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Ground improvement by creating a silicate grouted permeation plug in building pits

Amélioration du sol dans les excavations par la création d'un bouchon injecté à base de silicate

Thomas Sweijen
Crux Engineering BV & University of Utrecht

A.E.C. van der Stoel
Crux Engineering BV & University of Applied Sciences Amsterdam

ABSTRACT: Ground improvement by silica grouting is used on a large scale in the Netherlands in order to create a temporary artificial plug in building pits in sandy or gravely soils. Silicate grouting reduces the permeability in construction pits and prevents the use of underwater concrete, making the construction more economical and with less hindrance, disturbance and risks, especially in urban environment, than underwater concrete and/or dewatering. This article deals with several aspects of creating a silica grouted plug in building pits. After explaining the primary function and applicability, an elaboration on the design aspects is given, including guidelines for determination of groutability as well as for several laboratory tests. All methods of application are given and guidelines are discussed for execution, registration, dewatering and QA&QC. Special attention is given to the geochemical aspects of the grouting, including the grouting reactions, sensitivity for ground(water) pollution and the effectiveness over the lifetime. Also mitigating measures are discussed to be deployed when problems should occur with for instance D-walls, sheet pile walls and/or Cutter Soil Mix (CSM) walls. To conclude several case histories are discussed to illustrate the applicability with projects in civil engineering and high rise buildings / deep parking garages.

RÉSUMÉ : Les techniques d'injection sont beaucoup utilisées aux Pays-Bas pour réduire temporairement la perméabilité dans les excavations. L'injection de coulis à base de silicate (verre soluble) est la méthode la plus répandue pour ses avantages économiques et car elle limite les perturbations et les risques, en particulier en environnement urbain, comparé à du béton immergé ou au drainage de l'excavation. Cet article traite des différents aspects de la réalisation d'un bouchon d'injection en silicate dans une excavation. Dans un premier temps, les principales applications et propriétés de la méthode sont exposées. Ensuite sont abordées les différentes facettes de la conception ainsi que des directives pour la détermination de la capacité d'absorption du sol et pour les tests en laboratoire. Ces directives vont de l'exécution aux tests de qualité en passant par le drainage. Une attention particulière est portée à l'aspect géochimique du coulis, notamment les réactions, la question de la pollution des sols et la diminution d'efficacité avec le temps. Par ailleurs, des mesures d'atténuation sont évoquées en cas de problème avec par exemple une paroi moulée, des palplanches et/ou une paroi de type Cutter Soil Mix (CSM). Pour conclure, des cas sont étudiés pour illustrer l'application des bouchons d'injection sur des projets de génie civil et pour des immeubles de grande hauteur ou des parkings souterrains profonds.

KEYWORDS: Silicate grouting, ground improvement, permeation, building pits.

1 INTRODUCTION

Injection of soils, commonly known as the permeation grouting technique is frequently used to improve soil properties in civil engineering projects. Soil injections can stabilize and strengthen sandy soils allowing complex geotechnical engineering to take place and even reinforce foundations of monumental buildings [1]. Soil injections can also reduce the permeability of permeable layers in building pits. For example, in the Netherlands, where the groundwater tables are high, building pits often contain vertical walls (so called soil-retaining walls) and a horizontal layer of low permeability at the bottom. In combination with a minor dewatering activity, the building pit is dry for construction to take place. The horizontal layer can be an existing clay or peat layer, underwater concrete but also a soil injection layer of permeation grouting.

Permeation grouting can use various injection agents, such as cement suspensions and synthetic resins. However, the most frequently used 'grout' is a sodium silicate solution, which is injected alongside a solidifier and water. This solution is often referred to as "water glass". Sodium silicate solution that is mixed with a solidifier turns into a gel that closes the pores and eventually, depending on the percentage of sodium silicate solution and type of solidifier, glues the sand grains together. The mixture has a gelling time that varies between approximately 30 minutes and a couple of hours. Thus, the soil turns into a silicate-grouted plug.

To date, soil injections are frequently used in unconsolidated soils, which make up the Dutch subsurface. This article gives an overview of the state-of-the-art knowledge of soil injections and their applicability on geotechnical engineering.

2 APPLICATION OF SOIL INJECTIONS

Permeation grouting stands for the penetration of the soil with a liquid or suspension. Not surprisingly, the most important requirement for applying an injection is a high permeability of the soil; the success of soil injections depend on a good groutability of the soil. This groutability is closely related to the minimum pore size. Loam-, silt-, clay- and peat-soils have such a structure that they cannot be injected by means of a soil injection. Therefore, the application of soil injection is limited to sand and gravel layers. Various criteria exist in literature that relate the groutability to the grain size and grain distributions of the soil. The most practical evaluation of groutability is to evaluate the grain size distribution of a soil to the criteria of injections, as shown in Figure 1 (Van der Stoel, 2001).

In addition, layers of coarse gravel must be identified when evaluating the groutability of a soil. Particularly when the layers run obliquely (at an angle) through the intended soil injection layer. Coarse gravel layers are a potential risk of leakages in the soil-injection layer. An injection fluid can mix with groundwater in larger pores before it turns into a gel. In those cases, an injection of a cementitious material is more appropriate.

During the injection, flow of groundwater should be avoided to prevent movement and disintegration due to mixing of the injection liquid before it sets. In particular, caution should be taken with local dewatering activities that typically occur at construction sites, these local groundwater extractions exert strong gradients and flow that causes the injection to fail. Not only does a well affect the injection fluid, the injection fluid also has the potential to clog the well or drain. Ambient groundwater flow in the Netherlands is rarely an issue, simply because of its small hydraulic gradient.

3 PROPERTIES SOIL INJECTIONS OF WATER GLASS

Sodium silicate solution is a solution of dissolved silica (SiO2) with sodium hydroxide (NaOH) which is diluted with water. An injection fluid contains a mixture of approximately 20% water glass, 2% solidifier and approximately 78% water. Due to the high pH, caused by the presence of sodium hydroxide, dissolved silica remains in solution, such that the solution is injectable.

3.1 *Solubility silica*

An essential aspect of sodium silicate solutions is the amount of silica that can remain dissolved in water. For a neutral pH, the solubility of (amorphous) silica is approximately 0.1 to 0.2 g/l (Tarutani, 1989). The solubility of silica increases with temperature, but increases much stronger with increasing pH. Above a pH of 9 to 10, silica can remain in solution with significantly high concentrations for it to be valuable for engineering purposes.

3.2 *Polymer formation during condensation*

Dissolved silica in water glass can gelate (and eventually precipitate) due to a decrease in pH. This happens because dissolved silicon cations (Si^{4+}) with hydroxides (OH^-) are only stable at specific high pH values. If the pH value decreases, formation of silica polymers will occur (Owusu, 1982; Zhuravlev, 2000). During polymerization, silicon cations (Si^{4+}) will connect to each other via oxides (O^{2-}). The connection of Si^{4+} with O^{2-} is a stable connection (similarly to quartz, but amorphous). Figure 2 shows how an individual $Si(OH)_4$ molecule connects to various other $Si(OH)_4$ molecules to form a polymer. If sufficient molecules bind together, the polymer can grow and become visible. The polymer can grow into an individual grain (or colloid) or it can grow on sand grains (Dimas et al. 2009). Polymer formation results in gelation of the injection fluid. The degree of polymer formation determines the quality of a gel.

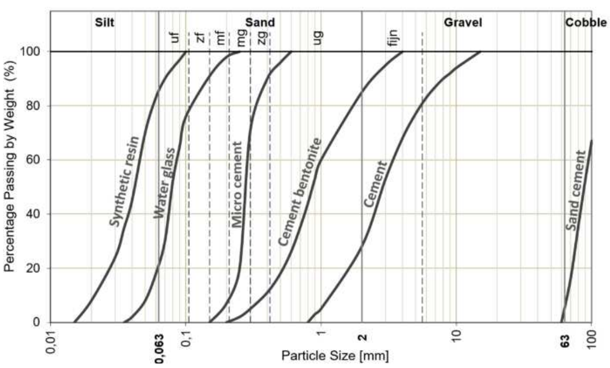

Figure 1. Lower limits of groutability with different kind of materials.

Gel is formed if the liquid is sufficiently ionic, that is, sufficient dissolved substances are present per volume of water. A firm gel can be obtained if complexes / polymers are also formed.

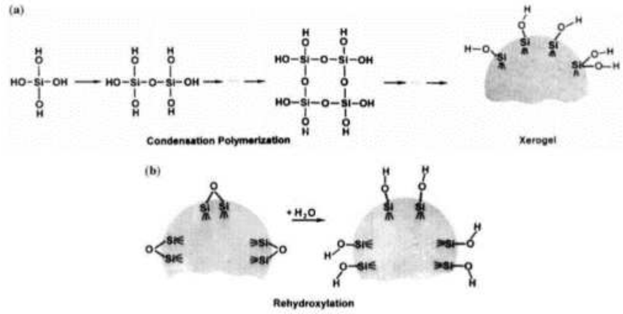

Figure 2. Forming of silicon hydroxides [5]

3.3 *Si/Na ratio and final quality of amorphous silica*

The final structure of the gel also depends on the type of water glass that is used. The ratio of dissolved silica to the sodium hydroxide solution (or alkali) appears to have a determining factor in this. This ratio ($^{SiO_2}/_{Na_2O}$) is approximately 3.22 for commercially used sodium silicate solutions.

3.4 *What is being injected into the soil?*

An injection of silicate grouting contains three ingredients, namely: sodium silicate solution, water and a solidifier. The mixing ratio of these ingredients depends on the intended properties of the injection, which are related to the purposes of the injection. A distinction is normally made between the following two applications:

- The realization of a flow-inhibiting layer. For this, a so-called softgel is injected, which contains relatively little water glass. The purpose of a softgel is to fill in pore spaces to reduce the permeability of the soil.
- Strengthening of the soil matrix. A so-called hard gel is used for this, which forms a structural layer. A hard gel contains a relatively large amount of water glass so that sand grains can be cemented by amorphous silica.

The terms softgel and hardgel should not be taken too literally: a softgel in its "cured" form is certainly not a gelatinous substance, but together with the injection medium (sand) forms a "sandstone-like" material.

3.5 *Solidifier*

To solidifier the injected solution, a hardener is mixed with the sodium silicate solution and water, so that the injection hardens to a certain extent. Solidifiers that lower the pH include Durcisseur, R100, triacetin, Condat stab soft, sodium carbonate. By lowering the pH, polymer formation of the dissolved silica is established.

3.6 *Neutralization*

The formation of a gel is typically described by a degree of neutralization of the hydroxide (Littlejohn et al., 1997). With a low degree of neutralization (20-30% of the hydroxide being neutralised) a soft gel is obtained and with a high neutralization (60-70%) a hard gel is obtained. The degree of neutralization indicates how much basic solution remains after the gel has hardened (in other words: how much base / alkali has been neutralized by adding acidifying hardeners). The properties of the gel strongly depend on the degree of neutralization.

4 HORIZONTAL PERMEATION GROUTING LAYER

A layer of horizontal permeation grouting acts as an artificial barrier against groundwater that has the potential to flow into a building pit from below (see Figure 3). The effect is comparable to that of a natural clay or peat layer, which can also close off a building pit from below. Together with vertical ground- and water-retaining structural walls, such as sheet piles or slurry walls, a dry building pit can be established where only a small flux of water has to be discharge. The methods has been used hundreds of times in the Netherlands alone over the past 30 years (Van der Stoel, 2013).

Layers of silicate grouting that inhibit groundwater flow are not suitable for permanent applications. The functioning of the layer is normally guaranteed for a period of up to 24 months. The layer will not suddenly disappear after that period, but the permeability will increase with time.

4.1 *Design*

Literature indicates that the permeability of a soil decreases by a factor 1000 when permeation grouting is used. Typically a hydraulic conductivity of 0,01 m/day is achieved by the injection layer within a medium to coarse sand, which often has a hydraulic conductivity higher than 10 m/day. When designing a soil injection, it is important to realize that these layers are flow-inhibiting layers. Contrary to what is required in many specifications, a fully water impermeable layer cannot be achieved.

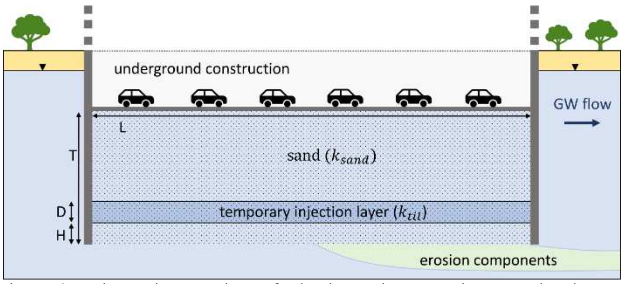

Figure 3. Schematic overview of a horizontal permeation grouting layer in the subsurface (Dekker et al., IN PRESS)

4.2 *Implementation*

The injection takes place via a series of injection points from where the injection fluid is injected into the soil. Injection points are typically aligned in a regular grid of points, where the distance between two points typically is 1,0 to 1,5m. The accuracy with which the points are placed is essential for the quality of the soil injection. At the surface, the accuracy of the location of points is easily obtained, but the accuracy at depths of 5- 15m below subsurface is difficult to obtain.

Injection points are established using a variety of methods among which:

- drilling;
- low-frequency vibrations;
- high-frequency vibrations;
- sonic intrusion.

After the injection points have been created at depth, the fluid is injected via HDPE tubes that go from the surface to a particular depth. At the tip of the tubing, the fluid will infiltrate the soil matrix and form spherical injection bodies (see Figure 4). The spherical injection bodies make up the injection layer.

During the injection, spherical injection bodies will grow and eventually overlap with neighboring injection bodies. The amount of injection fluid per injection point, and therefore the size of the spherical element, depends on the chosen injection pattern. The injection points are applied according to a preselected injection pattern (see Figure 5). The injection pattern consists of a triangle with equal sides, whereby the length of the sides can be varied. The amount of injection fluid per injection element is determined in advance based on the chosen pattern.
High accuracy of injection points is obtained with sonic drilling. At depths greater than 35m, sonic drilling has an accuracy of 1.0%.

Figure 4. Test box with spherical injection bodies.

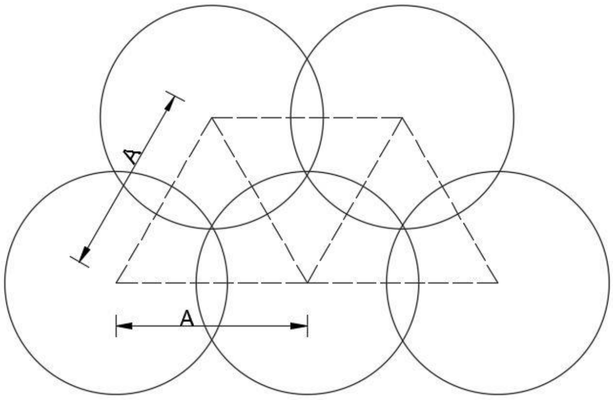

Figure 5. Map with injection pattern

4.3 *Influence of injection pressure and -flow rate when applying injection fluid*

To monitor the effectiveness of the injection layer, the groundwater table inside and outside the construction pit needs to be monitored during a pumping test. Thus monitoring of the groundwater drawdowns and pumping rates are essential. Pumping rates will be higher in the beginning of the dewatering activity, which is a result of drainage of the building pit and larger leakage rates that initially percolates through the sheet piles. When the pumping rates are stationary, the effectiveness of the soil injection layer is assessed and verified towards the requirements. The drop observed in the monitoring wells must then correspond to the pumped flow rate.

4.4 *Determining groutability*

Prior to a soil injection, the groutability has to be considered sufficient, for which an adequate number of soil samples must be taken. By performing sieve analysis in the laboratory, the grain size distribution and therefore the type of injection fluid can be established (based on Figure 1). After that, the correct mixing ratio of the injection liquid must be determined. For the mixing ratio, it is essential to know the existence of any soil or groundwater contamination as it affects the injection.

The injection layer must preferably be made after placing piles and/or anchors. In this way, the injection can be applied to close all the gaps between those elements. If the injection layer is placed prior, the risk of leakages is large as gaps between the injection layer and vertical elements may appear when installing these elements.

For drainage, it is important that the bottom of the drainage filters within the building pit are placed sufficiently far (1.5-2.0 m) above the soil injection layer, to prevent any execution errors and/or any negative influence of the injection material on the drainage.

4.5 *Durability*

A frequently asked question concerning silicate grouting is: how long will the injection last for? To answer this question, it is good to realize that a flow-inhibiting injection has different requirements than a constructive injection and strength and stiffness are no critical parameters.

The lifespan of a flow-inhibiting water glass injection is much shorter than that of a constructive water glass injection. Processes that decrease the lifespan of a flow-inhibiting layer are:

• Syneresis: gel shrinks and the permeability of the injected soil increases again.

• Physical erosion: erosion along imperfections of an injection layer such as along the connections of different injection spheres or along sheet piles. Along those imperfections, groundwater flow causes physical removal of the gel

• Chemical erosion: the dissolution of the gel as a result of passing groundwater which is often relatively acidic compared to the softgel

For the time being, the life span of a flow-inhibiting injection is not well known. Typically, in practice a lifespan of approximately 12 to 24 months is used for flow inhibiting soil injections.

4.6 *Reliability of dewatering systems (risk of clogging)*

Dewatering of a building pit, which has an injection of silicate grout is a tedious task. An injection increases the pH of groundwater in the building pit and consequently causes an increase in clogging rate of wells and drainage. Clogging can be caused by dissolved organic matter, residual silicates and mixing of groundwater with water that has a high pH. In practice, a couple of additional measures can be taken to increase the life time of a dewatering system. For example, it is recommended to divide the dewatering into two phases:

• start-up phase of draining the building pit;

• maintenance phase with maintaining the groundwater level in the building pit (whereby the focus must be on water stresses). Another aspect is to have sufficient space within the building side to replace wells and drains if they are clogged.

5 CONCLUSIONS

This article gives an overview of relevant aspects of applying soil injections of silicate grouting (a sodium silicate solution). Soil injections by permeation grouting are common in engineering projects to improve the soil conditions, either to strengthen the soil or to generate a flow-inhibiting layer. For building pits in unconsolidated soils, where groundwater is high, soil injections are valuable as a horizontal barrier against groundwater flow. It is important for applying soil injections to characterize the soil type and to consider the injection layer in the design of the building pit and to actively monitor the behavior of the water glass layer during its lifetime.

When permeation grouting soil injections are well-engineered, they can be employed as a powerful and versatile technique in civil engineering, in particular when groundwater levels are high, space is limited and soils are unconsolidated.

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