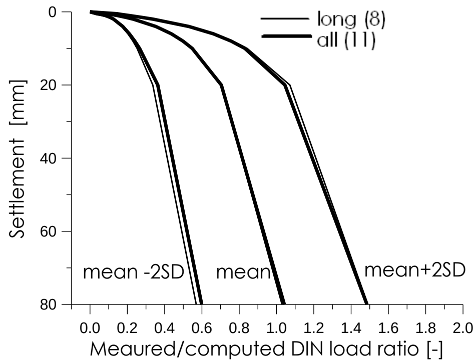

Figure B1b. The load - settlement curves normalized with the DIN bearing capacity, Group 2.

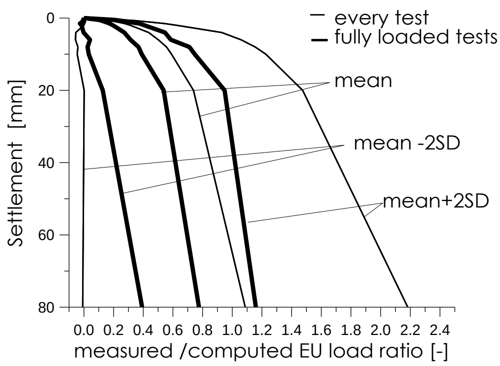

Figure B2a. The load - settlement curves normalized with the EU bearing capacity, Group 1.

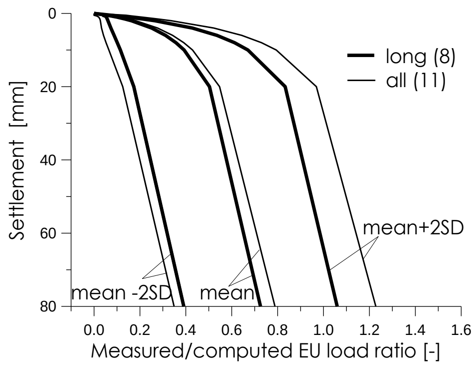

Figure B2b. The load - settlement curves normalized with the EU bearing capacity, Group 2.

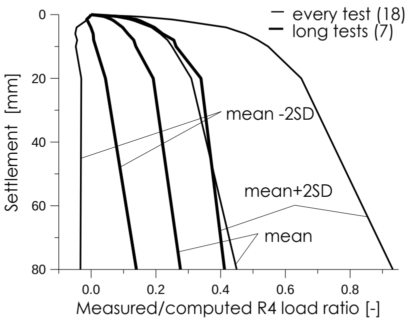

Figure B3a. The load - settlement curves normalized with the R4 bearing capacity, Group 1.

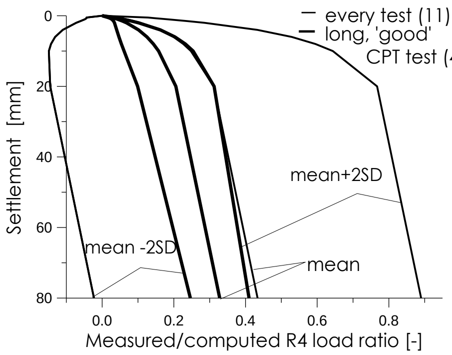

Figure B3b. The load - settlement curves normalized with the R4 bearing capacity, Group 2 with good CPT.

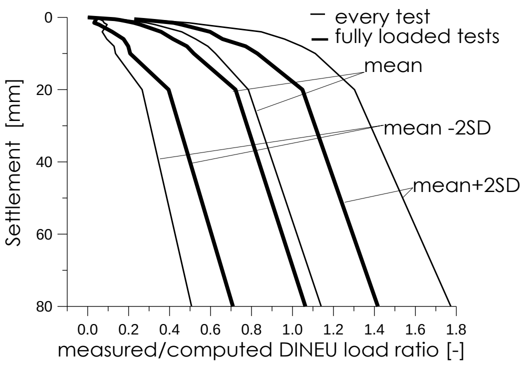

Figure B4a. The load - settlement curves normalized with the DINEU bearing capacity, Group 1.

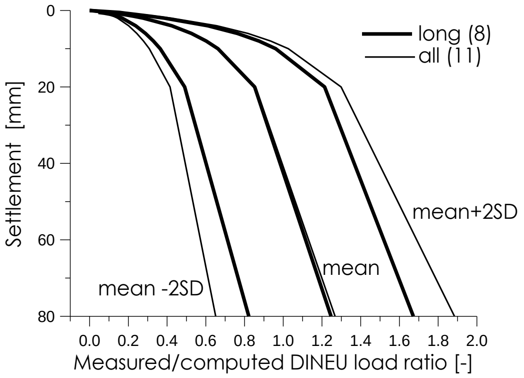

Figure B4b. The load - settlement curves normalized with the DINEU bearing capacity, Group 2

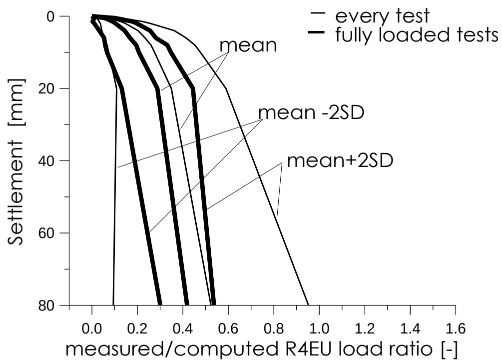

Figure B50a. The load - settlement curves normalized with the R4EU bearing capacity, Group 1.

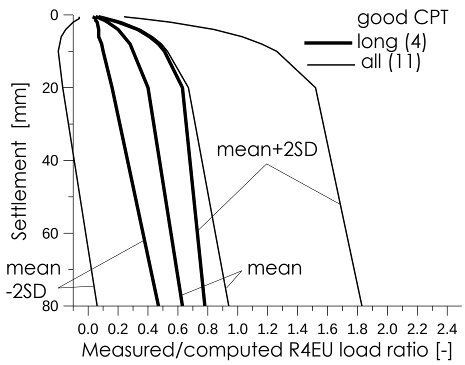

Figure B5b. The load - settlement curves normalized with the R4EU bearing capacity, Group 2 with good CPT.

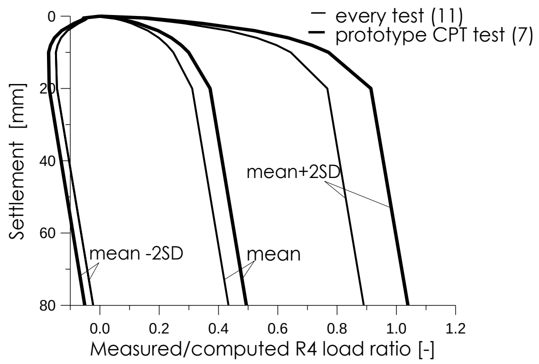

Figure B6a. Group 2, the load - settlement curves normalized with (a) the R4 and (b) R4EU bearing capacity.

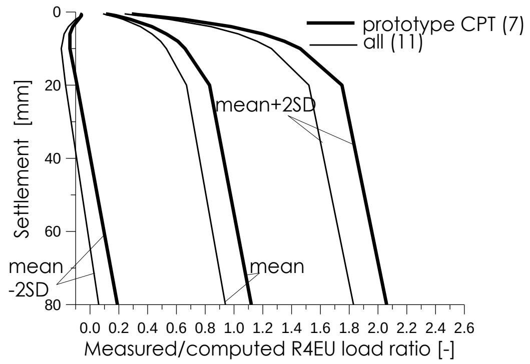

Figure B6b. Group 2, the load - settlement curves normalized with (a) the R4 and (b) R4EU bearing capacity.