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Fundamental research on penetration grouting with acrylates in porous media

Recherche fondamentale sur l'injection par pénétration d'acrylates dans milieux poreux

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ABSTRACT: The use of grouting materials is nowadays inevitable. In Germany sodium silicate aluminate was used mainly as chemical grouting material. This grout family leads to a pH value above 10 in groundwater and because of ecological reasons isn't longer approvable to use. In this research multi-component acrylates were investigated as a substitute for sodium silicate-sodium aluminate.

Focus was on the possibility of permeation grouting with acrylates and the strength of the grouting body. This paper presents the results of several-year research project to cover the following questions:

- The possibility of permeation grouting in the soil was investigated by several model tests.
- The influences of the grouting pressure and the degree of saturation have been investigated.

The acrylates have an extremely low viscosity, which is close to the viscosity of water. Because of that, it is possible to grout the acrylates in a very low permeability soil.

The shear parameters of the grouting body were determined by triaxial tests. Grouting body triaxial testing is performed using the hoek cell. By means of the Mohr–Coulomb theory, the shear parameters were determined. A significant increase in soil cohesion and a small reduction in the angle of friction can be seen after grouting.

At the end the experimental results were used for numerical calculations on the propagation of acrylates. Thus, it was achieved to define a completely new safety concept for the soil improvement by penetration grouting.

RÉSUMÉ: L'utilisation des matériaux de scellement est de nos jours inévitable. En Allemagne, on utilisait surtout le silicate de sodium aluminate comme matériau de scellement chimique. Il en résulte un niveau de pH dans les eaux souterraines supérieur à 10 et dans ce cas il n'est plus autorisé pour des raisons écologiques. Dans ce travail de recherche, les acrylates à plusieurs composants ont été analysés afin de substituer le silicate de sodium-aluminate de sodium.

L'accent était mis sur la possibilité d'une injection de perméation à l'aide des acrylates ainsi que sur la résistance du corps d'injection. Cet article présente les résultats d'un projet de recherche mené sur plusieurs années dans le but de trouver une réponse aux questions suivantes :

- La possibilité de l'injection de perméation dans le sol a été analysée dans plusieurs essais pilotes.
- Les impacts de la pression d'injection et du degré de saturation ont été étudiés.

Les acrylates disposent d'une viscosité extrêmement faible qui se rapproche de celle de l'eau. C'est la raison pour laquelle il est possible d'injecter les acrylates dans un sol à très faible perméabilité.

Les paramètres de cisaillement du corps d'injection ont été déterminés à partir d'essais triaxiaux. Le test triaxial du corps d'injection est réalisé sur la base de la cellule de Hoek. Les paramètres de cisaillement ont été déterminés à l'aide de la théorie de Mohr-Coulomb. On observe après l'injection une augmentation significative de la cohésion du sol et un léger rétrécissement de l'angle de frottement. À la fin, les résultats expérimentaux ont été appliqués pour les calculs numériques sur la propagation des acrylates. Il a ainsi été possible de définir un concept de sécurité complètement nouveau dans l'amélioration du sol à l'aide de l'injection par pénétration.

Keywords: Acrylate grouting material; Numerical calculations; Penetration grouting; Porous media; Shear parameters

1 INTRODUCTION

The use of grouting materials is largely implemented and many projects can only be realized through the use of penetration groutings.

In Germany sodium-silicate aluminate was mainly used as chemical grouting material. This grout family leads to a pH value above 10 in groundwater and because of ecological reasons isn't longer approvable to use.

In this research multi-component acrylates were investigated as a substitute for sodium silicate-sodium aluminate. This chemical multi-component grout materials are made from polymer solutions (acrylic acid or methacrylic acid) and, if necessary, additives. Due to a radical redox polymerization the polymer solutions generate a jelly-like end-product. (Wagner 2011)

Due to their low initial viscosity acrylate grouting material is used increasingly as waterproofing Systems for soil, construction or rehabilitation (Wagner 2011). It is used where soil particles are too small for cement grouting.

2 PROJECT DESCRIPTION

The aims of this research are the investigation of the injectability of acrylate gels in different soils and the change of shear parameters through grouting.

There is no replicable algorithm to calculation and development of grouting procedures. We propose a numerical method for calculation of grout range. The results of the experimental investigations are presented and compared with the results of the proposed numerical calculation method.

Solidcryl was chosen as grout material. Solidcryl is a four-component methacrylate grout material that hardens to a final product with high compressive strength. This material has a very low initial viscosity and can also be grouted in a low- permeable soil.

Four test soils with the grain size distributions (Figure 1) were used for the test. The test soils consist of three non-cohesive soils and a cohesive soil.

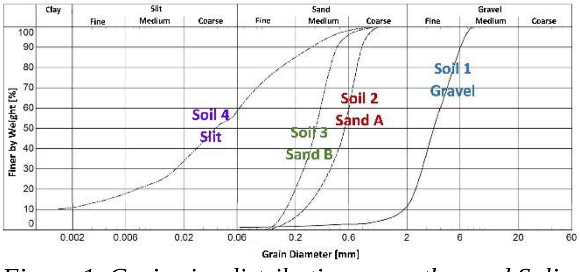

Figure 1. Grain size distribution curve the used Solis

The determined soil properties are summarized in Table 1.

Table 1. Soil properties

Soil type		d_{50} [mm]	ρ [g/cm³]	n [1]	D [1]	k_0 [m/s]
Gravel	Gr	3,474	1,60	0,40	0,94	2,98E-03
Sand A	Sa	0,553	1,70	0,36	0,99	1,51E-04
Sand B	Sa	0,305	1,62	0,40	0,77	2,51E-04
Slit	U	0,038	1,63	0,41	1,27	9,93E-07

As can be seen in the table, the grout material is grouted in tightly packed soils.

3 UNIDIMENSIONAL GROUTING TEST

The injectability of different types of soil taking into account grouting pressure is investigated by unidimensional grouting test.

The experimental equipment consists of an approximately 1 m long PVC cylinder with an outside diameter of 63 mm and a wall thickness of 4.7 mm. This cylinder is enclosed on both sides by a PVC blind flange (Figure 2).

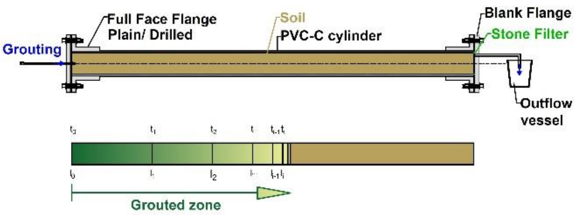

Figure 2. Unidimensional grouting test

The grout materials are dispensed into the soil using a dual cartridge dispense gun (Figure 3). The max. permissible working pressure of this device is 7 bar and the dual cartridge capacity is 1500 ml.

Figure 3. SULZER MixCoat^{TM} Dispenser

Due to the existing pressure ratio and due to the hydraulic and mechanical pressure losses in the system the grouting pressure ($P_{grouting}$) is lower than the set air-pressure (P_{air}) and can be determined by equation 1.

$$P_{grouting,i} = \overbrace{\boxed{0.8608 \cdot P_{air}}}^{\text{Pressure ratio}} - \underbrace{\boxed{113.56 \cdot \rho \cdot {v_{i-1}}^2/2}}_{\text{hydraulic loss}} - \overbrace{\boxed{2.95 * 10^4}}^{\text{mech. loss}} \qquad (1)$$

where $v =$ average flow velocity in the MIXPAC; $\rho =$ liquid density

In Figure 4 it is clearly visible that the range of grout zone increas by increasing the pressure in the sand A.

Figure 4. Increasing the range of grout zone in the sand by increasing the pressure

The measured range of grout zone as a function of the grouting pressure is shown in Figure 7. In the silt penetration grouting is nearly impossible and a soil fracturing is observed at the higher grouting pressures.

4 DEVELOPMENT AND VALIDATION OF NUMERICAL CALCULATIONS METHOD

To determine the range of the grout zone, we have developed a numerical calculation method. This numerical method was programmed in Matlab.

The flow chart of the numerical calculation method is shown in Figure 5.

The suction tension in the soil was determined by the van-Genuchten-method. For more information, see van Genuchten (1980).

The suction tension in the dry soil, which has been determined by the van-Genuchten-method, can be significantly greater than the measurable tension in the laboratory. Therefore, a maximum value is defined during programming.

The time evolution of the range of grout zone can be determined with equation I in the flowchart. For more information, see Forouzandeh, Boley and Tintelnot (2018). The flow rate determined by this value must not be greater than the maximum possible flow rate of the pump (equation II and III in flowchart).

This method is only suitable for laminar flow. If a turbulent flow exists, then the range of the grout zone is shorter than the determined value.

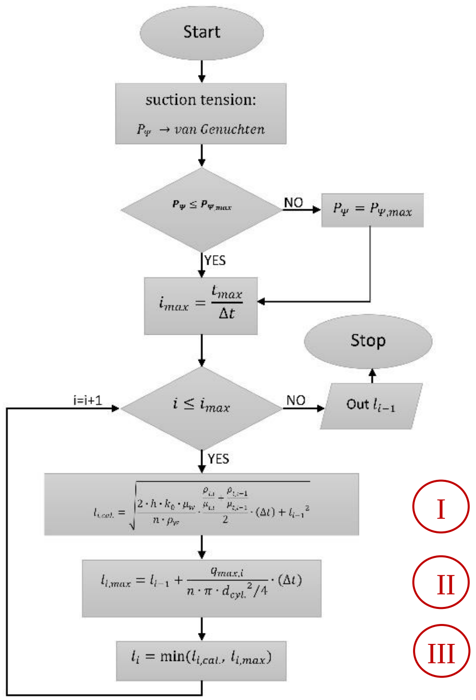

Figure 5. Flow chart of the numerical calculation

There are several proposed models that describe the evolution of viscosity (μ_t) over time (t). The model proposed by Finsterle, Moridis, and Pruess (1994) fits best for our grouting material (Eq. 2).

$$\mu_{t,i} = \mu_0 + a \cdot e^{b \cdot t} \tag{2}$$

where μ_0, a and b are the parameters obtained by fitting the above equation for the measured viscosity data with rheometer.

The exponential model presented in equation 3 fits well the evolution of the grouting material density.

$$\rho_{t,i} = \rho_{End} - c \cdot e^{-d \cdot t} \tag{3}$$

where ρ_{End}, c and d are the parameters obtained by fitting the above equation for the measured density data.

The determined viscosity and density parameters are summarized in Table 2.

Table 2. Viscosity and density parameters (Solidcryl)

Viscosity factor			Density factor		
μ_0	a	b	ρ_{End}	c	d
10.01	4.234E-02	1.475E-01	1210	163.4	0.9517

The results of a calculation using the proposed method are shown in Figure 6. In these calculations it is assumed that Solidcryl is grouted in Sand A and the air pressure is 2 bar.

As can be seen in Figure 6a and b, the grouting pressure at the start of grouting suddenly decreases because of the high flow rate (= high hydraulic pressure loss).

Figure 6c and d also show that the injectability is extremely dependent on viscosity and above a grout viscosity of approx 150 Pa·s Sand A is not injectable anymore.

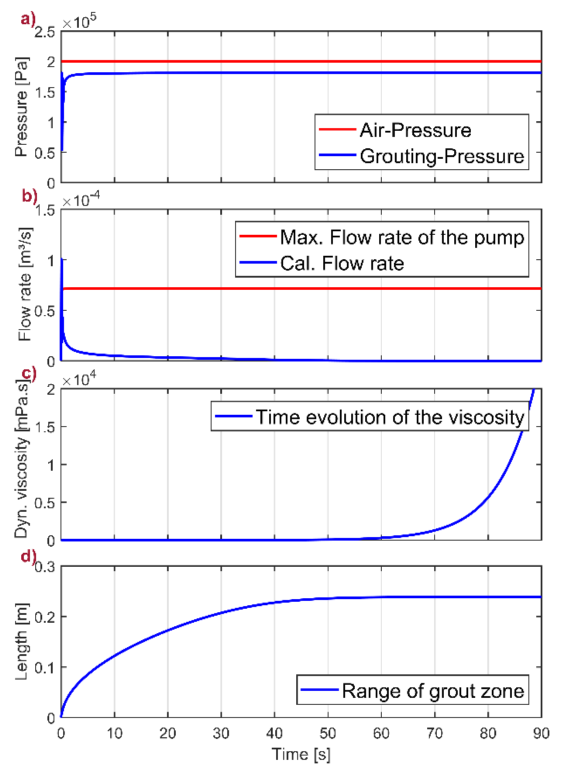

Figure 6. Calculated time course of the grouting parameters (Sand A+Solidcryl)

With the proposed numerical method the ranges of grout zone in the four presented soils using various grouting pressures were calculated. The results are shown in Figure 7.

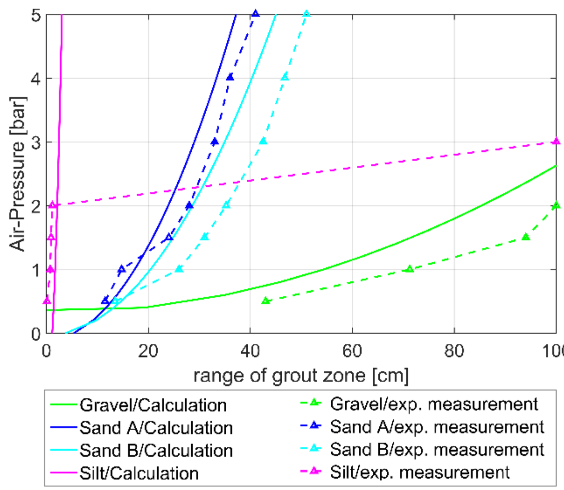

Figure 7. Validation of the numerical calculations - Solidcryl

As can be seen in Figure 7, the range of the grout zone in the cylinder can be determined by using the proposed numerical method as a good approximation.

5 SHEAR PARAMETERS OF THE GROUTING BODY

The shear parameters in the soil before and after the grouting are determined by means of the triaxial test after a week of storage in a moist curing room (the samples are produced with 2 bar air pressure). The influences of the degree of saturation have been investigated. The test specimens are inserted in the HOEK cell and sheared off with three different cell pressures. The samples have a diameter of 5.36 cm and a height of 10 cm.

Because a penetration grouting in the silt is nearly impossible, no sample could be prepared for triaxial test.

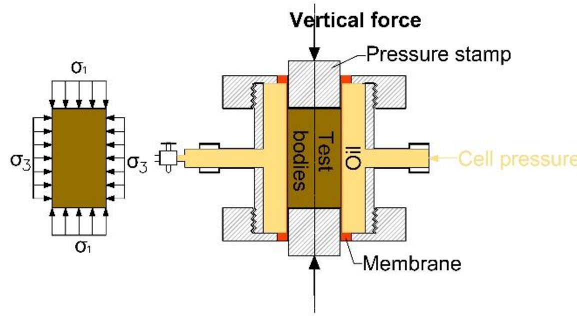

Figure 8. Hoek cell

Here it is assumed that there is a linear relationship between shear stress and normal stress of the grouted soil. The shear parameters are determined by means of Mohrs' stress circles. The samples are loaded until they break or reach maximum deformation of 20 %. The samples are deformation controlled sheared with a deformation rate of 0.1 mm/min.

The shear parameters of the soils before the grouting are determined by direct shear test in a dry state and by triaxial test in a saturated state. The determined shear parameters are summarized in Table 3.

Table 3. Shear parameters before and after the grouting with solidcryl

			Gravel	Sand A	Sand B
Soil (S_r=0)	**c´**	[kN/m²]	8.1	2.06	3.23
	φ´	[°]	53.67	45.14	43.16
Soil (S_r=1)	**c´**	[kN/m²]	2.71	13.86	9.46
	φ´	[°]	54.49	29.2	40.17
Soil (S_r=0) **+ Solidcryl**	**c´**	[kN/m²]	2808.03	1439.67	2016.53
	φ´	[°]	11.93	32.97	31.62
Soil (S_r=0.5) **+ Solidcryl**	**c´**	[kN/m²]		1330.67	
	φ´	[°]		24.85	
Soil (S_r=1) **+ Solidcryl**	**c´**	[kN/m²]		1058.12	
	φ´	[°]		30.74	

As can be seen in Table 3, the shear parameter of the sample is dependent on the degree of saturation of the soil before grouting. The grouting material is diluted with water from the soil, therefore, the concentration of the grouting material is reduced and as a result, the cohesion in the sample decreases.

Figure 9 shows the shear stress in function of normal stress and soil type before and after the grouting.

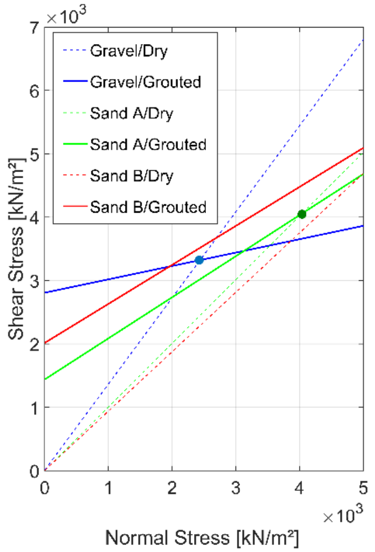

Figure 9. Shear parameters before and after the grouting with solidcryl

As can be seen in Figure 9, cohesion in soil is increased by grouting, and a loss of friction angle is expected. A soil grouting significantly increases the shear strength of the soil at low normal stress ranges, but if high normal stress is available, a soil grouting reduces shear strength of the soil. The point of intersection between two mohr-coulomb-envelopes before and after the grouting is the application limit of the grout material in different soil types (critical normal stress). For coarse-grained soil, the application area is smaller. The critical normal stress can be determined by the following equation

$$\tau = c_s + \sigma_{crit} \cdot \tan(\varphi_s) = c_{gs} + \sigma_{crit} \cdot \tan(\varphi_{gs})$$

$$\rightarrow \sigma_{crit} = \frac{c_{gs} - c_s}{\tan(\varphi_s) - \tan(\varphi_{gs})} \tag{4}$$

Where c_s and φ_s are the shear parameters in the soil and c_{gs} and φ_{gs} are the shear parameters in the soil after the grouting.

If normal stress is less than the critical normal stress, a soil grouting is safe, otherwise, it must be calculated, if shear stress is less than shear strength of the soil after grouting.

6 CONCLUSION

The presented results can be summarized as follows:

1. By a turbulent flow in the soil, the groutability can be reduced. The transition from laminar to turbulent flow can be determined by the Reynolds number ($Re_{crit.} = 10$).
2. With the proposed numerical method, the range of grout zone can be calculated with a good approximation.
3. A pump with a higher flow rate can increase the range of grout zone.
4. By grouting with acrylates cohesion in soil is increased, and a loss of friction angle is expected.
5. The grouting material is diluted with water from the soil, therefore, the concentration of the injection material is reduced and as a result, the cohesion in the sample decreases
6. If normal stress is less than the critical normal stress, a soil grouting is safe, otherwise shear strength must be determined.

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