

Impact of chemical grout injection on urban groundwater

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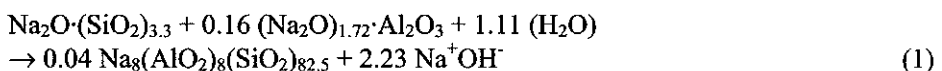
Abstract. In many urban areas, grout injections have been used to seal porous soil within the last decades. Silica hydrogels have been particularly applied in foundation engineering practice due to their wide applicability and economic advantages. For example in the City of Berlin between 1990 and 1995 about 100 000 m³ of silicate gels were injected into porous aquifers. Therefore the environmental authority of Berlin insisted on detailed investigations of potential groundwater contamination risks. This paper presents the results of detailed investigations on an excavation site over a period of two years. Two main topics are the use of artificial and natural tracers as well as transport modelling to quantify potential changes in groundwater chemistry and to predict both longevity and toxicity of silica grouts.

INTRODUCTION

Construction of horizontal grouted diaphragms, which are connected to impermeable vertical cut-offs, are required when excavations extend below the water table and groundwater lowering techniques cannot be used (Tausch, 1985; Nonveiller, 1989). Such diaphragms are usually 1–2 m in thickness. Because of the uplift pressure, they must be constructed at a level significantly below the proposed base of the excavation in order to prevent blow-out into the excavation (Bell, 1993). The design of a successful grouting programme requires the selection of a suitable grout material and the correct drilling equipment, procedures and grout-hole pattern (Karol, 1990). The most widely used chemical grouts are silicate grouts especially in medium and coarse sands. These chemical grouts are true solutions (Newtonian fluids) which contain no suspended solid particles and lack shear strength (Greenwood & Thomson, 1984; Littlejohn, 1985).

Silicate-aluminate grouts are dilute solutions of sodium aluminate (hardener) and sodium silicate, which are able to penetrate fine sands and sandy silts due to their low viscosity. On ageing the gel shrinks, becomes opalescent and cracks.

The commonly applied silica gel has a silica/soda ratio of 3.3 by weight. With the ratio of 2 vol. % sodium aluminate (Na₂O_m·Al₂O₃·18.9 H₂O), 18 vol. % filtered silica gel (Na₂O·(SiO₂)_n·27.6 H₂O) and 80 vol. % water the following chemical reaction occurs (Eiswirth *et al.*, 1997):



Equation (1) indicates that each mol applied silica gel produces 0.04 mol hydrogel mixture with albitic mineral composition and 2.23 mol caustic soda solution. As a result the pH value as well as the contents of sodium, silicate, aluminium and organic compounds are increasingly significant in the drainage water and temporarily in the adjacent groundwater. All chemical grouts are hydrogels and as such, may redissolve on prolonged contact with groundwater. The process of dissolution governs the permanence of the grout and grout treatment as well as the long term toxicity, if any, associated with such treatment.

CASE STUDY IN THE CITY OF BERLIN

In the City of Berlin about 100 000 m³ of silicate gels were injected into porous aquifers between 1990 and 1995, because groundwater lowering by dewatering techniques cannot be used for large excavations due to environmental hazards. The environmental authority of Berlin (SenSUT) therefore insisted in 1995 on detailed investigations of potential groundwater contamination risks due to silica grout injections. In February 1996 the Department of Applied Geology, University of Karlsruhe selected a test excavation in Berlin in order to carry out detailed field investigations (Fig. 1).

Geology and hydrogeology of the excavation site

The selected excavation site, Ringcenter II, is situated in the southern part of the Barnim upland area located at the boundary of the Warsaw-Berlin stream channel (Fig. 1). At this location glacial sands with a thickness of around 2 m are underlain by till with a maximum thickness of 12 m thinning-out to the stream channel boundary in the south. The till layer is underlain in places by a silt. The main aquifer below consists of medium to coarse grained glacial sands.

The main aquifer is located in the lower glacial sands and is bounded above by the silt and/or till at nearly 22 m above mean sea level (m a.m.s.l.), and below by Miocene brown-coal clay at about 90 m below sea level. The aquifer is confined with an estimated average thickness of around 110 m. Pumping tests, tracer tests and grain size analyses enabled the estimation of the following hydrogeological parameters: hydraulic conductivity (K) = 4.5×10^{-4} m s⁻¹, effective porosity (n_e) = 0.25, storativity (S) = 2.2×10^{-3} and transport velocity (v_a) = 0.3 m day⁻¹.

For the hydrological and hydrochemical investigations 28 of the exploration wells have been lined out to groundwater observation wells (Fig. 1).

The finite element simulation system FEFLOW[®] elucidates a regional groundwater flow from northeast to southwest with a gradient (I) of about 0.002. In the neighbouring area of the excavation, the groundwater flow changes direction but turns back after passing the excavation. With the numerical model it was possible to elaborate the exact position for the groundwater observation wells to place them directly downstream of the excavation. Consequently the hydrological and hydrochemical observation of the entire area downstream of the excavation Ringcenter II was permitted.

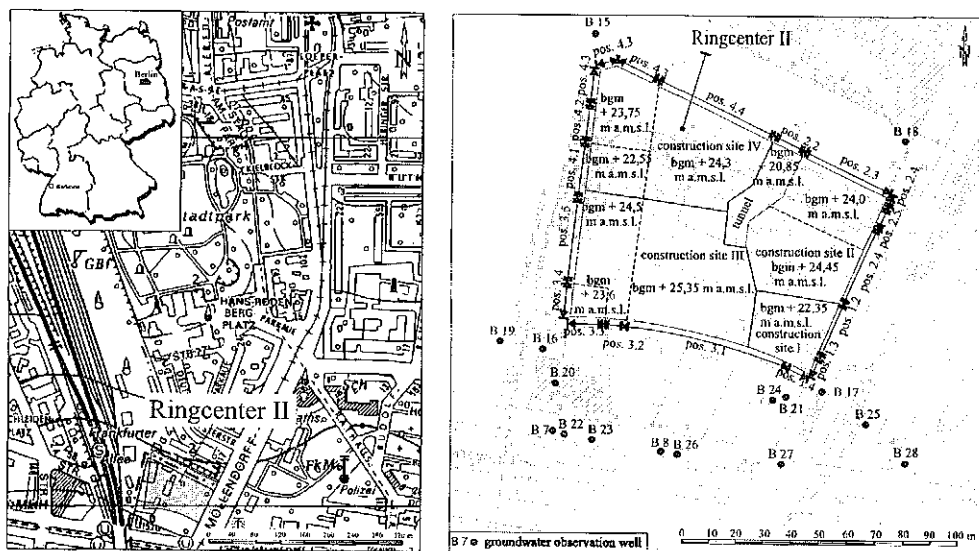


Fig. 1 Maps of the excavation Ringcenter II in Berlin, Germany and of the four main construction sites of the excavation with the position of the groundwater observation wells (bgm = base grout membrane).

The hydrochemical analysis of the groundwater has identified water of hydrocarbon, alkaline origin with a slight corrosive character. The parameters of pH-value, specific electrical conductivity (SEC), and chemical ion composition show values below the groundwater protection list of the City of Berlin.

SITE INVESTIGATIONS

In 1995 the Department of Applied Geology, University of Karlsruhe, started with detailed field investigations on a selected excavation in Berlin. Besides geological and hydrogeological studies, extensive chemical analyses have been carried out every week within 15 groundwater observation wells surrounding the excavation. The results of laboratory column and batch tests, together with the groundwater analyses after grouting, enabled the selection of groundwater parameters as natural tracers. In comparison to the transport behaviour of the natural tracers Na^+ , Al^{3+} and SiO_2 , the artificial tracers uranine, pyranine and sulphorhodamine were injected during different tracing experiments. The results lead to an estimation of the transport velocity v_a of about 0.30 m day^{-1} under natural flow conditions with a hydraulic gradient $I = 0.002$ (Eiswirth *et al.*, 1997). These results verified the data yielded from grain size analysis, pumping tests and numerical modelling.

Hydrochemistry of drainage water and groundwater

In order to estimate the influence of silica grouts on the adjacent groundwater, hydrochemical analyses of 28 groundwater observation wells, in addition to drainage water, have been carried out frequently (Fig. 1).

Drainage water The analysis of drainage water carried out during the dewatering period showed sodium, aluminium and silica as the chemical parameters significantly increasing in groundwater that contacted silica gel. Therefore these parameters can be used as natural tracers to estimate groundwater contamination by silica grouts. Beyond this, equation 1 indicates the formation of caustic soda solution which causes a distinct increase in the pH-value. As a result, humic substances are leaching out of the organic components of the sediment and this is expressed by the significant increase in the DOC and SEC (Fig. 2).

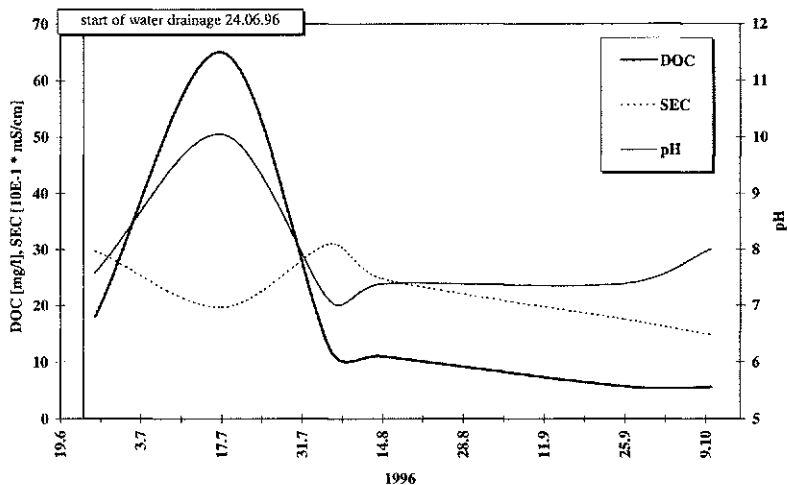


Fig. 2 Variation of the DOC, SEC and pH of the drainage water from excavation Ringcenter II.

Groundwater In contrast to drainage water, the groundwater showed no significant hydrochemical variations caused by the grouting. For example, the groundwater observation well B 17, at a distance of about 12.5 m downstream of the excavation, indicated no significant changes in water chemistry. All the hydrochemical variations in the groundwater observation well B 17 shown in Fig. 3 are unrelated to the silica gel grouting and are in fact of entirely natural origin.

The hydrochemical data for all other observation wells underline these results. Additionally it should be remembered that more than two years had passed since the grouting period started. Therefore it must be mentioned that there is a strong hint that the influence of silica grouting on groundwater is reduced to a zone of only a very few metres downstream of the silica grout diaphragm. This distance varies depending on the aquifer type.

Hydrochemical modelling and mass balance

For the injection of the silica grout diaphragm at excavation Ringcenter II, the following materials were used: 112.2 tons Solidur 274 S (sleeve grout), 1056.51 tons filtered silica gel, 108.96 tons 200 SB (sodium aluminate) and 3621.8 m³ water (Table 1).

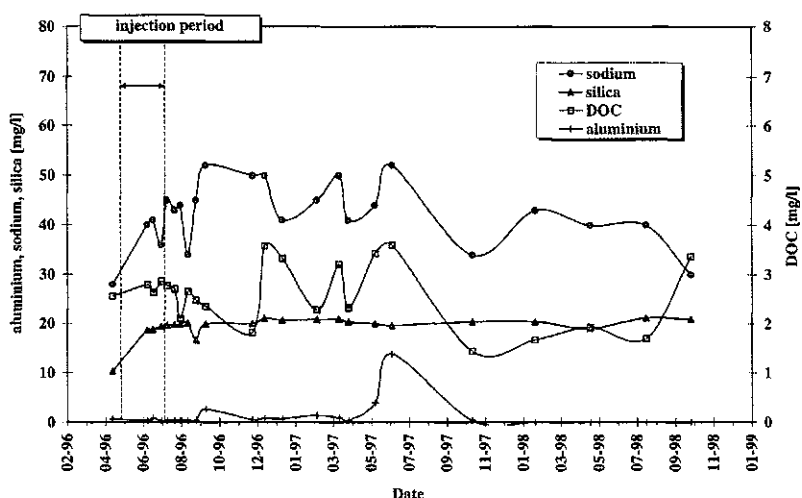


Fig. 3 Variation of aluminium, silica, sodium and DOC of groundwater observation well B 17.

Table 1 Silica gel grouting data of excavation Ringcenter II.

Construction sites	Injection period	Injection points	Injected grout mass (m ³)
Site I	5–18 June 1996	459	278.93
Site II	1–29 July 1996	1480	1151.64
Site III	12 June–10 July 1996	1763	1406.06
Site IV	11 July–7 August 1996	1422	1131.26
Total	5 June–7 August 1996	5124	3967.89

The calculations in Table 2 shows exemplarily the sodium compounds theoretically washed out of the diaphragm and pumped to the surface with the drainage water up to October 1996. Until October 1996, the sodium output with the drainage water is only about 7% of the input mass of the silicate grouts (Table 2).

Using equation (1), the injected 1056.51 tons of silica gel ($= 1.396 \times 10^6$ mol) produces a theoretical maximum of 3.113×10^6 mol NaOH equivalent to a theoretically leachable sodium mass of 71.6 tons. Hydrochemical analysis of the injected silica

Table 2 Sodium concentrations in drainage water and output mass calculation.

Start	Drainage water output (m ³)	Interval (day)	Output during interval (m ³)	Mean rate of prodn. (m ³ day ⁻¹)	Sodium conc. (g m ⁻³)	Sodium background (g m ⁻³)	Sodium output (gross) (g)	Sodium background (g)	Sodium output (net) (g)	Input (g)	Output (%)
24 June 1996											
25 June	10	1	10	10.00	54	40	13 500	10 000	3500		
17 July	260	22	250	11.36	420	40	705 200	162 400	1 542 800		
5 August	4320	19	4060	213.68	120	40	187 200	62 400	124 800		
14 August	5880	9	1560	173.33	180	40	708 000	824 000	2 884 000		
10 October	26480	57	20 600	361.40	100	40	267 000	106 800	160 200		
23 October	29150	13	2670	205.38							
Sum		121					5 880 900	1 165 600	4 715 300		
							Chemical analysis (Sodium content = 2 vol. %)			8.51E+07	5.54
							Reaction equation (with 1056 to silica gel)			7.26E+07	6.50

grouts (sodium aluminate + silica gel + water) yielded a sodium concentration of 2 vol. %. With the total gel injection mass of 4338.3 tons, a total of 86.77 tons sodium is put into the ground with the gel. This means at least 15.17 tons of sodium (= 17.5%) must be fixed within the gel diaphragm and is not leachable to groundwater.

In order to investigate the reactions and reaction products within the silica gel solution and the adjacent groundwater, geochemical calculations with PHREEQE (Apello & Postma, 1994) have been carried out. Using the chemical analysis of the silica gel solution applied at excavation Ringcenter II, the theoretical gel solution composition was calculated. As shown by Eiswirth *et al.* (1997) for the silica gel solution applied at Ringcenter II, mainly feldspars and voids have been produced and precipitated.

Beyond the above mentioned calculation, the mixing model of PHREEQE has been applied to model the mixing/titration of the silica gel solution with the groundwater. The results yielded, for nearly every mixing ratio, variable species distributions (Eiswirth *et al.*, 1997). For example Na-species (Na^+ 77%, NaHCO_3 22%), Al-species (AlOH_4^- 97%) and Si-species (H_4SiO_4 99%) have been mainly produced with the aluminium compounds occurring to 97% as aluminate which is regarded as immobile. Nevertheless, NaHCO_3 is formed and less than 77% of the total injected sodium is theoretically mobile in the mixing solution of silica gel and groundwater. This means that with the drainage water up till October 1996, more than 23% of the total injected sodium has been washed out of the gel diaphragm.

Using the results of the geochemical modelling and the laboratory tests, a numerical simulation of the leachates from the gel grout diaphragm will be carried out. In conclusion it can be stated that NaOH is leached out of the silicate grout diaphragm, but due to reactions within the buffering capacity of the aquifer, the dissolved Na^+ and OH^- ions will be fixed mainly as immobile carbonates and aluminates.

Laboratory tests

In order to carry out detailed investigation of the limited reaction zone between silica gel and groundwater, a special laboratory test was designed. Permeation and column tests with the original sediment from the excavation Ringcenter II, started at the beginning of 1998, as well as large scale laboratory tank experiments (Fig. 4). The main scientific goal of these tests will be the determination of chemical reaction isotherms. With the isotherms obtained, it should be possible to include complex geochemical processes within the three-dimensional (3D) transport modelling.

Numerical simulation of leachate transport and balancing

With the help of a 3D numerical transport model of the effluence of leachate and contaminants out of the silica grout diaphragm, a quantitative evaluation of the long-term behaviour of the diaphragm on the groundwater quality will be elaborated. The required hydrological and hydrochemical parameters have been produced by different scaled batch and percolation tests. With the results of the time-dependant chemical concentrations, the sorption and desorption isotherms can be quantified with the software program COTAM[®].

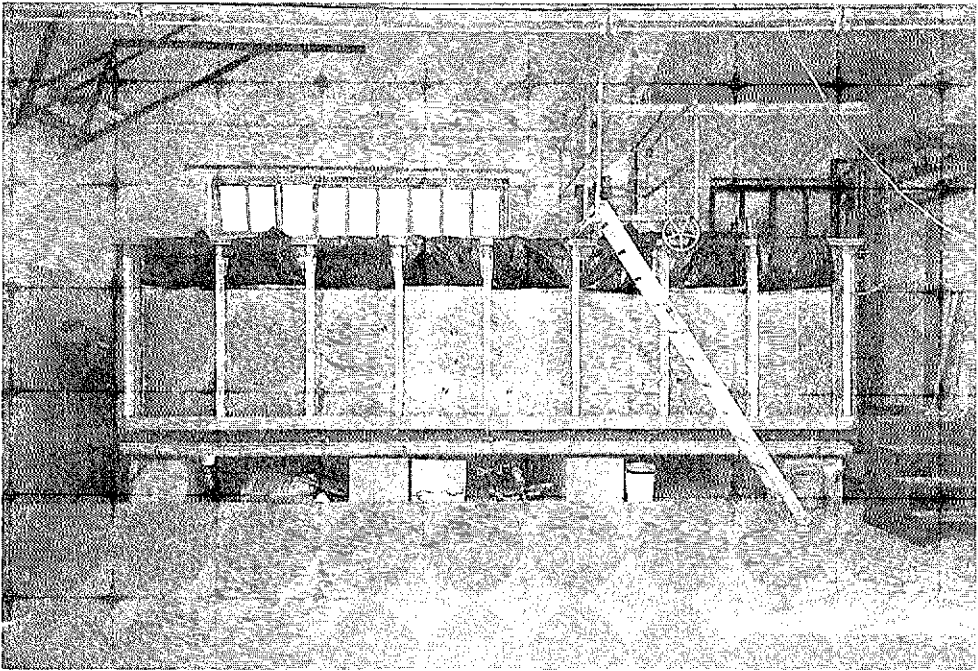


Fig. 4 Laboratory tank experiment.

These chemical species-dependant isotherms will be incorporated into a 3D numerical transport model, using the finite element simulation system FEFLOW®.

CONCLUSIONS

At the end of the investigation period (1998) no significant changes in groundwater chemistry had been detected. Only minor increases of sodium and silicate occurred in one observation well 8.5 m downstream of the excavation. Pumping tests and forced gradient tracer tests yielded an actual groundwater velocity of $3.5 \cdot 10^{-6} \text{ m} \cdot \text{s}^{-1}$ within the sandy porous aquifer.

The results of our investigations already show that the influence of silica grouting in porous aquifers is not as alarming as was previously supposed. Further effort will be placed on detailed investigation of hydrochemical and mineralogical processes in the zone of direct contact between groundwater and silica gel as well as the adjacent area some metres downstream of the silica grout diaphragm. The results of laboratory analyses (column tests, permeameter tests, X-ray diffractometry) combined with the hydrochemical analysis will be used as the basic input data for the 3D transport modelling. The main effort of the modelling concentrates on quantifying the potential toxic threat and predicting the geochemical balance of the system for a period of about 10 years.

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