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THE CONCRETE VIBRATION PILE – A MODERN KIND OF FOUNDATION – FABRICATION AND BEARING BEHAVIOUR

PIEU A BETON VIBRE – UN TYPE DE FONDATION MODERNE – FABRICATION ET TENUE EN CHARGE

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SYNOPSIS: Concrete vibration piles have been constantly advanced in recent years although a major breakthrough towards the use of this modern type of foundation element has not yet been achieved in the Federal Republic of Germany. In the meantime, Preussag has developed a new concrete vibration pile system which features maximum safety with respect to both pile fabrication and bearing behaviour. In this study details of pile fabrication as well as results of investigations into possible fields of application, application limits as well as bearing and deformation behaviour are given.

1 CLASSIFICATION OF THE PILE SYSTEM

The pile system developed by Preussag involves non-reinforced cast-in-place concrete piles fabricated by means of vibration tools. These piles must thus be classified as displacement piles the standardization of which is presently under preparation in Europe.

The concrete vibration pile is used to transmit building loads to deeper load-bearing subsoil layers. Due to the lack of reinforcement the piles are almost exclusively used in applications where vertical compressive loads must be taken.

2 PILE FABRICATION

The piles are fabricated by means of vibratory equipment (Fig. 1 and 2) consisting of a thick-walled driving tube (wall thickness 20 mm, tube shell diameter 510 mm) provided with a solid steel cone at its tip, and the vibratory unit. For the driving tube mentioned above hydraulic vibrating machines are used which have a total weight in excess of 10 t and a centrifugal force of more than 100 t with a vibratory rating of approximately 250 to 300 kW.

For the fabrication of the concrete vibration piles the vibratory equipment is placed in position and the concrete conveyor-pipe arranged in the driving tube is closed off at its bottom end by means of a steel cap. A position hold 3,5 tons in weight serves to prevent the equipment from being laterally displaced at working level during the vibrating operation (Fig. 1).

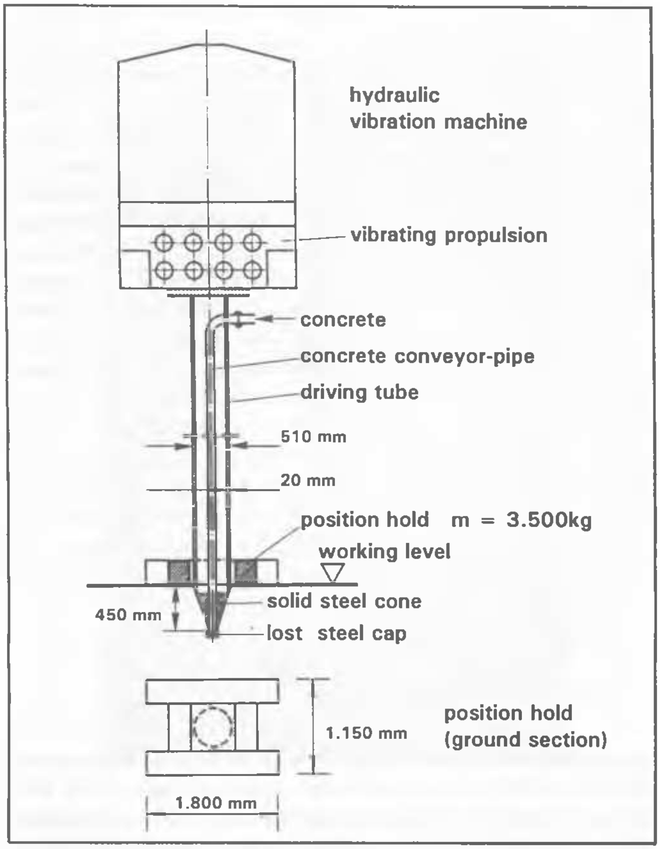

Figure 1 Vibratory Equipment for Fabrication of Concrete Vibration Piles (Preussag System)

Figure 2. View of the Complete Equipment Unit

The driving tube is vibrated into the ground down to load-bearing soil. When the bearing floor of the concrete vibration piles has been reached the soil in the pile footing area is compacted by briefly lifting and lowering the vibrating tool several times. During this operation the operating pressure of the hydraulic unit ranges between 200 and 250 bar. Subsequently, the concrete conveyor-pipe is filled with concrete.

For pile foot construction concrete of class K 2 (plastic concrete) and a strength class of at least B 25 according to DIN 1045 is injected intermittently at high pressure ($\geq$ 5 bar, determined at the concrete pump). After this, the pile shaft is made by withdrawing the vibrating tool while concrete is continued to be pumped. To increase skin friction vibratory action is also used in the pile shaft area provided the shear strength of the soil is sufficient. Throughout the entire pile fabrication process the concrete pressure and the power absorption of the vibratory equipment is monitored. This shall ensure that the mean pile diameter at least coincides with that of the driving tube. To check this as early as during pile fabrication the amount of concrete used can be compared to and must be greater than the theoretical volume of the driving tube.

The Preussag concrete vibration pile system described above meets applicable legislation needs and has been approved by building supervision authorities in the Federal Republic of Germany. Application necessities linked with this approval such as areas of use and bearing behaviour are discussed below.

3 FUNDAMENTAL TESTING

3.1 INTRODUCTORY NOTE

The use of the concrete vibration piles is being limited to subsoil conditions which has an undrained shear strength of not less than c_u = 15 kN/m². These soil-mechanical as well as process-related (geometric) and concrete-specific requirements and obligations were to be investigated and checked by performing fundamental tests.

3.2 TEST CRITERIA — SCOPE OF TESTS

Fundamental testing was to be conducted on 4 concrete vibration piles the minimum diameters of which were 510 mm and minimum length 5,0 m. The subsoil should contain a reference soil type having an undrained shear strength of c_u < 25 kN/m², and the concrete strength should be that of a B 25 concrete according to DIN 1045.

3.3 RESULTS OF SOIL-MECHANICAL TESTS

To be able to investigate the subsoil conditions soil-mechanical tests were performed both in the field and laboratory.

According to the tests the natural ground strata of the reference soil in the test area consisted of fine-sandy, clayey, partly highly organic silts, which could also be regarded as sapropel, all deposited under loosely to densely packed fillings of dirt material, building debris, silt and mineral aggregate. Below this marl has been found. The thickness of the filled soil is approximately 4.0 m while the natural silt layers underneath are at least 4.0 m thick (see Fig. 6).

The grain size analyses performed (Fig. 3) show that the reference soil consists of coarse silts with a sand content ranging between 7 and 22 % by mass and a clay content of approx. 10 to 15 % by mass. The organics content (loss on ignition) ranges between 2 and 14 % dry basis.

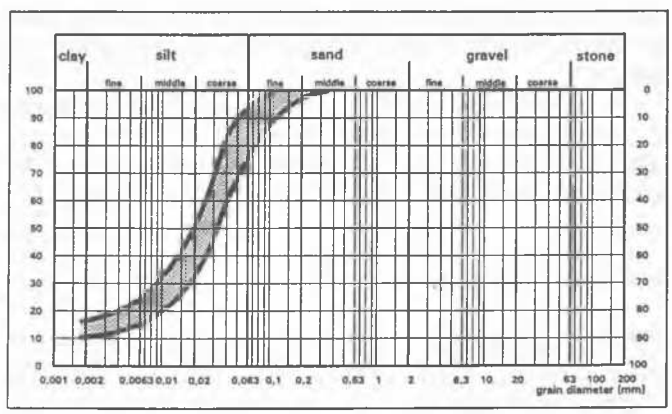

Figure 3. Granulometric Composition of the Reference Soil: Coarse Silts, Fine-Sandy, Clayey, Organics Content Low to High

Moreover, tests were conducted to determine the density, water content, consistency limits and shear strength characteristics. A compilation of all soil-mechanical test results has been given in Fig. 4. In addition, Fig. 5 shows the undrained shear strength c_u as a function of the water content w.

The undrained shear strength values c_u detected sometimes fall short of and partly exceed the required value of c_u = 25 kN/m². The consistency index of $I_C \leq 0,75$ determined for the reference soil are indicative of a soft and occasionally pasty condition. The prescribed soil-mechanical requirements and conditions for implementation of fundamental testing have thus been fulfilled.

concrete vibration pile	labor No.	density		organic content	consistency limits		natural water content	plasticity and consistency index		undrained shear strength c_u [kN/m²]		
		ρ_s [t/m³]	ρ_d [t/m³]	V_{gl} [%]	w_L [%]	w_P [%]	w_N [%]	I_P [%]	I_C [/]	vane test	direct shears test	unconfinded compression test
1	5561	2,39	1,28	13,80	46,51	28,66	36,77	17,85	0,546	20,6	21,7	-
1	5562	-	1,17	-	-	-	47,15	-	-	28,5	-	-
2	5563	-	1,56	-	-	-	27,50	-	-	32,3	-	-
2	5564	2,64	1,67	1,65	28,67	19,41	22,15	9,26	0,704	25,3	(10,6)	-
2	5565	2,64	1,63	1,31	-	-	22,80	-	-	36,4	(24,1)	-
3	5566	2,46	1,40	9,39	-	-	31,15	-	-	22,4	22,9	-
3	5568	-	1,56	-	-	-	25,75	-	-	25,2	-	-
3	5570	-	1,52	-	-	-	27,45	-	-	21,4	-	-
4	5571	2,43	1,56	11,41	34,96	21,92	32,77	13,04	0,168	27,8	24,4	-
4	5572	-	1,53	-	-	-	27,00	-	-	32,9	-	-
4	5573	2,48	1,31	8,80	42,05	26,92	31,53	15,13	0,695	17,8	17,6	-
4	5574	-	-	8,97	-	-	-	-	-	23,9	-	35,8
4	5575	-	1,38	-	-	-	32,10	-	-	20,7	-	-

Figure 4. Compilation of All Soil-Mechanical Test Results of the Reference Soil

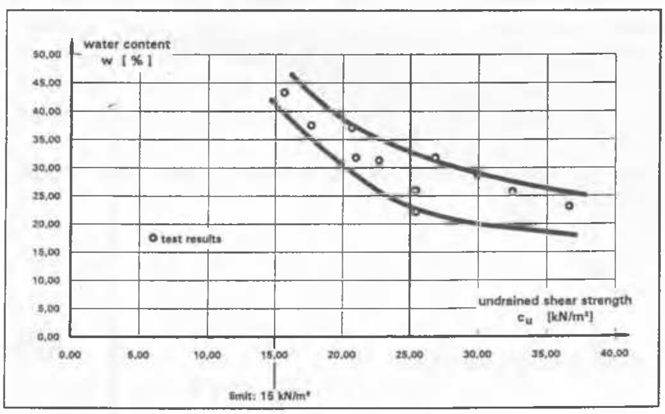

Figure 5. Connection Between the Undrained Shear Strength c_u and the Water Content w (Results of Direct Shear Tests)

3.4 PROCESS-RELATED TEST RESULTS

The process-related parameters were primarily checked by measuring the geometrical quantities (diameter, length of piles, concrete volume etc.) and characteristics relating to process operation (concrete pressure, vibrator rating etc.). Only the measurements of the geometrical quantities shall be introduced and elucidated on the following pages. It is to be noted, however, that the operation-related characteristics were found to satisfy the specific needs of the process.

The records of the concrete consumption during the fabrication of the concrete vibration piles showed distinctly higher cubic quantities than could be expected theoretically from the dimensions of the driving tube.

After completion of pile fabrication the piles were exposed and measurements taken. Fig. 6 shows the respective pile cross sections over the pile length together with the relevant subsoil characteristics. Fig. 7 is the photo of a pile after recovery.

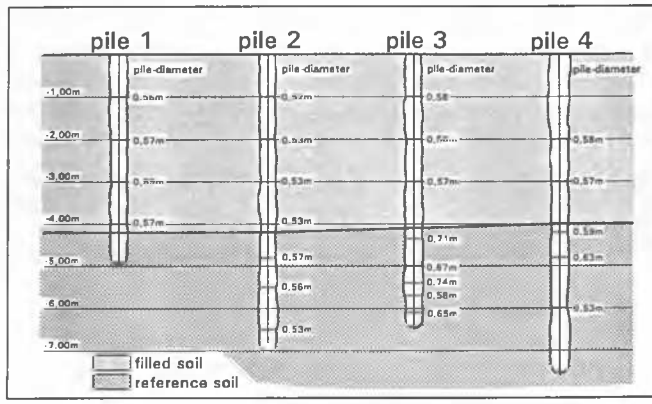

Figure 6. Cross Sectional Dimensions of Piles over the Pile Length Including Subsoil Characteristics

Figure 7. Recovery of a Test Pile

Voids and neckdown of the pile cross section were not detected. The pile diameter over the entire pile length is clearly greater than that of the driving tube. In soil areas where low shear strength properties prevailed (c_u less than 25 kN/m²) the pile cross section widened out up to a diameter of 740 mm (pile 3). Therefore, the process-specific requirements and provisions have also been met.

3.5 CONCRETE-TECHNOLOGICAL TEST RESULTS

A concrete of strength class B 25 according to DIN 1045 was used. In the interest of good pumping characteristics the following mix was prescribed:

Cement:	400 kg HOZ 35 L
Aggregate:	Gravel-sand, grading curve AB 16 (favourable range)
Water-cement ratio:	W/Z = 0,47
Consistency range:	K 2 - 3
Slump:	41 - 43 cm

To be able to cope with operational failures which might occur during the provision of the concrete vibration piles a retarding agent was added to the concrete to ensure its workability for a period of three hours. The ready-mix concrete supplier furnished evidence as to the correct composition of the mix. While the concrete vibration piles were made the slump of each concrete batch supplied was determined and two series of test cubes prepared.

After the four concrete vibration piles had been exposed a visual inspection showed a continuous transition between the concrete and the soil solidified and adhering due to the action of cement slurry. Apparent voids in the concrete were not found. Regarding the cross sectional dimensions generally exceeding the theoretical diameter of 51 cm details can be seen from Fig. 5.

From the recovered pile shafts four sections were cut from which two drill core samples (100 mm in diameter) each were taken with total lengths ranging between 530 and 650 mm.

A visual inspection showed that the concrete had a flawless structure. Voids, pore clusters or rock pockets could not be detected. To carry out strength tests three specimens (h = 100 mm) were cut from the drill cores and suitably ground to achieve even and plane-parallel end faces.

By taking the drill core samples vertically to the longitudinal axis of the piles and preparing three specimens per drill core it was possible to obtain information about the strength of the concrete in radial direction of the vibration pile.

The bulk density and compressive strength of the 24 specimens were determined. The concrete strength value determined on one drill core (d = 100 mm, h/d = 1,0) is equal to the compressive cube strength. The test results have been summarized in Table 1.

Table 1. Concrete-Technological Test Results

pile	specimens number	bulk density $\bar{\rho}$ [t/m³]	compressive strength $\bar{\beta}_C \hat{=} \bar{\beta}_W$ [N/mm²]	variation coefficient v [%]
1	6	2,32	55,4	3,6
2	6	2,31	54,3	6,2
3	6	2,33	54,4	9,9
4	6	2,33	56,5	9,4

In a statistical evaluation the average and the variation coefficient of the established compressive strength values were determined for each pile section and for all of the test specimens. The arithmetic mean of all specimens indicates an average compressive strength of $\bar{\beta}_C$ = 55,2 N/mm² at a standard deviation of 4 N/mm²; on this basis the variation coefficient is calculated at 7,4 %. The mean bulk density has been determined to be 2,32 t/m³ with the standard deviation being 0,02 t/m³. The variation coefficient amounts to v = 0,8 %.

From these values it can be concluded that there was a uniform concrete quality over the entire cross section. Additionally, the fractile value was calculated to be $\beta_{C5\%}$ = 45,5 N/mm². Judging from the above indicated characteristics the concrete used for the piles can be grouped in strength class B 45.

All concrete-technological requirements have thus been fulfilled.

4 BEARING BEHAVIOUR

Both the internal and the external bearing capacity has to be determined for the non-reinforced concrete vibration pile. While the internal pile bearing capacity is exclusively determined by the compressive and shear strength of the pile concrete used the bearing behaviour of the piles is primarily governed by the shear strength and compressibility of the subsoil.

When determining the internal pile bearing capacity the admissible compressive pile force of a centrically loaded concrete vibration pile is

$$R_{di} = {}^{1}/_{\gamma} \cdot A_b \cdot \beta_R$$

when using the commonly employed concrete of strength class B 25 (calculated compressive strength value of the concrete amounts to β_R = 17,5 MN/m²).

For the minimum pile diameter of d = 510 mm as indicated above and a safety factor of γ = 2,5 (non-reinforced concrete) a permissible compressive pile force of R_{di} = 1.430 kN is thus obtained. According to the concrete-technological tests performed (cf. chapter 3.5) the compressive strength of the concrete was $\beta_{C5\%}$ = 45,5 MN/m². From this value a permissible compressive pile force of R_{di} = 3.710 kN could even be derived.

The determination of the external pile bearing capacity has been effected by carrying out loading tests in situ. In the meantime, numerous measuring results from such loading tests performed in different types of soil are available. The results are indicated in detail in Fig. 8.

According to the above, the pile bearing capacity limits were not always reached. The design value is R_{da} = 600 kN at a safety factor of γ = 2,0 against failure. The associated settlement values amounting to s = 1 to 10 mm are of minor degree and are typical of the bearing behaviour of displacement piles.

For comparison, the design values pertaining to the bearing capacity of bored piles of identical diameters are of roughly the same magnitude or just slightly higher. However, the associated settlement figures of s = 10 to 20 mm are significantly higher.

5 OUTLOOK

It is this favourable bearing behaviour that makes the concrete vibration pile an interesting, economically efficient, and innovative foundation element. Even larger pile cross sections are attainable when more powerful hydraulic vibration machines are employed. Considering the more and more stringent provision minimizing building settlement specifications this pile system is an advantageous and future-oriented type of foundation under technical as well as economic aspects. Aside from this, it is also an effective settlement retarder when incorporated into combined pile-raft foundation systems.

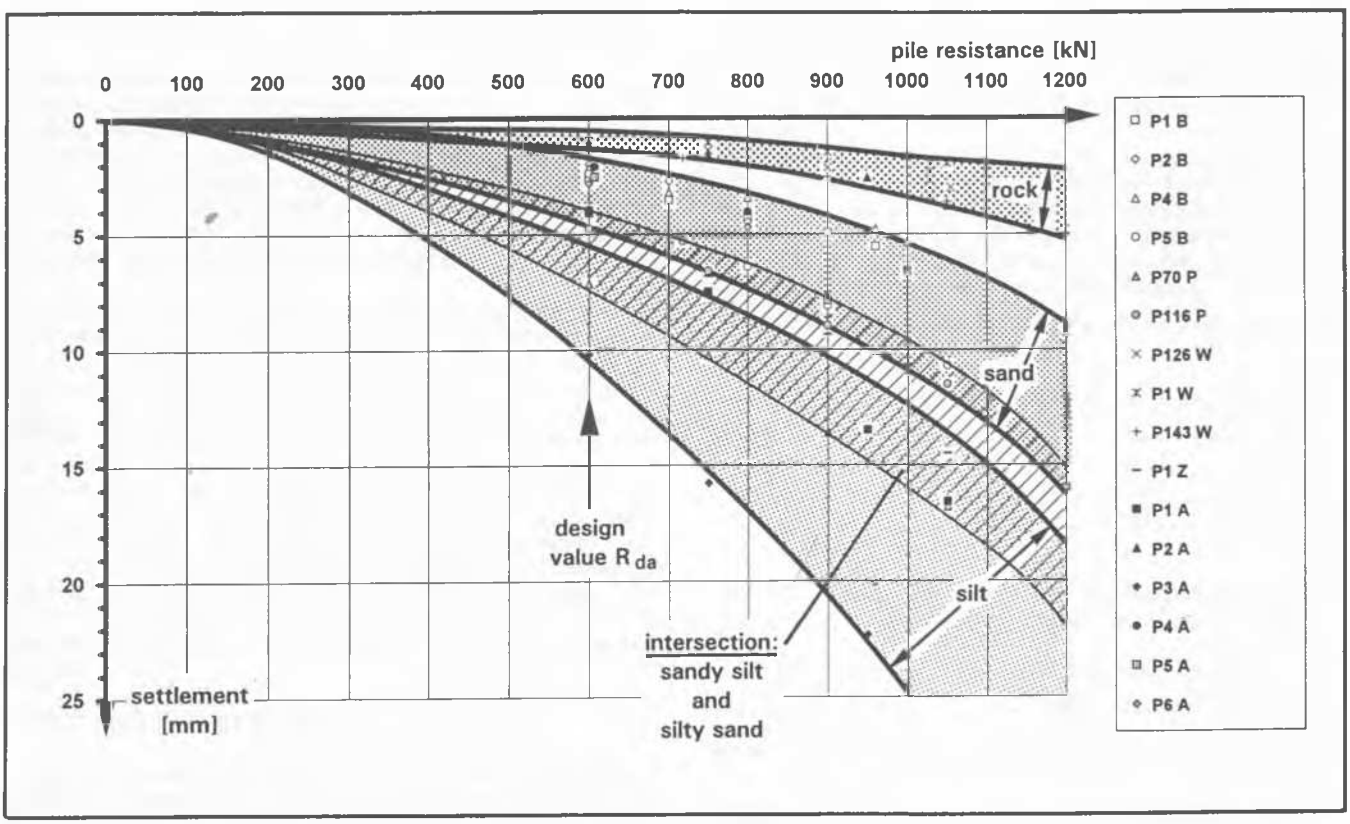

Figure 8. Working Curves of the Concrete Vibration Piles Tested in Various Types of Subsoil (Subsoil Conditions in the Pile Footing Area)