Proceedings of the XVII ECSMGE-2019
Geotechnical Engineering foundation of the future
ISBN 978-9935-9436-1-3

doi: 10.32075/17ECSMGE-2019-0424

XVII European Conference
ECSMGE 2019
Reykjavik
on Soil Mechanics
and Geotechnical Engineering

Stability analysis of polymer-fluid-supported earth walls and influence of type of polymer in solution

Analyse de stabilité de parois soutenues par polymères en solution et influence du type de polymère en solution

R. Verst
University of Wuppertal, Wuppertal, Germany

W. Lieske
University of Bochum, Bochum, Germany

M. Pulsfort
University of Wuppertal, Wuppertal, Germany

ABSTRACT: Polymer solutions are used increasingly to replace bentonite-based slurries as a support medium or as a slurry additive for the construction of piles and diaphragm walls as well as for tunnels with fluid-supported TBM. However, the application of polymer solutions in geotechnical environments so far mainly relies on information from trial holes and trenches for certain polymer products. Detailed knowledge on the influence of polymer properties on the flow behaviour of polymer solutions in a porous environment is essential in order to perform stability checks for precalculations, as the time-dependent penetration of the stabilising fluid needs to be taken into account. Laboratory experiments were performed with anionic polyacrylamide polymers and a polymer product mix specially designed for application in diaphragm walling and pile drilling. They reveal a significant influence of concentration, charge, density, molecular weight and type of polymer on the flow behaviour of the solution. These findings measured by rheological index tests as well as in-situ flow tests in sand were integrated within the framework of a semi-analytical stability assessment for polymer-fluid-supported earth walls based on existing stability approaches for polymer solutions. In particular, a nonlinear pressure drop curve and membrane effects were observed which significantly influence the pressure gradient near the earth face and thus increase the critical stand-up time of the fluid-supported earth wall.

RÉSUMÉ: Les solutions de polymères sont fréquemment utilisées pour remplacer les boues de forage à base de bentonite comme fluide de soutènement ou comme additif de boue dans la construction de pieux forés et de parois moulées. Cependant, l'application des polymères en solution dans un contexte géotechnique s'appuie surtout sur des informations données par des trous d'essais avec certains produits de polymères. Une connaissance profonde de l'influence des proprietés des polymères sur le comportement d'écoulement dans un environnement poreux est essentiel pour pouvoir effectuer des analyses de stabilité en amont car la pénétration dans le milieux poreux en fonction du temps doit être prise en compte. Une expérience de laboratoire a été pratiquée sur des polymères de polyacrylamide anionique et des produits spécialement conçus pour l'application de parois moulées et de pieux forés. Les résultats montrent une influence considerable de la concentration, de la charge, de la densité, du poids moléculaire et du type du polymère sur le comportement d'écoulement de la solution. Les essais réalisés avec des tests rhéologiques d'indice et des tests d'écoulement „in situ" ont été implémentés dans la structure d'une évaluation de stabilité semi-analytique pour les parois stabilisés par polymères en solution. Les calculs s'appuient sur des approches existantes et prennent en compte, en particulier, la courbe non-linéaire de la chute de pression et des effets de membrane observés qui influencent considérablement le gradient de pression proche de la paroi et, par conséquent, augmentent le temps que la paroi reste stable.

Keywords: Polymer support fluids; stability analysis, diaphragm walls, drilled piles

1 INTRODUCTION

Polymers in aqueous solutions, mostly of synthetic polyacrylamide or modified natural cellulosic polymers, are used increasingly around the world to replace bentonite-based slurries as a support medium for pile drilling and diaphragm walling as well as for tunnel construction. Reasons to choose polymer solutions over (modified) bentonite slurries may be operational, environmental as well as economic (Lam et al. 2018, Ouyang et al. 2018, Borghi 2006).

In contrast to bentonite, polymers encompass a large variety of chemical compounds, both natural and synthetic, of which only some are applicable as additives for fluid support.

The general term ‘polymer’ describes a group of large macromolecules consisting of a large number of repeating units called monomers. These units are formed by so-called backbones of covalently connected atoms, most commonly carbon, and side groups of different sizes and charges. They can be connected in a linear form or as branched or networked (cross-linked) structures. The structure and chemistry of the polymers dictate their solubility as well as their conformation and elasticity. However, chemistry, structure and conformation may in turn be changed by chemical (solvent, pH, salinity etc.) and mechanical (e.g. geometric) boundary conditions (Teraoka 2002, Brazel et al. 2012).

The European standards EN 1536 (2015) and EN 1538 (2015), which regulate the application of support fluids for drilled piles and diaphragm walls, allow the use of polymer solutions only with prior investigations from trial holes or trenches or with site experience from comparable grounds. The European standard EN ISO 13500 (2011) specifies some limiting values for index tests for certain natural or modified natural polymers for petroleum and natural gas drilling.

First approaches for stability calculations, preferable for safety reasons and for economic precalculations at an early stage, exist from Steinhoff (1993) and Lesemann et al. (2016) for diaphragm walls and drilled piles. They are derived fron a semi-analytical stability concept for earth walls supported by clay suspensions which is integrated within the German standard DIN 4126 (2013). Polymer solutions according to this concept are represented in an integral way as purely viscous fluids following the power law rheological model.

With respect to the sensitivity of polymer solutions to boundary conditions, the question arises whether the in-situ flow behaviour of all types of polymers in aqueous solutions can be adequately described in this integral way. It is assumed that linear chain polymers such as polyacrylamides will behave differently in a porous environment compared to more complex network structures. Even within a certain group of polymers, differences in e.g. molecular weight, charge density or concentration can affect their performance.

This paper aims at verifying whether this integral approach suffices in describing the relevant mechanisms underlying polymer-soil interaction for fluid support.

‘Pure’ linear polyacrylamide polymers and a mixed product are compared experimentally to assess the influence of polymer property variation on the stability performance. Additionally, a semi-analytical assessment of the stability of polymer-fluid-supported earth walls

Table 1. Polymer properties

	Concentration [g/l]	Molecular weight* [Da]	Charge density* [%]	Marsh time t_{Marsh}**[sec]	Polymer type* [-]
S075M S150M	0.75 / 1.50	Low	Medium	48 58	PHPA
L075M L150M	0.75 / 1.50	High	Medium	107 144	PHPA
M075L M150L	0.75 / 1.50	Medium	Low	45 50	PHPA
M075M M150M	0.75 / 1.50	Medium	Medium	68 95	PHPA
M075H M150H	0.75 / 1.50	Medium	High	61 82	PHPA
L075mix L150mix	0.75 / 1.50	Unknown	Unknown	105 138	PHPA, unknown polymeric additives

* Information from manufacturer ** Measurement at 1000 ml

derived from the existing design approaches is discussed.

2 EXPERIMENTAL INVESTIGATION

2.1 *Materials and methods*

Laboratory index tests of the bulk material as well as one-dimensional flow tests in sand were performed with different polymer solutions.

Synthetic polymer products with their respective properties given in Table 1 were chosen as these enable detailed property variation. Linear copolymers of acrylamide (non-ionic) and acrylate (anionic) of high molecular weight (chain length), commonly named PHPA, were tested with average molecular weights around $5..30 \cdot 10^6$ Da and different charge densities defined by the degree of anionicity of the polymer chain between 5 % and 70 %. Concentrations of 0.75 g/l and 1.50 g/l in aqueous solution were chosen as a lower and upper boundary. L075mix and L150mix represent a polymer product mix specially designed for application in diaphragm walling and pile drilling which contains PHPA polymers and other polymeric additives of unknown properties. The polymer solutions were prepared with granular polymer material slowly sprinkled into deionized water at pH 7 according to a fixed size distribution of the polymer granules using a magnetic stirrer at maximum speed for dispersion (5-10 min) and subsequently a mechanical stirrer at 500 rpm (50-55 min).

The bulk fluid index tests consisted of rheometer tests to assess the bulk rheological behaviour and filter paper tests to account for solution stability against the release of water.

The rheometer tests were performed using a rotational rheometer. Viscosity was recorded with decreasing values of the shear rate.

The filter tests, similar to those described by Buja (2009), consisted of a cylindrical ring (h = 2 cm, d = 7 cm) which was placed on regular filter paper (d = 18 cm) and filled with the test solution. The saturation propagation of the filter paper was measured over time.

Based on these index tests, a range of polymer solutions was selected for one-dimensional flow tests in sand. The experimental setup of the “in-situ“ test consisted of a cylindrical container of acrylic glass (h = 100 cm, d = 20 cm) filled with sand at high compaction (ρ_d = 1.67 g/cm^3, void ratio e = 0.59, $k_w = 2 \cdot 10^{-3}$ m/s, d_{10} = 0.2 mm). A perforated plate and filter gravel were used at the bottom and top to ensure vertically uniform flow. 12 pressure transducers distributed along the height were installed to measure the pore pressure over time, with one transducer placed at each end of the sand column within the gravel material to control the pressure boundary conditions. The time-dependent penetration was measured through permanent weighing of inflow and outflow. After full saturation with water, penetration with polymer solution was performed at p_{min}= 0.4 bar and Δp = 0.15 bar (hydrostatic pressure excluded). Food colouring powder brilliant blue was added to the deionised water used to mix the polymer solution and enabled a visualisation of the approximate penetration depth.

2.2 Experimental results and discussion

2.2.1 Bulk Rheology

Exemplary flow curves of the polymer solutions are given in Figure 1 for selected polymer solutions at a concentration of 1.50 g/l. The highest resistance against flow was achieved by a PHPA polymer of high concentration, high molecular weight and medium charge density.

In all cases, higher viscosity values were obtained with an increase in polymer concentration from 0.75 g/l to 1.50 g/l while the curvature remained relatively unchanged.

In accordance with Brazel et al. (2012), it can be seen that an increase of the average molecular weight significantly increases the measured viscosity of the PHPA solution, especially at shear rates below a value of approximately 100 1/sec when the flexible PHPA chains leave their parallel orientation during flow.

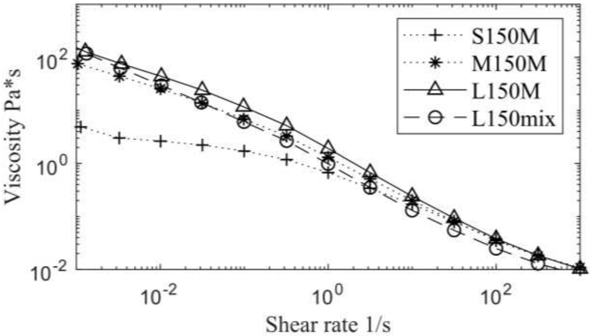

Figure 1. Exemplary rheometer flow curves

A similar rise in viscosity was observed with an increase in charge density from low to medium, as the repulsive forces along the chain result in an elongation of the polymer chain comparable to an increase in chain length. However, a further increase of the charge density and thereby rigidity leads to a reduction of the chain length and thus reduction in viscosity.

The mixed product L150mix displayed a flow behaviour very similar to M150M and L150M, which represent a medium to high molecular PHPA polymer with medium charge density.

2.2.2 Solution stability

The solution stability against release of water for all polymer solutions was compared to a bentonite suspension (Na-bentonite at 60 g/l) and water. Figure 2 shows exemplary results, Table 2 gives the quantitative results. Full saturation of the filter paper was reached with water, bentonite slurry (Fig. 2 left), M150L and S150M (Fig. 2 centre). All other polymer solutions with higher values of charge density or chain length reached a stagnation point with only a slight propagation around the cylinder (Fig. 2 right). It may be concluded that charge density and molecular weight stabilise the solution against separation.

Figure 2. Filter tests

Table 2. Results of filter tests

Type of fluid	Propagation at 5 min / 60 min [cm]	Saturation/ stagnation
Water	Full / Full	3.5 min (sat.)
Bentonite slurry	2.90 / Full	30 min (sat.)
M150L	1.25/ Full	30 min (sat.)
S150M	0.70 / 1.50	14 h (sat.)
M150H, L075M, L150M, L150mix	0.3 / 0.7	60 min (stagn.)

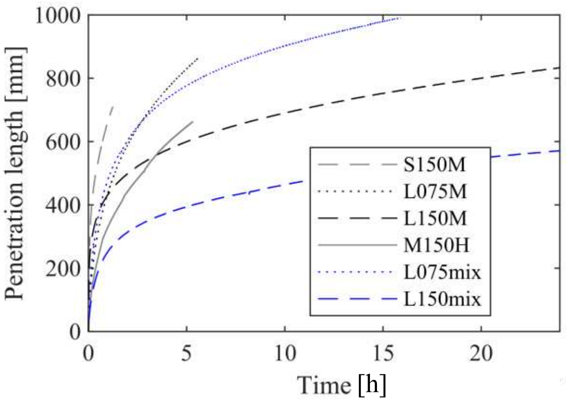

Figure 3. Comparison of the penetration over time

2.2.3 *"In-situ" flow tests*

One-dimensional flow tests in sand were performed with four PHPA polymer solutions and with the mixed products. A comparison of the penetration over time induced by a differential pressure of $\Delta p = 0.15$ bar is given in Figure 3.

As expected from the rheological index tests, the penetration velocity of the PHPA solutions decreases with increasing molecular weight, charge and concentration of the polymer. The penetration rate of the mixed product decreases significantly faster than all PHPA products of the same concentration within the first two hours of penetration. Then, the penetration rate of both L075mix and L150mix adjusts to the slope of L150M. It may therefore be assumed that the subsequent flow behaviour is governed by PHPA molecules of high molecular weight.

Figure 4 shows the corresponding pressure drop curves for two representative products at progressing penetration levels (light grey towards black) for both concentrations. The curvature of the remaining pure PHPA solutions exhibits a behaviour similar to L075M and L150M and is therefore not displayed. The curves of the pure PHPA product for both concentrations are clearly arched with the arch following the penetration level calculated from volumetric inflow and outflow measurements. In contrast, the curves of the mixed product reveal the development of a significant reduction in pressure in direct vicinity of the interface between sand and gravel with progressing penetration.

It may be concluded from the time-dependent evolution of the pressure drop of the mixed products independently of the penetration level that extensive local filtration effects create a certain pressure-adsorbing membrane effect. This effect can be compared to the membrane effect of a bentonite filter cake, except that the pressure adsorbed by the polymer membrane in this case is lower by approximately 20-25 %. However, the effect causing the formation of the membrane is different as the hydrated polymer molecules are of relatively small size compared to bentonite grains.

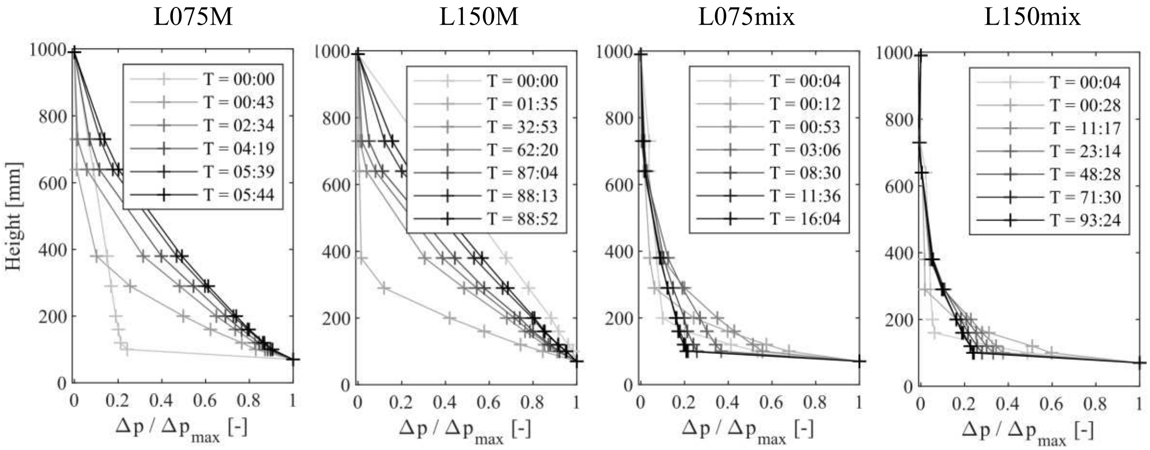

Figure 4. Change of the pressure drop along the height of the cylinder over time

This substantially different behaviour cannot be derived from the aforementioned index tests on the bulk solution. The index tests show no significant deviation between the two product types. However, the membrane formation might be explained from the specific properties of the mixed polymer product. It could be the result of the presence of cross-linkers, which are able to create network structures by bridging adsorption and form swellable hydrogels as pore blockers. Flow resistance through these dense networks could then also be affected by the stability of the solution, i.e. the resistance of the solution against separation.

Both the bi-linear and the arched course of the pressure drop result in a pronounced increase of the pressure gradient f_{s0} at the earth face compared to the pressure gradient $f_{s0,DIN} = \Delta p^*/s$ which reflects a linear pressure drop along the penetration s. This linear pressure drop is assumed for bentonite suspensions according to DIN 4126 (2013) if penetration occurs.

Figure 5 shows the development of the pressure gradient $f_{s0,wall}$ over time measured between the first two pressure transducers (distance approx. 2 cm) at the interface between sand and gravel for all tested polymer solutions.

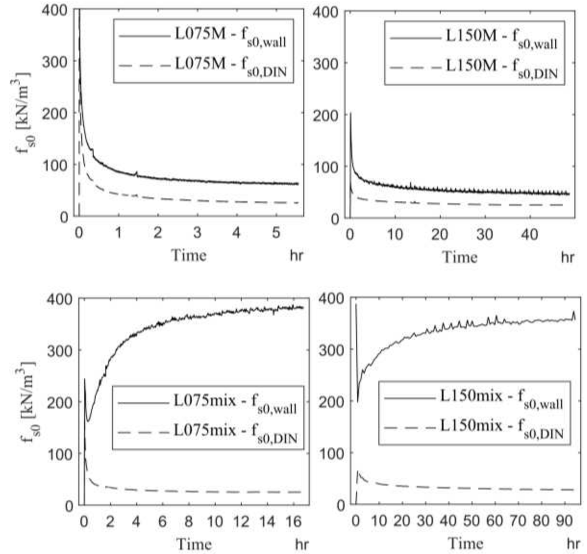

Figure 5. Comparison of pressure gradients at the interface between gravel and sand

The second curve represents the pressure gradient according to DIN. The deviation ranges from a factor of 1.35-2.5 for the PHPA solutions to 12.78-15.16 for the mixed products.

However, the two product groups show a diverging evolution of the gradient value. As the measured values of the PHPA polymers decrease over time, the aforementioned factors can only be guaranteed within a certain time span. In contrast, the assumption of an earlier value of the pressure gradient for the mixed products L075mix and L150mix will be on the safe side.

3 STABILITY ANALYSIS

The experimental investigations show significant differences between the flow behaviour of bentonite suspensions and the tested polymer solutions and even between the different types of polymer solutions. Nevertheless, the general stability concept for fluid-supported earth walls according to DIN 4126 (2013), described in more detail in Haugwitz & Pulsfort (2018), is independent of the type of fluid and can therefore be applied to all of the above support fluids. The concept is based on three analytically formulated failure mechanisms: groundwater inflow (Equation 1), sloughing or the successive removal of grains from the earth wall (Equation 2) and shear failure of a three-dimensional monolithic soil body (Equation 3).

$$p_{w,dst} \leq p_{F,stb} \tag{1}$$

$$f_{s0,wall} \geq f_{s0,req} = \frac{\gamma''_d}{\tan \varphi'_d} \tag{2}$$

$$\max\left(\frac{E_{ah,dst}(\vartheta,T)}{S_{k,stb}(\vartheta,T)}\right) \leq 1 \tag{3}$$

Stability according to the first mechanism is guaranteed if the stabilizing pressure $p_{F,stb}$ created by the hydrostatic pressure of the support fluid exceeds the opposing groundwater pressure $p_{w,dst}$ and can be formulated independently of time and mainly depending on the density of the support fluid which, in all cases considered, will be approximately equal.

The second failure mechanism requires a minimum pressure gradient $f_{s0,req}$ at the earth face to locally stabilise the grains against sloughing if the fluid is able to penetrate into the ground. This failure is assumed to occur when the gravitational force of a differential soil volume $G = \gamma'' \cdot V$ exceeds the stabilizing frictional force $F_v = F_{flow} \cdot \tan \varphi'$ induced by the flow force $F_{flow} = f_{s0,wall} \cdot V$. A rearrangement of both sides gives the stability fomulation from Equation 2. A pressure gradient $f_{s0,wall} = 2 \cdot \eta_F \cdot \tau_F / d_{10}$ for clay suspensions according to DIN was determined from experimental measurements which found a proportional factor of 2 between the pressure gradient and the ratio of the static yield strength τ_F of the slurry and the effective grain diameter d_{10} of the soil when stagnation is reached. η_F thereby represents a correction factor for fluctuations of τ_F due to simplified measurements on site. However, fluid penetration resulting in a local stability problem is only considered if $f_{s0,wall} < 200$ kN/m³. Above this limiting, it may be assumed that no penetration occurs (Haugwitz & Pulsfort 2018).

The second stability check can equally be formulated independently of time for polymer solutions if a minimum pressure gradient $f_{s0,wall}$ can be found as in the case of the mixed polymer product. As both mixed polymer solutions create a pressure gradient of >200kN/m³, local stability should be guaranteed. However, for all other cases, this stability check may be reformulated in terms of a critical time $T_{max} \leq T_{crit}$ up until the required pressure gradient $f_{s0,req}$ does not exceed the measured gradient $f_{s0,wall}$. This concept as well as formulations to analytically predict the time-dependent penetration can be found in Steinhoff (1993) for PHPA solutions without any membrane effect.

The third failure mechanism opposes the destabilizing horizontal earth pressure E_{ah} and the stabilising pressure S_k. E_{ah} for diaphragm walls can be calculated by assuming a prismatic failure body with shear forces T at the triangular edges to account for arching effects due to the influence of friction and cohesion on the pseudo-spatial problem (Figure 6). Earth pressure calculations for drilled piles can use the spatial approach by Walz & Hock (1987). The stabilizing force S_k in the case of a membrane formation may be calculated from the percentage adsorbed by the membrane and can be formulated independently of time if the assumption for the decrease in pressure at the earth face is on the safe side (bentonite slurry, network polymer). If penetration occurs and no pressure adsorbing membrane is built at the earth face, the stabilising force can be calculated from flow forces transmitted to the granular structure and integrated along the effective penetration length within the respective failure body as described by Lesemann et al. (2016). If no stagnation or approximate stagnation can be measured within a relevant time span, the stability format should again be rearranged to obtain a time T_{crit} at which failure will occur.

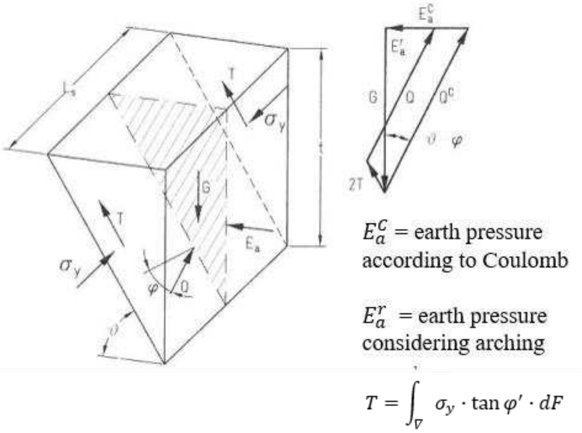

Figure 6. Prismatic failure body according to DIN 4126 (Haugwitz & Pulsfort 2018)

4 CONCLUSION

Polymer solutions are a promising alternative to bentonite suspensions with regard to the fluid support of earth walls. However, polymer products can vary greatly and the influence of this variability on stability calculations is still subject of further research.

Detailed knowledge on the influence of polymer properties on the flow behaviour in a porous environment has proven to be essential to perform realistic stability checks. Index tests can be a good indicator to obtain flow parameters or to assess the solution stability. These may be used to conservatively quantify the flow behaviour of certain polymers in a porous environment.

The polymer variation presented here shows the influence of slight variations of properties such as charge density, chain length, concentration and especially additives. Other types of polymers, especially natural or modified natural polymers, can be considerably different in structure and may therefore behave differently within the same field of application.

Despite significant deviations in flow behaviour, stability checks for fluid-supported earth walls based on the concepts underlying DIN 4126 (2013) can be applied to all kinds of support fluids. Calculations can be formulated independently of time for certain polymer solutions for which pronounced pressure adsorbing membrane effects can be measured in representative porous environments. It could be shown that pure PHPA solutions are not able to form such a membrane. Further research is necessary to define the factors which ensure a membrane formation.

5 REFERENCES

Borghi, F. 2006. Soil conditioning for pipe jacking and tunnelling. Doctoral dissertation, University of Cambridge.

Brazel, C. S., Rosen, S. L. 2012. Fundamental principles of polymeric materials. John Wiley & Sons.

Buja, H. O. 2009. Handbuch der Baugrund-erkennung. Vieweg+Teubner.

DIN 4126 2013. Stability analysis of diaphragm walls. Beuth Verlag.

EN 1536 2015. Execution of special geotechnical work - Bored piles. German version DIN EN 1536:2010+A1:2015.

EN 1538 2015. Execution of special geotechnical work - Diaphragm walls. German version DIN EN 1538:2010+A1:2015.

EN ISO 13500 2011. Petroleum and natural gas industries – drilling fluid materials – specifications and tests. German version DIN EN ISO 13500:2011-04.

Haugwitz, H. G., Pulsfort, M. 2018. Pfahlwände, Schlitzwände, Dichtwände. Witt, K.-J (ed), *Grundbau-Taschenbuch* 8(3). Ernst & Sohn.

Lam, C., Jefferis, S. 2018. Polymer support fluids in civil engineering. London: ICE Publishing.

Lesemann, H., Vogt, N., Pulsfort, M. 2016. Analytical stability checks for diaphragm wall trenches and boreholes supported by polymer solutions. *Proceedings of 13th Baltic Sea geotechnical conference*, 231-238. Lithuania.

Ouyang, Y., Jefferis, S., Wiltcher, P., Suckling, T. 2018. A major infrastructure project and the formation of the UK‘s largest rotary pile under polymer support fluid. *DFI-EFFC International conference on deep foundations and ground improvement*, 541-550.

Steinhoff, J. 1993. Standsicherheitsbetrachtungen für polymergestützte Erdwände. *Forschungs- und Arbeitsberichte aus den Bereichen Grundbau, Bodenmechanik und Unterirdisches Bauen an der Bergischen Universität - GH Wuppertal* (13). Wuppertal.

Teraoka, I. 2002. Polymer solutions: an introduction to physical properties. John Wiley & Sons.

Walz, B., Hock, K. 1987. Berechnung des räumlich aktiven Erddrucks mit der modifizierten Elementscheibentheorie, Bergische Universität - GH Wuppertal