Lehrstuhl und Prüfamt für Grundbau, Bodenmechanik, Felsmechanik und Tunnelbau

Technische Universität München – Zentrum Geotechnik

Application of polymeric supporting fluids for the construction of bored piles and diaphragm walls

– Summary –

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1   Introduction

The construction of bored piles and diaphragm walls in unstable ground conditions requires a temporary support of the borehole or trench. A convenient procedure for this purpose is the hydraulic support by means of a supporting fluid. As such, bentonite suspensions have been successfully used for a long time (WEIß, 1967; WALZ, 1989; TRIANTAFYLLIDIS, 2004). Particularly in the USA and in Asia, but also increasingly in European countries (outside Germany), polymeric supporting fluids have been used for several years (MAJANO / O´NEILL, 1993; BROWN ET AL., 2002; BUSTAMANTE / BOATO, 2005; HEIZMANN ET AL., 2008).

Polymers consist of macromolecules whose molecular structure can be characterized by a repeated sequence of certain structural units (BENEDIX, 2003). Biopolymers, semi-synthetic polymers (manufactured by conversion of natural macromolecules) and fully synthetic polymers can be distinguished according to their manufacturing. Polymeric supporting fluids are colloidal solutions, i.e. the solute particles (polymer molecules) are much larger than the solvent particles (water molecules). These solutions are prepared on site or in the laboratory by mixing the polymers which are delivered as powder, granulate, emulsion or in aqueous solution with water. The fact that the viscosity of polymer solutions depends on the shear rate can be explained by an increasing parallel alignment of the rigid polymer chains at higher shear rates, so that the inner resistance against the shear deformation is reduced (SORBIE, 1991 and STEINHOFF, 1993).

The main difference between polymeric supporting fluids and bentonite suspensions with regard to the supporting behaviour is that polymeric supporting fluids normally show a very small or no yield strength and consequently their penetration into the ground would theoretically never stop. The design concept according to German standard DIN 4126 (1986 and draft standard of 2004, respectively) for the support using bentonite suspensions (stability analyses regarding failure mechanisms of single grains and of sliding surfaces after an infinite period of time) is not applicable without extensions, since in no case stability could be proved. STEINHOFF (1993) therefore deduced a time-dependent stability analysis based on the fact that hydraulic support also results from the dynamic shear stresses (flow induced mass forces) applied on the particle matrix. This support, however, is reduced the longer the borehole or trench is kept open due to the fact that the proportion of the support force which is applied within a critical soil block (failure mechanism regarding sliding surfaces) and the hydraulic gradient (failure mechanism regarding single grains) decrease with the advancing penetration of the supporting fluid. A fundamental requirement for this type of stability analysis is an adequate comprehension of the flow behaviour of the supporting fluid.

The main advantages of the application of polymer solutions are a simplified construction process and – at least outside Germany – lower disposal costs. Polymer solutions neither require high-speed mixing nor time to swell and as a consequence of the non-existent yield strength normally not even a separation plant, but only sedimentation basins. The reduced space requirements are of particular benefit for inner-city site installations. Lower disposal costs have frequently been quoted in non-German publications, since the relevant polymers are usually considered eco-toxicologically safe. Whether this advantage will also take effect in Germany is yet to be seen. In any case, an

advantage of polymeric supporting fluids in comparison with bentonite suspensions is the higher consistency of the excavated soil, which is more favourable with regard to disposal.

The indicated advantages may also result in economic benefits despite relatively high material costs for the polymers. A detailed profitability study had to consider numerous factors, such as costs for site installation compared to production costs, costs for transportation, energy, disposal, etc. The huge number of reference projects outside Germany where polymers were favoured even though bentonite had been available, at least indicates the existence of economic incentives.

STEINHOFF (1993), however, has so far published the only research in the field of civil engineering investigating in detail the penetration of the polymer solutions into the ground. Other research projects focussed, for instance, on the load-bearing capacity of piles constructed under polymeric supporting fluids (MAJANO / O´NEILL, 1993) or the sedimentation properties of soil particles in supporting fluids (KHENG, 1989) and dealt only qualitatively and marginally with the supporting effect. In practice the dimensioning of the construction method had to be based on experience only (often depending on manufacturer´s data) or trial trenches or trial boreholes needed to be executed in advance of a project. Up to now, polymer solutions virtually have not been used for the construction of bored piles and diaphragm walls in Germany.

In the course of the research project the knowledge of the method and the applicability depending on present boundary conditions should be improved and documented to facilitate the planning and a safe and responsible application in practice. To achieve this, the theoretical background was investigated and numerical simulations as well as laboratory and field tests were conducted. The laboratory tests aimed exclusively at the rheological properties, the flow behaviour und the supporting effect of polymeric supporting fluids, while the field tests should additionally answer questions (or reveal new ones) regarding execution issues. The field tests included the construction of 6 full-scale test piles. Load tests were performed after hardening of the piles and subsequently the piles were excavated near surface.

The eligible polymer products for the application investigated here have already been used in Germany as additives for bentonite suspensions or in their pure form for other applications (e.g. well drilling or hydro shield tunnelling). Nevertheless a verification of environmental compatibility was demanded for their application for the construction of bored piles and diaphragm walls. For this reason the environmentally relevant aspects of the construction method were exposed and discussed with technical authorities. In addition, eco-toxicological tests were initiated and the impact on the groundwater during and after the construction of the bored piles was examined by means of a monitoring programme within the scope of the field tests.

2   Theoretical background

The theoretical part of the research report presents an overview of scientific approaches to the flow behaviour of non-Newtonian fluids in porous media. Descriptions of porous media flows based on rheological models for the regarded polymer solutions, equations for capillary flow of such solutions and the combination of these equations with pore space models are demonstrated.

Table 2.1 shows the most important rheological models in this context and the related equations for capillary flow (e.g. SORBIE, 1991; BALHOFF, 2005 or CHHABRA, 2007).

Table 2.1: Rheological models and related equations for capillary flow

Model	Viscosity function	Flow through a capillary
Newton	$\eta(\dot{\gamma}) = \text{constant}$	$q = \dfrac{\pi \cdot \Delta p \cdot R^4}{8 \cdot \eta \cdot l}$
Ostwald-de Waele (or „power law")	$\eta(\dot{\gamma}) = K \cdot \dot{\gamma}^{m-1}$	$q = \dfrac{\pi \cdot m \cdot R^{(3 \cdot m + 1)/m}}{3 \cdot m + 1} \cdot \left(\dfrac{\Delta p}{2 \cdot K \cdot l} \right)^{1/m}$
Ellis	$\eta(\dot{\gamma}) = \dfrac{\eta_0}{1 + \left(\dfrac{\tau(\dot{\gamma})}{\tau_{1/2}} \right)^{\alpha-1}} = \dfrac{\eta_0}{1 + \left(\dfrac{\dot{\gamma} \cdot \eta(\dot{\gamma})}{\tau_{1/2}} \right)^{\alpha-1}}$	$q = \dfrac{\pi \cdot R^4 \cdot \Delta p}{8 \cdot \eta_0 \cdot l} \cdot \left[1 + \dfrac{4}{\alpha+3} \left(\dfrac{\Delta p \cdot R}{2 \cdot \tau_{1/2} \cdot l} \right)^{\alpha-1} \right]$
Herschel-Bulkley	$\eta(\dot{\gamma}) = \dfrac{\tau_H}{\dot{\gamma}} + K_H \cdot \dot{\gamma}^{m_H - 1}$ when $\tau > \tau_H$ $\eta \to \infty$ when $\tau < \tau_H$	$q = \dfrac{\pi \cdot R^3}{K_H^{1/m_H} \cdot \tau_W^3} \cdot (\tau_W - \tau_H)^{\frac{1}{m_H}+1}$ $\cdot \left[\dfrac{(\tau_W - \tau_H)^2}{\dfrac{1}{m_H}+3} + \dfrac{2 \cdot \tau_H \cdot (\tau_W - \tau_H)}{\dfrac{1}{m_H}+2} + \dfrac{\tau_H^2}{\dfrac{1}{m_H}+1} \right]$ with $\tau_W = \dfrac{\Delta p \cdot R}{2 \cdot l}$ (wall shear stress)

In the simplest case a pore space model consists of N straight capillaries of constant radius R (model (a) in Figure 2.1). Postulating the same pore volume and permeability k (with reference to Newtonian fluids) for the model and the represented porous medium, N and R can be derived uniquely (with γ_W = specific weight and η_W = viscosity of water at 10 °C):

$$R = \sqrt{\frac{8 \cdot \eta_W \cdot k}{n \cdot \gamma_W}} \quad \text{and} \quad N = \frac{n \cdot A}{\pi \cdot R^2} = \frac{n^2 \cdot \gamma_W}{8 \cdot \pi \cdot \eta_W \cdot k} \cdot A$$
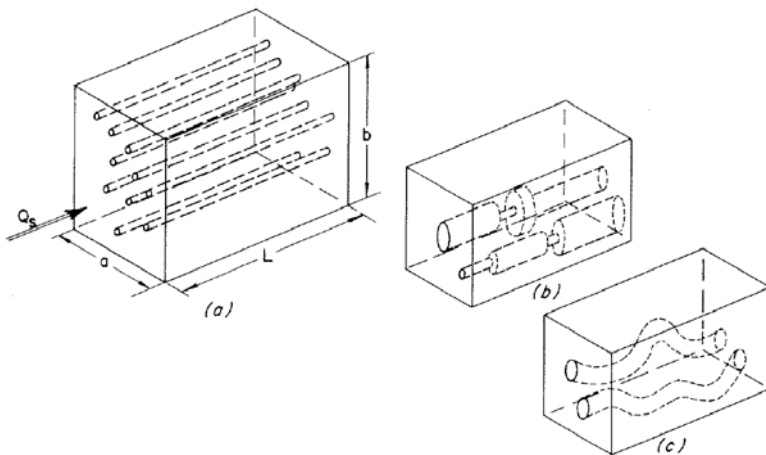
Figure 2.1: Examples of pore space models as capillary bundle models after BEAR (1988)

This pore space model may be developed further in many ways. Some authors suggest to arrange one third of the capillaries in each Cartesian coordinate direction to implement permeability in all directions. The pore volume of the pore space model and the porous medium are still kept equal. For the modified system of equations R_{3D} and N_{3D} can be determined:

$$R_{3D} = \sqrt{\frac{24 \cdot \eta_W \cdot k}{n \cdot \gamma_W}} \quad \text{and} \quad N_{3D} = \frac{1/3 \cdot n \cdot A}{\pi \cdot R_{3D}^2} = \frac{n^2 \cdot \gamma_W}{72 \cdot \pi \cdot \eta_W \cdot k} \cdot A$$

If this pore space model is applied for an Ostwald-de Waele (power law) fluid, an analytical solution for the penetration length l as a function of time t is obtained. The basic idea of the derivation is that the fluid volume of an incompressible fluid which passes through a cross-section area A within a time increment dt must be equal to the pore volume filled within this increment. The flow rate of the fluid through the cross-section area is the product of the flow rate through a single capillary and the number N_{3D} of capillaries perpendicular to this cross-section. The potential difference (i.e. the difference between the potential head of the supporting fluid in the trench and that at the end of the actual penetration length) is assumed constant. The pore volume can be calculated from the porosity n of the soil, flow cross-section area A and penetration length increment dl.

$$l = \left(\frac{(m+1) \cdot n \cdot \gamma_W \cdot R_{3D}^{(3 \cdot m+1)/m}}{72 \cdot \eta_W \cdot k \cdot (3 \cdot m+1)} \cdot \left(\frac{\Delta u \cdot \gamma_F}{2 \cdot K} \right)^{1/m} \cdot t \right)^{\frac{m}{m+1}} \quad \text{with} \quad R_{3D} = \sqrt{\frac{24 \cdot \eta_W \cdot k}{n \cdot \gamma_W}}$$

For alternative rheological models analogue derivations are possibly far more complex or an analytical solution does not even exist. Instead the penetration length at a given time can be obtained via numerical integration.

In the report the influence of the selected pore space model on the relation between potential gradient and flow velocity is questioned and exemplarily quantified with a model of two types of capillaries differing in radius. Any number of such pore space models may be defined, which cause identical flow velocities (as function of the potential gradient) when applied to Newtonian fluids but differing results when applied to non-Newtonian fluids. A definition of complex pore space models aiming to gain a more general validity though requires more parameters than just permeability and porosity of the soil. In practice these parameters had to be deduced from the grain size distribution or provided as empirical values. For this reason the simple pore space model already chosen by STEINHOFF with uniform straight capillaries is regarded more target-directed for the investigated application.

The report also touches further problems, e.g. the influence of a variable polymer concentration along the penetration length due to adsorption or interaction with groundwater or the influence of unsaturated conditions in case of a polymer penetration above the groundwater level. Of particular importance is the permeability reduction along the penetration length due to filtration of soil particles which have been previously released by the drilling action. An appropriate approach to include filtration in the above models of the penetration mechanism has yet to be developed.
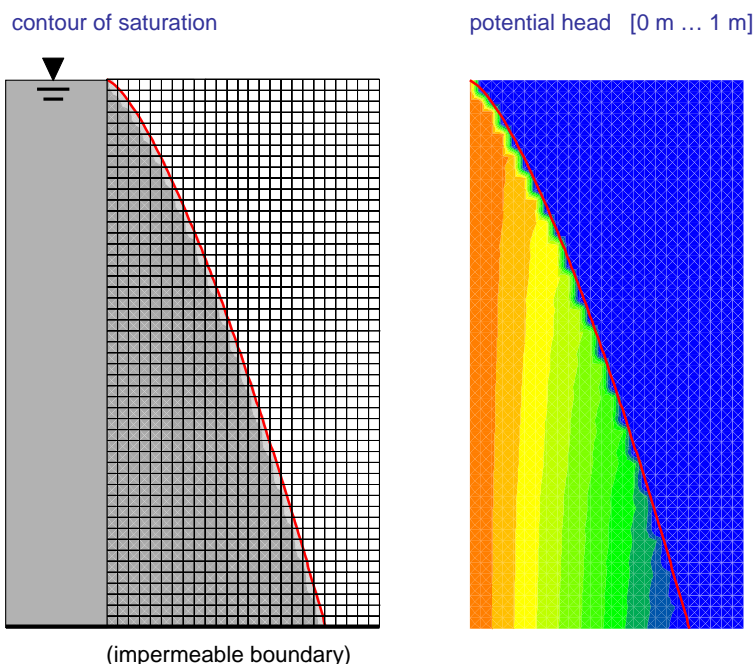
Polymer solution (m = 0.4), isotropic permeability

contour of saturation   potential head   [0 m … 1 m]

(impermeable boundary)

Figure 2.2: FLAC^{3D} model and analytical solution (red curve)

Moreover, it is demonstrated in the report how the flow of non-Newtonian fluids can be implemented in a Finite Differences software for geotechnical calculations (here: FLAC^{3D}, version 3.1 of Itasca Consulting Group, Inc., USA) utilising the "apparent viscosity". The numerical model was verified by analytical calculations both for one-dimensional flow and for radially symmetric conditions. The results revealed that vertical flow components were negligible for pseudoplastic support-

ing fluids. Therefore numerical models offer no substantial advantage over analytical calculations with regard to the calculation of penetration lengths. The input files included in the appendices of the report allow the use and further development of the presented models (e.g. implementation of alternative rheological models or coupling of flow calculations and stability analyses).

3   Laboratory tests

In laboratory tests the rheological properties and the flow behaviour of polymer solutions were investigated in particular. In the tests four customary polymer products were used, three of them provided by the German company Süd-Chemie AG and the last one by the US American company KB International LLC (Table 3.1).

Table 3.1: Tested products

Material	Product name
polyacrylamide (anionic)	SC MUD P
carboxymethyl cellulose	SC VIS HV P
xanthan gum	SC X GUM
vinyl polymer	KB SlurryShield FGP

In anticipation of the groundwater monitoring programme for the field tests a simple procedure had to be found to determine the concentration of a polymer solution. Measurements of the TOC (total organic carbon) of sample solutions confirmed, as expected, a linear dependence of this parameter on the polymer concentration.

In a series of rheological tests the effects of polymer concentration, mixing-water, mixing conditions and temperature were quantified. Based on the results of viscosimeter measurements parameters of rheological models were determined as well by means of regression. Figure 3.1 shows:

- Fitting to Newton model (straight)
- Fitting to Ostwald-de Waele model (exponential curves through origin)
- Fitting to Herschel-Bulkley model (exponential curves with positive value on vertical axis)

The fitting curves attest good approximations to the measured data in a shear rate interval between 7 s^{-1} and 381 s^{-1} (measuring range of the viscosimeter) both for the Ostwald-de Waele model and the Herschel-Bulkley model. For shear rates < 7 s^{-1} – which are important for the 1D flow tests – uncertainties remain.
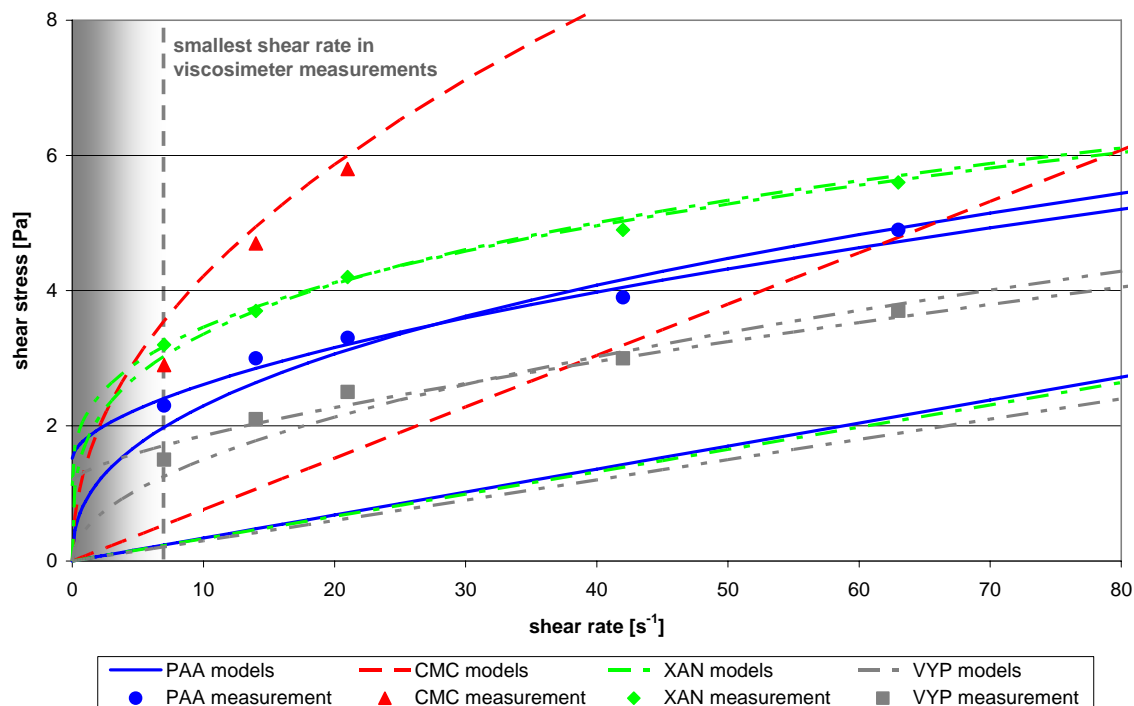
Figure 3.1: Flow curves of fitted models

The focus within the laboratory tests was on 1D flow tests (Figure 3.2) which were intended to measure the time-dependent penetration of polymer solutions into a soil column. With the chosen experimental set-up and uniform sands as test soils (grain sizes of 0.1 – 0.5 mm, 0.6 – 1.2 mm and 1.0 – 2.5 mm) test results with low scattering could be achieved with three out of the four polymer products (Figure 3.3). The polymer products and polymer concentrations as well as the test sands and the predefined potential head difference were varied in the test series. The measured penetration curves were recalculated based on the Ostwald-de Waele model (power law model). The model parameters had been previously deduced from viscosimeter measurements by regression. An evaluation on the base of alternative models like the Ellis model or the Herschel-Bulkley model would have been possible as well using the equations given in Table 2.1. However, the viscosimeter measurements show no indication of a rheological behaviour corresponding to these models within the range of examined shear rates.

Relatively large deviations between the penetration curves measured in 1D flow tests and the recalculated ones were observed (cf. for example Figure 3.4). Possible causes may have been in particular the simplification of the real pore space by the chosen pore space model and the discrepancy between the range of shear rates examined with the viscosimeter measurements and the range of shear rates relevant in the test soil column. On the contrary, very good predictions could be obtained by the use of model parameters that have been derived by fitting of the recalculated penetration curves to the measured curves („in situ parameter"), if they were adopted for different test sands or potential head differences (Figure 3.5). Finally, the potential head variation over the penetration length was measured during the flow tests to investigate the effect of a possible poly-

mer membrane as it is described by some polymer manufacturers. One of the tested polymer products showed a distinct non-linear potential head variation in some tests. This could be regarded as an indication of an existing membrane. Then again, the potential head variation was almost linear in other tests with the same product. With a second product only a slight tendency of a non-linear potential head variation was observed. Therefore a final conclusion could not be drawn.
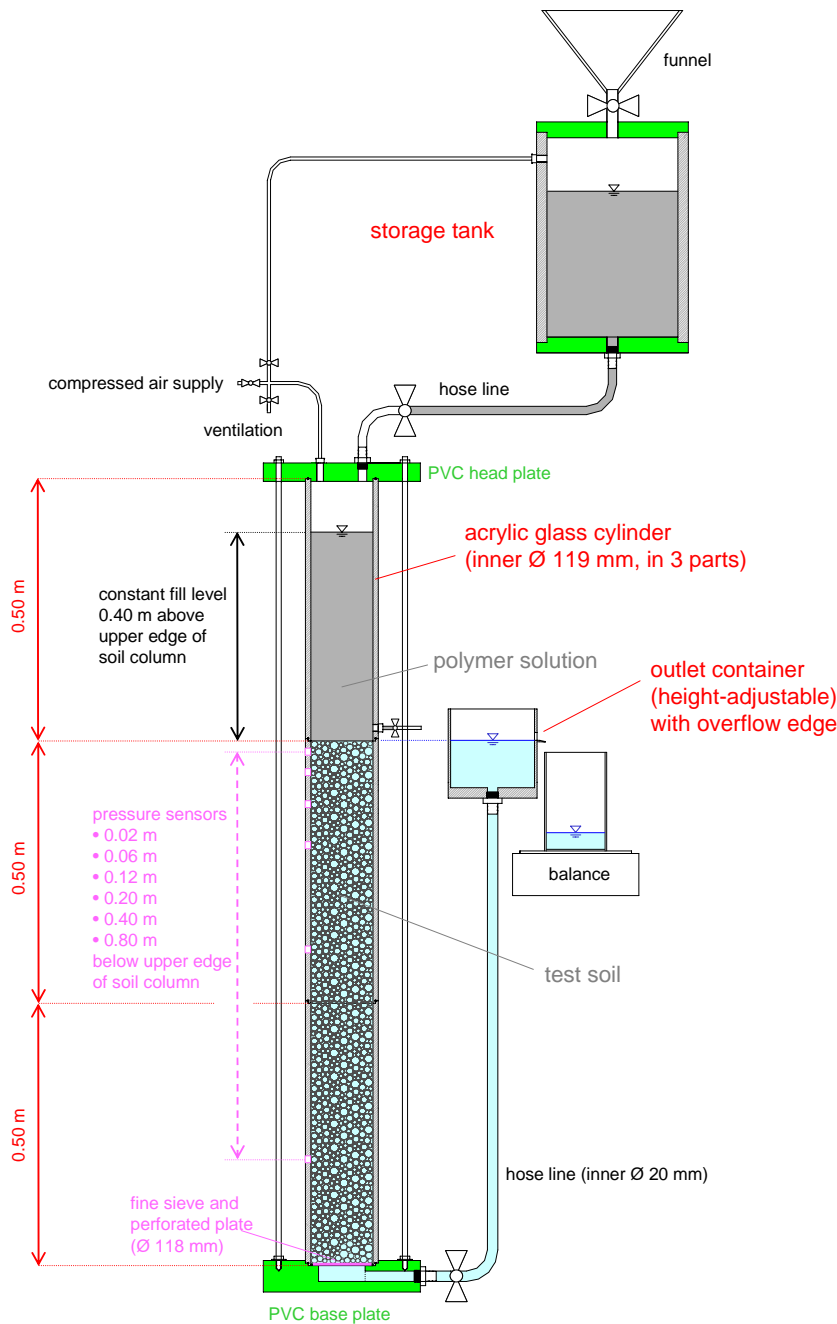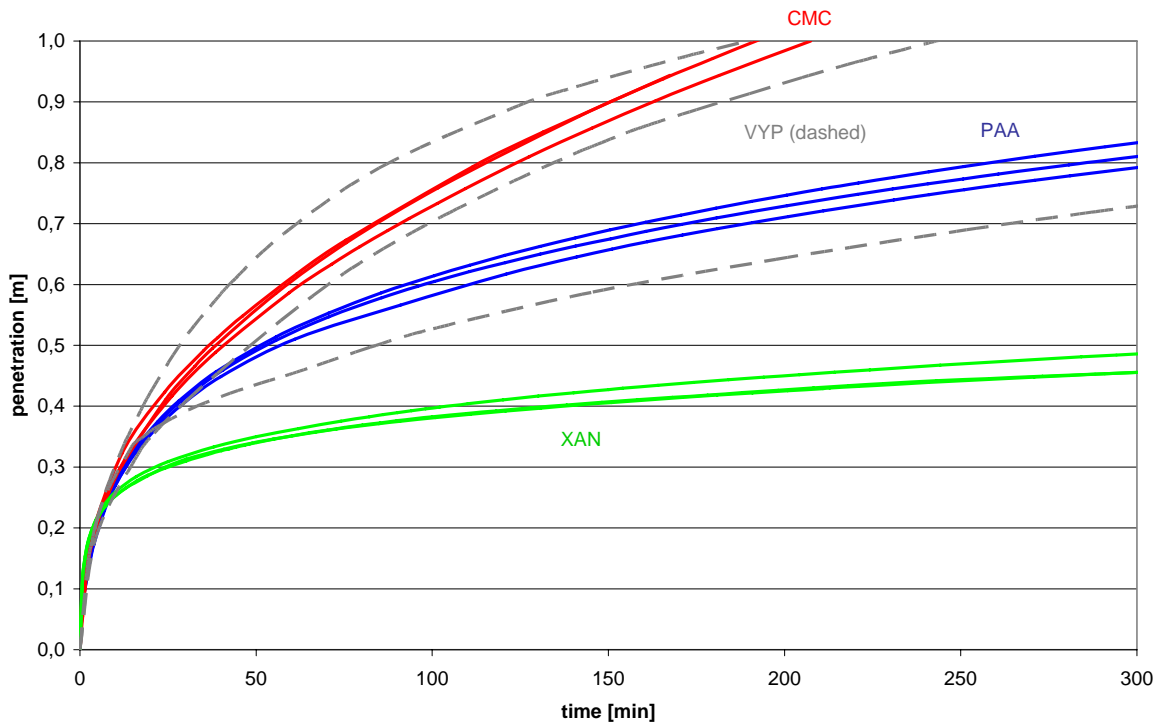

Figure 3.2: Sketch of test rig for 1D flow tests

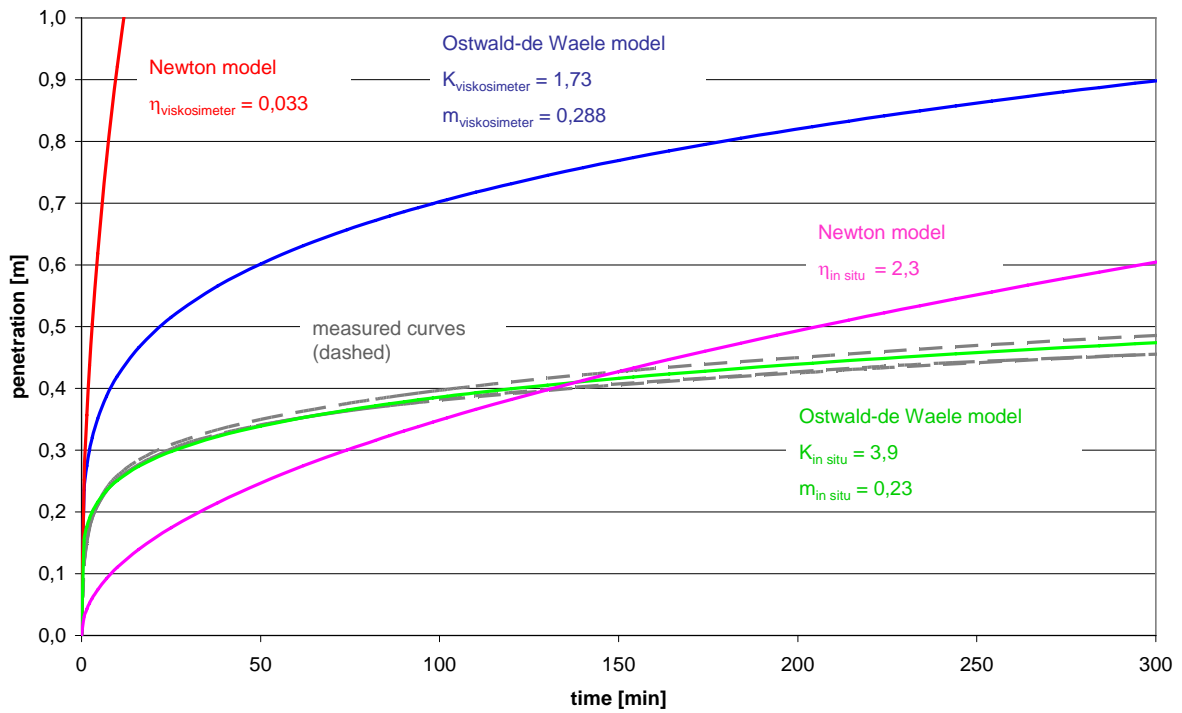**Figure 3.3: Penetration under standard conditions**

Figure 3.4: Penetration of XAN (model calculation and curve-fitting)
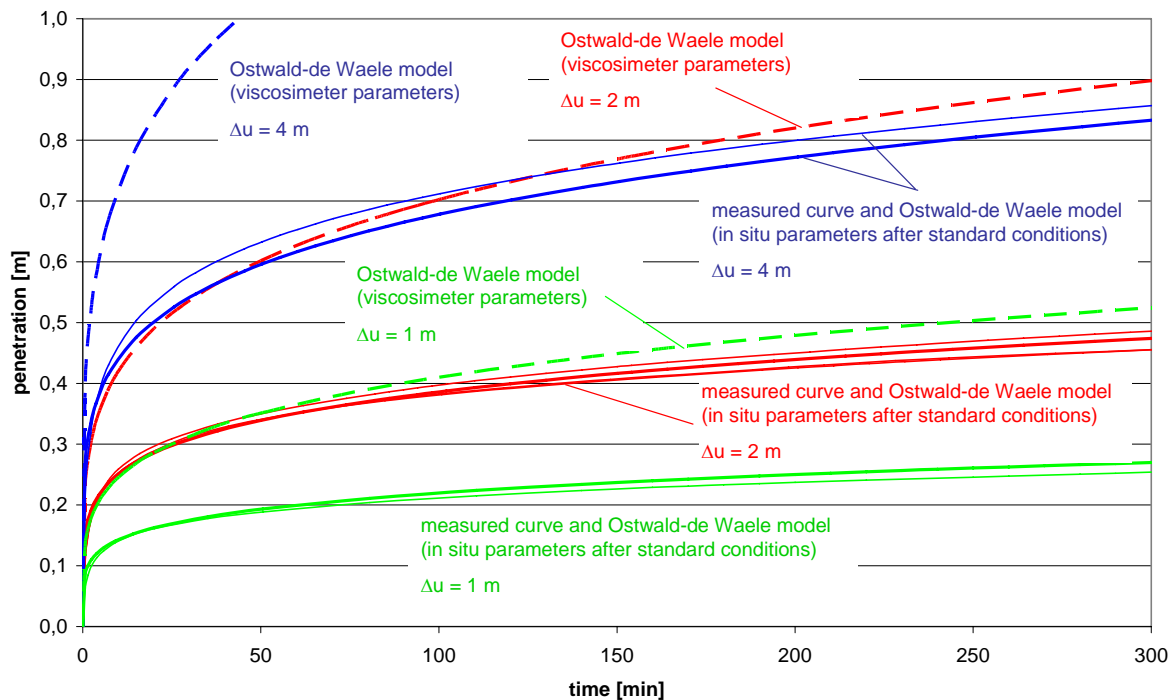
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Figure 3.5: Penetration of XAN, variation of potential head difference

Additional laboratory tests were carried out with a model trench to investigate penetration behaviour in a 2D system as well as the time-dependent loss of hydraulic support by the polymer solutions. Model calculations with in situ parameters from 1D flow tests could predict both penetration progress and duration until loss of stability of the trench relatively well. This test is nevertheless rated as a rather illustrative test. For quantitative investigations the 1D flow test is more appropriate, since test conditions can be defined more flexibly (potential head difference, saturated or unsaturated conditions) and penetration progress as well as potential head variation can be measured more precisely and more easily.

4   Field tests

Within the framework of the field tests in total six piles were constructed, load tested and later excavated near surface. The boreholes of five piles were supported with polymer solutions while in one case a bentonite suspension was used for comparative purposes (Figure 4.1 and Table 4.1). The field tests demonstrated in particular the general applicability of the method even in coarse-grained, highly permeable soils (cf. subsurface profile in Figure 4.2).

The rheological properties of the polymer solutions mixed on site were not as good as those of equivalent solutions mixed under laboratory conditions. (This fact could have been compensated with a somewhat higher concentration if needed.) The observed losses of support fluid during ex-

cavation of the boreholes under hydraulic support were lower than expected according to predictive calculations (cf. Figure 4.3). These calculations were performed using the Ostwald-de Waele model. The model parameters had been previously deduced from additional 1D flow tests with soil material from the groundwater wells (in situ parameters), so that a best possible prediction accuracy could be expected. The lower measured losses in the tests were attributed mainly to the favourable effect of filtration into the borehole wall of soil particles which were enclosed in the supporting fluids.
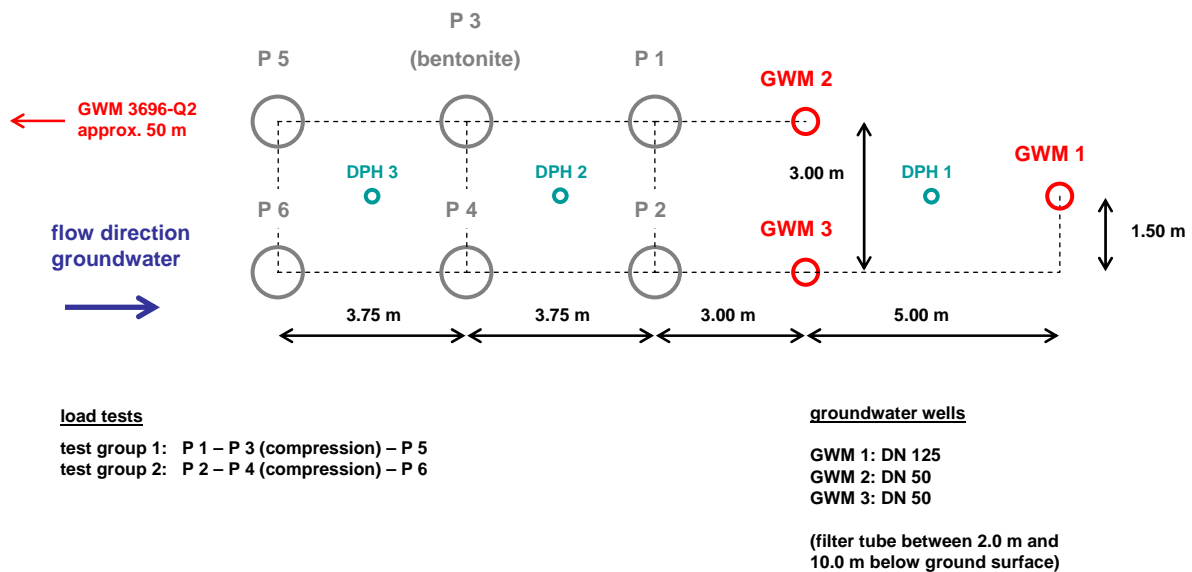

Figure 4.1: Site plan of field tests

Table 4.1: Overview of test piles

Pile name	P 1	P 2	P 3	P 4	P 5	P 6
date of construchtion	MO, 30-Mar	TU, 31-Mar	MO, 06-Apr	WE, 01-Apr	TU, 07-Apr	TH, 02-Apr
type of pile	tension	tension	com-pression	com-pression	tension	tension
product	PAA	PAA	bentonite (Tixoton)	XAN	CMC	XAN
concentration	6 g/l	2 g/l	50 g/l	2 g/l	4 g/l	4 g/l
groundwater	approx. 2.0 m below ground level					

Excessive fall-out of soil particles from the borehole walls or actual stability problems were not observed during construction of any of the boreholes and could neither be detected in ultrasonic borehole logs with a KODEN drilling monitor. Both boreholes constructed with xanthan gum as supporting fluid could not be measured with this device in the upper borehole sections, probably due to the high content of trapped air bubbles.
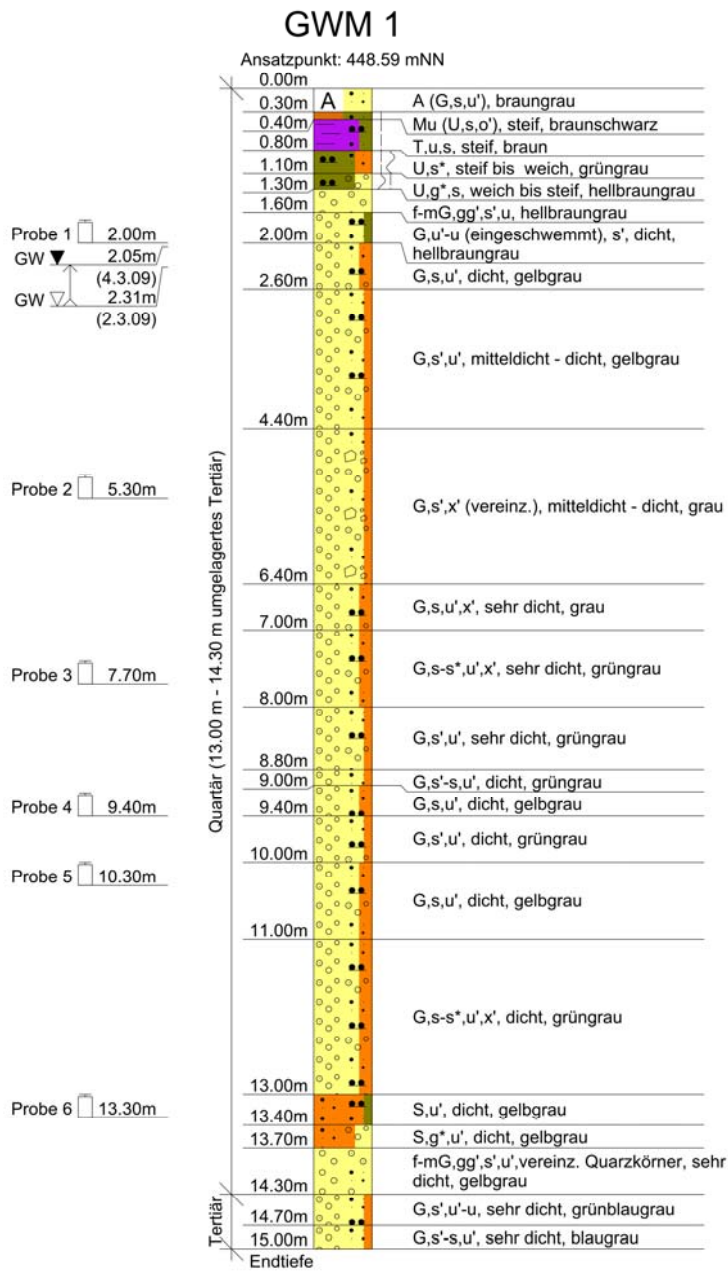
GWM 1

Ansatzpunkt: 448.59 mNN

Depth	Description
0.00m	
0.30m	A (G,s,u'), braungrau
0.40m	Mu (U,s,o'), steif, braunschwarz
0.80m	T,u,s, steif, braun
1.10m	U,s*, steif bis weich, grüngrau
1.30m	U,g*,s, weich bis steif, hellbraungrau
1.60m	f-mG,gg',s',u, hellbraungrau
2.00m	G,u'-u (eingeschwemmt), s', dicht, hellbraungrau
2.60m	G,s,u', dicht, gelbgrau
4.40m	G,s',u', mitteldicht - dicht, gelbgrau
6.40m	G,s',x' (vereinz.), mitteldicht - dicht, grau
7.00m	G,s,u',x', sehr dicht, grau
8.00m	G,s-s*,u',x', sehr dicht, grüngrau
8.80m	G,s',u', sehr dicht, grüngrau
9.00m	G,s'-s,u', dicht, grüngrau
9.40m	G,s,u', dicht, gelbgrau
10.00m	G,s',u', dicht, grüngrau
11.00m	G,s,u', dicht, gelbgrau
13.00m	G,s-s*,u',x', dicht, grüngrau
13.40m	S,u', dicht, gelbgrau
13.70m	S,g*,u', dicht, gelbgrau
14.30m	f-mG,gg',s',u',vereinz. Quarzkörner, sehr dicht, gelbgrau
14.70m	G,s',u'-u, sehr dicht, grünblaugrau
15.00m	G,s'-s,u', sehr dicht, blaugrau
Endtiefe	

Probe 1 2.00m
GW ▼ 2.05m
(4.3.09)
GW ▽ 2.31m
(2.3.09)

Probe 2 5.30m

Probe 3 7.70m

Probe 4 9.40m

Probe 5 10.30m

Probe 6 13.30m

Quartär (13.00 m - 14.30 m umgelagertes Tertiär)

Tertiär

Figure 4.2: Subsurface profile in GWM 1

Unexpected problems appeared during concrete placement of the first pile (P 1), which could only be successfully completed in the third attempt and after the polymer solution in the borehole had been replaced by water. A causal relation with the highly dosed polyacrylamide solution used at this borehole is not unlikely. Concrete placement of the remaining boreholes could be carried out normally.

In general, the load tests demonstrated high load-bearing capacities of the test piles. Comparing the two compression piles, pile P 3 constructed under bentonite suspension exhibited a somewhat better load-bearing behaviour than pile P 4 which had been constructed under polymeric supporting

fluid. However, pile P 4 had a structural defect between pile shaft and enlarged pile head, which probably was not related to the hydraulic support. For both piles the proportion of the pile base resistance was significantly low compared to the shaft resistance even at the maximum applied force. The ultimate load-bearing capacity was obviously not reached. The tension piles, which had all been constructed using polymeric support, showed a relatively consistent load-bearing capacity.
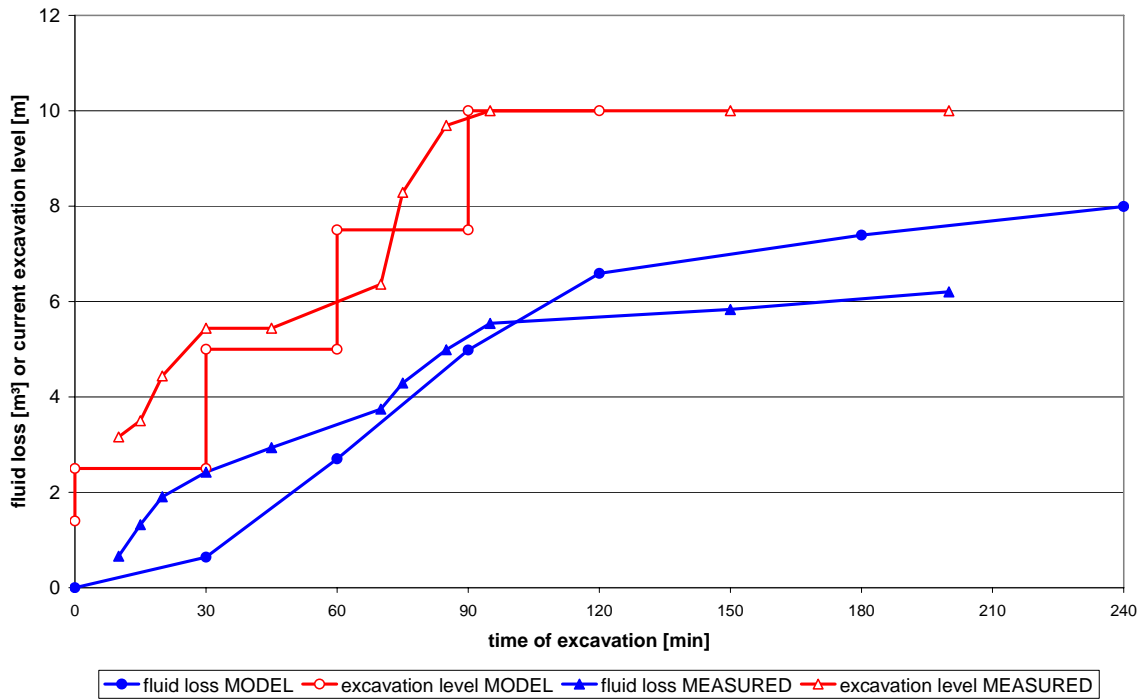

Figure 4.3: Measured and predicted fluid loss for pile P 4

Figure 4.4: Photos of pile P 3 (bentonite) and pile P 5 (polymer)

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The piles were excavated up to approximately 2 m below ground surface. The exposed piles were of good quality (except for the structural defect at pile P 4 as indicated earlier) with only minor enlargements and very good contact with the surrounding soil (Figure 4.4). Only directly at the shaft of pile P 1 very rare remains of polymer solution could be found.

5   Stability check

In a separate chapter of the report a possible mathematical procedure for pre-dimensioning based on the results of this research work is explained. After the penetration of the supporting fluid within a defined maximum excavation time for the borehole or trench is calculated (and later verified on site if possible) according to the equations of the theory chapter, stability analyses can be continued basically in an analogous way as in German standard DIN 4126. Some method-specific characteristics of these analyses are considered in the report. This includes, for instance, the non-linear potential head curve over the penetration length in case of a borehole (cf. Figure 5.1 with potential head curves of Ostwald-de Waele fluids with varying exponents m and 1.0 m of penetration from a borehole of 0.6 m diameter) or the generally more complex (compared to bentonite support) determination of the effective supporting force.
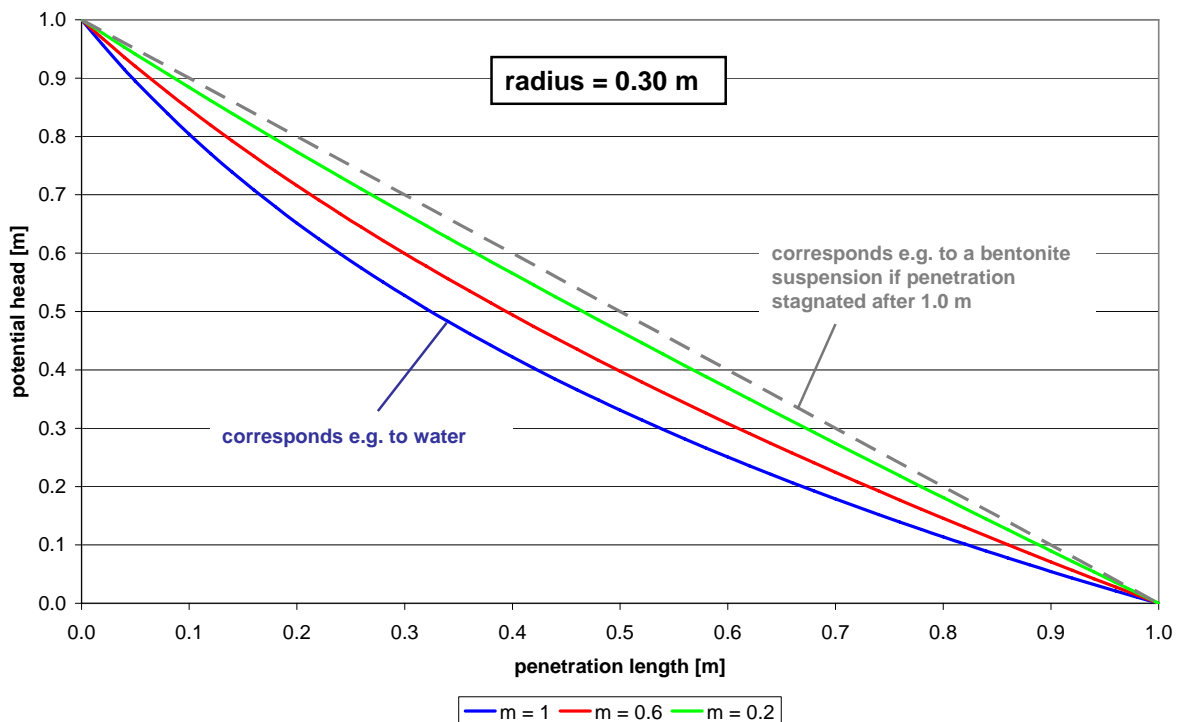

Figure 5.1: Influence of exponent m on the potential head curve in the case of radial symmetry

6   Environmental aspects

Another chapter of the report contains the investigations regarding environmental compatibility. In particular, preliminary considerations regarding the conditions for approval of water authorities for the field tests and the groundwater monitoring programme within the framework of these tests are presented. The monitoring programme consisted of the following measures:

- detailed registration of supporting fluid losses for each borehole (fluid volume and concentration)
- groundwater sampling in three downstream groundwater wells in direct vicinity of the piles and in an upstream reference groundwater well
- excavation of the piles to the section below the casing and inspection for possible remains of polymer solution around the piles

In water samples from the groundwater wells downstream of the test boreholes (cf. site plan in Figure 4.1) the measured TOC values (Figure 6.1) were only temporarily and marginally increased (compared to typical values of pure polymer solutions). Furthermore, the oxygen content in these water samples was significantly lower.
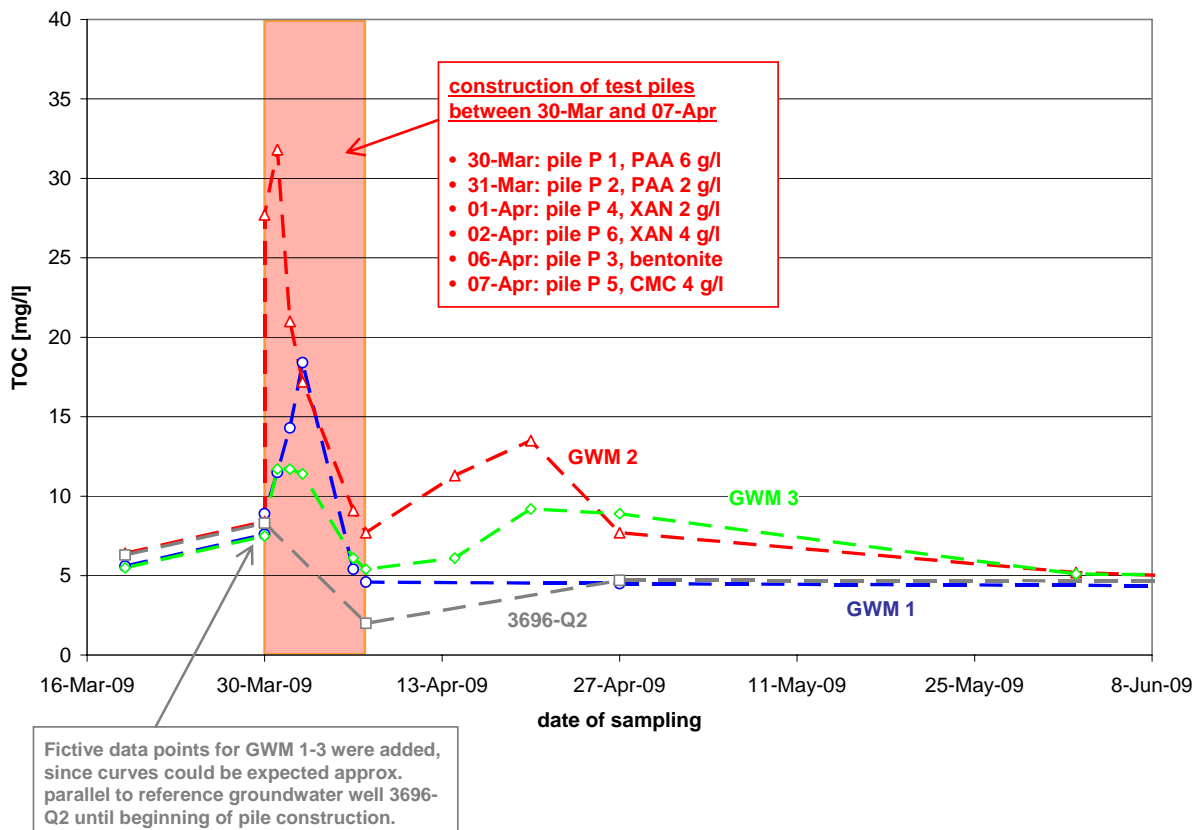

Figure 6.1: Measured TOC in groundwater samples

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7   Outlook

Future investigations should focus on the potential effects that the polymeric supporting fluids may have on concrete quality and bonding between rebar and concrete. Additionally, for the realisation of upcoming projects a standardised and binding concept for the evaluation of environmental issues would be exceedingly helpful. For this, the preliminary considerations in the report (which have been stipulated with the Deutsches Institut für Bautechnik, DIBt) in conjunction with the results of the groundwater monitoring programme can provide a basis.

From a soil mechanic point of view a detailed investigation of the permeability reduction near the borehole wall caused by filtration or if applicable by a polymer membrane and the deduction of an analytical model considering these effects would be interesting. For this problem the rheological properties of the supporting fluid, soil properties and other boundary conditions like geometrical dimensions, employed excavation tool and intended excavation duration have to be taken into account.

The documentation of future project data (polymer products and concentrations, soil conditions, penetration lengths or observed fluid losses etc.) might be suitable to confirm the modelling approaches presented in the report.

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