Research on the Load-Bearing Behaviour of Bored Piles with Different Enlarged Bases

La recherche sur le comportement portante de pieux forés avec diverses bases élargies

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ABSTRACT: According to DIN EN 1536 overboring of the bottom of drilled piles to increase the EC7-1: bearing resistance is permissible up to three times the pile diameter. The former German standard DIN 4014, however, permitted only an overboring of up to double the pile diameter. The bearing resistance was reduced to 75% in order to take into account the EDZ (excavation disturbed zone) caused by the overboring process. This special area of foundation engineering has been largely unexplored until the early tests by FRANKE/GARBRECHT, and reliable data is not yet available for the new possible pile-base enlargement according to DIN EN 1536. Therefore, model tests at a scale of 1:25 were performed. The experiments were also based on the geometry of the new-type overboring excavation method by BAUER. Thus, new knowledge was obtained on the bearing and settlement behavior of large overbored pile bases with enlargements of one-, two-, and three-times the pile diameter. The tests first showed that an enlargement contributes significantly to an increase in bearing resistance or in limiting pile settlement. More efficient pile foundations are technically possible. A further result is that by the use of a reduction coefficient of 0.75 for the bearing resistance, covering the effects of the drilling the enlargement, the bearing resistance is underestimated. The results were evaluated against the available results of large 1:1 drilled pile experiments. The results of the full-scale tests were assessed regarding their Serviceability Limit State. The available results are to be evaluated by further investigations.

RÉSUMÉ: Selon la norme DIN EN 1536 l'élargissement du fond des pieux forés pour augmenter la capacité de support de charge est permis jusqu'à trois fois le diamètre du pieu. L'ancienne norme allemande DIN 4014, cependant, est premise seulement pendant un alésage allant jusqu'à doubler le diamètre du pieu. Le palier de capacité a été réduite à 75% afin de tenir compte de l'EDZ (excavation zone perturbée) causée par le processus d'élargissement. Étant donné que cette région est en grande partie inexplorée à part les essais antérieurs de FRANKE/GARBRECHT et que les études pour l'élargissement de la nouvelle base de pile possible selon DIN EN 1536 ne sont pas encore disponibles, des essais selon un modèle à l'échelle 1:25 ont été effectués. Les essais se sont également basés sur la géométrie de la nouvelle méthode de type d'excavation de BAUER. Ainsi, de nouvelles connaissances relatives à la capacité de charge et au comportement de déformation, en cas d'élargissements du diamètre du pieu d'une, de deux et même trois fois ont ainsi été obtenues. Les essais ont montré, en premier lieu, qu'un élargissement selon cette nouvelle méthode contribue à une augmentation de la capacité portante ou à une limitation de tassement du pieu. Techniquement, des fondations plus efficaces des piles sont possibles. Une autre conséquence est que le coefficient de réduction de 0,75 pour la résistance de roulement, justifiée par l'influence de la technique de forage dans la production de l'expansion, conduit à une valeur calculée qui contient un facteur de sécurité élevé. Les résultats ont été évalués en fonction des résultats disponibles des essais de forage 1:1 des pieux. Les résultats des grands essais ont été évalués quant à leur fonctionnalité. Les résultats disponibles doivent être évalués par des enquêtes ultérieures plus approfondies.

KEYWORDS: Drilled Pile, Pile foot expansion, reducing coefficient, pile diameter, EDZ excavation disturbed zone

1 INTRODUCTION

Specialized foundation engineering literally lays the groundwork for almost any construction project. On poor, inadequate subsoils, the use of shallow foundations is not acceptable due to excessive settlements. Wooden piles were already being used more than 4000 years ago for foundation construction in weak soils. This made it possible to transmit loads into deeper soil layers with a higher load-bearing capacity. Today wooden piles are only used occasionally for small, temporary buildings.

Along with various other pile foundations, as for example driven piles, displacement piles and micropiles, bored piles are a current standard for deep foundations, especially when high loads must be supported. Special types of the bores piles are bored piles with bottom enlargement according to DIN EN 1536. With this system an increase of the load- bearing capacity is achieved through an enlargement of the supporting cross-sectional area. As a result of the larger area of the base in addition to the skin friction, larger bearing resistance can be attained where the area of the bottom, D^2, is larger or the enlargement will preserve the assigned Serviceability Limit State (SLS). Normally a pile with a base enlargement would first have the point bearing with the skin friction determined and then be designed predominantly based on a point-bearing pile (see also Herrmann, Lauber).

The aim of this test series was to test the load-bearing capacity the afore-mentioned pile system with different diameters. This need for the tests arose from the issuance of the European standard DIN EN 1536. This standard permits an expansion of up to twice the pile diameter, whereas DIN EN 1536, which replaces the old German standard DIN 4014, permits a cross-section enlargement of up to thrice the pile diameter (see DIN 4014 and Franke/garbrecht).

In order to obtain and afterwards compare the differences in the load-bearing behaviour due to the increased base areas, static axial tests (compression tests) were carried out on scale model piles (smooth probe rod (d= 36 mm) with turned pile foot (hard plastic)) at a scale of 1:25 (see Figure 1).

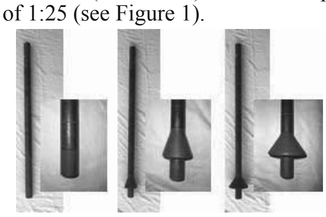

Figure 1. Pile models without (1xD), and with 2 - (2xD) and 3 -(3xD) times the pile diameter bottom enlargements

2 PILE SYSTEM

2.1 *General*

A drilled pile with base enlargement functions like a large drilled pile in accordance with DIN EN 1536 which is manufactured with or without suspension support depending upon the stability of the ground. Subsequently, the bottom of the borehole will be enlarged by the assistance of a special drilling tool, the Belling bucket (see Figure 2).

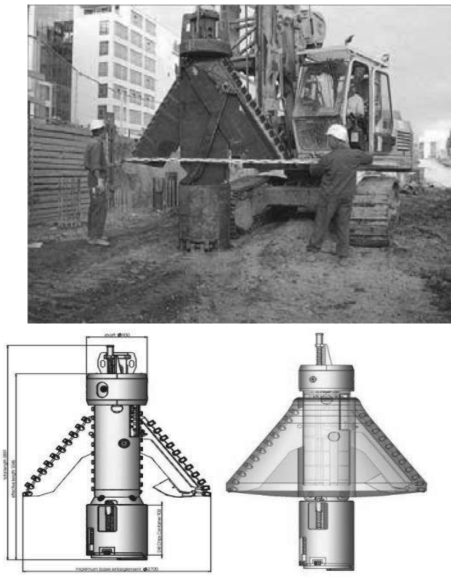

Figure 2. Belling bucket Bauer

This aforesaid drilling tool is denoted as a pile base extension cutter and generally consists of two cutting arms and a cutting body that functions as a borehole reamer to produce a pile (an under-pile) beneath the pile base enlargement.

2.2 *Advantages of the Pile Base Enlargement*

- Higher load-carrying capacity of the single pile or settlement reduction
- Fewer piles under concentrated loads
- Simple pile head construction (none or smaller pile head slabs)
- Reduced pile shaft diameter with shallower drilling depths
- Smaller drilling equipment (more favorable BE/BR, lower costs)
- Savings on pile concrete (more favorable relationship load/m^3 concrete)

2.3 *Pile geometry*

2.3.1 *Pile Shaft*

The drilled pile shaft exhibits a constant cross section, which is selected according to the static requirements for the internal bearing capacity from the top of the pile down to the beginning of the enlargement. Usually the pile is manufactured using a C30/35 concrete. Unreinforced or partially reinforced piles are permissible in principle, while at the same time the load distribution according to EC 2 must be considered. With wide base enlargements and high pile loadings, high-strength concrete can be used, permitted in accordance with DIN EN 1536, or steel fiber reinforcing would be useful.

2.3.2 *Pile base*

It must be noted foremost, that the widening of the foot of the pile is dependent on the basic geometry of the drilled pile, meaning the diameter of the shaft and the overboring equipment used. This is due to the different opening mechanisms of the cutting arms. Modern cutters, like those presented in the current paper, are able to produce flat bottoms within the area of the widening, which was not the case with older models. Also with these types of devices, depending on the manufacturer, an under-pile beneath the enlargement with the same diameter as the shaft is created. This has a positive influence on the friction of the base of the overboring to provide additional support and provides a stopper effect which mechanically increases the bottom of the pile. Investigations by BAUER showed that with these new type cutting devices, even the largest, all pile foot enlargements according to DIN EN 1536 can be manufactured in the soils envisioned for special foundation construction safer and with a higher quality.

According to DIN EN 1536 the area of the foot enlargement is reduced as follows depending of the soil in the base area:

- with cohesionless soils (See Figure 3):
  a) Foot height / Foot Overboring = h_{Base} / $Ü_F \geq 3$ (similar to DIN 4014)
  b) max. permissible pile foot diameter = 2 x pile shaft diameter, d_{Base}

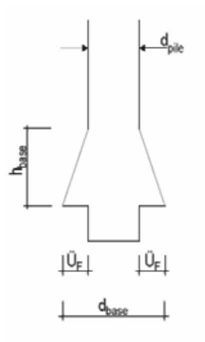

Figure 3. Pile foot base enlargement in cohesionless soils

- In cohesive soils (See Figure 4):
  a) Foot height / Foot Enlargement = h_{Base} / $Ü_F \geq 1.5$
  b) max. allowable pile foot diameter = 3 x pile shaft diameter, d_{Base} (1.5 fold value from DIN 4014)
  c) max. allowable pile foot area = 10 m²
  max. allowable pile foot diameter = 3.57 m

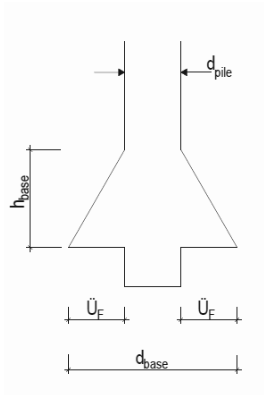

Figure 4. Pile foot base enlargement in cohesive soils

2.4 *Pile tests*

2.4.1 *Pile tests Description*

The investigation of the differences in the bearing capacities of the piles depending on the different pile foot base enlargements (see Tinteler, Herrmann) was carried out with load tests on scale models. (see figure 5).

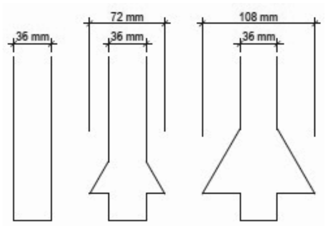

Figure 5. Cross section of the pile models (M = 1:25)

In each case two tests conditions were investigated: using a casing in order to eliminate skin friction and to measure point resistance R_b only, and without a casing to determine the entire pile resistance R_{b+s}. The experimental soil was a sand with a uniformity coefficient, U, of 2.5 – 2.8. It can further be said that this soil was prepared by an in-place compaction, I_D, of approximately 0.74, which corresponds to a dense condition.

For statistical reasons and to acquire meaningful strong results, for each case three identical loads (in each case three per cross section with and without casing – altogether 18 trials) were applied with the different models (See Figures 1 & 5).

3 TEST SEQUENCE

After complete installation of the appropriate test pile (see Installation- /Soil parameter Table 1):

1. Placement /Compaction 1. Layer
2. Placement /Compaction 2. Layer
3. Centering/Plumbing test pile in the container
4. Placement /Compaction 3.-6. Layer,

Table 1. Installation- /Soil parameter

Installation- /Soil parameter		
$d_{Container}$	[cm]	70
h_{layer} (1-6)	[cm]	14.5
M_{layer} (1-6)	[g]	15867
D	[g/cm³]	1.71
g_s	[g/cm³]	2.65
I_D	[-]	0.74

in the test soil (dense sand), the experimental container (steel cylinder) was centered under the cross beam and hydraulic press. After installation of the measuring bridge (See Figure 6) a seating load, F_i = 250 N, was applied to eliminate any slack in the loading system and to adjust the strain gauge.

The experimental models 1xD and 2xD were loaded in increments of 250N, and model 3xD in 500N steps. After each increment of loading the load was held for 10 minutes. Settlement readings were made after 0, 1, 2, 3, 5 and 10 minutes. The failure criterion for the test loadings was taken to be when the pile sank continuously into the soil under a constant load.

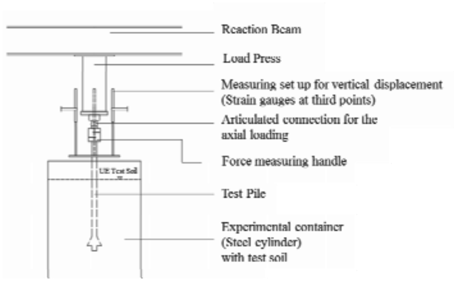

Figure 6. Test Set-Up

3.1 *Results of the Load Tests*

On the basis the measured values of the applied loads and associated vertical displacements, a graphic evaluation of the various test loads was made. The bearing resistance dependant on the pile settlement is illustrated in the following (see figure 7) by the average resistance-settlement curve (average values of the R_{b+s} and R_b test loadings).

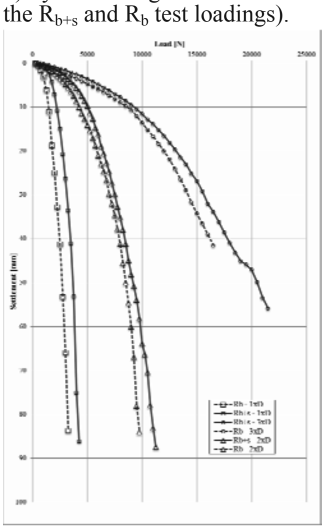

Figure 7. Load Test Resistance-Settlement Curves, R_{b+s} and R_b (average values in each case from 3 test load trials)

4 EVALUATION OF THE RESULTS

For the evaluation of the results and the comparative analysis, the three tests per pile were averaged. The calculated average values were used as the representative values for the respective pile models for all of the following comparisons and computations.

Table 1 shows that all three models had comparable mobilized skin frictions from 6131.1 to 762.0 N. The skin friction appears to be a constant value with it's proportion of the load decreasing greatly with increasing base enlargement so that a shift in the resistance occurs from a skin friction/point bearing to a predominantly point bearing pile. The existing technical assumption/theory that there is an "arching effect" regarding the stress distribution with a base enlargement by activating higher skin friction stresses cannot be substantiated by this test series.

Table 2. Results of Test Models 1xD, 2xD, 3xD, Comparison of results with and without skin friction

Test Pile	Point bearing (R_b) +Skin friction (R_S) R_{b+s} [N]	Point bearing R_b [N]	Skin friction (R_S) Absolute [N]	Relative [%]
Model 1xD	1645.4	1032.3	613.1	37.2
Model 2xD	4505.2	3743.2	762.0	17.1
Model 3xD	9684.5	9013.1	671.4	6.8

According to FRANKE the evaluation of the FRANKE/GARBRECHT investigations shows that for bearing structures with acceptable deformation ranges of 2 to 4 cm and different loadings, it is possible to equalize settlements by the use of pile foot base enlargement (see Table 4).

Table 3. Comparison of the results of model tests 1xD, 2xD, 3xD

Test Pile		1xD	2xD	3xD
Base diameter	[mm]	36	72	108
Contact area	[mm²]	1017.88	4071.5	9160.88
Settlement limit s_{gr}	[mm]	3.6	7.2	10.8
$R(s_{gr})_{b+s}$ from tests	[N]	1645.4	4442.5	9645.9
Proportional increase related to the 1xD-pile	[%]	-	270.0%	586.2%
$R(s_{gr})_b$ from tests	[N]	1032.3	3743.2	9013.1
Proportional increase related to the 1xD-pile	[%]	-	362.6%	873.1%

5 COMPARISON WITH IN SITU TESTS

For the evaluation of the results, there are at present only the investigations by FRANKE/GARBRECHT in the form of full-scale tests, which are drilled piles 6 to 14 m long with pile (b) and pile base diameters (b_f) from 1100 to 2100 mm hat were manufactured with and without base enlargements in medium dense sands and were load tested with deactivated skin friction (using a bentonite filled ring gap) (see Table 3).

The results of the investigations by Franke/Garbrecht indicate that the ratio of the breaking stress for the enlarged to the normal pile amounts to approximately 0.94 to 0.95 (see Table 4 $\sigma b(s_{gr})^{(1)}$ to $\sigma b_f(s_{gr})^{(1)}$). This with the reducing coefficient for characteristic pile resistances, $\alpha_{enlarged}$ = 0.75, verifies the manufacturer's partial safety factor, γ > 1.25 (see Eq. 1 resp. Eq. 2 / Table 4),

$R_{bf}(s_{gr}) / (R_{bf}(s_{gr}) \cdot 0,75) > 1,25$ (Eq. 1)

$\sigma b_f(s_{gr})^{(1)} / (\sigma b_f(s_{gr})^{(1)} \cdot 0,75) > 1,25$ (Eq. 2)

the acceptable safety representative of the researched pile foot base enlargement.

Table 4. Comparison of the results of Franke/Garbrecht with own Tests

FRANKE/GARBRECHT					
Pile	b resp. b_f	Ratio b_f resp. b [-]	Pile foot base area [m²]	$\sigma b(s_{gr})^{(1)}$ resp. $\sigma b_f(s_{gr})^{(1)}$ [N/mm2]	$\sigma b(s_{gr})^{(1)}$ to $\sigma b_f(s_{gr})^{(1)}$

	[m]				[%]
1** (b)	1.10	1.44	0.95	3.60	-5.90
2** (b_f)	1.58		1.96	3.40	
3++ (b)	1.50	1.36	1.77	4.20	-31.30
4++ (b_f)	2.04		3.27	3.20	
5## (b)	1.10	1.39	0.95	3.80	-5.60
6## (b_f)	1.53		1.84	3.60	
7*+ (b)	1.50	1.40	1.77	3.80	-5.00
8*+ (b_f)	2.10		3.46	4.00	
Own Tests					
Pile	b resp. b_f [m]	Ratio b_f resp. b [-]	Pile foot base area [m²]	$\sigma b(s_{gr})$(1) resp. $\sigma b_f(s_{gr})$(1) [N/mm2]	$\sigma b(s_{gr})$(1) to $\sigma b_f(s_{gr})$(1) [%]
1xD (b)	3.60		1017.90	1.01	-
2xD (b_f)	7.20	2.00	4071.50	0.92	-10.20
3xD (b_f)	10.80	3.00	9160.90	0.98	-3.00

(1) $\sigma b(s_{gr})$ resp. $\sigma b_f(s_{gr})$
$= R_b(s_{gr})$ resp. $R_{bf}(s_{gr})$ / ((b resp.bf) · π) / 4)
$s_{gr} = 0.1 \cdot$ b resp. b_f
**, ++, ##, *+ Comparable piles comparable lengths, Without base enlargement (b) /with base enlargement (b_f)

Note: Pile No. 4 is not comparable because of a shorter pile length, i.e. not included in the evaluation.

In summarizing, two informative results come from the test loadings on the scale model test piles. This is on the one hand the realization that the base enlargement of a drilled pile to three times it's shaft diameter would increase the load-bearing resistance expected due to the effect of D^2 was fair.

On the other hand it turned out that a pile base enlargement according to DIN 1054 (or EA-Pfähle) using the reducing coefficient $\alpha_{enlarged}$ = 0.75 for calculating the pile base resistance contains a high safety factor.

Fundamentally, it is to be noted, however, that in the context of this work the results obtained are based on tests at a small scale (model tests). Further, are factors (ground-water flows, inhomogeneous soils) that were left out of consideration, which could possibly have an influence on the bearing behavior of in situ piles. This is especially true if, due to pile settlement, a displacement of the soil in the area of the pile foot base can take place. Therefore no clear conclusions on the actual bearing behavior of large drilled pile with base enlargements can be drawn.

Table 5: Evaluation of In Situ Load Tests by Franke/garbrecht for various related Settlements, s/D

Pile	Pile base dia-meter [m]	Pile foot area [m²]	s/D(2) [-]	Settle-ment [cm]	$\sigma b(s)$(3) resp. $\sigma b_f(s)$(3) [N/mm2]	$R_b(s)$ resp. $R_{bf}(s)$ [MN]
1** (b)	1.10	0.95	0.02	2.2	1.7	1.6
			0.03	3.3	2.0	1.9
			0.10	11.0	3.6	3.4
2** (b_f)	1.58	1.96	0.02	3.2	1.8	3.5
			0.03	4.7	2.1	4.1
			0.10	16.0	3.4	6.7
3++ (b)	1.50	1.77	0.02	3.0	1.7	3.0
			0.03	4.5	2.3	4.1
			0.10	15.0	4.2	7.4
4++ (b_f)	2.04	3.27	0.02	4.1	1.4	4.6
			0.03	6.1	1.7	5.6
			0.10	20.4	3.2	10.5
5## (b)	1.10	0.95	0.02	2.2	1.5	1.4
			0.03	3.3	1.8	1.7
			0.10	11.0	3.8	3.6
6## (b_f)	1.53	1.84	0.02	3.1	1.3	2.4
			0.03	4.6	1.8	3.3
			0.10	15.3	3.6	6.6
7*+	1.50	1.77	0.02	3.0	1.5	2.7
(b)			0.03	4.5	2.0	3.5
			0.10	15.0	3.8	6.7
8*+ (b_f)	2.10	3.46	0.02	4.2	1.9	6.6
			0.03	6.3	2.3	8.0
			0.10	21.0	4.0	13,9

(2) D = b_f resp.b
(3) $\sigma b(s)$ resp. $\sigma b_f(s)$ =
= $R_b(s)$ resp. $R_{bf}(s)$ / ((b resp.bf) · π) / 4)
s = s/D · b resp. b_f
**, ++, ##, *+ Comparable piles comparable lengths, Without base enlargement (b) /with base enlargement (b_f)

Note: Pile No. 4 is not comparable because of a shorter pile length, i.e. not included in the evaluation.

However, since there appears to be a discrepancy between theory and practice, a continuing analysis would be meaningful and necessary based on full-scale tests up to the 1:1 scale, since the reliable data collection on the influence of manufacturing variabilities can only be investigated in full-scale tests. This evaluation is valid in particular under the aspect that there are new techniques and geometries for pile base enlargement – as were considered in this presentation – to produce new types of pile foot base enlargements with positive influences on the bearing behavior or the piles.

Thus, these drilled piles represent a new system for deep foundation with a special capability regarding the loads and the deformation limitations. It is of special importance that all of the new pile cutting equipment for pile foot base enlargement according to DIN EN 1536 – including the largest – can assuredly manufacture piles in the soils envisaged for it by specialized foundation engineering.

If these investigations would lead to a confirmation of available findings, a safe and economic adjustment of the reducing coefficient would be possible. Therefore, the work on this topic should be continued.

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