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Investigations of material discharge caused by groundwater flow during the installation of bored piles

Investigations sur le déversement de matériaux causé par l'écoulement des eaux souterraines lors de l'installation de pieux forés

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ABSTRACT: Bored piles are often installed below the groundwater level. During installation, it has to be ensured that groundwater flow does not lead to a reduction of the pile integrity from pouring until the concrete has stiffened. The European Standard EN 1536, the German Recommendations on Piling "EA-Pfähle" (2013) and international guidelines refer to possible problems resulting from groundwater flow. However, no information is given as to which groundwater flow velocity is critical in which ground. In order to be able to estimate the risk of cement particle removal or redistribution, model piles were installed with the tremie method at the University of Wuppertal in a joint research project. These piles were exposed to several water flow velocities during installation. The created flow velocities were substantially higher than the groundwater flow velocities which occur in field. In a first series of tests, the focus was on test piles made of tremie concrete which were placed in sandy soils. In a second series of tests, a variation of concrete mix design and surrounding soil was performed to obtain a more general statement. In summary, it could be shown that no critical flow velocity could be reached which lead to a "washing-out effect" of cement on the pile surface within the scope of both series of tests.

RÉSUMÉ: Les pieux forés sont souvent installés sous le niveau de la nappe. Lors de l'exécution, il faut s'assurer que l'écoulement des eaux souterraines ne remette pas en cause l'intégrité du pieu, à partir du bétonnage et jusqu' à la prise du béton. La norme européenne EN 1536, les recommandations allemandes sur les pieux "EA-Pfähle" (2013) et les recommandations internationales font référence aux problèmes possibles résultant de l'écoulement des eaux souterraines. Cependant, aucune information n'est donnée quant à la vitesse d'écoulement de la nappe phréatique qui est critique dans chaque terrain. Afin de pouvoir estimer le risque d'arrachement ou de redistribution des particules de ciment, des pieux tests bétonnés au tube plongeur ont été installés à l'université de Wuppertal, dans le cadre d'un projet de recherche partenariale. Ces pieux ont été exposés à plusieurs vitesses d'écoulement de l'eau pendant leur exécution. Les vitesses d'écoulement imposées étaient considérablement plus élevées que les vitesses d'écoulement des eaux souterraines observées in situ. Dans une première série de tests, l'accent a été mis sur les pieux d'essai bétonnés au tube plongeur, qui ont été réalisés dans des sols sableux. Dans une deuxième série de tests, des compositions du béton a été étudiée, dans des sols également différents, pour obtenir une analyse plus générale. En conclusion, il a pu être montré qu'aucune vitesse d'écoulement critique pouvant entraîner un "effet de lavage" du ciment à la surface du pieu lors des deux séries de tests n'a pu être atteinte.

Keywords: Bored piles; groundwater flow.

1 INTRODUCTION

Bored piles (EN 1536) are used in a variety of applications and often extend below the groundwater table. Below the groundwater table, they are produced by using the tremie method with temporary casing or with support fluid (e.g. EFFC/DFI Concrete Task Group, 2018). In international standards and recommendations, it is pointed out that high groundwater flow velocities can lead to erosion of particles from the fresh concrete. As a result, the cement particles may be redistributed or removed from the freshly concreted pile.

The European Standard covering bored piles EN 1536:2010 points out that special attention must be paid to groundwater flow. Accordingly, groundwater flow can lead to a "washing-out" effect and reliable protection is advised, e.g., by permanent casing or lining. Related guidance can be found in other international standards and recommendations as:

- Finland: "Instructions for drilled Piling - Design and Execution Guide" (FINNRA, 2003)
- Germany: Recommendations on Piling "EA-Pfähle" (2013)
- United States of America: "Drilled Shafts: Construction Procedures and Design Methods" (Brown et al., 2018)
- Europe: Displacement piles (EN 12699: 2015).

There is consensus in all standards and recommendations that there is a potential risk of discharge of cement particles by groundwater flow. However, there are no limits given for a critical flow rate, neither could scientific studies be found which address this subject.

In 2012, laboratory tests were carried out on jet columns with cement paste at the University of Wuppertal (Department of Geotechnical Engineering). It could be shown that high groundwater flow can lead to a removal of cement paste which changes the shape and size of jet columns (Drzewiecki, 2012). However, the results cannot be transferred one-to-one to concrete piles, so further tests were carried out.

2 IMPLEMENTATION OF THE EXPERIMENTAL STUDY

2.1 Experimental set up

A test set up was designed at the University of Wuppertal for a systematic investigation of the influence of groundwater flow on bored piles (Fierenkothen et al., 2020). This set up enables the investigation of different groundwater flow velocities and different methods for the execution of bored piles such as borehole support by casing or by support fluid. The dimensions of the test set up are shown in Figure 1.

A temporary casing with an external diameter of 219.1 mm was used for the construction of the model piles. For technical reasons, it was necessary to install the casing first. Afterwards, the sand was placed under water in layers and compacted. For the construction of model piles with excavation supported by support fluid, the suspension was first placed under the protection of the temporary casing. Before concreting, the casing was pulled except for a small part that remained as lead-in tube and the borehole was left under fluid support for 30 min.

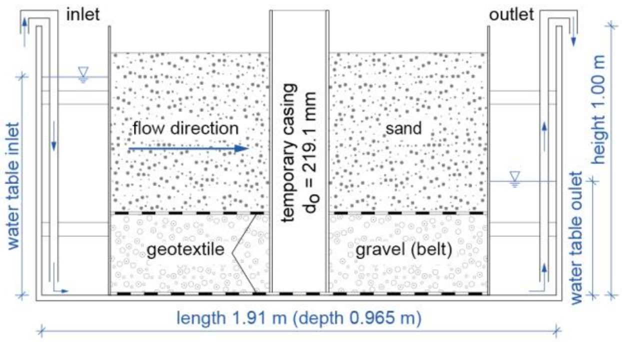

Figure 1. Test set up for the test with gravel belt, before concrete placement.

A pump circuit ensured a continuous flow through the experimental box. Inlet, outlet and flow direction are shown in Figure 1. For an evaluation of potential cement erosion at the pile cubature due to flow, the cured piles were recovered, visually inspected, and measured.

2.2 Experimental boundary conditions

Flow velocity, soils and concrete mixtures were varied in two series of tests. In the first series of tests, the filter velocity and the support of the borehole wall were investigated in particular. Two different sands were used as surrounding ground. The second series of tests focussed on the influence of the concrete mixture and a more coarse-grained soil as surrounding soil. The test stand allows for medium gravel as an upper limit. An overview of all tests and selected boundary conditions is given in Table 1.

Narrowly graded soils were investigated as surrounding ground, as these have a high permeability. In addition, they have a lower filter stability towards cement paste than wide-graded soils. For the second test series with gravel as surrounding soil, the challenge was to create a flow velocity as high as possible in the experimental box. This was achieved by arranging a gravel belt.

The grain size distributions of the three soils tested are shown in Figure 2. The estimation of the permeability coefficients was carried out according to Darcy and Beyer & Schweiger.

Table 1. Matrix of the physical model experiments.

soil		**concrete / suspension mix design**				**support**	**filter velocity v_f**
type	k_f	max. grain size	distribution	fly ash	plasticiser		in m/day
sand1	$k_{f,1}$	(cement paste)	-	yes	-	TL	100
		8 mm	B8	yes	p1	SF	120
			B8	yes	p1	TL	15 / 115 / 150
		16 mm	B16	yes	p1	TL	145
sand2	$k_{f,2}$	(cement paste)	-	yes	-	SF/TL	280/290
		2 mm	-	no	-	TL	435
		8 mm	B8	yes	p1	SF	380
			B8	yes	p1	TL	65 / 350 / 700
		16 mm	B16	yes	p1	TL	670
			A16	yes	p1	TL	280 / 295
gravel (belt)	$k_{f,3}$	2 mm	-	no	-	TL	1310 / 1540
		8mm	B8	yes	p1	TL	>> 846
			B8	no	p1 / p2	TL	1445 / 1320
			C8	no	p1	TL	1355
		16 mm	B16	yes	p1	TL	1365
			B16	no	p1/p2	TL	1330 / 1335
		32 mm	A32	no	p1	TL	1380
			B32	yes	p1	TL	1285
			B32	no	p1 / p2	TL	1575 / 1350

Explanation of abbreviations:

- $k_{f,1}$, $k_{f,2}$, $k_{f,3}$: permeability coefficients of the soils tested;
- distribution: grain size distribution as standardised in the German National Annex DIN 1045-2 to EN 206-1;
- p1, p2: different types of superplasticiser used for the concrete mixture;
- SF: support fluid;
- TL: temporary casing.

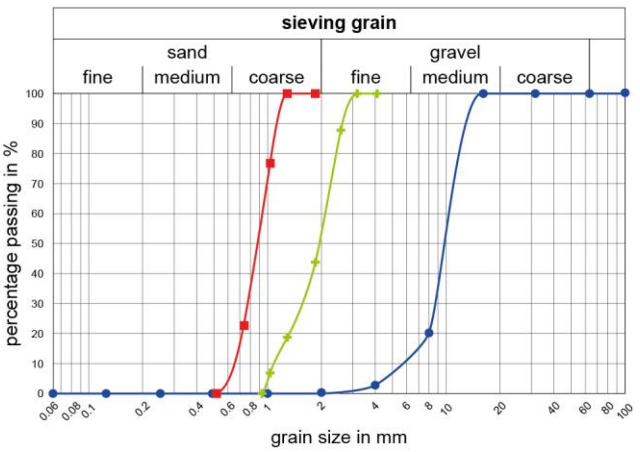

Figure 2. Grain size distribution of the surrounding soils. red = sand1, green = sand2 and blue = gravel (belt).

This results in the following permeability coefficients for the investigated soils:

- sand1: $k_{f,1} \sim 4 \cdot 10^{-3}$ m/s
- sand2: $k_{f,2} \sim 1 \cdot 10^{-2}$ m/s
- gravel: $k_{f,3} \sim 4 \cdot 10^{-1}$ m/s.

Different filter velocities were investigated. The filter velocity (v_f) is calculated as the ratio of the flow rate to the cross-sectional area of the groundwater flow at the location of the model pile. Depending on the soil and the flow velocity, different phreatic lines occur between inflow and outflow. As a result, only the lower part of the piles are exposed to groundwater flow (Figure 3 and Figure 4).

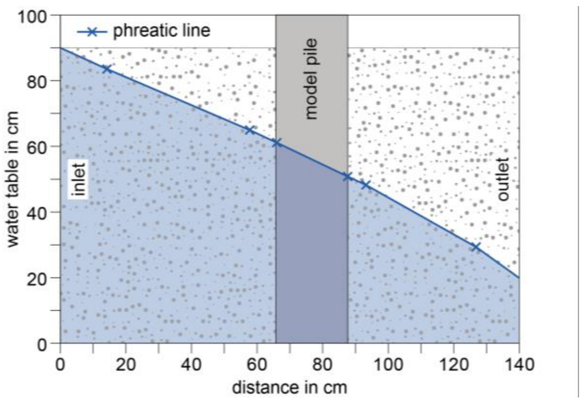

Figure 3. Exemplary phreatic line of the sands with representation of the level measurement points for sand1 with v_f = 120 m/d, according to Fierenkothen et al., 2022.

The mix design for the concrete consists of water, cement (CEM III/B 42,5), fly ash, aggregate and superplasticiser. In order to exclude the possibility of a different result when using a particle size distribution with a drop-out grain size or other admixtures, the grain size distribution and the admixtures were also varied in the concrete mixture.

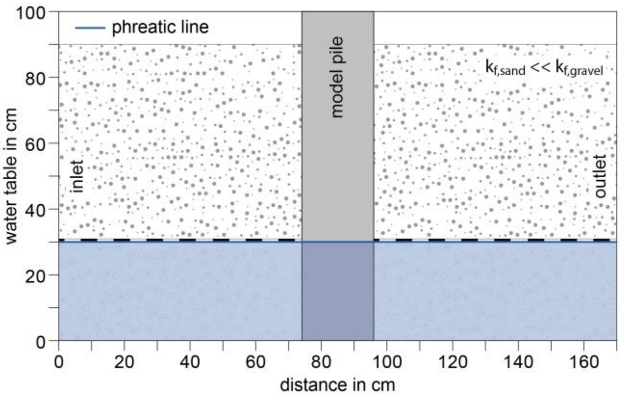

Figure 4. Exemplary phreatic line for the gravel belt.

Fly ash and superplasticizer have a strong influence on the consistency and stability of fresh concrete. Since the mode of action of the superplasticizer depends on the type of superplasticizer, a second type was used for the investigation. Superplasticiser p1 is based on a polycarboxylate ether and superplasticiser p2 is based on melamine/naphthalene sulphonate. In order to investigate the influence of fly ash, mix designs with and without fly ash were examined.

In addition, model piles were made using cement paste and mortar.

3 RESULTS

3.1 Bored pile excavation supported by casing

The cast in situ concrete model piles with temporary casing in both sand and gravel showed no visible anomalies in the contour after uncovering (Figure 5). Likewise, no visual anomalies could be observed on the cured and excavated model piles after pile installation in gravel (belt), regardless of the concrete mix.

For all cast-in-place concrete model piles with temporary casing, no critical flow velocity could be achieved which lead to anomalies. It was not possible to determine significant differences in pile diameter in and across the flow direction. Even though the flow velocities examined were often significantly higher than those occurring in practice (Table 1).

In contrast the model piles made of pure cement paste (in sand1 and sand2), clearly showed redistribution of the cement particles (Figure 6). The redistributions were significantly greater in the model pile with the higher flow velocity in sand2.

The cement particles have deposited as a plume in the shadow area of the model piles. The investigations showed that the strength of the deposits decreased with increasing distance from the pile.


a) b) c)

Figure 5. Contour of cast in situ model piles with temporary casing and max. grain size 8 mm: a) sand1: v_f = 115 m/d; b) sand2: v_f = 700 m/d (Fierenkothen et al., 2020); c) gravel (belt): v_f = 1445 m/d.


Figure 6. Exposed cement/sand plume of the model pile from cement suspension in sand2: v_f = 290 m/day (Fierenkothen et al., 2020).

3.2 Bored pile excavation supported by fluid

While a redistribution of cement particles was observed on the model piles made of cement paste with excavation supported by casing, in contrast, with support fluid (bentonite slurry), no discharge of the cement particle could be detected (Figure 7c).

Similarly, no visible discharge of cement particles was detected on the model piles made of concrete in sand with support fluid. During production, the support fluid was able to penetrate approx. 5 cm into the soil – except for the area of the lead-in tube at the pile head (Figure 8). A filter cake was formed due to penetration of the support fluid into the soil. No visual removal or displacement of penetratet support fluid resulting from groundwater flow could be detected.

a) b) c)

Figure 7. Contour of model piles constructed under support fluid: a) sand1: concrete with max. grain size 8 mm, v_f = 120 m/d; b) sand2: concrete with max. grain size 8 mm, v_f = 380 m/d; c) sand2: cement paste, v_f = 280 m/d (Fierenkothen et al., 2022).

a) b)

Figure 8. Penetration of the support fluid into the soil for sand2: cement paste, v_f = 280 m/d (Fierenkothen et al., 2022).

The model piles could be produced without anomalies in the contour due to the protection of the filter cake of the support fluid. It has been shown that the filter cake forms a protective layer against the discharge of cement particle.

All tests with the gravel belt with concrete as pile material and temporary casing showed no visual discharge of cement particles of the concrete. Therefore, concreting under support fluid was not further investigated.

4 CONCLUSIONS AND FUTURE PERSPECTIVES

During the investigations which were carried out in this study, no visible discharge of cement particles could be detected for the cast in situ concrete piles with excavation supported by casing or by support fluid. The investigated flow velocities were significantly higher than those generally observed in nature.

During the tests with cement paste (supported by casing), cement particles were redistributed into the surrounding soil. The production under support fluid prevented discharge. The filter cake of the suspension support forms a protective layer against an influence from groundwater flow.

The restrictions from standards and recommendations could not be confirmed for cast in situ concrete piles in sand and medium gravel. The contours of the piles did not show any changes. Additional investigations of the hardened concrete properties of the model piles are planned. In particular, it should be investigated whether there has been a change in the structure and strength of concrete in the edge area of the piles.

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