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TOC value as an indicative parameter for determining the spread of grouting materials

La valeur COT comme paramètre guide pour déterminer la diffusion des matériaux d'injection

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ABSTRACT: The grouting measures are essentially planned and carried out using many years of empirical experience. Most of these empirical approaches have no in-depth theoretical background and therefore do not provide reproducible algorithms, which could serve for a reliable prognosis in the planning of grouting measures and procedures. A flow calculation method for determining the grouting range was developed using experimental and theoretical investigations. In order to investigate the reliability of the developed method on a large scale, a field grouting was carried out on a construction site. Acrylic gel is used as grouting material. The dimensions of the grouting bodies were recorded with a ToF 3D camera. The grouting material can increase the TOC content in the soil. This can serve as a guide for the detection of grouting materials in the ground. The investigation has shown that the grouting range on a large scale can also be determined with a good approximation using the developed method. The acrylic gel in the soil can be detected with the TOC content. A method was developed that allows the TOC value determined with the solid analysis to be used as an indicative parameter for determining the spread of grouting materials in the soil.

RÉSUMÉ : Les mesures d'injection sont principalement planifiées et exécutées sur la base de nombreuses années d'expérience empirique. La plupart de ces approches empiriques n'ont pas de fond théorique approfondi et ne fournissent donc pas d'algorithmes reproductibles, qui pourraient à leur tour être utilisés pour un pronostic fiable dans la planification des mesures et des procédures d'injection. Une méthode de calcul d'écoulement pour déterminer la plage d'injection a été développée à l'aide d'investigations expérimentales et théoriques. Afin d'étudier la fiabilité de la méthode développée à grande échelle, une injection de terrain a été réalisé sur un site de construction. Le gel d'acrylate est utilisé comme matériau d'injection. Les dimensions des corps d'injection ont été enregistrées avec une caméra ToF 3D. Le matériau d'injection peut augmenter la teneur en COT dans le sol. Cela peut être utilisé comme guide pour la détection des matériaux d'injection dans le sol. L'enquête a montré que la plage d'injection à grande échelle peut également être déterminée avec une bonne approximation en utilisant la méthode développée. Le gel d'acrylate dans le sol peut être détecté avec la teneur en COT. Une méthode a été développée qui permet d'utiliser la valeur COT déterminée par les analyses de solides comme paramètre guide pour déterminer la dispersion des matériaux d'injection dans le sol.

KEYWORDS: flow calculation method, grout body, grouting range, TOC value.

1 INTRODUCTION.

Many projects can only be realized through the use of penetration grouting. The grouting measures are essentially planned and carried out using many years of empirical experience. Most of these empirical approaches have no in-depth theoretical background and therefore do not provide reproducible algorithms, which could serve for a reliable prognosis in the planning of grouting measures and procedures.

To facilitate the planning of grouting measures, a flow calculation method is tested. Based on laboratory tests, taking into account e. g. the suction tension, effective porosity and viscosity curve of the grouting material, the spread of the grouting material can be calculated. In order to verify the laboratory and theoretical investigations on a large scale, a large-area grouting test with an acrylate gel was carried out.

Acrylate gels are multi-component grouting materials, which consist of monomers that form chemical chains with a catalyst. These chains form a network and are decisive for the gel properties (Koltzenburg et al. 2014, Weber et al. 2012). The initial viscosity of the acrylate gel is comparable to that of water. The flow properties change over time. When the gel point is reached, the grouting stops.

With this in mind, grouting was carried out at 4 contiguous points in a triangular grid on a construction site and the grout was then exposed 0.65 [m] below the subsurface. A ToF 3D camera was used to precisely record the dimensions of the grouting body.

Total organic carbon (TOC) is a sum parameter in environmental analysis that can have natural and industrial origins. The grouting material can increase the TOC content in the soil. This can serve as a guide for identifying grouting materials in the ground. For this reason, the concentration of the grouting materials in the soil was examined at several points by TOC analyzes. The evaluation showed that the acrylate gel in the soil can be detected by the TOC analyzes and can therefore be used as an indicative parameter for the spread of the grouting material in the soil.

2 MATERIALS AND METHODS

2.1 *Grouting material*

In the present case, a three-component, water-swellable acrylate-based hydrogel was used, which hardens to form a rubber-like, flexible product. The polymere gel is formed by a radical polymerization of monomers and an initiator solution. The monomere part consists of two components (component A) which have to be mixed before the initiator solution (component B) will be added. By mixing the A and B components with the same volume fraction (1: 1), a chemical reaction is started, which results in a time-dependent increase in viscosity up to hardening. In addition to the time, the flow rate and the temperature also have an influence on the viscosity.

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 the used grouting material (see Eq. 1).

$$\mu_t = \mu_0 + a \cdot e^{b \cdot t} \tag{1}$$

where μ_0, *a* and *b* are the parameters obtained by fitting the above equation for the measured viscosity data with a rheometer. The determined viscosity parameters at 15 [°C] are summarized in Table 1.

Table 1. Viscosity parameters.

μ_0	*a*	*b*
2.342	8.89E-12	4.1E-3

2.2 *Soil parameters*

The soil in the grouting depth consists for the most part of a densely packed gravel-sand mixture with a measured permeability coefficient of $1.1 \cdot 10^{-4}$ [m/s]. Due to the pronounced stratification of the subsoil, the horizontal permeability can be significantly greater than the vertical permeability. For the calculations with the program, it was therefore assumed that the horizontal permeability coefficient is $k_{f,x} = 1.66 \cdot 10^{-4}$ [m/s] and the vertical permeability coefficient is $k_{f,y} = 4.16 \cdot 10^{-5}$ [m/s]. The effective porosity in the test field was assumed to be 0.2. The groundwater with a temperature of 15 [°C] was at a depth of 3.60 [m] below the ground.

2.3 *Grouting patterns*

The test field consists of four adjacent grouting points (see Figure 1). Four grouting points form a parallelogram. Height and side length of the parallelogram is 1.70 x 1.90 [m] (grouting grid). The area of influence of the grout is thus 3.23 [m²].

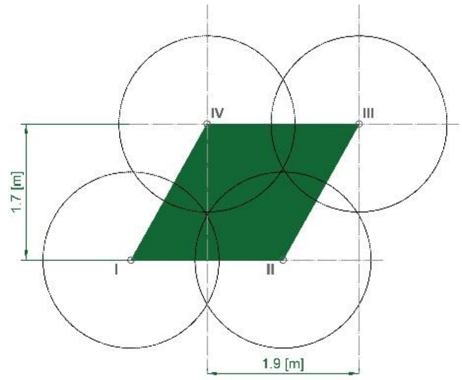

Figure 1. Grouting patterns in the test field.

Placing the grouting lances in the ground is associated with unavoidable deviations. The given deviations are measurable. The calculations in the next steps were carried out taking into account the measured lance distances.

2.4 *Measurement of the grout bodies*

A 3D camera (ToF) was used to precisely record the dimensions of the grout body. The ToF camera (Time-of-Flight) measures for each recording pixel the time required, which needs a light pulse for a round-trip between the camera and the obstacle. Each recording frame contains a 3D point cloud (x, y and z values). In order to be able to generate a complete 3D image, the point clouds from the various directions and angles must be combined with one another. This was done with the programs "CloudCompare" and "Matlab".

2.5 *Determining the grouting range*

The question that must be answered when planning a grouting measure is how the grouting materials spread in the soil. To answer this question, an analytical method was developed at the Institute for Soil Mechanics and Geotechnical Engineering of the Bundeswehr University Munich. This method is able to determine the range of grout, taking into account soil properties such as permeability, water content, suction tension and pore proportion as well as taking into account grouting parameters such as the physical properties of the grout, the grouting pressure and the delivery rate of the pump.

An assessment tool was developed using the presented method. Taking into account the time-dependent viscosity of grout, this tool can determine the development of the grouting pressure and range of grout over time. Figure 2 shows the program flow chart of the assessment tool.

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 soil on the test field was fully saturated. Therefore, the suction tension was not taken into account in the calculations.

Depending on the reaction time of the grout, the calculation is divided into i-time steps (see Figure 2). The smaller Δt is chosen, the more precise the results are. The developed analytical equation is used for i-time steps. The determined flow rate must not be greater than the maximum possible flow rate of the pump. In this way, the time courses of the grouting parameters can be calculated and the range of the grout can be predicted. 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.

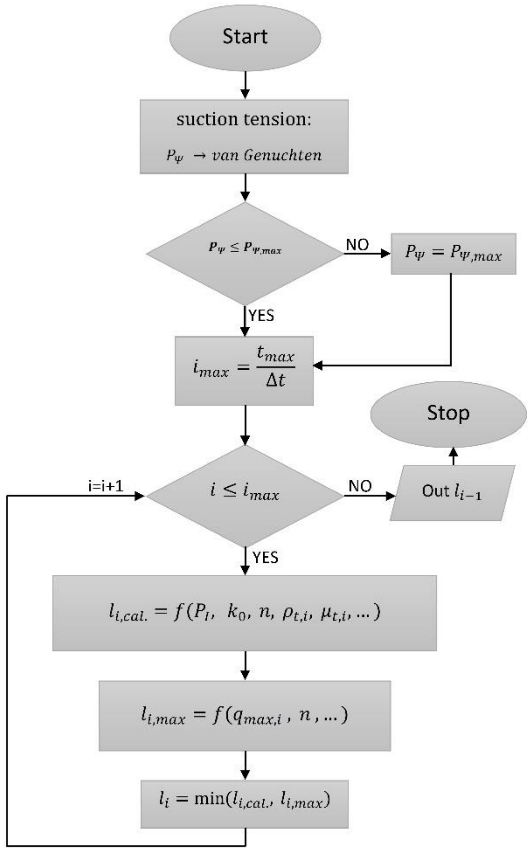

Figure 2. Flow chart of assessment tool.

The results of the presented analytical methods were validated by means of unidimensional grouting tests by varying the grouting pressure, mixing ratio and degree of saturation. A comparison between the measured and determined ranges shows that the range of grout in these tests can be determined with a good approximation using the presented method (see Figure 3). The analysis method developed was expanded for three-dimensional spreading shape (spherical, cylindrical and elliptical). For more information, see Forouzandeh, Boley and Tintelnot (2018).

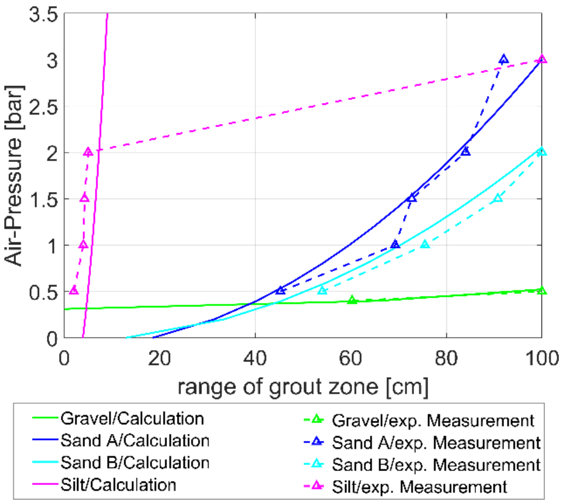

Figure 3. Validation of the developed method - Comparison between the calculated and measured grouting ranges for an acrylate gel.

Before the calculation, the pump must be calibrated by determining the friction and hydraulic losses and the transmission ratio of the pump. The pump used for the experiment is operated with air-pressure (P_{air}). Taking into account the pressure losses and the transmission ratio, the grouting pressure ($P_{grouting}$) for the 2-component pump can be determined using equation 2:

$$P_{grouting,i} = \underbrace{\boxed{36.47 \cdot P_{air}}}_{\text{Pressure ratio}} - \underbrace{\boxed{3.44 \cdot 10^2 \cdot \rho \cdot v^2/2}}_{\text{hydraulic loss}} - \underbrace{\boxed{8.7 * 10^5}}_{\text{friction loss}} \quad (2)$$

where v= average flow velocity; ρ= liquid density.

The flow rate or the grouting-pressure can be adjusted by adjusting the air-pressure during the grouting process. The grouting was carried out with a constant air pressure of 1.7 [bar]. This means that the maximum flow rate of the pump is approx. 8.0 [l / min]. 550 liters of grout were grouted into the ground per lance. The time dependent grouting parameters were determined using the developed assessment tool. The calculation results are shown in Figure 4.

With the set air pressure, a spheroid grouted body can be produced which is 2.56 [m] wide and 1.28 [m] deep. This requires 882 liters of grouting material. If 550 liters of material are grouted into the ground, the grouting body is 2.19 [m] wide and 1.10 [m] deep. Due to the difference in density between the grout and the groundwater, a drop of 4.53 [cm] is to be expected due to the effect of gravitational force.

Because of the overlaps with already solidified grouting bodies, few grout is used for the same dimensions of the grouting body. The size of the grouting body increases step by step, because the volume of grout per lance does not change (550 liters) and because of the overlap increases. The determined grouting ranges taking into account the overlaps are summarized in the Table 2.

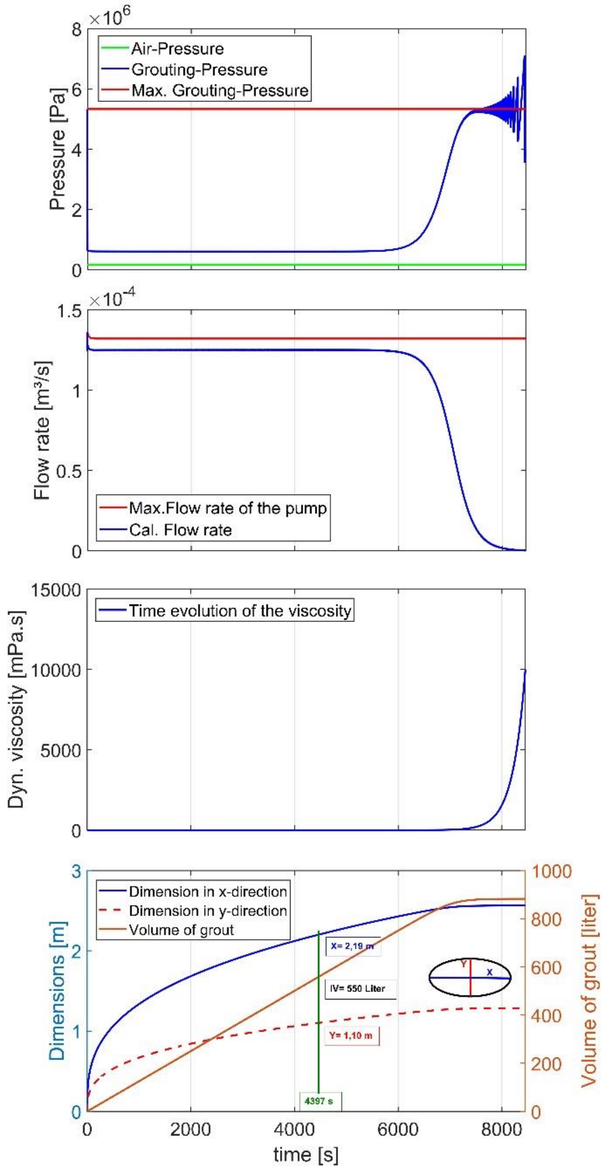

Figure 4. Calculated time course of the grouting parameters.

Table 2. Determined grouting ranges taking into account the overlaps.

Radius	*I*	*II*	*III*	*IV*
horizontal direction (R)	109.6	110.7	111.0	114.8
vertical direction (r)	54.8	55.35	55.5	57.4

2.5 *TOC analysis*

Total organic carbon (TOC) is a parameter for a wide variety of applications. Organic carbon in the soil is created by the decomposition of plant and animal residues and thus serves as the main food source for microorganisms and plants. The TOC analysis therefore provides basic information about the microbiological activities and organic substances in order to be able to assess the soil and sediments in this regard (Alloway 1999).

Acrylate gels consist of monomers which are transformed into polymers through radical chain polymerization. The basic components of these monomers are carbon atoms, which are primarily derived from petroleum, coal, etc. as the starting materials (Benedix 2011).

A TOC solid analyzer (soli TOC cube) from Elementar Analysensysteme GmbH was used to determine the total organic carbon content of samples. In the three-stage temperature ramp process with a heating rate of 70 [°C] per minute, the samples were heated to the prescribed temperatures of 400 [°C], 600 [°C] and 900 [°C], which were then held for a certain time. The carbon released at the respective temperatures combines with the carrier gas O_2 to form CO_2, which is measured by an NDIR detector. Nitrogen is used as an inert gas between measurements in order to avoid reactions with atmospheric oxygen (Benedix 2011). The carbon released at approx. 400 [°C] is the TOC_{400}. The ROC is the remaining oxidizable carbon, including elemental carbon, which is determined between the signal minima at 400 [°C] and 600 [°C]. This form of carbon is not bioavailable i.e. not environmentally relevant. The TIC (total inorganic carbon) is determined at 900 [°C]. For the following investigations, the TOC content was determined, which is calculated from the sum of the two parameters TOC_{400} and ROC.

The samples to be tested were not crushed, e.g. to exclude contamination from grinding tools and they were not acidified.

The grouting material that was used in the large-scale experiment was measured after the gel point had been reached.

The TOC values of the soil were determined using soil samples from the grouting field. All samples were taken 10 [cm] below the excavation subgrade with a scoop and a spatula in order to exclude contamination from the excavation vehicle as well as from carbon on the hands. A filling to the brim in closable glass containers should minimize the influence of the ambient air on volatile organic compounds. The subsequent storage took place in a lockable transport container on the construction site in order to keep the storage conditions of the samples identical and to reduce the effects of light. The above-mentioned measures were carried out to prevent or slow down chemical, physical and biological changes as far as possible. After the return transport, the samples were protected from light and stored at 3 [°C] until the measurement. The uniform weight in the crucible for the measurements was 0.1 [g]. The determined TOC values are shown in Table 3.

Table 3. Determined TOC values of the acrylate gel and the soil.

Sample type	*Acrylate gel*	*soil*
TOC value [%]	19.71	0.095

The measured TOC values show that the determined values of the soil samples and the values of the acrylate gel show a large difference. This dictated the TOC value as an indicative parameter for determining the spread of the grouting material.

3 EVALUATION AND RESULTS

3.1 *Comparison between the measured dimensions with calculation results*

To measure the dimensions of the grouting bodies, the upper half was exposed (see Figure 5). The height of the grouting bodies in different steals are shown on Figure 6. This figure was created from the images taken with the ToF-camera and post-processed with CloudCompare. The exposed volume was 9.515 [m³] and the surface area was 18.911 [m²].

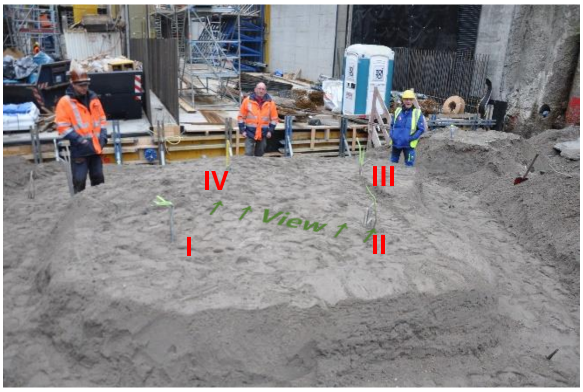

Figure 5. Exposed grout body with grouting sequence.

The measured and determined dimensions are compared in Figure 7. Despite the inhomogeneity of the soil, a comparison between the measured and determined ranges of grout show a good agreement. The assessment tool provides plausible results for the test grout. The dimensions of the grouting bodies are a bit larger than the determined dimensions. This is because the acrylate gels are hydrophilic and dilute in the groundwater. The effect of dilution can be considered as a safety margin in the calculations.

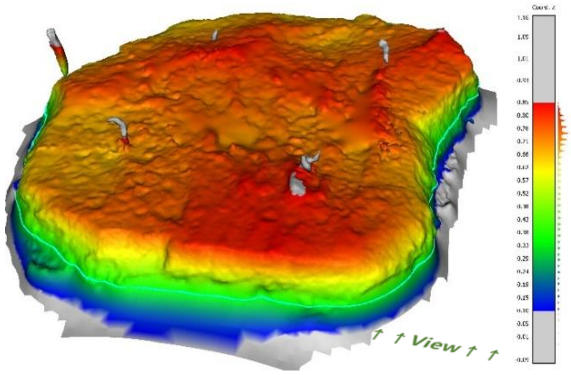

Figure 6. ToF camera recorded dimensions of the exposed grout body (height in the colors from blue to red).

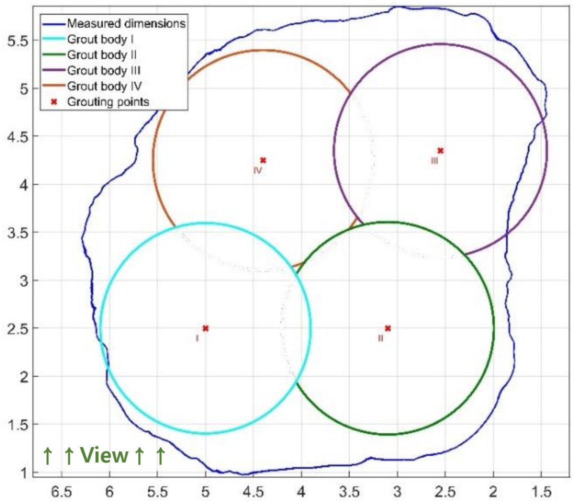

Figure 7. Comparison of the measured and determined dimensions.

3.2 *Comparison between the measured dimensions with TOC values*

The 5x5 meter extraction stand for TOC sampling (see Figure 8) was chosen on the basis of the assumption that a grouting body has a radius of approx. 1 [m]. A total of 39 samples were taken. Despite the large-meshed grid, a change in the TOC content and thus an indication of the dilution of the material at a distance from the grouting point can be seen. It can also be seen that some of the grouting bodies do not overlap at the examined height. It was therefore necessary to take a closer look at the cross-section.

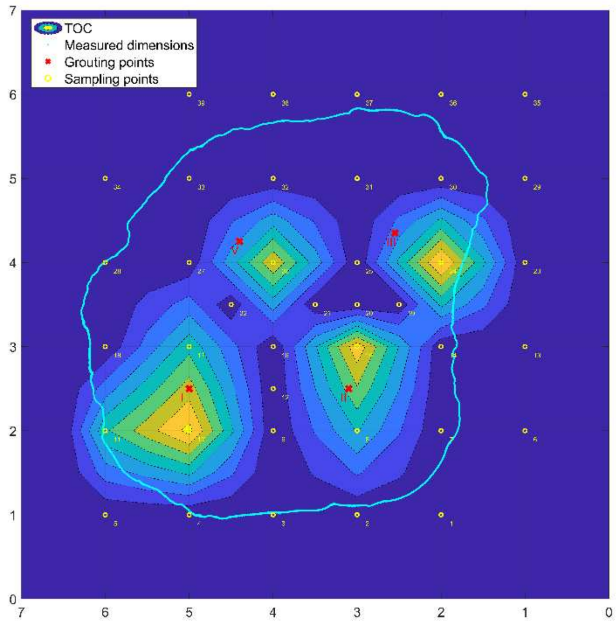

Figure 8. Comparison of the measured dimensions and those determined with the TOC values.

The in-depth effect of the groutings was examined with a cross-section at grouting sites I and II. The grouting bodies only overlap between the grouting points at a depth of 0.7 [m] with a height of 0.25 [m]. 5 verification measurements on the cross-section (see Figure 9) confirmed the measurements in Figure 8. The red extraction point in Figure 9 is at the same level as the top view of Figure 8. Assuming an effective porosity $n_e = 0.2$, the maximum achievable TOC content TOC_{max} is 4.018 [%]. All extraction points were evaluated in relation to the maximum possible TOC content.

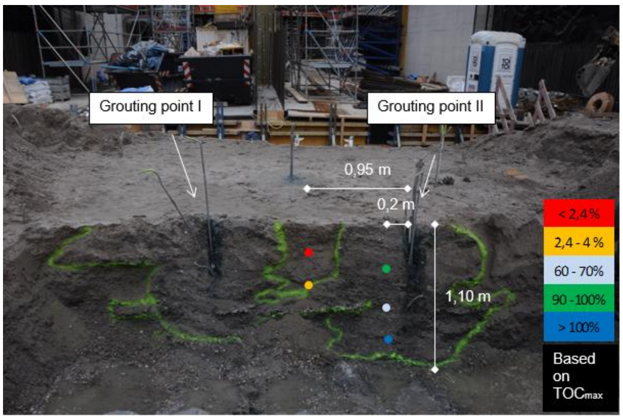

Figure 9. TOC sampling points in depth.

4 CONCLUSIONS

The presented results can be summarized as follows:

1. For the used grout, the development of the viscosity over time can be described as a good approximation with the model proposed by Finsterle, Moridis and Pruess (1994).
2. The dimensions of the grouting body can be easily measured with a high degree of accuracy using a ToF camera.
3. The calculations have shown that, despite the inhomogeneity of the soil, the range of the grouting material can be determined with a good approximation.
4. The acrylate gels are hydrophilic and dilute in the groundwater. The effect of the dilution is not taken into account in the calculations and can be considered as a safety margin.
5. Despite the large-meshed grid, a change in the TOC content and thus an indication of the dilution of the material at a distance from the grouting point can be seen.
6. The TOC tests can be used to determine whether or not acrylate gel is present in the soil. This allows conclusions to be drawn about overlapping of the grouting bodies. Therefore, the TOC value can be used as a safety-relevant indicative parameter for the spread of the grouting material in the soil.

5 ACKNOWLEDGEMENTS

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