DEEP FOUNDATIONS ON SCREW PILES

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ABSTRACT : The design of a deep foundation by means of whatever a scientific method has to take into account the influence of the installation of the piles on the soil parameters to be implemented in the shaft and base capacity. Especially when discussing screw piles, the details of the pile installation technique are of outmost importance. New developments in screw pile techniques, over the last decade, show this type of deep foundations to be probably one of the most promissing for the future.

TYPE OF SCREW PILES AND THEIR TODAYS' IMPORTANCE ON THE EUROPEAN MARKET

For simplicity let's distinguish two well recognizable groups : the screw piles with soil displacement on the one hand and those with soil excavation on the other hand. The characterisation soil"displacement" and "excavation" is only relevant at the penetration of the auger and or casing. In table I the proposed classification is indicated. In table II the estimated todays' relative importance out of gathered data in the various countries, for each of the mentioned pile type is indicated.

TABLE I

Screwed piles

soil displacement during penetration	soil excavation during penetration
* Prefabricated pile type	* Partial flight auger on steel casing
* Lost auger head + regained casing type	° prefabricated
° Screwing down pulling up	° cast-in-situ
° Screwing down Screwing up	* Continuous flight auger
	° small Ø stem, cast-in-situ
	° large Ø stem, cast-in-situ

Variety of pile systems in each cast-in-situ
sub-groups due to the various methods for pouring the concrete

° contractor method
° under additional hydraulic pressure
° combined with expansive mortars
° additional grouting under pile tip
° expander body pile tip
° combined with driven pile tip

TABLE II

1994-1995 (adapted from former data)

A importance of each type of pile
B total length of piles on an average

				Data on different type of piles in the indicated countries													
				Italy		Germany		the Netherlands		U.K.		France		Belgium		Austria	
				A in %	B in km	A in %	B in km	A in %	B in km	A in %	B in km	A in %	B in km	A in %	B in km	A in %	B in km
				15000 km		15000 km		12000 km		10000 km		6000 km		1000 km		2000 km	
With soil displacement	Driven	Cast in place (regained and lost casing)		12	1800	15	2250	8	960	7	700	27	1650	32	320	6	120
		Prefabicated	steel	1	150	5	750	-	-	4	400	1	60	2	20	3	60
			concrete	5	750	10	1500	44	5280	11	1100	0.2	12	10	100	5	100
			timber	0	-	0	-	15	1800	0	-	0	-	0	-	1	20
	Scre-wed	lost auger head + cast -in-situ or prefabricated		-	-	9	1350	8	960	6	600	6	240	30	300	2	40
With soil excavation	Auger + Bored piles	large Ø (>0.65m) - bentonite- (excluded diaphragm wall)		41	6150	28	4200	0.1	10	30	3000	40	2400	2	20	53	1060
		- large Ø - with lost steel casing						-	-					-	-	-	-
		continuous flight auger (small and large Ø stem)		15	2250	15	2250	23	2760	40	4000	20	1200	15	150	10	200
		jet grouted columns and related techniques		10	1500	12	1800	2	220	-	-	2	120	7	120	10	200
		root piles and grouted micro pile		16	2400	6	900			2	200	4	240	2	20	10	200

EXAMPLES OF EXISTING INSTALLATION TECHNIQUES FOR SCREW PILES WITH AND WITHOUT SOIL DISPLACEMENT DURING AUGER PENETRATION

In figures 1 to 8 some examples are given of screwed displacement type of pile ; the prefab screw piles obviously only can be applied in very soft layers for its limited allowable torque (≤ 70 kNm). The Fundex screw pile is famous for its intense pile tip - soil interaction because the entire pile tip - auger is left behind in the soil. The casing behind the pile tip is vertically pulled up at casting concrete ensuring a continuous smooth concrete pile shaft. The Atlas-Franki screw pile, leaving only a small tip underneath the augerhead in permanent contact with the soil is wellknown for its double screwing installation procedure. The augerhead is screwed in at the required depth and subsequently screwed out during upheave and casting the concrete. The augerhead has only one flange, the torque can be as high as 450 kN/m. The pile shaft is very rough and an intense shaft-soil interaction is guaranteed.

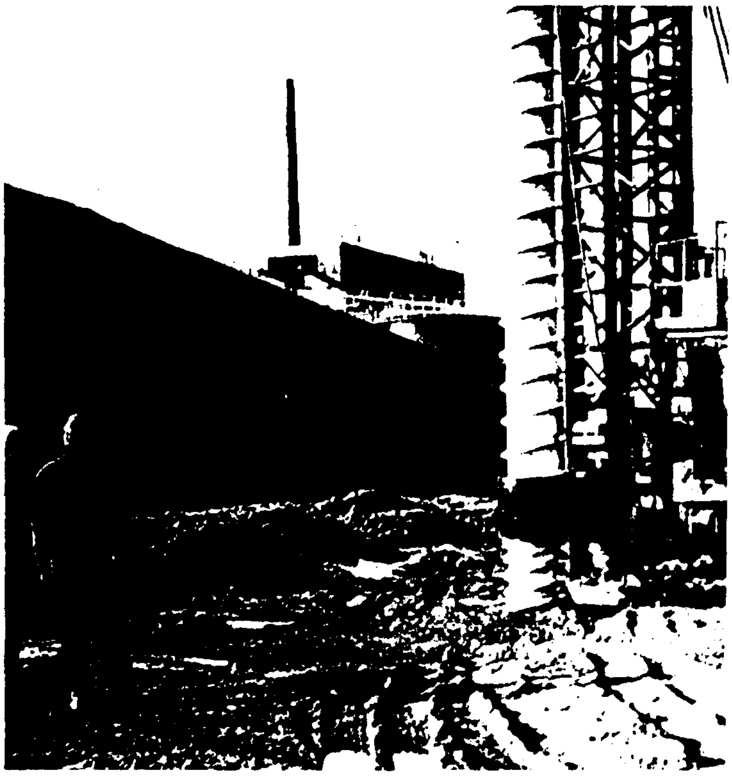


Fig. 1 : Mega-prefab screw pile

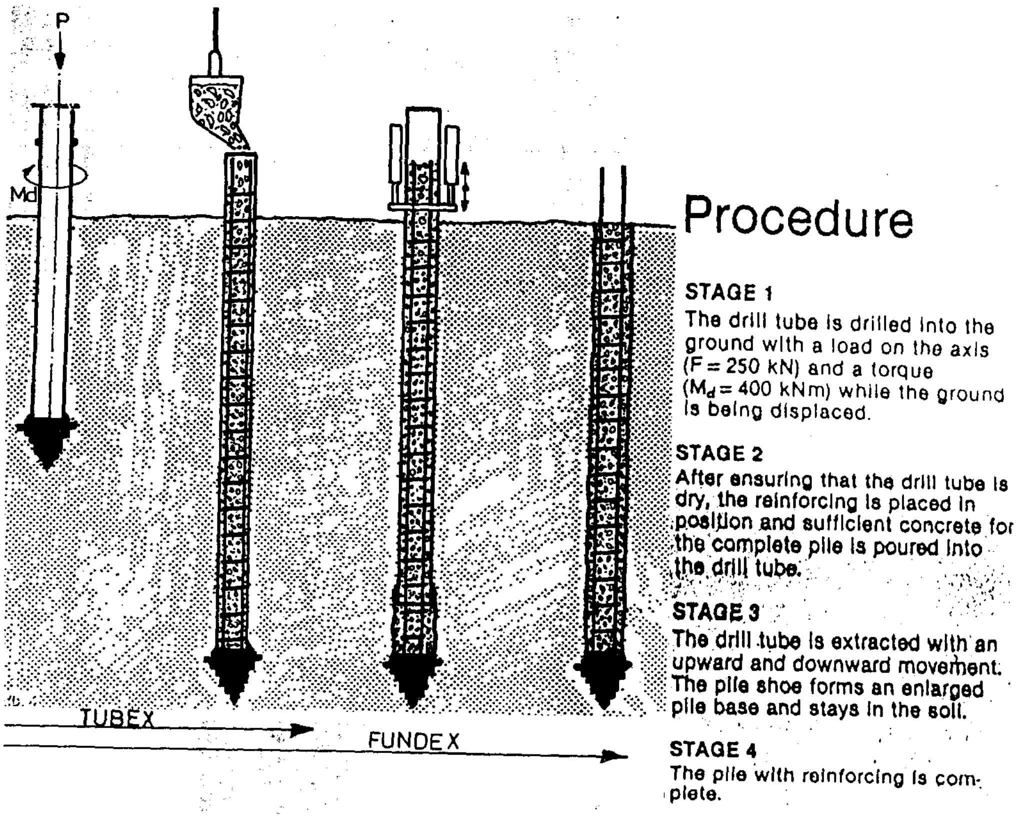


Fig. 2 : Fundex screw pile

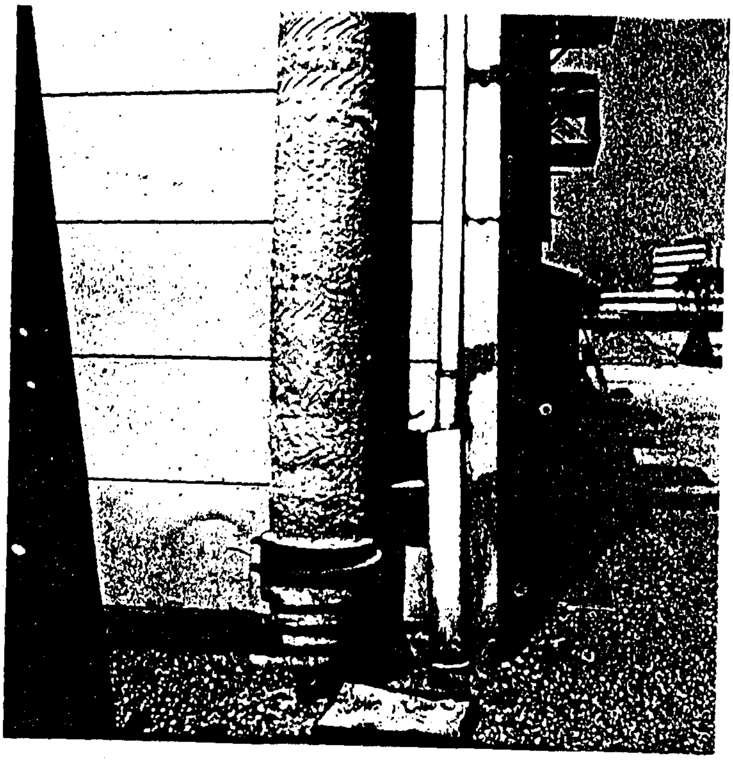


Fig. 3 : Fundex screw pile

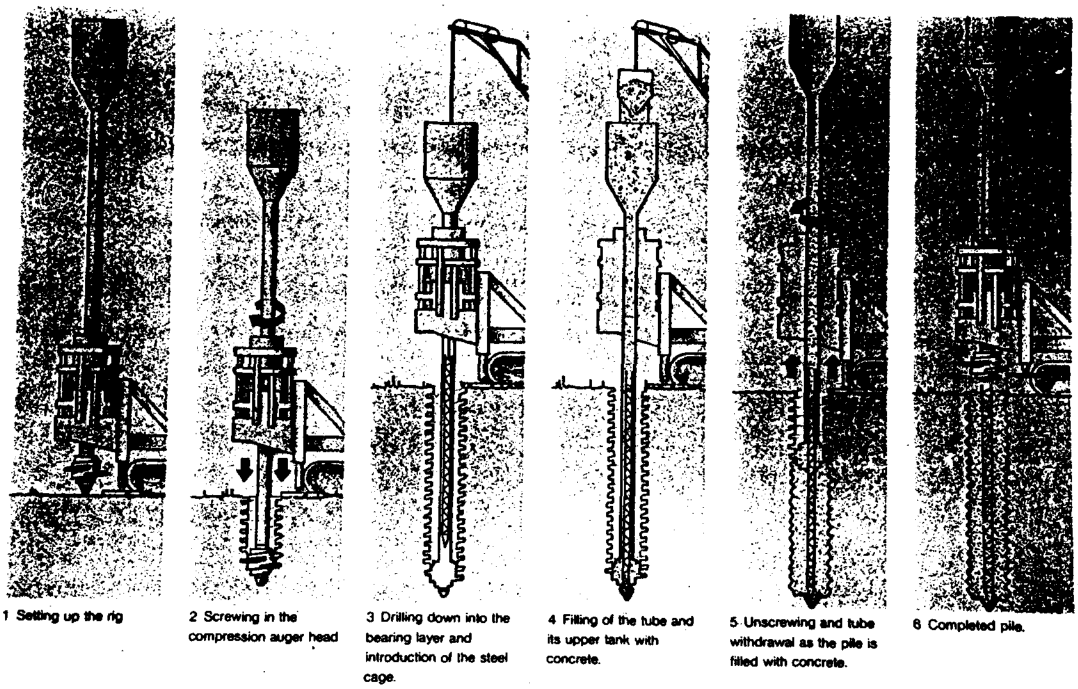


Fig. 4 : Atlas screw pile

Fig. 5 : Atlas screw pile

Fig. 6 : Atlas screw pile

A most renewing and promissing soil displacement screw pile is called the Ω-pile. The Ω-screw pile is a soil displacement auger pile based on a screwing in - screwing out procedure. The displacement auger head (fig. 7 and 8) consists of a discontinuously diameter - increasing steel tip, on top of which the continuous screw flange with variable pitch is mounted. The soil displacement is cinematically ensured by downwardly oriented slots mounted on the auger head at different well chosen locations on the flanges. Above the full diameter body, the soil displacement, at severly reduced transfer energy, is due to the downwardly inclined overlapping of various stell shields oriented in a opposite inclination as the flanges below the full diameter body. The shape of the auger was developed in such a way that the increasing volume of the transported soil between the flanges of the screw can be stored at each level for the different sections of the auger head, for a given rotation speed (n) and vertical translation speed (v). This leads to a very efficient lower energy screwing - in sequence of the pile and consequently to a high penetration rate. An example of the execution process sheet is shown in fig. 9.

The auger is screwed in with lateral soil displacement. An additional thrust is eventually activated. Once the adequate depth is reached, concrete is casted under pressure through the hollow stem of the auger while the auger is retrieved, still rotating in the same direction as for the downward screwing sequence. The tip underneath the auger displacement body is lost. The reinforcement can be introduced either before or after the grouting of concrete. The first fully instrumented pile test results are very encouraging. As it can be deduced out of fig. 10, the displacement of the soil is effective.

Fig. 7 : Ω screw pile

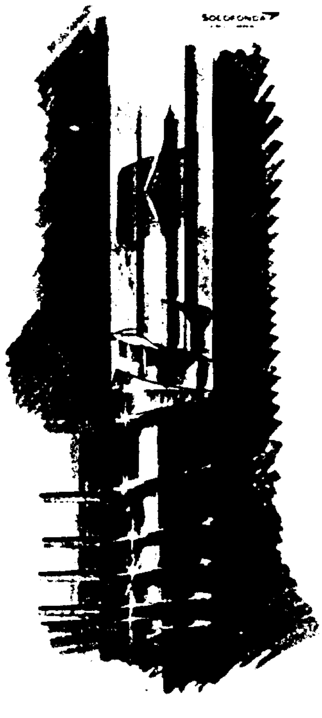


Fig. 8 : Ω screw pile

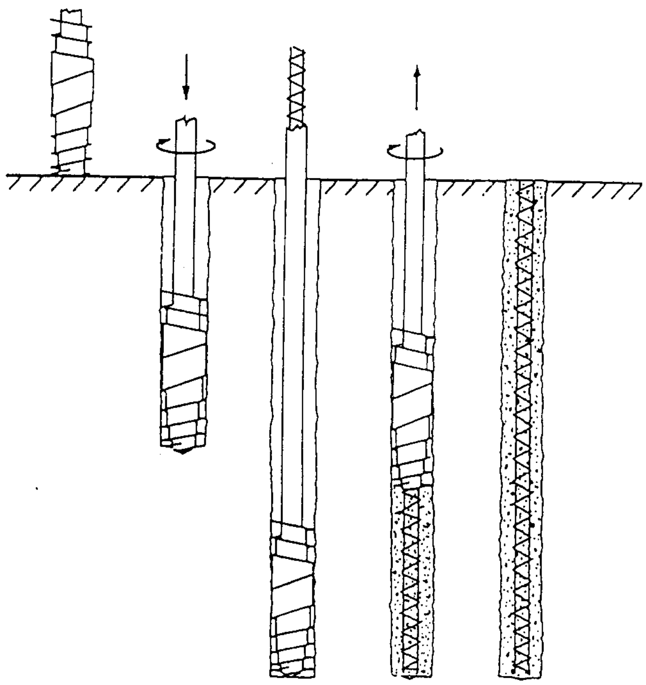


Fig. 9 : Execution process of the Ω screw pile

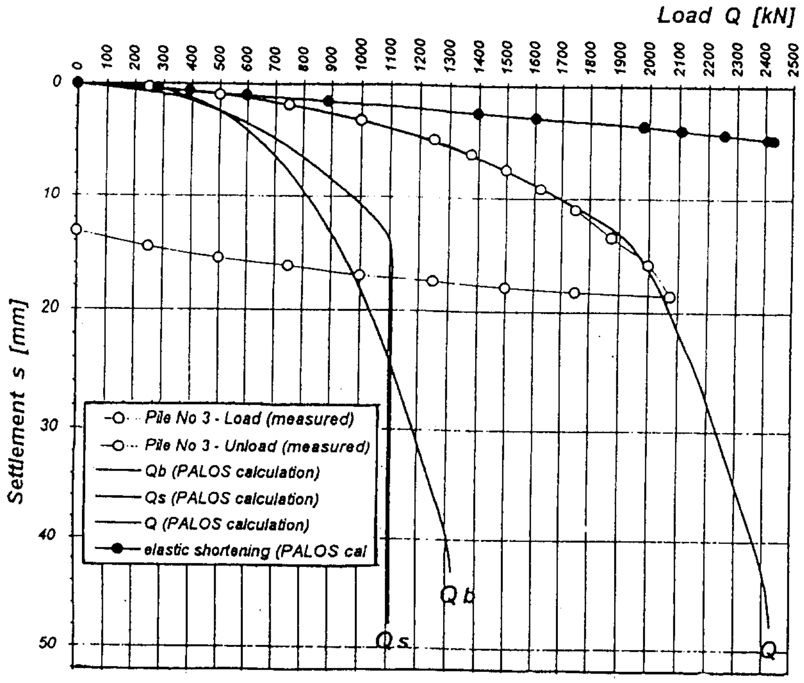


Fig. 10 : Load-settlement curves for pile N° 3 ; (∅ 0,41 m) Ω screw pile

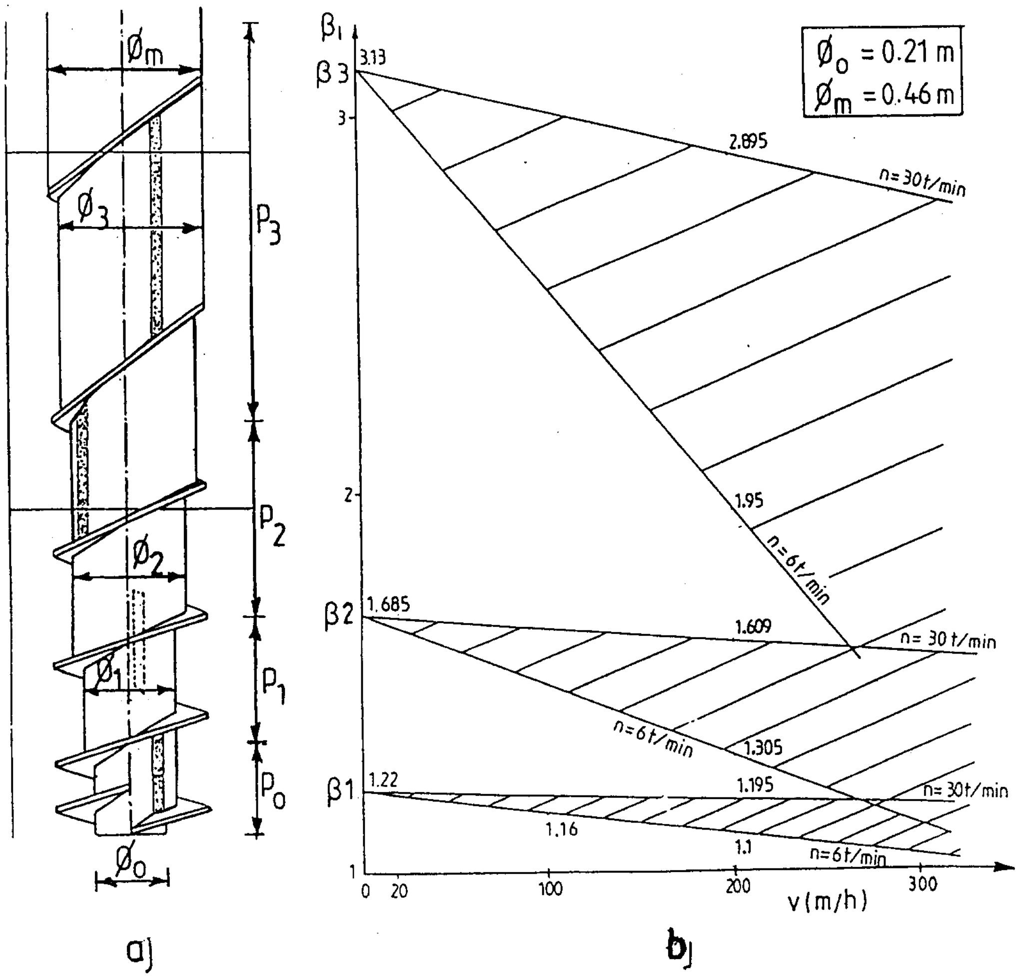


Fig. 11a : Schematic cross-section of the Ω-augerhead
b : Relation of β_i as function of v and n

Viggiani (1993) provided some interesting analysis concerning the link between the installation parameters and the final capacity of CFA piles. The first part of the Ω-pile screwhead can be compared to an auger with a variable inner stem diameter provided with flanges with a variable pitch. The mentioned analysis so could easily be extrapolated. Assuming a constant variation of the inner stem diameter between $\varnothing_0$ and $\varnothing_m = \varnothing_0 + 4\Delta\varnothing$ one can write that the volume of the displaced soil in the different sections is given by (fig. 11a) :

$$V_{\varnothing i} = \frac{\pi \varnothing_i^2 \cdot p_i}{4} \quad (1)$$

for i = 0 tot 3

where :
$\varnothing_i$ = inner stem diameter in section
p_i = pitch of section i

The volume of removed soil can be written as :

$$V_{ri} = \frac{\pi}{4}\left(\varnothing_m^2 - \varnothing_i^2\right) . (np_i - v) . \Delta t \quad (2)$$

for i = 0 tot 3

One can analyze that, for the volume of the transported soil stored increasingly without compaction in the different sections of the auger, this leads (for a given inner stem diameter with a starting pitch p_o)
to :

$$p_i = 10 . \beta_i \quad (3a)$$

with

$$\beta_i = \frac{n . \left(\varnothing_m^2 - \varnothing_0^2\right) - \left(\varnothing_i^2 - \varnothing_0^2\right) . v}{n\left(\varnothing_m^2 - \varnothing_i^2\right)} \quad (3b)$$

with

n = number of revolutions of the auger/min
v = rate of vertical downward penetration
This relation 3b is graphically summarized in fig. 11b, where a variation range for n is supposed to be 6 T/min. < n < 30 T/min and for $\phi_0 = 0.21$ m and $\phi_m = 0.46$ m.

Referring now to the auger piles with soil excavation, the most wellknown family of such type of piles is considered to be one of the CFA-piles. Fig. 12 and 13 show the examples of small and larger stem CFA piles.

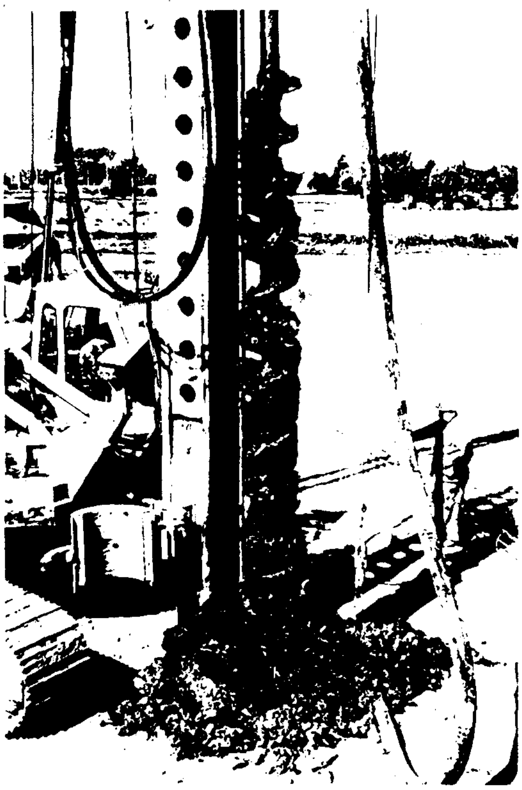


Fig. 12 : Small stem CFA

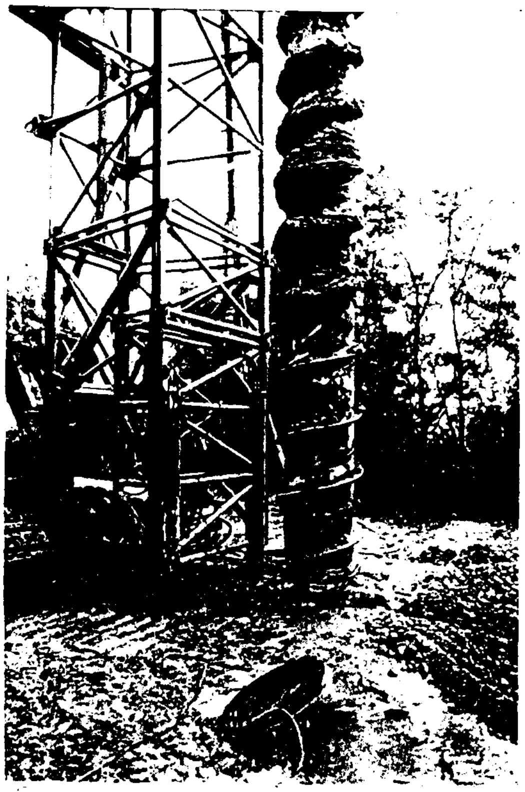


Fig. 13 : Large stem CFA

Generally spoken, comparison of overall static pile loading tests, on non-instrumented piles, suggest a much stiffer soil-pile interaction behaviour for soil displacement type of screw piles ; but one has to be very cautious, since the influence of installation details for each of such type of piles is predominantly governing the initial part of the load settlement diagram. Moreover even at very well controlled installation conditions, the so called correction factors ε_b . α_b on the pile tip capacity and ε_f on the pile shaft capacity (fig. 14) have to be clearly defined at well known levels of relative pile deformation (ε) (table III), if one would like to design those piles, going out from standardized analyses (Van Impe, De Beer, 1986). It so can be expected from table III for example, that the optimum unit pile capacity mobilisation for the Fundex type of screw pile is to be fixed at $\varepsilon = \pm 5$ %, although for Atlas and Ω-screw piles $\varepsilon \geq 8$ % looks more appropriate ; and for the small stem CFA it will be even higher.

$$q_{r,b} = \alpha_b \cdot \varepsilon_b \cdot q_{r,b}^*$$

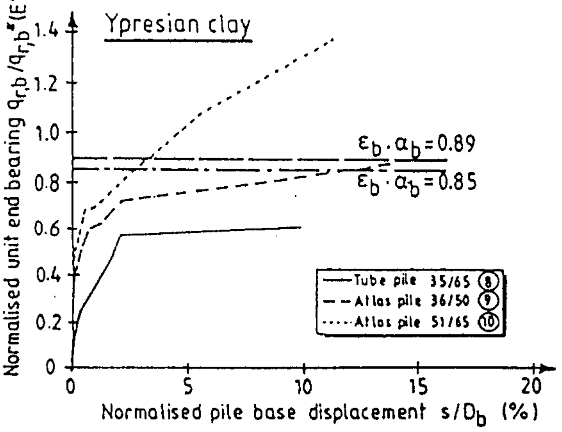
in which :

$q_{r,b}^*$: the ultimate end bearing capacity obtained from the CPT-test result

α_b : a coefficient taking into account the installation procedure of the pile

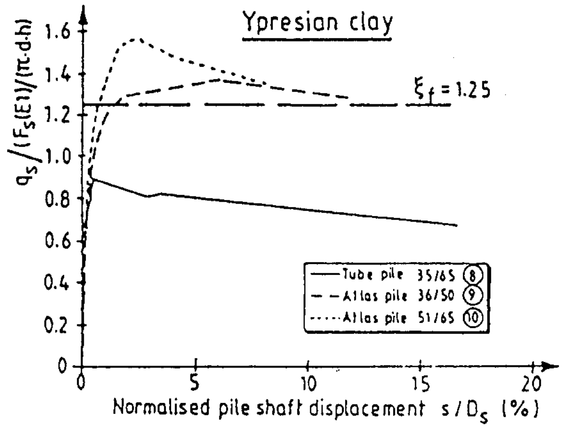
ε_b : a parameter referring to the scale effect from the fissuring of the soil.
Belgium one proposes :

Example of Atlas-screw pile results



$$q_{r,s} = (\eta_p \cdot q_c)_{burried} \cdot \xi_f$$

Example of Atlas screw pile results



CFA-pile design

* $q_{r,s} = K_s \cdot \sigma_{v,o} \cdot tg\varphi$ (sand)

→ K_s = 0.3 to 0.8 depending on installation parameters

* (in stiff clay) : $K_s = 1$

Fig. 14 : Basic concept of screw pile design

TABLE III

Loading tests at Gent

1	2	3	4	5	6	7	8	9	10	11	12
						log - log curve					
Type of pile	Dimensions width	Dimensions embedded lenght	s $(\frac{s}{B_b}=2\%)$	Q_l $(\frac{s}{B_b}=2\%)$	$\varepsilon_{2\%}$	s_i	$\frac{s_i}{B_b}$	Q_l	s $(\frac{s}{B_b}=10\%)$	Q_r^{conv} $(\frac{s}{B_b}=10\%)$	$\varepsilon_{10\%}$
	mm	m	mm	MN		mm	%	MN	mm	MN	
driven prefab concrete XI b	320x320 B_{eq}=369	13.27	7.38	2.20	1	8.15	2.21	2.35	36.9	3.1	1
screwed in Atlas	B_b =450 B_s =360	12.50	9.0								
VI				1.44	0.65				45.0	2.8	0.90
X				1.57	0.72				45.0	≤3.5	
									$(\frac{s}{B_s}=10\%)$ 36	3.1	1.0
screwed in Fundex	B_b=460 B_s =460	13.0	9.2								
III				1.82	0.83				46.0	2.3	0.74
VIII				1.78	0.81				46.0	2.1	0.67
continuous flight auger	B_b =450 B_s =450	14.50	9.0								
V				1.40	0.63				45.0	2.3	0.74
IX				1.35	0.61				45.0	2.25	0.72
bored pile (guess)	B_s =369	13.27	7.38	1.10	0.50				36.9	1.68	$0.54=\frac{168}{310}$
driven concrete computation			$Q_{b,r}^{conv}$ = 1.13 MN		$F_{s,r}^{conv}$ = 1.62 MN					2.75	$0.61=\frac{168}{275}$

EXAMPLES OF Ω-PILE TEST RESULTS

The piles were installed at Vilvoorde in an area characterized by CPT results shown in fig. 15. The level of each pile base is indicated as well. The soil profile comprises five layers. The first layer, direct below ground surface, is about 1 m. thick. The layer number 2 is about 3,5 m. thick and described as a soft cohesive layer with q_c = 1 MPa to 3 MPa. The layer number 3 is a more sandy soil of about 5,5 m, with q_c = 5 MPa to 10 MPa. The tips of the piles n°5 and n°4 are ended in this layer, (cfr. fig.15). Below, another weak soil is situated. The clay layer number 4 is about 3 m thick. The sandy bearing layer 5 finally has a cone resistance q_c = 20 MPa. In the layer number 5 the piles n°3 and n°1 are stopped. The detailed pile test and soil testing results (CPT) are given elsewhere (Van Impe, Gwizdala, 1994).

SOIL PROFILE FOR PILE TESTS AT VILVOORDE

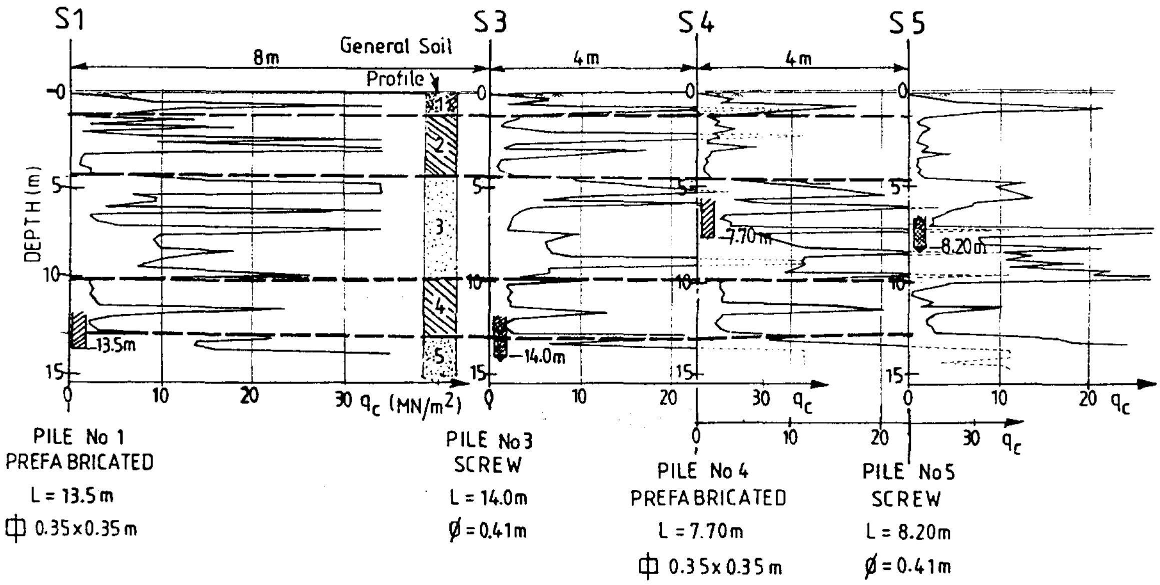


Fig. 15 : Soil profile for pile tests at Vilvoorde

Load Test Results, For Pile n°5 - Ω-Pile (short)

The pile was loaded by the hydraulic jack and a dead weight system.

The settlements of the pile load head were controlled by three dial gages connected by three steel arms, length about 5 m connected to pile head. For the determination of the load at pile tip and along the pile shaft, two tell-tale rods were installed into the pile, fig. 16. The loading program is shown in fig. 17a. The first four loading increments are equal to ΔQ = 150kN and next twelve to ΔQ = 75 kN.

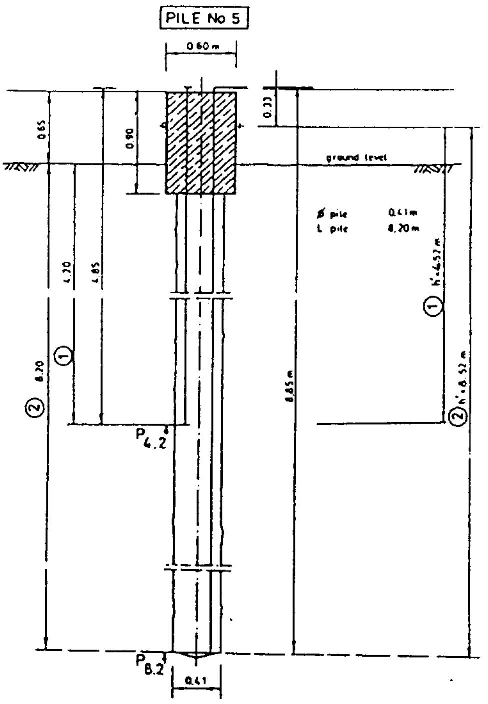


Fig. 16 : Tell-tale instrumentation of pile N° 5

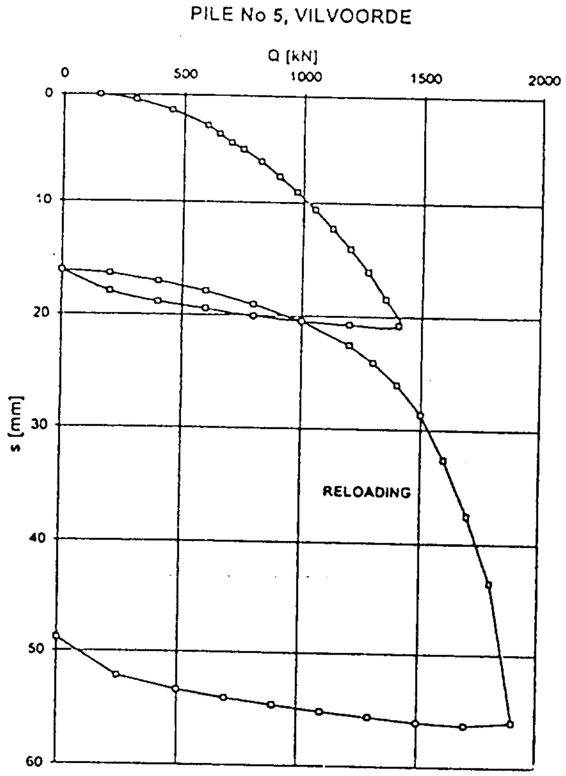


Fig. 18a : Load-settlement curve of pile N° 5

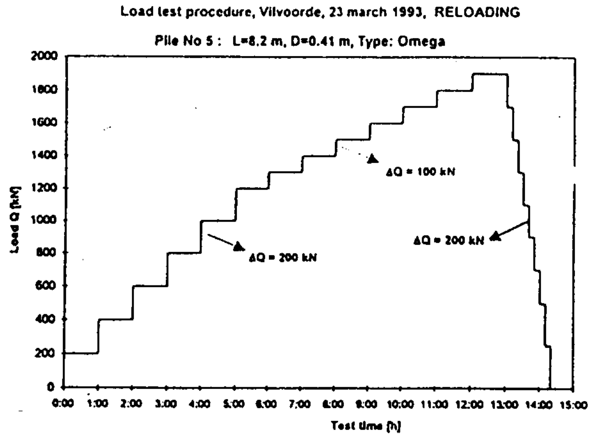


Fig. 17a : Load test procedure of pile N° 5

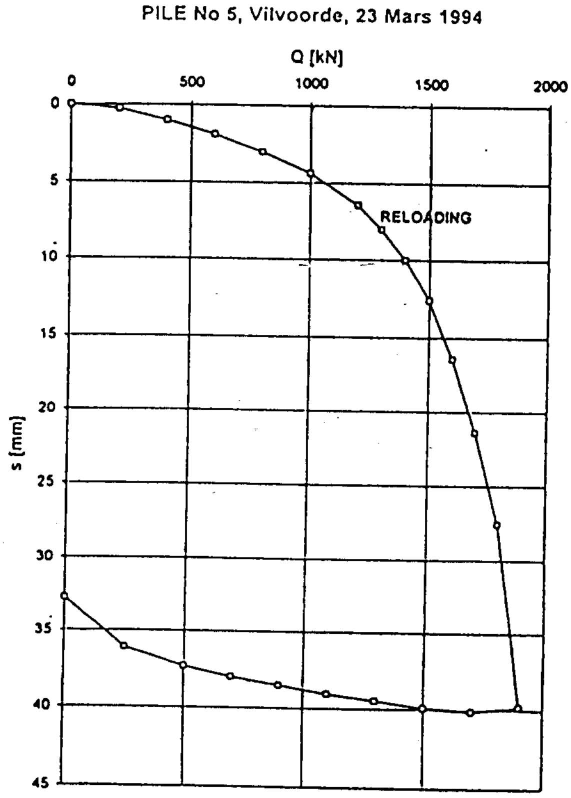


Fig. 18b : Reloading-settlement curve of pile N° 5

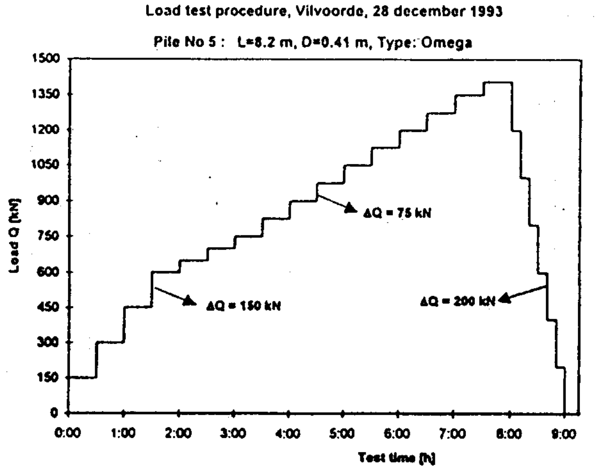


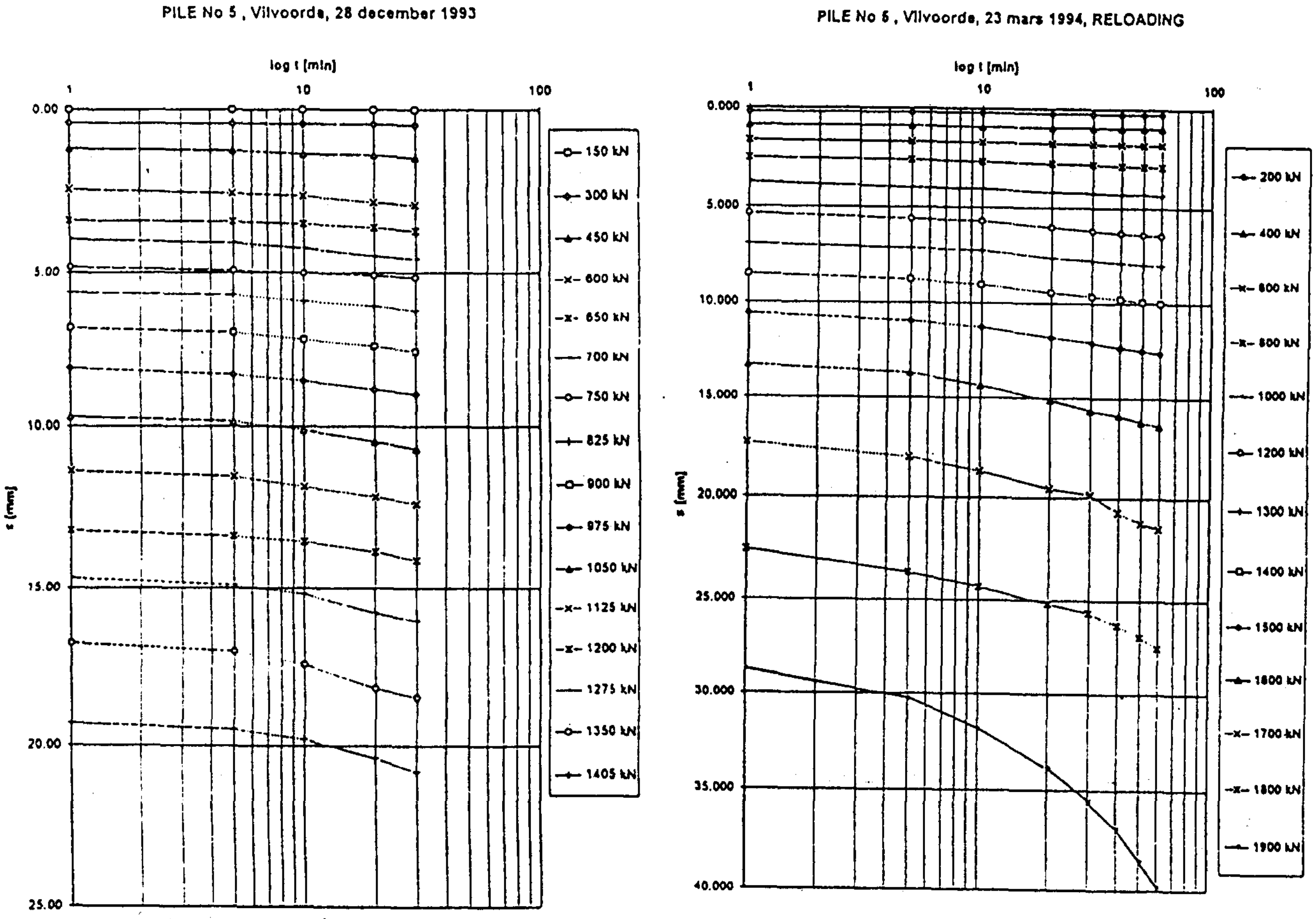
Fig. 17b : Reloading test procedure of pile N° 5

The basic results of the test, (the load-settlement curve) is shown in fig. 18, and the main values of pile load versus pile head settlement are included in table IV, as well.

TABLE IV
Main pile load tests results for piles at Vilvoorde.

Pile number	Load level	Load (kN)	Settlement (mm)		
			Total	Plastic	Elastic
n°5	Q_i^1 (intermediate)	750	5,16	-	-
Ω-pile	Q_i^2 (intermediate)	1405	20,79	16,11	4,68
	Q_{max} (max. reloading)	1900	55,93	48,85	7,08
n°4	Q_i	600	5,69	-	-
prefab	Q_{max}	1100	76,60	71,04	5,56
n°3	Q_i	1250	4,81	-	-
Ω-pile	Q_{max}	2075	18,66	13,19	5,47

The time interval of 30 min for each level and the corresponding reading in three dial gages were taken as follow : 0, 1, 5, 10, 20 and 30 min, (fig. 19a).
This first part of pile n°5 head has been implemented on 28th of december 1993.



a)   b)

Fig. 19 : Time-settlement curves of pile N° 5

The full load tests on pile n°5 (reloaded) was performed on 23th of march 1994. The load test reaction system remained the same, only dead counter weight was increased. The settlement of pile head was controled by four dial gages. The reference beam, steel profile I 220 x 220 mm with length 8,5 m, was supported by the pile n°4 (one side and) on the ground surface (other side). The tell-tale rods were improved as well, and distribution of the load at pile tip and along the pile shaft were accurately measured. The loading program is shown in fig.17. The first six loading increments are equal to $\Delta Q = 200$ kN and next seven to $\Delta Q = 100$ kN the whole load-settlement relationship is shown in fig. 18.

The time interval, for reloading, was 60 min (for each load level) and the readings were taken at : 0, 1', 5', 10', 20', 30', 40', 50' and 60 min, fig.19b

Load Test Results For Pile n°4 - Prefab Driven Concrete Pile

The pile n°4 was loaded by an hydraulic jack in 5 even increments, four to $\Delta Q = 200$ kN and three to $\Delta Q = 100$ kN, respectively, see in fig. 20.

The relationship between the load level and pile settlements is presented in fig. 21 the time-settlement results were shown in fig. 22. The time interval again was 60 min for each load level and the readings in four dial gages were taken at 0', 1', 5', 10', 20', 30', 40', 50' and 60 min, see in fig. 21

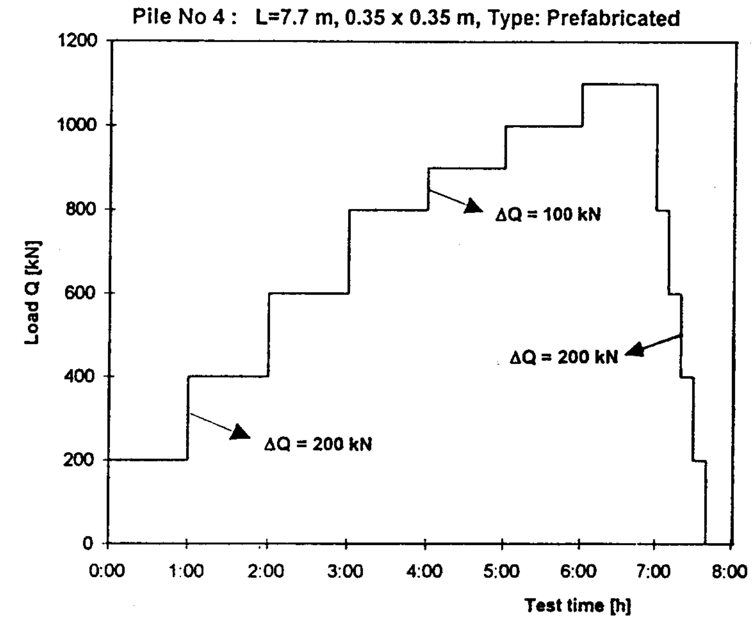


Fig. 20 : Load test procedure of pile N° 4

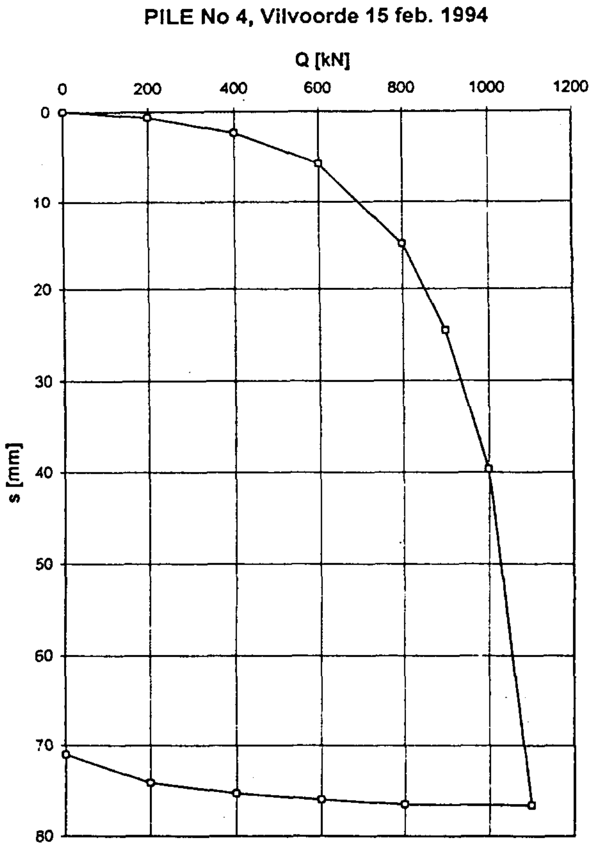


Fig. 21 : Load-settlement curve of pile N° 4

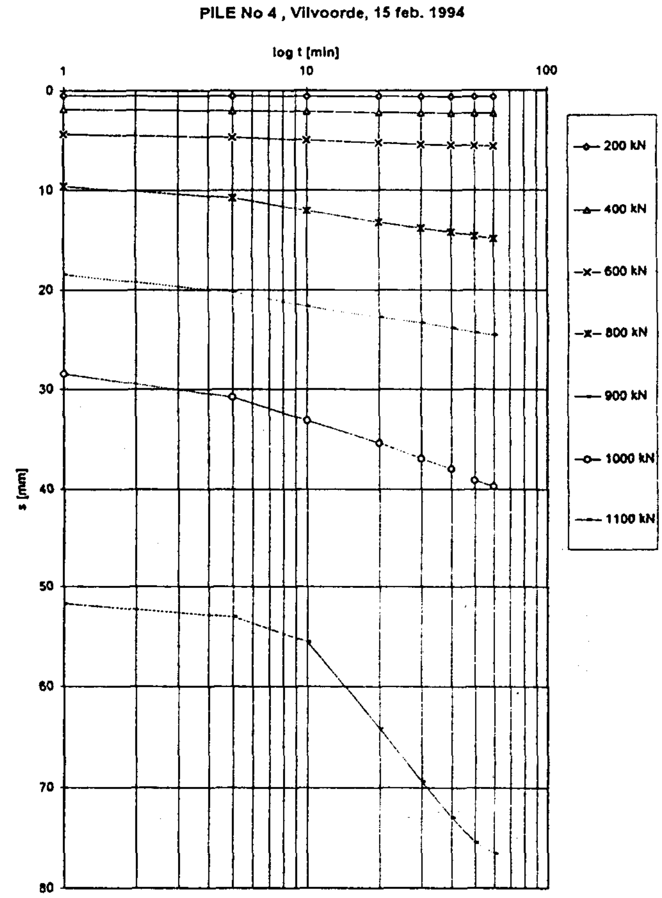


Fig. 22 : Time-settlement curves of pile N° 4

Load Tests Results For Pile n°3 Ω-Pile (long)

The test results and tell-tale instrumentation are given on fig. 23 and 24.

The bearing capacity of the piles was evaluated based on the CPT results according to De Beer and Van Impe, 1988 (Orlando).

The unit skin friction $q_{s,z,D}$ on the pile shaft was related to the corresponding cone resistance $q_{c,z}$ according to the proposals Van Impe 1988 and 1991 :

$$q_{s,z,D} = \xi_f \cdot \eta_p \cdot q_{c,z}$$

where :
η_p = coefficient related to the soil nature and pile type ; values assumed in this analysis are shown in fig. 25

The general q_c-values and evaluated ultimate unit shaft resistance are shown in table IV. The best fitting values, with measured values of $q_{s,z}$ from tell tale analysis, of the coefficient ξ_f are 0,95 to 1,00 for Omega piles and 0,84 for prefabricated pile (see table V). This means that the Omega pile, as far as shaft-soil interaction is concerned, can be considered in this test case at Vilvoorde, effectively as a non-decompacting type of pile.

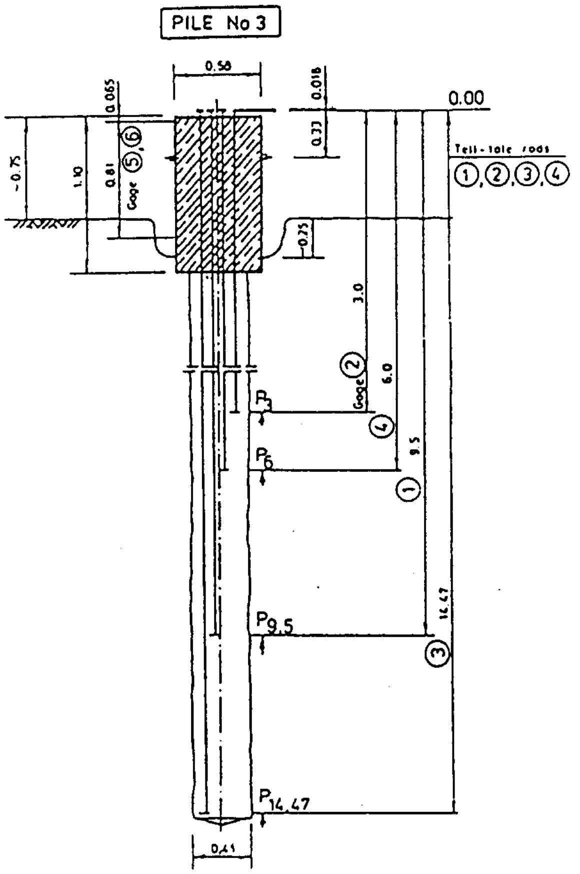


Fig. 23 : Tell-tale instrumentation of pile N° 3

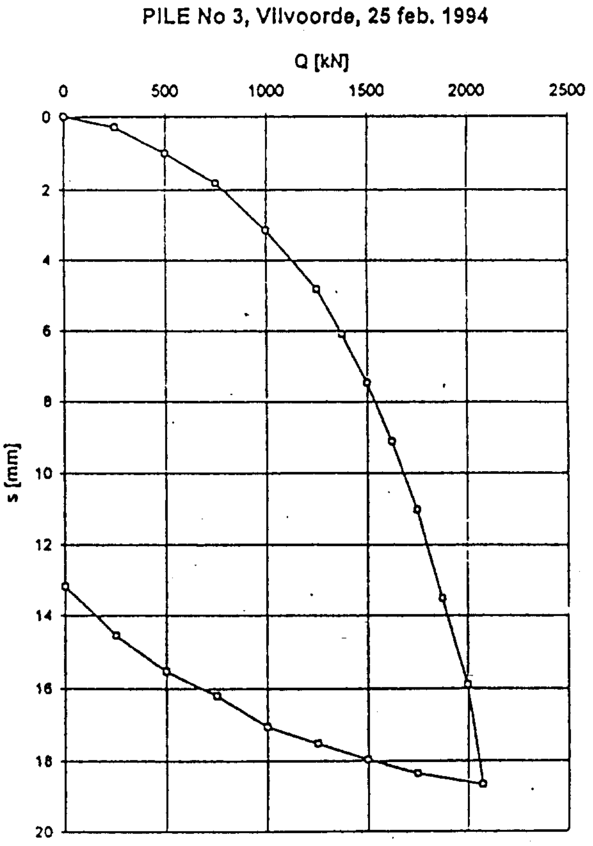


Fig. 24 : Load-settlement curve of pile N° 3

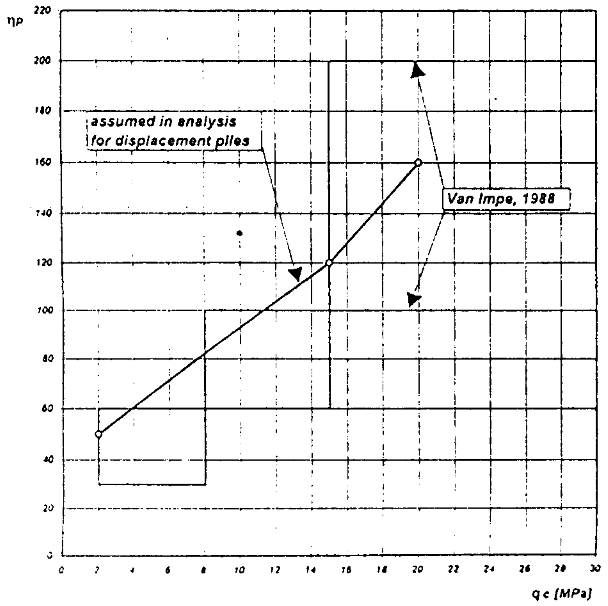


Fig. 25 : Driven and displacement piles, shaft resistance on CPT

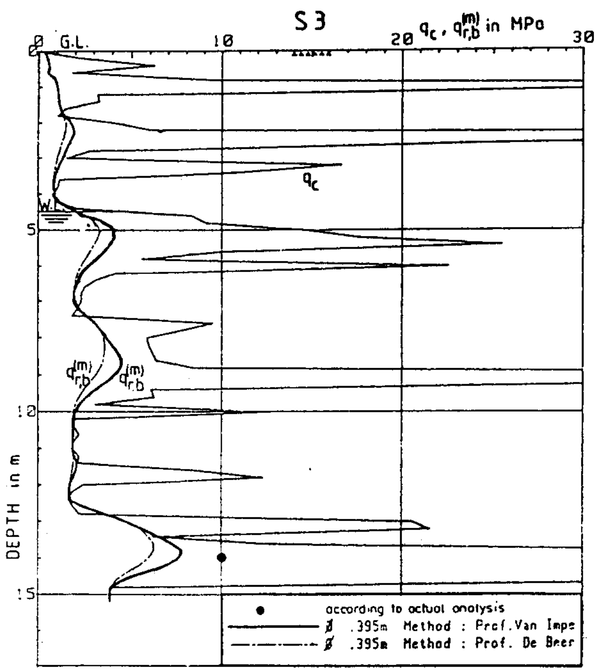


Fig. 26a : CPT-results and derived ultimate unit pile base resistance

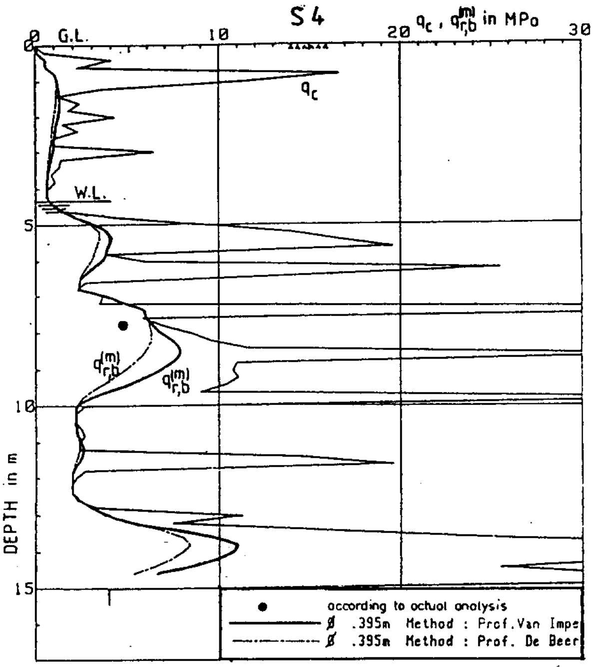


Fig. 26b : CPT-results and derived ultimate unit pile base resistance

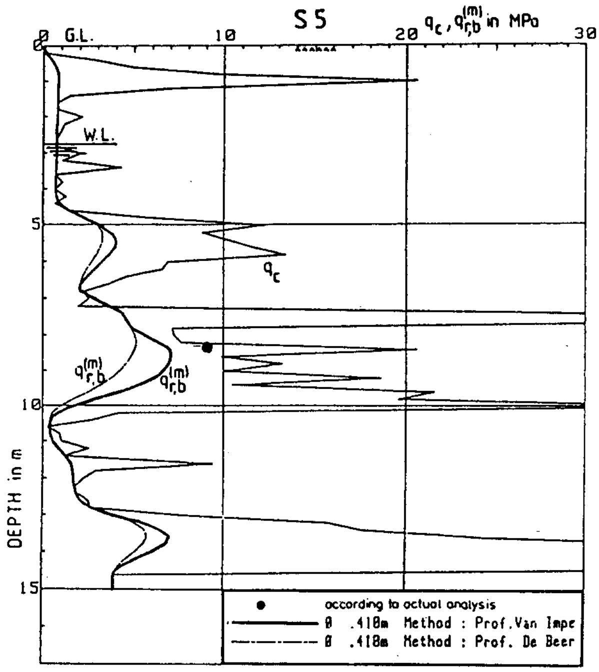


Fig. 26c : CPT-results and derived ultimate unit pile base resistance

TABLE V
General soil profile, Vilvoorde

Layer	$q_c^{(m)}$ (MPa)	Pile n°3 (Ω)			Pile n°4 (prefab)			Pile n°5 (Ω)		
		q_c (MPa)	$q_{s,z}^D$ (kPa)	ξ_f	q_c (MPa)	$q_{s,z}^D$ (kPa)	ξ_f	q_c (MPa)	$q_{s,z}^D$ (kPa)	ξ_f
layer 1 1.0 m	5	4.0	65.0	0.975	5.0	64.0	0.844	6.0	80.0	0.947
layer 2 4.5 m	1-2	2.0	40.0	1.0	1.5	25.0	0.833	1.0	20.0	1.0
layer 3 10.0 m	3-10	5.0	75.0	0.989	5.0	64.0	0.833	6.0	80.0	0.947
layer 4 13.0 m	2	2.0	40.0	1.0	2.0			1.5		
layer 5 16.0 m	> 20	> 20	125.0	1.0	> 20			> 20		

The ultimate unit end bearing is calculated from the following formula:

$$q_{r,b}^* = \alpha_b \,.\, \varepsilon_b \,.\, q_{r,b}^{(m)}$$

values of $q_{r,b}^{(m)}$ are shown in fig. 26a, b, c according to De Beer and Van Impe, as derived from the q_c values out of CPT.

α_b = installation coefficient for the pile tip-soil interaction
ε_b = measure of natural fissuring of the surrounding soil ;
(ε_b = 1 means no fissuring).

The results of the pile load tests as compared to this analysis for the pile tip capacity are given in table VI.

TABLE VI
Prediction of the tip bearing capacity, Vilvoorde

Pile number	Method	ε_b	α_b	$q_{r,b}^{(m)}$ (Mpa) (meas)	$q_{r,b}$ (Mpa) (meas)	$\Omega_{p,b}$ (m^2)	$Q_{r,b}$ (kN) (meas)	$Q_{r^*,b}$ (kN)
n°3	Van Impe (assumpt)	1.0	1.0	7.517		0.1320		992.2
	De Beer (assumpt)	1.0	1.0	5.934				783.2
	Van Impe (from measurements)		1.33	10.000				
	De Beer (from measurements)		1.69	10.000				
l = 14.0 m Ø = 0.41 m	Measured				10.000		1320	
n°4 prefab bb	Van Impe (assumpt)	1.0	1.0	6.138		0.1225		751.9
	De Beer (assumpt)	1.0	1.0	6.080				744.8
	Van Impe (from measurements)		0.75	4.600				
	De Beer (from measurements)		0.76	4.600				
l = 7.7 m 0.35x0.35 m^2	Actual analysis				4.600		564	
n°5	Van Impe (assumpt)	1.0	1.0	6.327		0.1320		835.2
	De Beer (assumpt)	1.0	1.0	5.169				682.3
	Van Impe (from measurements)		1.42	9.000				
	De Beer (from measurements)		1.74	9.000				
l = 8.2 m Ø = 0.41m	Measured				9.000		1188	

The α_b-installation factors ($\alpha_b > 1$) are guaranteeing a soil displacement character of the pile installation. One can clearly estimate the in this test case at Vilvoorde obtained, from the above table, large α_b-values for the Ω-pile.

INFLUENCING INSTALLATION PARAMETERS FOR SCREW PILES

Summarizing the most important installations parameters to be discussed, one could list the following features :

* soil type

$(L/\varnothing)_{pile}$ ↔ cohesive ↔ high water table ↔ normally consolidated
granular low water table overconsolidated

* installation energy ($v\downarrow$, $v\uparrow$, $M_{i/u}$, n, σ_{conc}, N_d, N_t)

* shape of auger head

* location of turn (or screwing) table (↔ torque)

* uplift acceleration ↔ casting concrete method and type of concrete (W/C)

* $\Delta T_{auger\ tip}$ ↔ (W/C)

* general required pile geometry (rough/smooth shaft, "flanges" continuous or not,...)

<u>The influence of the soil type</u>

For a given pile slenderness $(L/\varnothing)_{pile}$ and a well defined installation procedure, the interfearing parameters related to the soil type are the differences in cohesive and granular soils, the high to low natural ground water level and the NC to OC stress history. In fig. 27, 28, 29, 30, 31 and 32 examples of very well known installation effects of soil displacement and soil excavation screw piles are given, reflecting the large differences related to the soil characteristics the various pile installation parameters had.

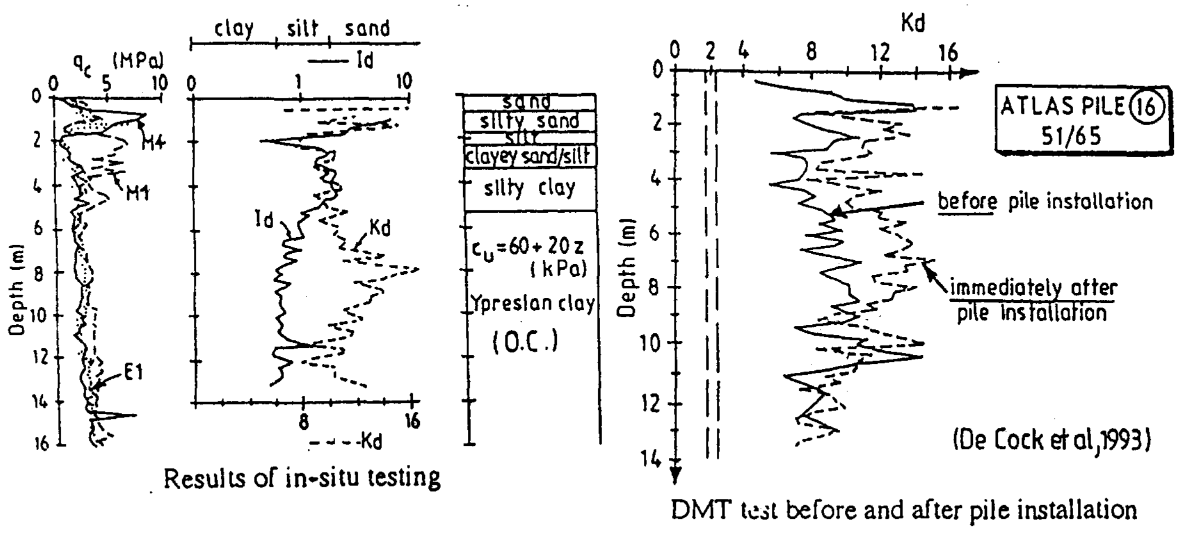


Fig. 27 : DMT test before and after Atlas screw pile installation in O.C. clay

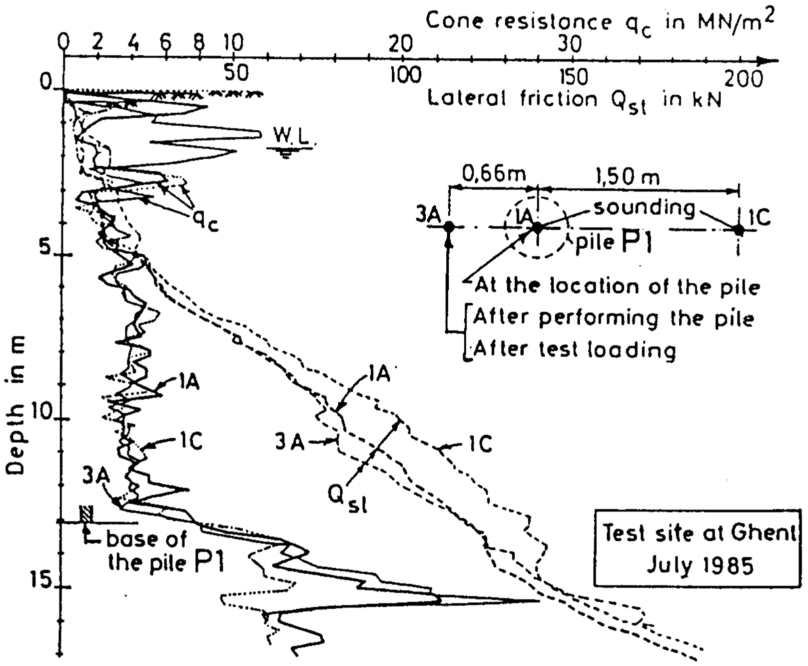


Fig. 28 : CPT-comparison at displacement pile installation

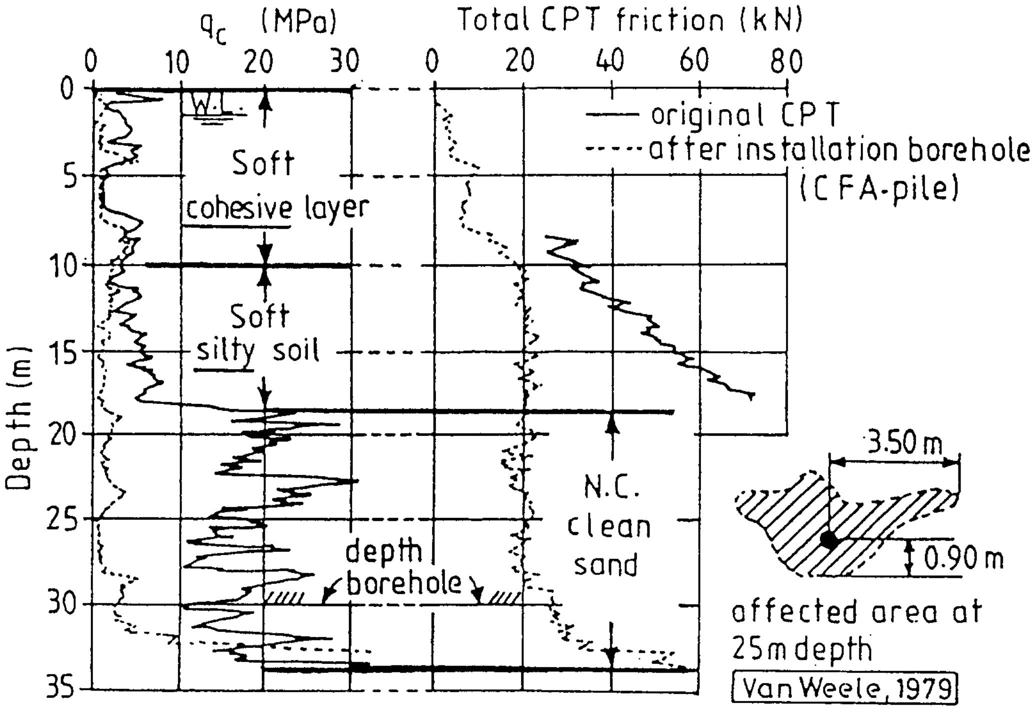


Fig. 29 : Installation effects of small stem CFA in sand, at low v↓ and too high v↑

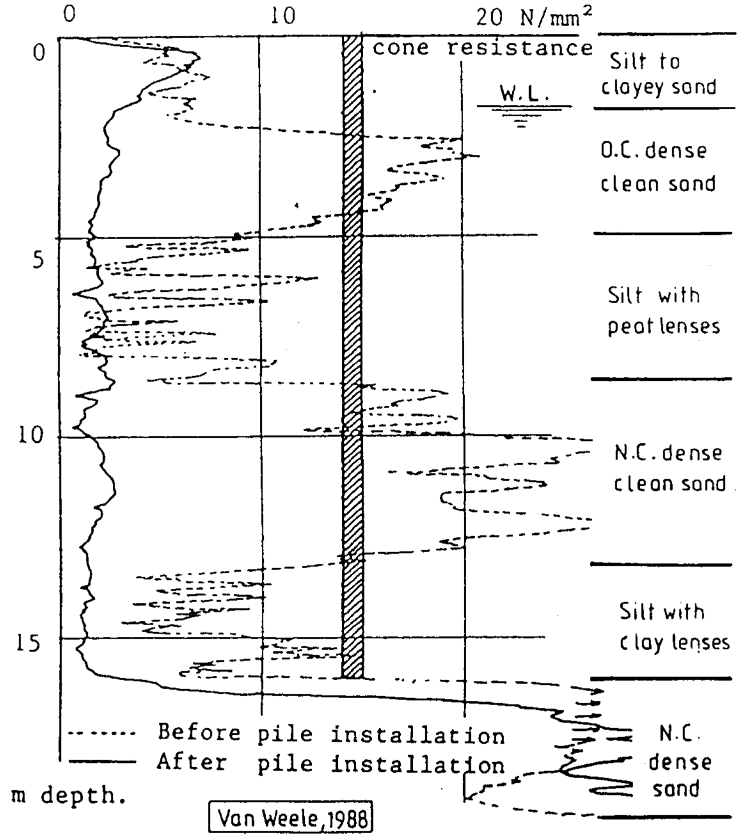


Fig. 30 : CPT-comparison of installation effects of CFA pile in sandy soil, at too low v↓ and too fast v↑

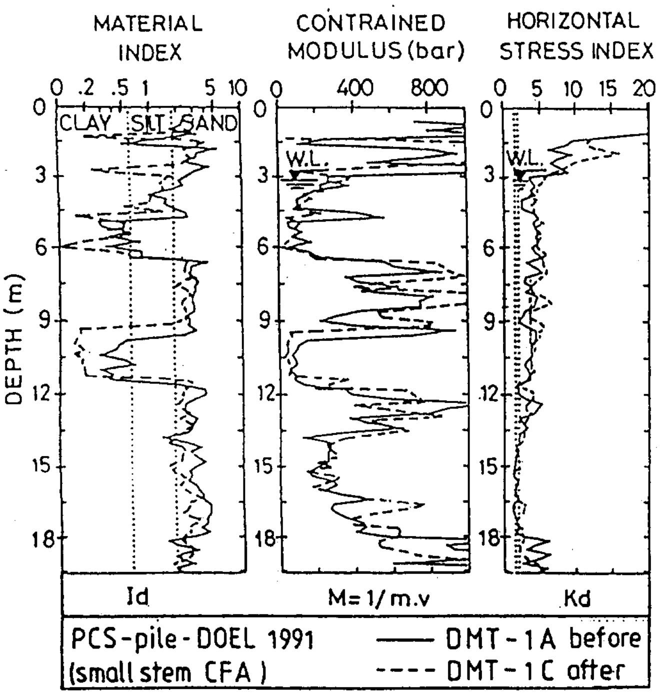


Fig. 31 : DMT-comparison of carefully installed small stem CFA under additional casting pressure

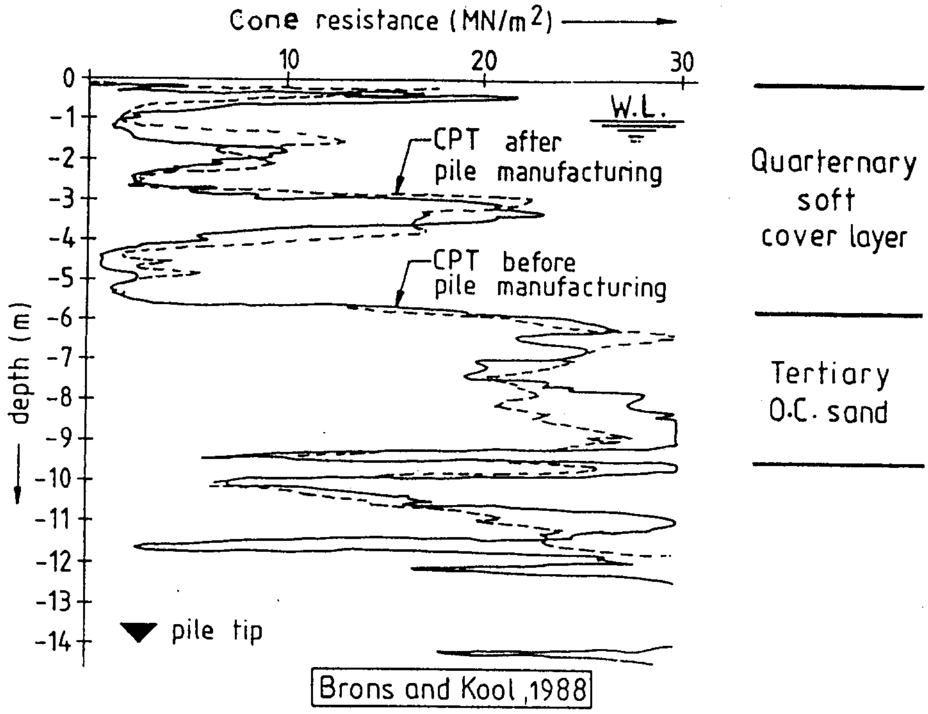


Fig. 32 : Comparison between CPT-result before and after pile manufacturing (auger and tube system) (Brons and Kool, 1988)

It looks as if the starting vertical upward acceleration of the withdrawal (the hoisting) has a very pronounced influence, certainly in combination with the vertical downward installation speed of the auger, as will be discussed lateron.

Speedy hoisting (or v↑) of the grab is usually the most dangerous parameter, because of the underpressures. These underpressures are temporarily creating decreased total stresses at the bore hole walls. The effective stresses in cohesive soils, (having usually a low permeability) are not sensitive to such changes in total stress of limited duration ; and during the entire period of excavation they may even keep almost the same magnitude as originally, before the excavation of the hole started. Holes under such circumstances are quite stable, and the soil is not too muchdamaged. Non-cohesive soils however with high permeability, their effective stresses show a more rapid (and often an immediate) reaction to changes in total stress. The lateral effective stresses so will obtain temporarily very low values resulting in a loosening of the soil. Granular soil will move towards the hole under influence of the decrease in lateral effective stress. This will of course never take place exactly uniformly along the periphery of the pile.

In conclusion,in stiff cohesive soils the excavation of the soil is at first sight less detrimental, although one can expect an immediate loss of overall total stress around the pile (fig. 33). It's however well recognized that a quite rapid and remarkable recovery of the total soil stresses is assured only very few weeks after the pile installation, (fig. 34). One can expect in any case the effective stresses in such case not to be noticeably affected accordingly.

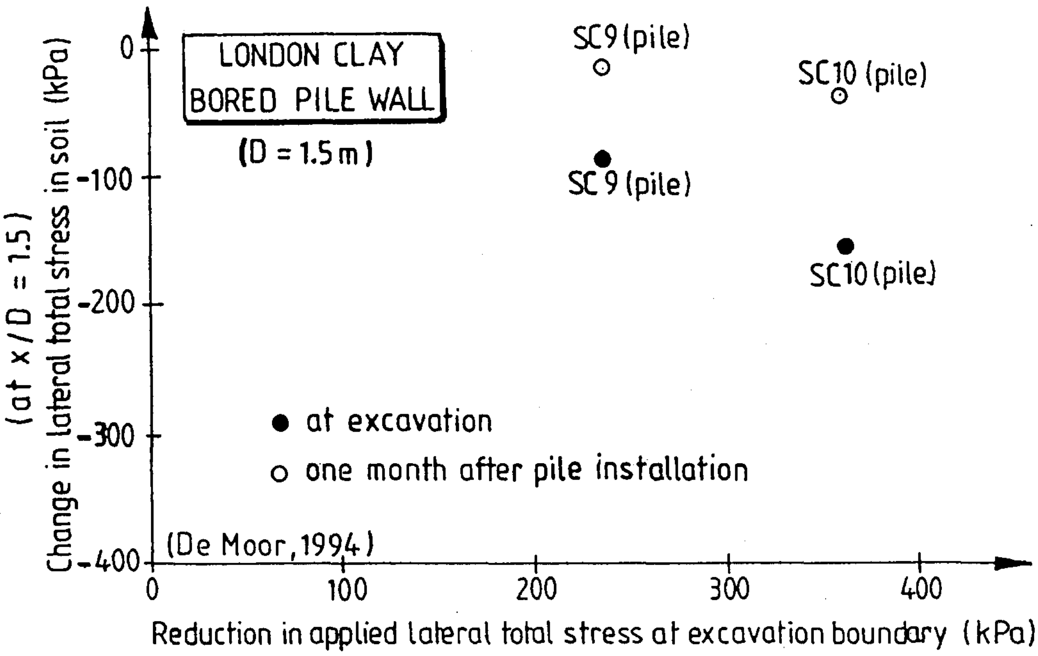


Fig. 33 : Results of total lateral stress reduction along bore pile walls

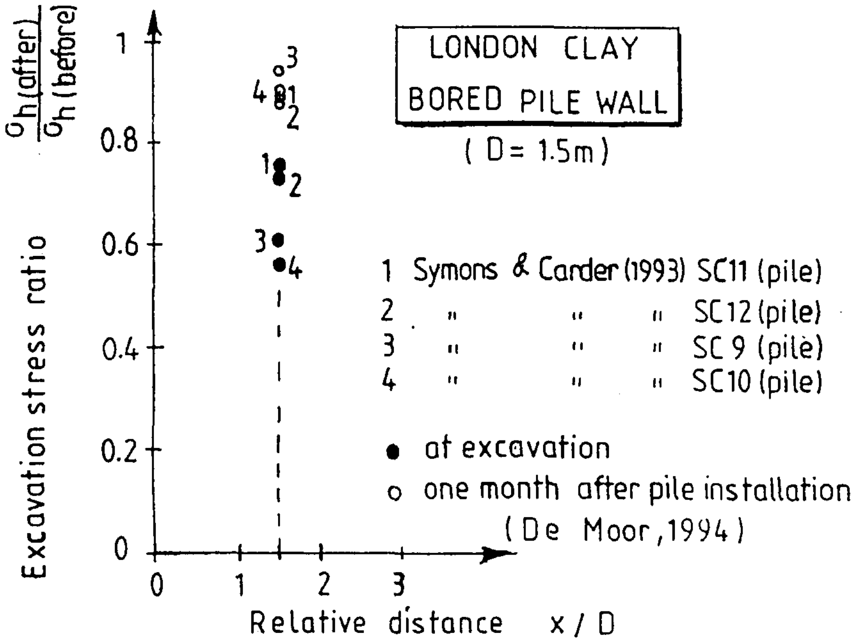


Fig. 34 : Results of total lateral stress reduction along bore pile walls

Installation energy parameters

More attention should be paid to some details related to the global installation energy (E_s) of screw piles. The approach to this specific installation energy is a combination of E_s (1) and E_s (2) out of fig. 35.

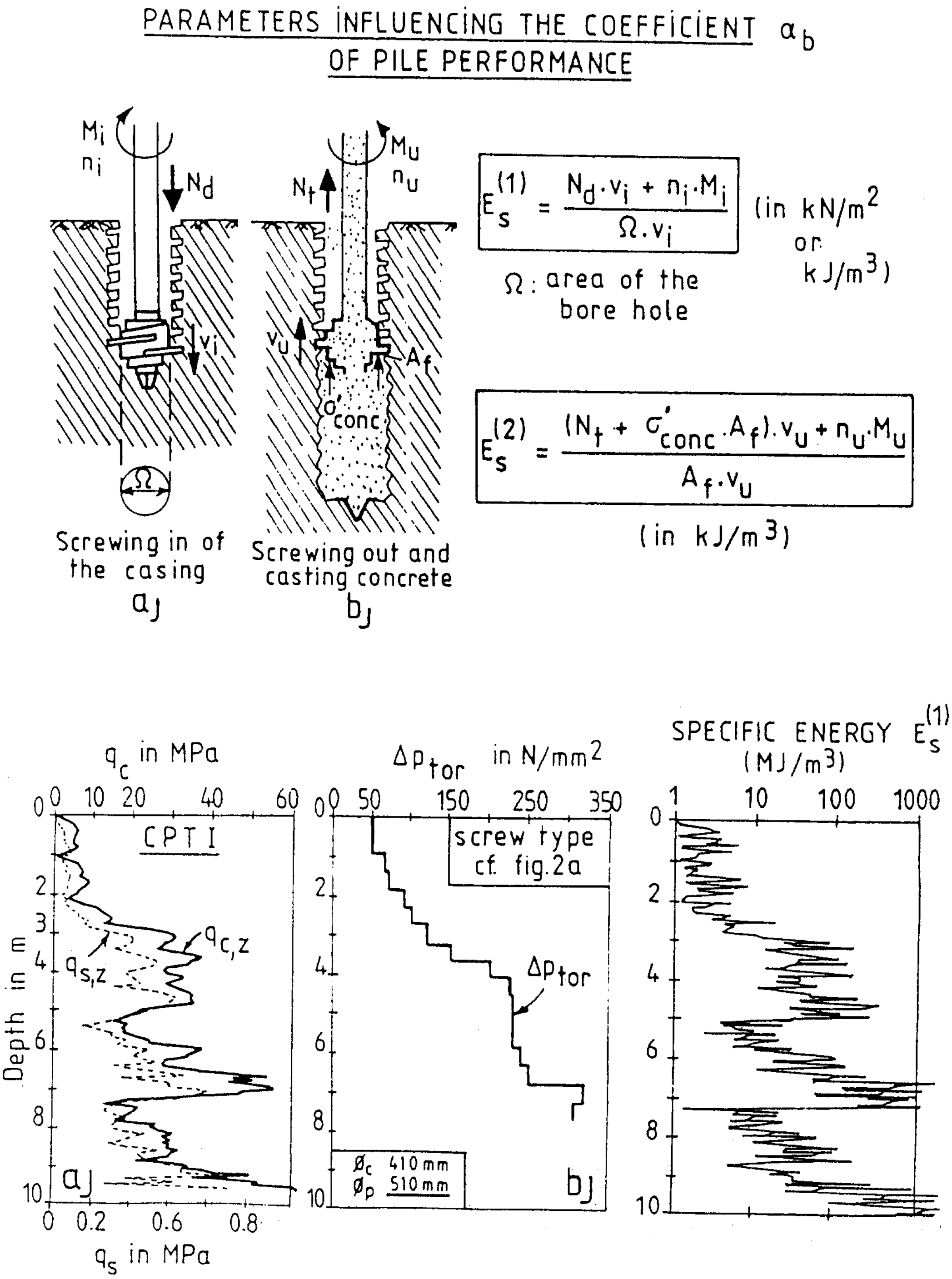


Fig. 35 : Energy parameters influencing the coefficient α_b of pile performance

For CFA screw piles, it seems the vertical downward speed, its scraping effect versus its efficiency to penetrate, is one of the more important sub-parameter to control (fig. 36) in combination with the additional vertical downward thrust (Q) available at the pile rig (fig. 37). It comes out to be very important of disposing for each fixed relative CFA stem diameter $\varnothing_i/\varnothing_0$, of a high enough additional downward thrust Q up to a given relative depth $\frac{z}{\varnothing_0}$.

If such additional thrust Q is not available, one has to decrease the $\varnothing_i/\varnothing_0$ value in order not to decompact too much the soil because of a decreasing (to a very low value) vertical downward penetration speed. So, even at maximum torque, the soil scraping and over-excavation governs at that moment the CFA pile installation, which is detrimental to its load settlement behaviour.

As suggested by Fleming (1994), one has to analyze the CFA penetrability also taking into account the facility of upward soil movement, after excavation, along the auger flanges, (fig. 38). In order to analyze such situation it is necessary to regard the soil on the auger flights as a continuous ribbon, but it should be recognized that this is not strictly true because of seepage of groundwater towards the rising soil mass. The only force available to allow the movement of the soil along the flanges upward and prevent the auger blocking is influenced by the hoop stress at the bore wall, necessary to sustain stability of the wall. The method proposed by Terzaghi for calculating the lateral stability of the walls of a schaft is in this respect very useful, (fig. 39 and 40). On the other hand the forces (P_d) resisting the upward soil movement, result from self weight and the downdrag acting against the upward flow at the bore wall. The ratio of the upward required (T_s) to downward acting forces (P_d) is termed the "Flighting Ratio".

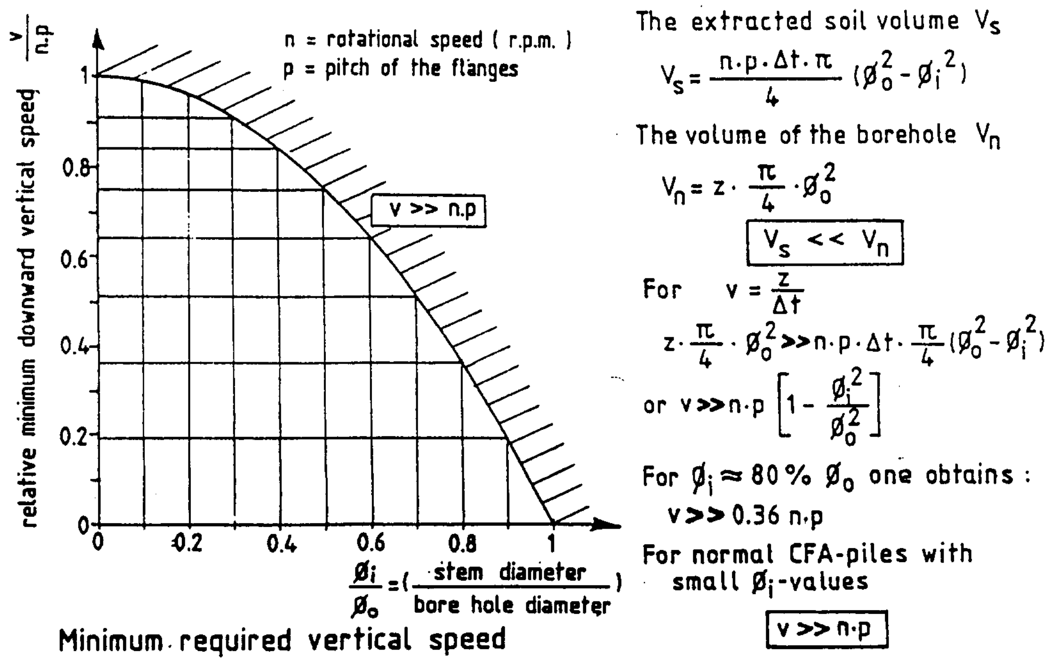


Fig. 36 : Requirements for mechanical CFA installation parameters

CFA No decompaction Effects

$$\frac{v}{n \cdot p} \geq 1 - \frac{\varnothing_i^2}{\varnothing_o^2}$$

Or $v \geq n \cdot p \left(1 - \frac{\varnothing_i^2}{\varnothing_o^2}\right)$; $\frac{\varnothing_i^2}{\varnothing_o^2} \geq 1 - \frac{v}{n \cdot p}$

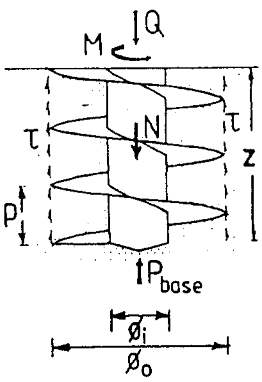
Required capacity of the equipment (Viggiani, 1993)

$N + Q > P_{base}$ $[N = \psi(M, \tau_{soil})]$

Simplified penetration model in dry uniform sandy soil at whatever a torque value:

$$Q_{(z)} = \gamma \cdot \varnothing_o^2 \cdot \frac{\pi z}{4} \left(N_q \cdot \frac{\varnothing_i^2}{\varnothing_o^2} - 2k \, tg\varphi \, \frac{z}{\varnothing_o}\right)$$

γ = effective unit soil mass
k = appropriate earth pressure coefficient
N_q = appropriate capacity factor



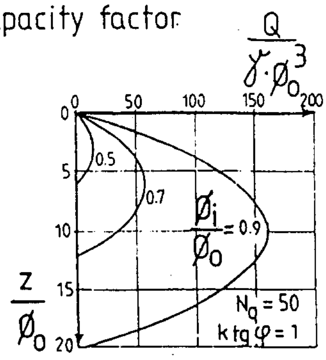
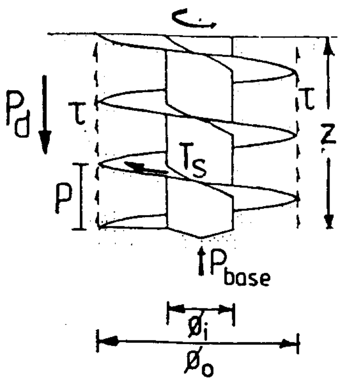


Fig. 37 : Flighting ratio principle



$\frac{T_s}{P_d}$ = flighting ratio

Fig. 38 : Flighting ratio principle

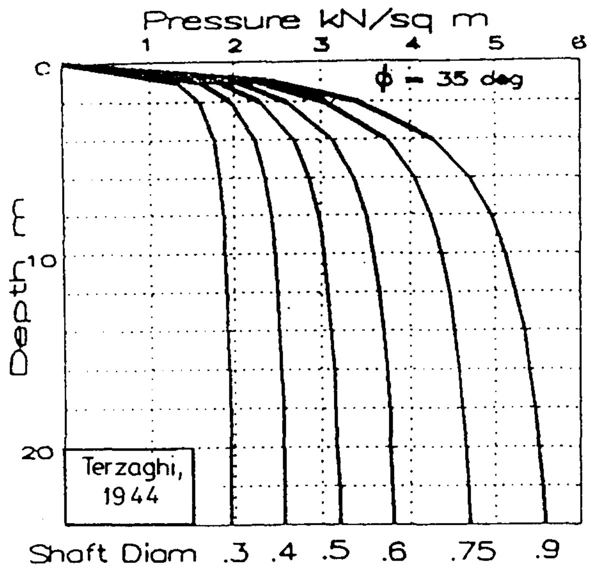


Fig. 39 : Hoop stresses in sandy soil required to sustain the bore hole

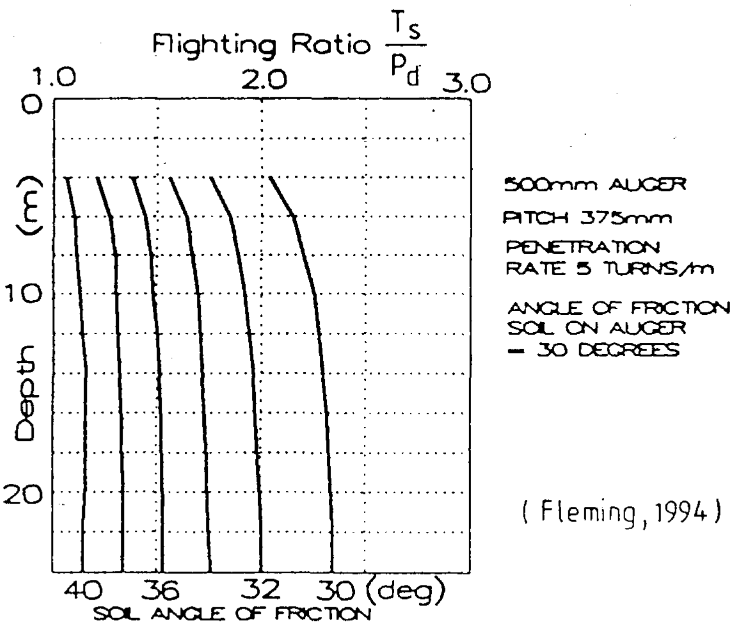


Fig. 40 : Hoop stresses in sandy soil required to sustain the bore hole

Some of the general findings (Fleming (1994) are :

1. The occurrence of excessive flighting is more likely with large than with small diameter augers
2. Flighting of soil becomes smaller as the flight angle is steepened
3. Excessive flighting becomes smaller as the shear angle of the undisturbed soil increases.

Normal augers should be controlled in their descent so that the maximum torque of the machine is consistently mobilised. In loose sands where the boring is easy, the penetration rate should automatically be increased, while in dense sands it could be limited. In case of well designed soil displacement auger heads, the thrust Q can be very low, since the auger head is easier gripping into the resistant soil layer. This means that even almost without vertical downward additional thrust Q, the penetration of well designed displacement auger heads into a resistant soil layer, appears to be quite possible.

Influence of the auger head shape

In case of screw piles, it's well known the angle of the flighting, the variability of the pitch and the increasing diameter of the auger head have beneficial influences on the penetrability or the screw pile installation. In this respect the experience with a specific comparing test case of the Atlas screw pile (fig. 41) is all explaining. In the ideal Atlas screw pile flange-type (a) of fig. 41, a small intersection for opening the flange over a few centimeter (fig. 41b) was tried out as an experiment. The efficiency of pile installation velocity for the new pile type flange, (fig. 41b) almost doubled, the required torque (or its derived hydraulic pressure Δp) was much lower, cfr. fig. 41d, than for the normal Atlas flange shape, (fig. 41a). Although, the pile-soil interaction stiffness for the type b-flange Atlas pile appeared to be lower in comparison to the excellent results with the normal type of Atlas auger head type. All of this are reasons for carefully rethinking the entire auger head design, as a result of which the already shown Ω-auger head (fig. 7-9) for example was patented in Belgium at the end of 1993 (fig. 42) by Socofonda.

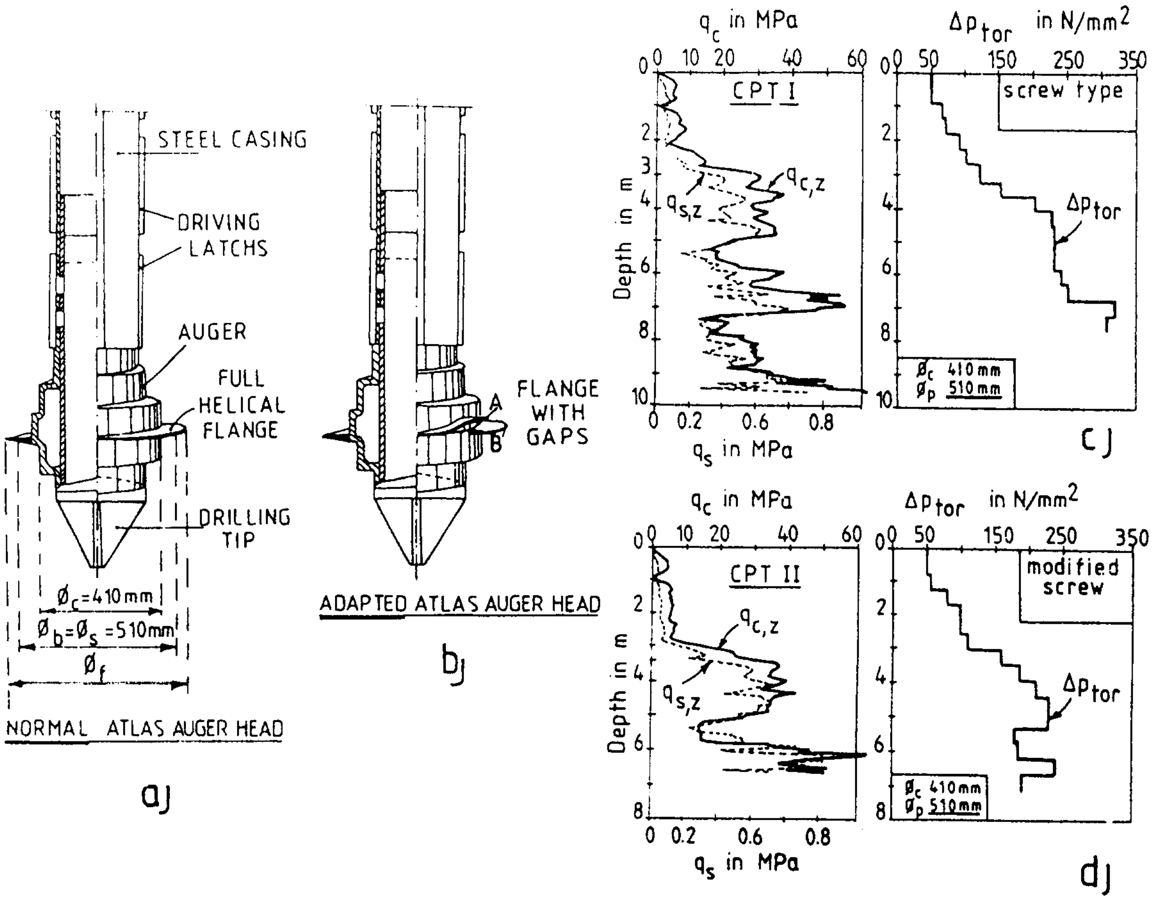


Fig. 41 : Example of the influence of auger head shape

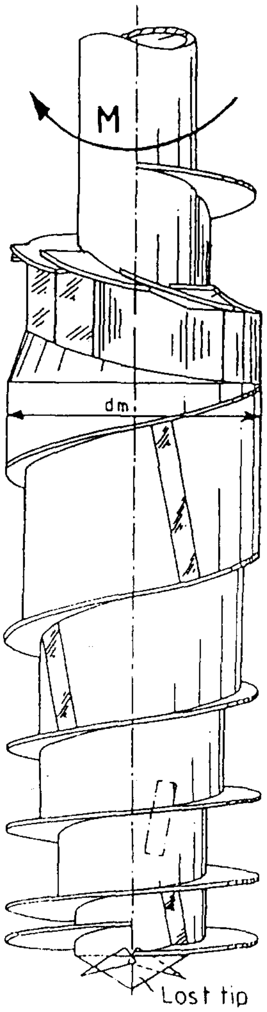


Fig. 42 : Detail of Ω-auger head

The tip of this specific auger head is, in the usual way, removably mounted onto the auger head in such a manner that it remains in the ground upon screwing the auger head out, as a result of the concrete casted under an overpressure. In order to displace laterally the ground situated on top of the auger head, during the screwing out, the displacement body of the auger head has in the embodiment an upper portion with a core diameter decreasing in the direction away from the tip. This upper portion comprises further four screw flange parts, each extending over about 225 degrees and overlapping each other over about 45 degrees. Since the screw flange parts are inclined in opposite direction during screw out, these screw flange parts will provide the ground situated on top to be displaced once again downward. In the embodiment according to figure 42 the upper portion of the displacement body comprises first of all a series of fins, overlapping each other partially. These fins are disposed according to a screw direction, during auger penetration, opposite to the screw direction of the screw flange and extend in particular over about one turn around the auger head. For displacing the ground radially when screwing the auger head out, an inclined displacement body is arranged underneath each of the fins.

The combination of the increasing pitch, the stepwise growing auger head diameter and the upper counter screw part, guarantees a much better lateral soil displacement and a by far better penetrability even in cemented sand layers, without any soil being transported upward.

<u>Influence of the location of the turn (or screwing) table on the rig</u>

The location of the turn table (fig. 43 and 44) with respect to the dimensions and the location of the gravity centre of the pile rig, is of great influence to the maximum available torque during the pile execution.

But even more important is the maximum allowable torque, at each depth of the penetrating auger head, with respect to the required pile soil interaction. Whenever the turn table is mounted upon the auger itself, and therefore is lowered together with the auger penetration into the soil (fig. 45 and 46), it is unavoidable the auger stem continuously is moving in a cone shaped surface during penetration of the auger head (being the top of this cone). This type of auger penetration movement creates a lot of over-excavation and therefore is very detrimental to the soil characteristics around the theoretical pile shaft.

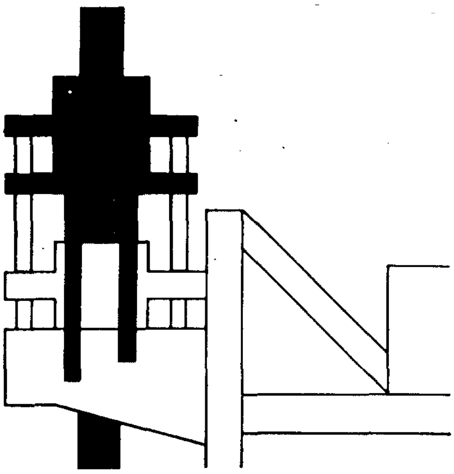


Fig. 43 : Atlas pile screw table

Fig. 44 : Atlas screw pile rig

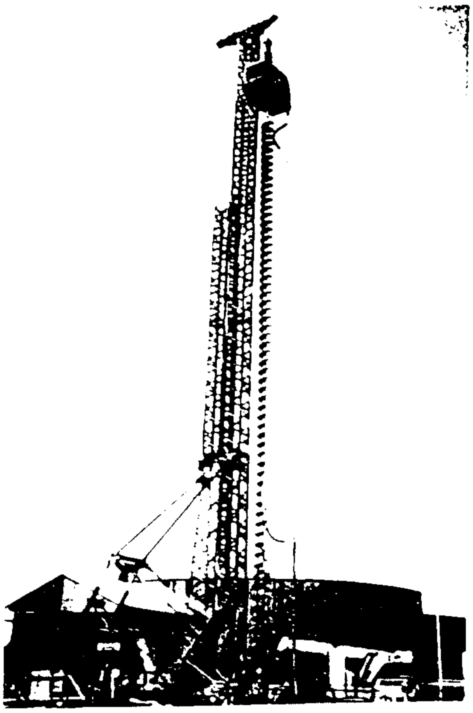


Fig. 45 : CFA turn table

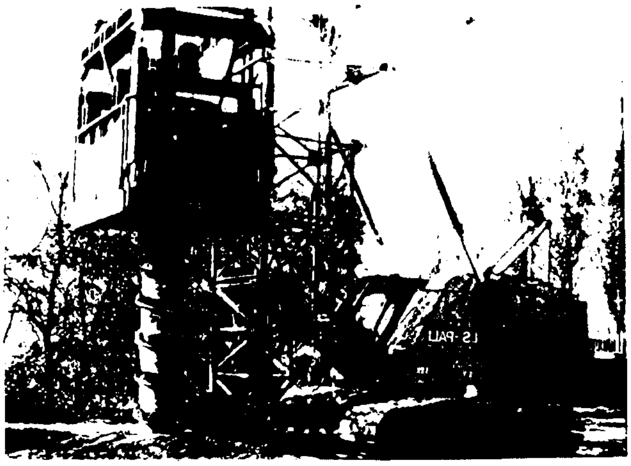


Fig. 46 : Large stem CFA turn table

Parameters linked to the casting concrete procedure

During concreting it is common, monitoring the supply to an accuracy of better than 5 %, to set a target for overconsumption of about 25 %. The pressures required to expand a pile shaft in sand at depth are large because of the large passive pressure which can be mobilised around the hole. Such pressures are not normally available from any conventional concrete pump. The aim of oversupply control in this case is only to ensure that the concrete rises relative with respect the auger at all times. Under-supply would be a hazard to the proper formation of a pile shaft.

Another problem of concrete flow concerns the occurence of blockages. In order to minimise this phenomenon, it is necessary to use a concrete mix with optimized flow characteristics (a slump of 150 mm is normally adopted). The best practice when casting continuous flight auger piles in sandy soils seems to rotate the auger in the initial stages of concrete pumping in order to carry concrete up onto the CFA flange ; thereafter to cease rotation for the remainder of the extraction or to permit rotation (throughout the lifting process) only at the lowest available speed.
In connection with the casting concrete influence : the type of concrete, its permeability, its W/C - ratio, the overconsumption ratio, the rate of casting, the influence of the uplift acceleration (hoisting) the auger tip temperature at casting ; all of those parameters do have an important influence on the so called silo-effect of the casting concrete process. This silo-effect is a combination (fig 47) of the silo-action of the fresh concrete in the newly excavated "bore"hole on the one hand and the arching of the fresh concrete in the stem tube of the auger itself.

Concreting is usually done by pumping or by casting through a tremie pipe. The fresh concrete acts as a fluid. The lateral total stress exerted against the sides of the hole will increase. The faster the concrete casting takes place, the larger the lateral total pressures. The higher W/C, the higher the pressure ; the lower the concrete permeability "k_{cr}" the longer the concrete remains fluid. The smaller the soil permeability "k", the longer the concrete will keep its fluidity. The finer the cement and the finer the aggregates, the lower the "k_r"-value. The use of a superplastifier increases "k_{cr}"(fig. 48)

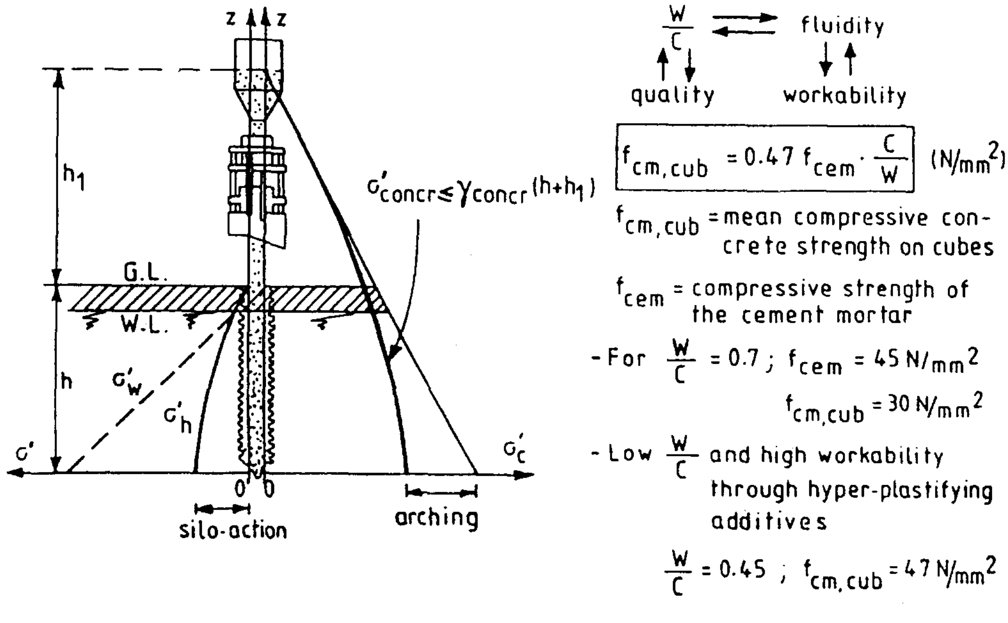


Fig. 47 : Silo effect parameters

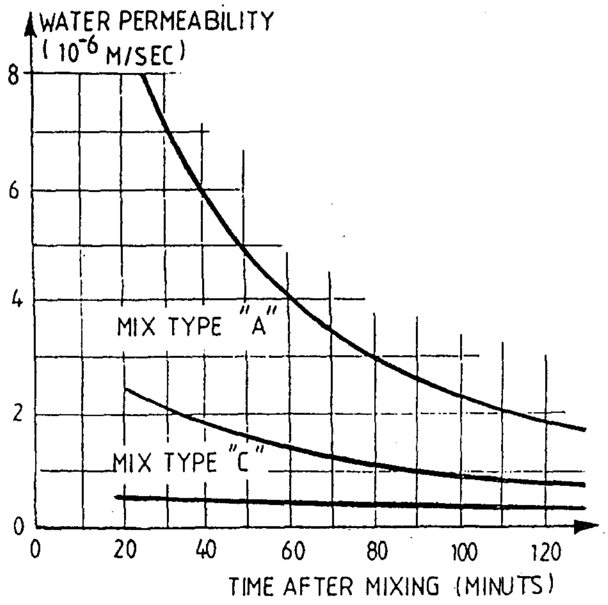


Fig. 48 : Waterpermeability of fresh concrete for a great number of different mixes (Van Weele, 1988)

The designer and the crew on site should always aim at maximum fluidity of the concrete during and immediately after casting. This can be achieved guaranteeing :

- Fast rate of casting
- Maximum fluidity of the concrete
- Low permeability "k_{cr}" of the concrete itself.

Especially in soils with a low groundwater level and/or a large permeability "k", these factors are more important to adhere to.

Drainage towards the soil of excess porewater out of the fresh concrete goes fast, as the drainage path is short and the compressibility of the fresh concrete low. It is more pronounced near the pilefoot than near the piletop. The concrete in the lower pile sections already gets the first hardening at the moment the casting reaches the piletop. So the weight of fresh concrete near the top is carried to a certain extent already by the effective stresses in the concrete near the foot. Lateral total stresses exerted by the concrete to the soil in these lower parts of a pile, will be less than those according to hydrostatic conditions. That's what we usually call the silo-action.

In addition to this silo-action, the arching of the fresh concrete in the stem casing itself is also contributing to the overall sillo-effect.

Large differences in the fresh concrete pressure that can occur with only slight variations in stem diameter, W/C-factor and additional auger head concrete pressure, are clearly shown in the examples of fig. 49and 50. Nor the example of fig. 49, nor the example of fig. 50 is part of an acceptable installation technique, since in the first case, the arching is so largerly dominating that almost no concrete pressure is available at the pile tip ; in the cast of fig. 50 the too elevated fresh concrete pressure is hydraulically fracturing the soil, which is also detrimental to the overall pile load settlement behaviour.

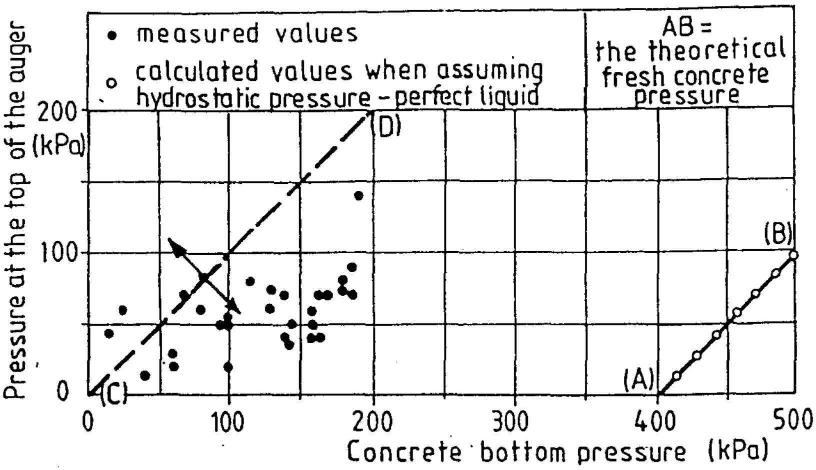


Fig. 49 : Example of effect of arching in CFA stem (Brons and Kool, 1988)

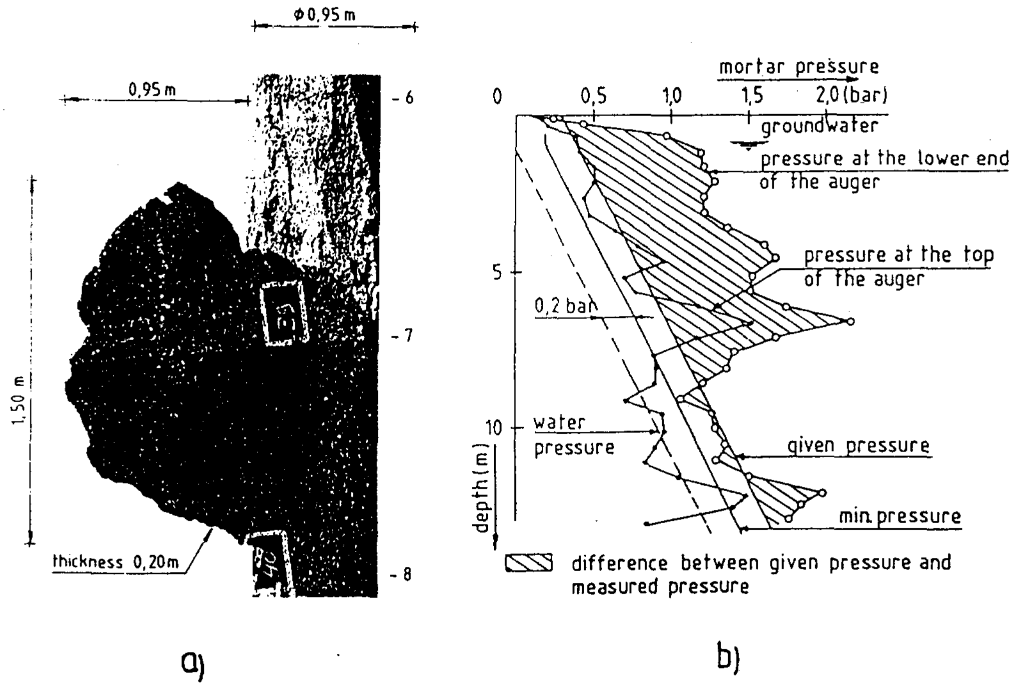


Fig. 50a : Fracturing in soft material due to uncontrolled pumping pressure during the formation of the pile shaft
b : Pressure measured at the top and the bottom of the auger on the basis of the personal judgement of the operator (Brons and Kool, 1988)

Finally, it's worthwhile, to stress the influence of the auger tip temperature increase (Δt) at the start of the casting of concrete, since this is also influencing the arching effect. One could conclude that large stem CFA-screw piles are probably not that sensitive to this phenomenon, since the auger flange area contributing to the soil excavation, is large. On the contrary, it can be expected for single flange auger heads to develop, especially in granular soils, inner casing temperature increase values of $\Delta t > 80°$ C, which obviously is influencing the flow capacity and the fluidity of the fresh concrete arriving at the pile tip. In this respect it is preferable to develop auger heads with more extended flanges, as in the Ω-pile type for example ; the inner temperature increase in such case should remain below $\Delta t < 40°$ C, since the area of the outer cooling surfaces is very important.

Screw pile preloading influence

For obvious reasons, fig. 51, many procedures have been developed to improve technically, in the field, the quality of contact between screw pile tip and the surrounding soil, in order to balance the problems arizing from arching of the fresh concrete in the stem, the silo-action and detrimental effects of a too speedy hoisting of the auger head. In the figures 52 to 59, wellknown auger pile tip stiffening procedures are shown.

One could stress that indeed such pile tip preloading is highly beneficial to the single pile load-deformation behaviour as suggested by fig. 58. However, it is equally important to be aware of the very limited beneficial impact this pile tip preloading has on the overall pile group behaviour ; at least for pile groups combining for example more than 6 piles relative at pile-interdistances $d/\varnothing_{pile}$ lower than about $d/\varnothing \leq 4$ and relatively stiff pile caps. For low-stiffness pile caps, short piles and limited pile interdistance, the uprising percentage of (interaction) capacity of the pile cap with respect to the load taken by the pile head, can feel some small benefit by the stiffening of the soil mass in between the piles due to the preloading procedures after single pile installation.

In our opion, the conclusion is that in most cases such single pile preloading effects should not be overestimated. In case of CFA piles in cohesive soils, which is by far the most relevant example when talking about screw pile installation in Europe, one could suggest that simply "preloading" technique as implemented in the Starsol principle (nowadays also in every common careful CFA installation procedure), starting from the principle of fresh concrete overconsumption at the start of the auger uplifting, can already guarantee a remarkable pile-tip-soil interaction.

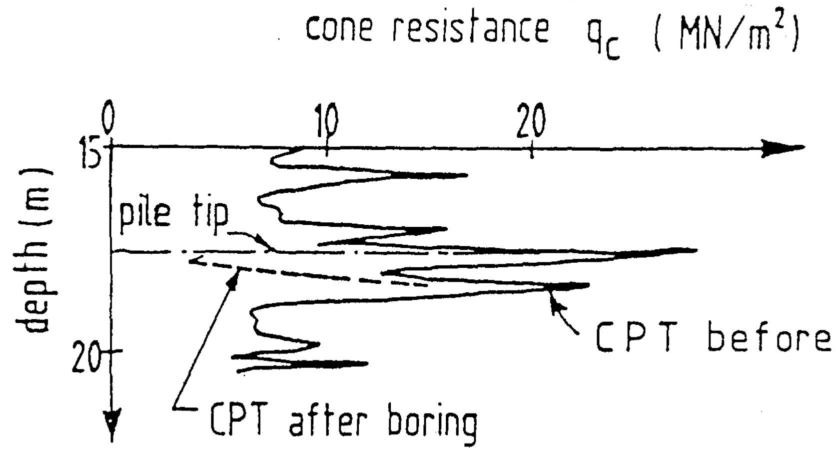
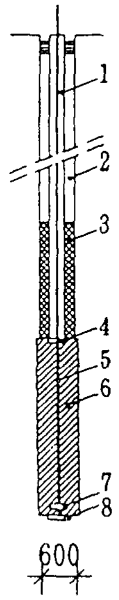


Fig. 51 : Original CPT and CPT made below the CFA-piletip (after Brons & Kool,1988)



1 = prefab shaft
2 = water or fill material
3 = quick hardening grout (dämmer)
4 = steel plate
5 = tension bar
6 = expansion mortar
7 = anchor plate
8 = bottom plate

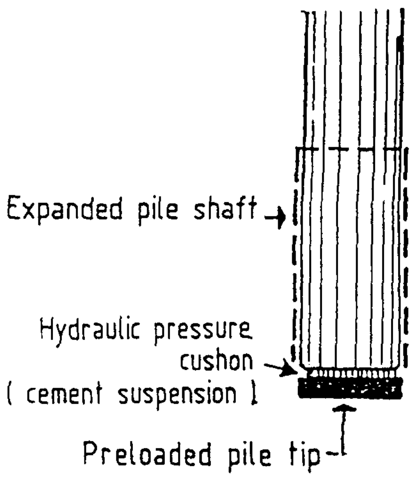
(van Bijsterveld,1993)

THE EXPANDING MATERIAL

$$4CaO.3Al_2O_3.SO_3 + 6CaO + 8CaSO_4 + 96H_2O \rightarrow$$
$$\rightarrow 3[3CaO.Al_2O_3.3CaSO_4.32H_2O]$$

Ettringite needles formed under a counterpressure of 0.08 MPa.

Fig. 52 : SES-pile



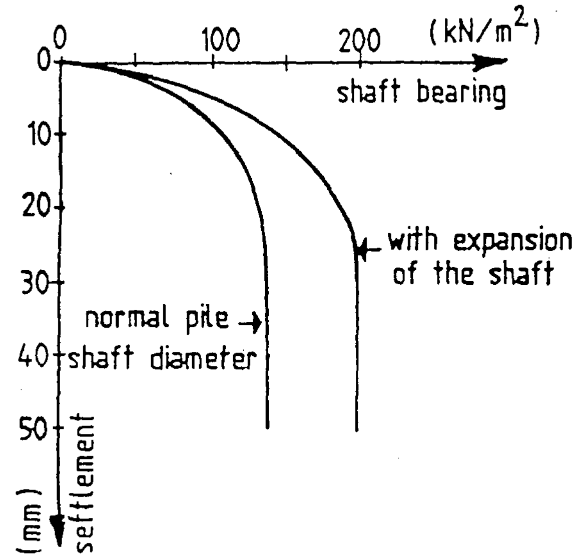


Fig. 53 : Effect of pile tip preloading

Fig. 54 : Bauer pile tip expanding model

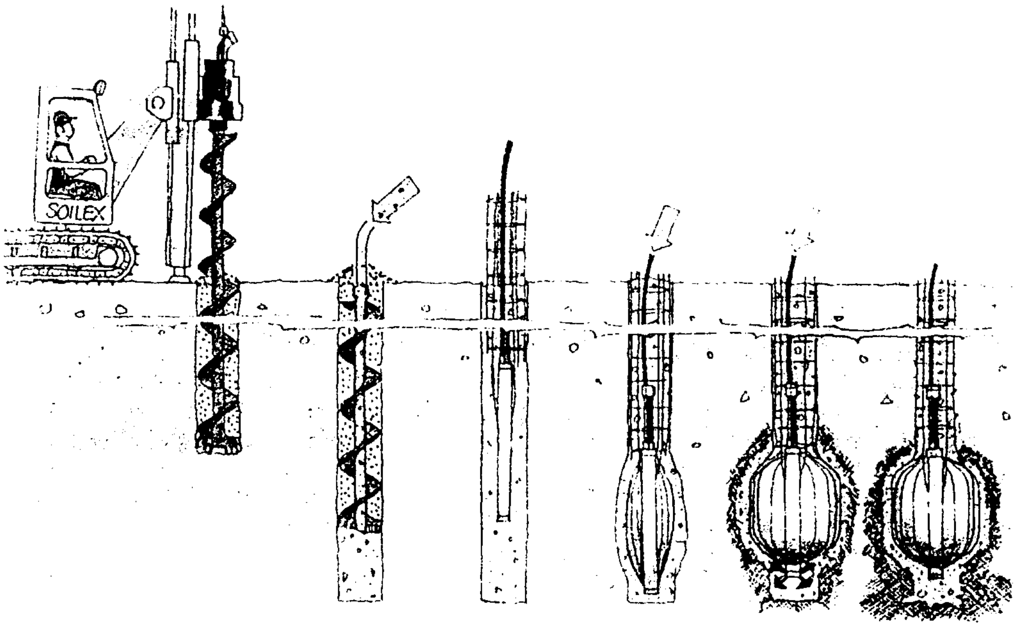


Fig. 55 : Installation phases of the Soilex pile, type CFA (Massarsch & Wetterling, 1993)

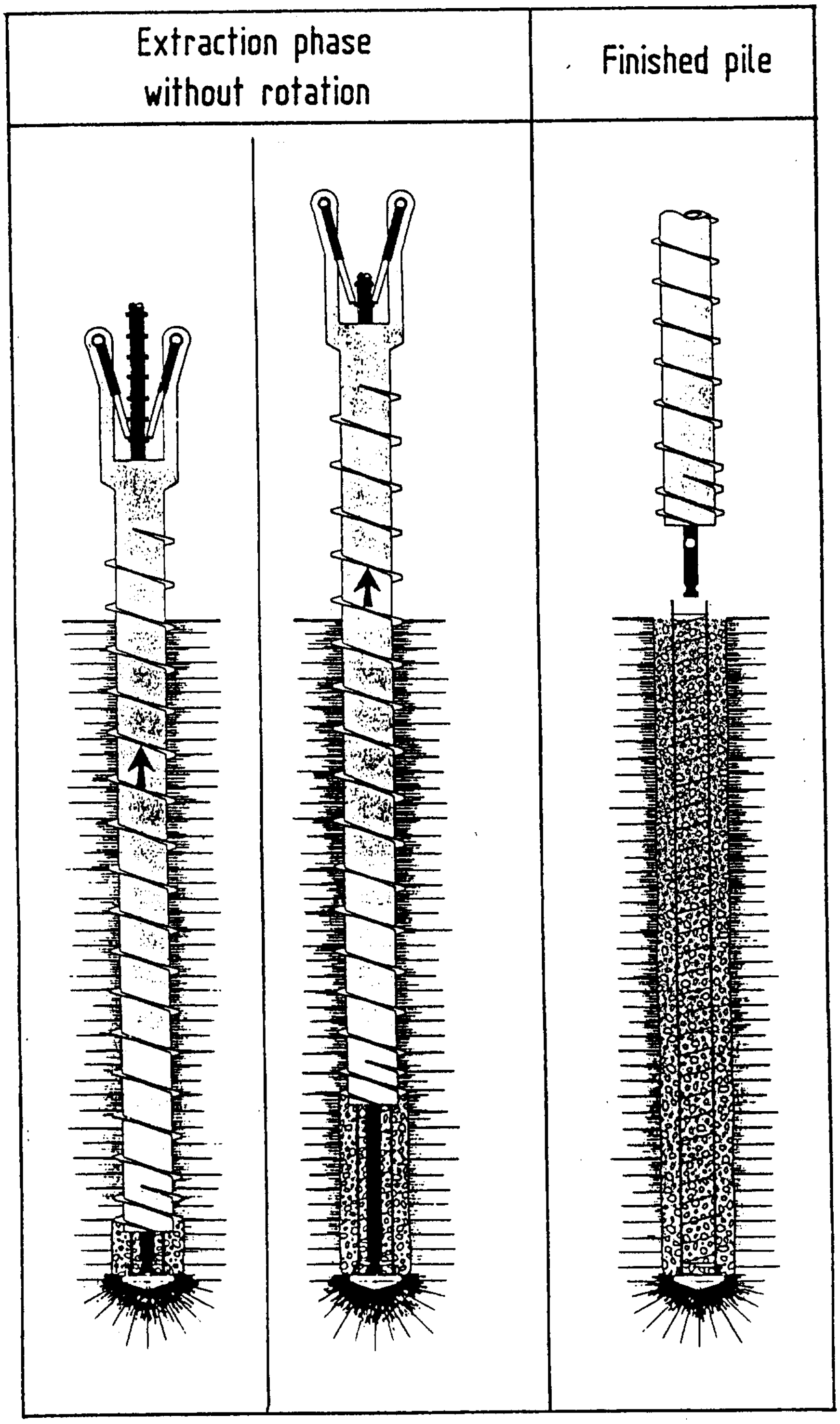


Fig. 56 : Presso-Drill pile

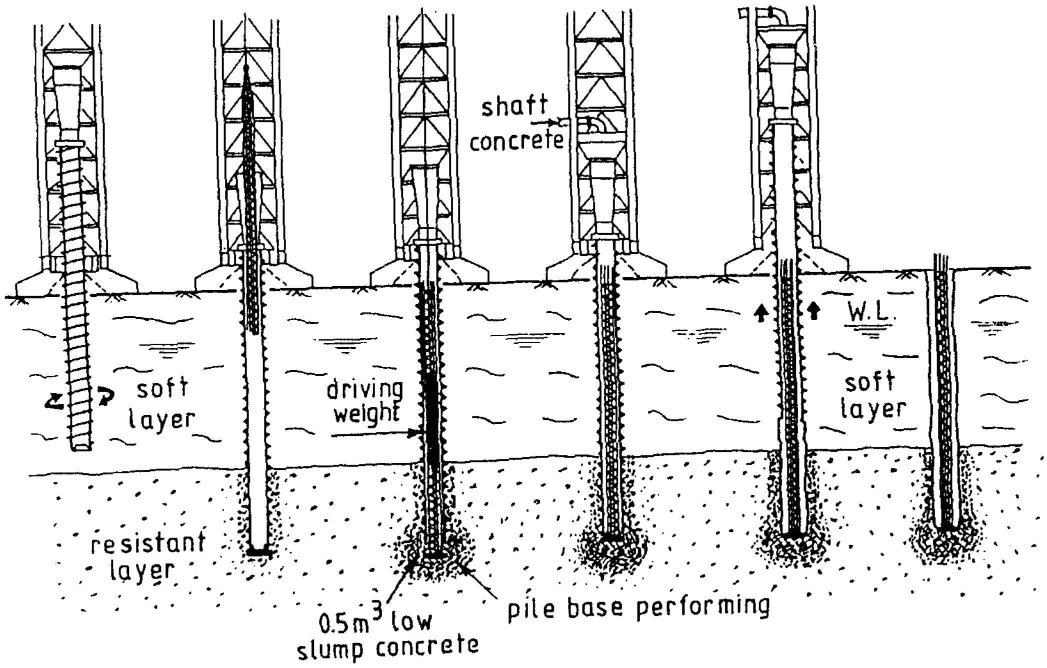


Fig. 57 : VB-Franki Auger pile

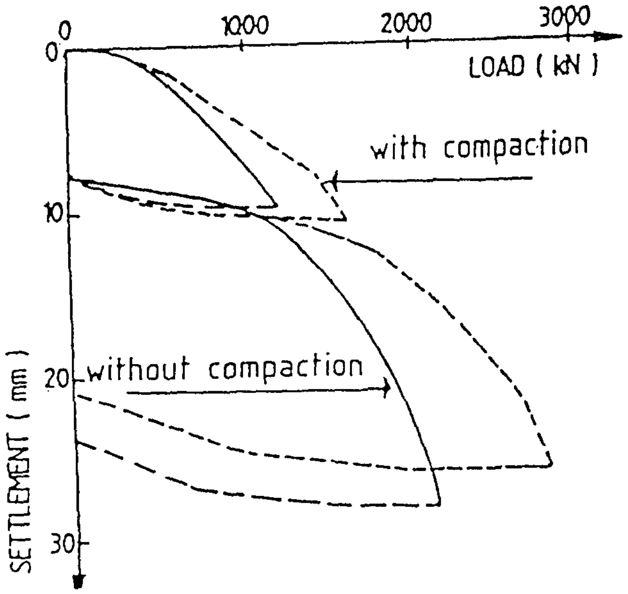


Fig. 58 : Results of VB-auger pile load test (Massarsch, 1988)

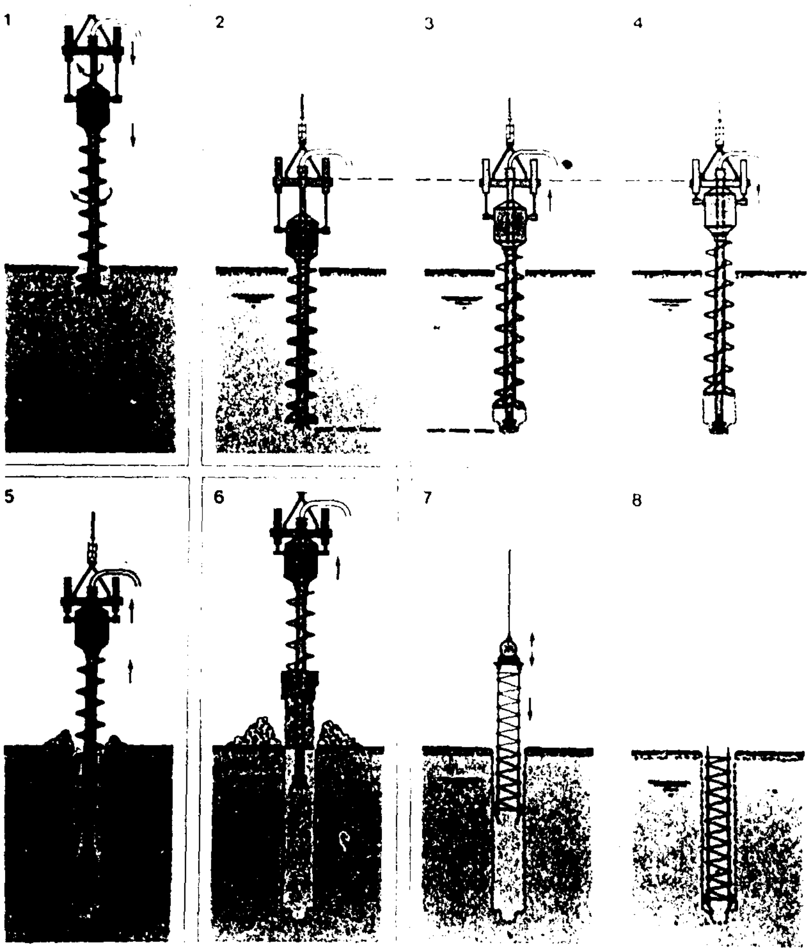


Fig. 59 : Starsol pile

CONCLUSION

Screw piles are of ever increasing importance in the todays' deep foundation design and represent an important step towards more effecient deep foundation engineering. Installation details are however more predominantly than for other pile type governing the pile behaviour. Fully automatic registration of all installation parameters is therefore required. Adapted pile capacity control methods and pile testing techniques should be implemented.

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