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Environmental remediation and geotechnical design in a cyanide-contaminated area

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ABSTRACT

In the frame of a construction project in a metropolitan area, a cyanide-polluted site was treated. The area has been the target of numerous construction and demolition projects over the past few decades, but the underground portions of facilities, including an underground tar pit, remained. Soil investigations performed at the site revealed soil contamination by cyanides (total cyanides: max. 210 mg/kg, 610 µg/l), polycyclic aromatic hydrocarbons (PAH; max. 10,000 mg/kg, 200 µg/l) and total petroleum hydrocarbons (TPH; 2,300 mg/kg, 490 µg/l) to depths of up to 13 m below ground level (bgl).
In consideration of maximum efficacy in soil remediation and the planned construction, it was decided that the entire site be excavated to a depth of approx. 8 m bgl for which a geotechnical design was required. Specific project challenges included the partly unknown state and extent of underground facilities and contamination, the constrained space due to adjacent buildings and the tramway running along the adjacent street. Due to these boundary conditions, numerous types of excavation pit liners were designed, such as bored piles, overcut bored piles and soldier pile walls.
A groundwater remediation plant was installed prior to the start of excavation to treat the cyanide groundwater contamination and prevent the migration of further pollutants off-site. Throughout the soil remediation measure, cyanide concentrations in groundwater decreased from approx. 1,500 µg/l prior to remediation to less than 50 µg/l, therefore meeting the target remediation value and successfully remediating the groundwater plume.

Keywords: geotechnical design; groundwater; cyanide; remediation

1 INTRODUCTION

The German federal state North Rhine-Westphalia used to operate approximatively 230 coal gasification plants (Ministry for Environment, Agriculture, Conservation and Consumer Protection of the State of North Rhine-Westphalia, 2003). Coal employed for pyrolysis is subsequently cooled and cleaned of unwanted by-products using a washing medium such as ammonia solution. By-products refer to tar products collected in tar pits, and cyanide-enriched solid waste, which was usually used for levelling the ground or spread for regeneration. This could lead to an enrichment of cyanides in soil and groundwater. Cyanides are a group of chemical compounds that contain in their structure the –C≡N functional group. In the environment, cyanides can be found in many different forms (e.g. hydrogen cyanide or complexes). Hydrogen cyanides are rapidly acting, highly volatile toxins that inhibit oxygen transfer into cells and may cause serious health problems. On the other hand, cyanide complexes are more common (in the environment), less toxic and some of them are used in the food industry. However, complexes of cyanide disaggregate when exposed to UV light creating free toxic cyanides. Moreover, some cyanide complexes are very soluble in water. Therefore, it is essential to remediate the cyanide contamination at the project site. Several techniques are employed for the pollution remediation, e.g. Haneef et al., 2020; Patel et al., 2020; Dhar et al., 2022. This work aims to illustrate both environmental remediation and geotechnical design of a project site of approx. 4,000 m² located near the centre of a metropolitan area in Western Germany (Fig. 1), which was used as coal gasification plant in the late 19th century. During the last decades, the site has been subject to various construction and demolition activities, while the underground sections of the coal gasification plant relevant to environmental contamination were left untouched. The main challenge for the remediation of the site were the unknown size and condition of these underground facilities. Previous soil and groundwater investigations revealed an underground tar pit and both soil and groundwater contamination mainly by cyanides but also by polycyclic aromatic hydrocarbons (PAH). The excavation of the contaminated soil was chosen as the most effective and less costly rehabilitation procedure. This allowed the construction of a multi-storey office building with two basement floors for underground parking after the completion of the excavation works.

Geotechnical challenges during design included the densely populated area and limited available space due to a tramway running in an adjacent street, extra construction measures to uphold escape routes from surrounding office buildings, limitation of machine size and number of disposal trucks to avoid disruption of tram-line traffic. Moreover, it was intended to connect the new building to the two-storey basement of one of the existing buildings. These boundary conditions resulted in the design and installation of various types of excavation pit lining (i.e. anchored bored piles, anchored soldier piles and jet grouting).

To avoid further groundwater contamination by mobilization of contaminants caused by the installation of the excavation pit lining, general disruption of soil during the excavation, the removal of the surface sealing and use of heavy machinery, a groundwater remediation plant was installed prior to starting the excavation and operated throughout the excavation works.

2 GEOLOGICAL AND GEOTECHNICAL BACKGROUND

2.1 Geological setting

The study area is located in the Rhine area in West Germany. It belongs geologically to the Lower Rhine Bay. Below the fillings, near the surface in the investigation area, Holocene deposits are present, which

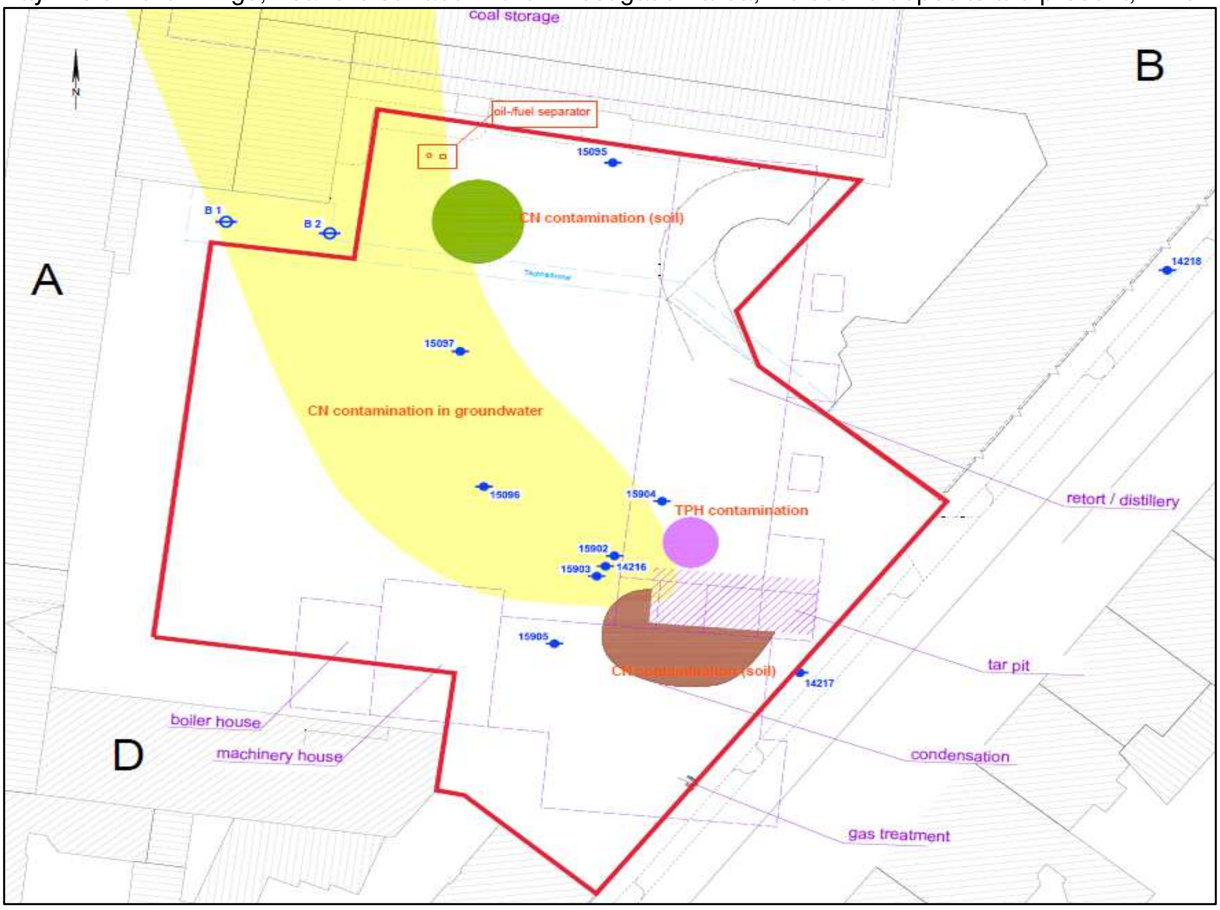

Figure 1. *Site overview including previously known contamination areas and former buildings:*

consist of loamy-sandy high flood formations. Below that, clastic sediments from the Weichselian glaciation are located. These are formed by sand and gravel from an older lower terrace. Concerning the study area, the quaternary sediments reach a maximum of 20 m thickness. The Quaternary sediments overlay tertiary silty fine sands, which were not revealed by the investigations performed at the site.

2.2 Geotechnical parameters

As part of the subsoil investigation, the following direct and indirect subsoil investigations were performed for site characterisation for geotechnical and waste-related laboratory analyses:

- 6 small percussion boreholes exploration (up to 16.0 m depth below ground level);
- 12 heavy dynamic probing (DPH 101 to DPH 112), (up to approx. 16.0 m depth below ground level).

A predominantly homogeneous subsoil stratification was interpreted from small percussion bores. A non-cohesive soil, sometimes mixed-grain to cohesive fillings were identified up to 1.3 and 3.7 m a depth, which overlay a sand and gravel unit up to16 m thickness. In the west and east areas soil profiling consists of gravel content with varying percent of sand content. In the middle and in the north of the area, sand with different percent of gravel was observed at different depths. In some locations, a 0.4 to 0.7 m thick sandy silt unit was encountered above the lower terrace.

Tab. 1 summarize soil unit description and corresponding geotechnical parameters obtained from laboratory. Permeability values of the different layers were obtained according to DIN 18130 (2015) providing values from 1 x 10^{-3} m/s (for the sand and gravel layer) to 1 x 10^{-9} m/s for silt layers.

In addition to general geotechnical parameters, grain size distribution, consistency limit and water content were measured from soil samples. Particle size distribution (PSD) and sedimentation to determine the particle size distribution was carried out in accordance with DIN 18123 (2011). The state limits were determined in accordance with DIN 18122 (1997). The water content was determined in accordance with DIN 18121 (1998). Results are summarized in Tab. 2.

Table 1. *Geotechnical parameters of the area*

Layer	Description	Thickness (m)	Dry density (kN/m^3)	Friction angle (°)	Cohesion (kPa)	Elastic modulus (MPa)
Filling soil	Gravel, sandy, partly silty, partly slightly silty. Sand, slightly gravelly to heavily gravelly, partly slightly silty	1 to 6	9-11	25-30	≈0	6-20
Silt	Silt, very sandy, slightly clayey to clayey, slightly gravelly	0.4-0.7	10	25	5	6
Sand and gravel of the lower terrace	Sand, slightly gravelly to heavily gravelly Gravel, sandy to very sandy, partly slightly silty	>3 for sand >14 for gravel	11	35	0	40-80

Table 2. *Laboratory soil properties*

Sample	Depth (m)	Test	Value (%)
MP 1	6.5-7.4	PSD acc. to DIN 18123	0/5.3/51.4/43.3 [a]
MP 2	2.0-2.3	Water content acc. to DIN 18121	w_n = 15.9 [b]
MP 2	2.0-2.3	Atterberg limits acc. to DIN18122	LL = 25.5 PL = 13.9% PI = 11.6% I_C = 0.65
MP 3	2.0-2.3	PSD acc. To DIN 18123	21.3/32.1/41.8/4.9 [a]

[a] Clay/Silt/Sand/Gravel

[b] LL = liquid limit; PL = plastic limit; w_n = natural water content; PI = plasticity index; I_C = consistency index

2.3 Typical groundwater conditions

The study area is located within the catchment area of the Rhine River, which is located approx. 1.5 km northwest of the site. The general groundwater flow direction is to the northwest towards the Rhine river at a hydraulic gradient of approx. 0.002 (0.2 %). The main aquifers at the study area are the sand and gravel in addition to the fine sands and silts, which form one coherent porous aquifer.

The bottom of the quaternary lower terrace sediments was found to be at 11-14 meters above sea level (m asl) in drillings in the surrounding area. The total aquifer thickness of quaternary and tertiary sediments is estimated to range between 15-18 m. According to pumping tests, the hydraulic conductivity of sediments can be quantified of about $4x10^{-3}$ m/s and approx. $1x10^{-5}$ m/s for the Quaternary and Tertiary sediments respectively. The average groundwater level is stated to be 28.2 m asl, (i.e. approx. 8.4 m bgl). Depending on the season, the groundwater level at the site varies between 27 m asl and 30.5 m asl according to measurements obtained from 1990 to 2022 (Fig. 2).

In case of flood events, the groundwater flow direction change to the north or northeast and the hydraulic gradient decrease to 0.00007 (0.07%). Due to the high hydraulic conductivity and proximity to the Rhine River, the groundwater level changes at short notice when floods occur.

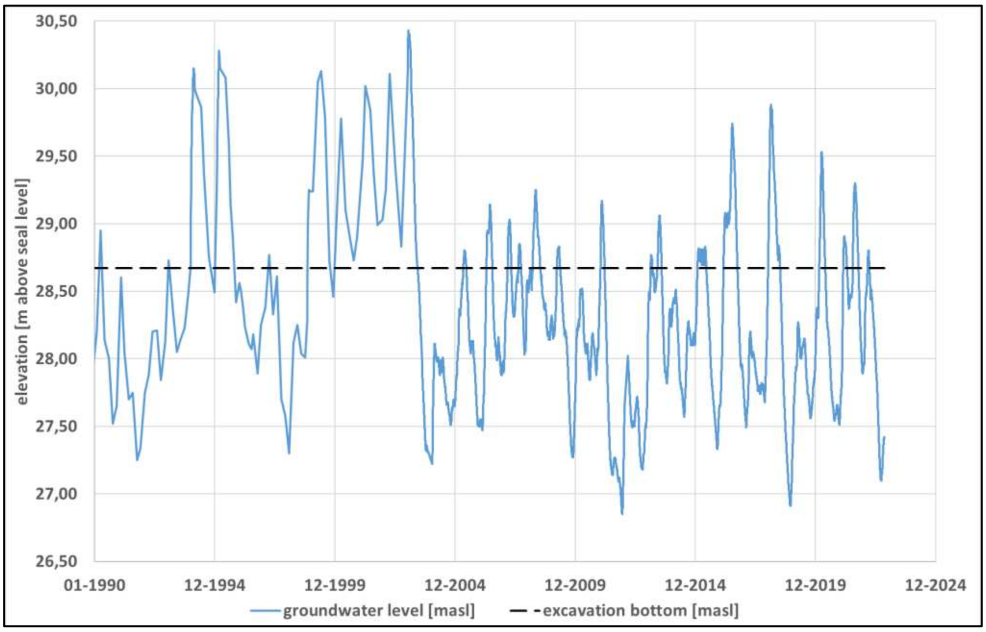

Figure 2. *Measured groundwater level at* Rhine River*.*

2.4 Contamination background

During the last two decades, several environmental investigations were performed at the site to investigate the source of cyanide contamination in groundwater and the environmental impact of the coal gasification plant. Investigations showed that the site still featured an underground tar pit of unknown depth and size, which was congruent with the suspected source area of cyanide contamination. Nearby a small-scale TPH impact by total petroleum hydrocarbons (TPH) was found in soil. In the northern part of the study area, the investigations revealed further soil contamination by cyanides. The maximum concentrations detected during soil investigations were 210 mg/kg CN_{tot}, 10,000 mg/kg PAH and 2,300 mg/kg TPH in soil and 610 µg/l, CN_{tot}, 200 µg/l PAH and 490 µg/l TPH in leachate. Previous groundwater investigations detected two cyanide contamination plumes originating from the site of the previous coal gasification plant. The area of the former gasworks exceeded the area of the remediated site considerably. In 2019, the western plume was characterized by maximum cyanide concentrations in the range of 100-500 µg/l and a plume length of about 400 m, while the eastern plume featured cyanide concentrations in the range of 500-1,000 µg/l and a plume length of approx. 100 m. The plume is delineated by a concentration isoline of 50 µg/l cyanides according to German guideline values (insignificance threshold values). The western plume has been under remediation since 2012 and is not subject of this paper. At the start of this project, groundwater remediation of the eastern plume had not yet begun. Groundwater investigations at the site revealed contamination by cyanides only, which were concentrated on the upper approx. 3 m of the aquifer. Groundwater monitoring wells screening at larger depths showed no cyanide impacts.

To remediate the soil and groundwater impacts, the environmental agency and the property owner agreed on meeting specific target remediation values for CN_{tot}, CN_{free}, PAH, Naphthalene and TPH in unsaturated soil, saturated soil and groundwater (see Table 3).

Table 3. *Target remediation values*

Sample			CN_{tot}	CN_{free}	PAH	Naphthalene	TPH
Unsaturated soil	Soil	mg/kg	100	-	10	10	1,000
	leachate	µg/l	50	10	0.2	2	200
Saturated soil	Soil	mg/kg	3	-	5	5	500
	Leachate	µg/l	50	10	0.2	2	100
Groundwater		µg/l	50	10	0.2	2	100

3 METHODOLOGY

3.1 Investigations of contaminated areas

3.1.1 Raster soil sampling

During excavation, it was found that cyanide contamination in soil was heterogeneously distributed regarding location, depth and magnitude. Therefore, additional soil investigations were performed to facilitate the excavation and disposal process. The respective areas of known cyanide contamination were divided into sections of approx. 5x5 m². Then one percussion drilling was performed at the centre of each section to a depth of approx. 8 m to investigate the entire soil profile until reaching the planned excavation depth. Soil samples were taken for each soil unit, at one meter frequency and in case of organoleptic conspicuities. Soil samples were mainly analysed for CN_{tot} in soil and leachate and PAH in soil. Areas with known or suspected TPH contamination were additionally analysed for TPH concentration. A total of 38 percussion drillings were performed at the site. Analyses of cyanides (CN_{tot} and CN_{free}) in soil were performed according to ISO 17380:2013 in soil and according to ISO 14403-2:2012 in leachate, both using the continuous-flow analysis method. PAH were analysed according to ISO 18287:2006 (gas chromatography with mass spectrometric detection; GC-MS) in soil and according to ISO 17993:2002 (HPLC with fluorescence detection after liquid-liquid extraction) in leachate. TPH analyses were performed by gas chromatography according to ISO 16703:2004 in soil and according to ISO 9377-2:2000 using solvent extraction and gas chromatography for leachate analysis.

3.1.2 Soil investigation at tar pit

To prevent migration of contaminants within the tar pit, soil investigations through the base of the tar pit were avoided. After removal of the tar pit, additional soil investigations were required to assess potential leakage of it and to provide a general overview of contamination underneath it. If contaminant concentrations were above the target remediation values or conspicuous, further drillings were required to greater depths to assess and delineate the contamination. In total, 11 percussion drillings were performed to a depth of at least 10 m below the groundwater level. The maximum depth was

16.2 m depth. Soil samples were taken for each soil layer at one meter frequency and in case of organoleptic conspicuities. Soil samples were analyzed for all target contaminants (CN_{tot}, CN_{free}, PAH and TPH) in soil and leachate.

3.2 Geotechnical design approach

For the new building with two basement levels, an over 8 m deep excavation pit had to be executed (Fig. 3). Due to the different buildings in the direct area of influence of the excavation pit, the pit area needed to be designed according to the actual boundary conditions. The open pit boundary has been designed according to the DIN EN 1997 (2014). The perimeter of the open pit consisted of bored piles with a diameter of 900 mm and a depth of 11.50 m, which were installed using a casing by means of the continuous flight auger (CFA) technique (Fig. 4). In the area of the open pit close to nearby buildings, the piles were overcut in order to guarantee low (maximum of 2 cm) or no settlements at all. The bearing capacity of the piles were calculated according to the recommendations of DGGT (2012), considering both shaft capacity and point bearing capacity taking into account the general pile bearing capacity equation. The open pit walls were tied back by temporary anchors designed according to the DIN EN 1997 (2014) considering 2 cm head deformation and pre-tensioned and taking into account the equilibrium with the surrounding loads. The traffic load on the roads has been taken into account. The special load cases such as hydraulic failure or loads on the soldier beam walls have been considered. The soldier pile wall was used in some areas of the open pit for economic reasons and where the restriction about settlements was not given (maximum 5 cm). A soldier pile wall is an excavation pit wall that prevents soil from sliding down into an excavation pit. Steel girders consisting of two welded U-profiles were inserted and infilled with planks parallel to the excavation. The bottom of the open pit was densified at 100% Proctor density by means of a vibrating plate. In some areas, in order to prevent settlements of the nearby buildings, underpinning jet grouting columns were installed.

In one area of the open pit, an additional smaller pit needed to be excavated in order to eliminate the source of pollution. The smaller open pit was closed by sheet piles, which were installed by vibration at an additional depth of 6 m. The DIN EN 1997 (2014) was used to design the sheet piles. The polluted soil within the smaller pits was removed and substituted with liquid soil and clean soil, the latter being compacted in order to reach the same stiffness of the original soil (about 40 to 80 MPa).

Figure 3. *An overview of the open pit*

To determine any deformations occurring in the open pit, the pile heads were measured and their positional stability was further observed during excavation.

For the excavation pit, the variable groundwater level during the construction period had to be taken into account. The foundation base with the deeper lift basements and pump sumps should already be concreted in autumn so that they can be built without dewatering. The groundwater level regularly rise to the level of the upper edge of the foundation, which is why the basements were designed with a waterproof concrete.

Figures 4. *CFA piles during the excavation (A). pit excavation within excavation (B)*

3.3 Soil removal and soil remediation

Over the course of approx. 12 months, the soil within the pit was excavated until the design depth of approximatively 7.9 m below ground level (bgl) was reached. As the underground tar pit contained a viscose mixture of tar (mainly PAH) and debris extra precautions were required during removal. These included fencing off the area of the tar pit to minimize human contact with the contaminated material, wearing protective clothing and covering the soil and lorry tires during loading of contaminated material to prevent contamination of clean soil. Additionally, excavation activities within the area of the tar pit removal were restricted to days of no or little rain to prevent an increase of contaminated mass and migration of contaminants into the soil and underlying groundwater. In case of rain or inactivity in this area, the tar pit area was covered with impermeable foil.

3.4 Groundwater remediation

To prevent further migration of contaminants from the site, two remediation wells were installed downstream of the excavation area to abstract and remediate groundwater (pump&treat, here abbreviated as P&T) in a groundwater remediation plant before discharging the remediated water into the public sewer system. The P&T remediation was chosen as the installation of the P&T system is relatively cheap compared to other remediation options, the remediation duration was expected to be limited due to the comprehensive source removal by soil excavation and successful application on a nearby cyanide contamination in groundwater. In principle, abstracted groundwater is treated by removing coarse particles in bag filters and then removing the cyanides in a physical-chemical treatment process by pumping groundwater into two successive vessels filled with ion exchanger (0.5 m^3 each; filled with weak base anion resin substrate). Cyanide ions are bound by the resin, which in turn release less hazardous chloride ions. The remediated groundwater is then discharged into the public sewer system. Abstracted groundwater from each remediation well is treated separately by installing separate lines for inflow, water loggers, bag filters and ion exchangers. After each device, valves allow for sampling of abstracted groundwater if required. The different treatment lines merge shortly before discharging the clean water into the sewer system.

The pumping rate of each remediation well was determined by groundwater modeling of the ideal position of each remediation well and the expected migration of contaminants and groundwater flow direction. The final pumping rates were 4.5 m^3/h and 5.5 m^3/h, respectively.

3.5 Groundwater monitoring

3.5.1 Monitoring of groundwater levels

As groundwater abstraction in the course of groundwater remediation may lead to the development of a cone of depression, it was required to monitor the groundwater level in three groundwater monitoring wells via data loggers. To be able to react quickly in case of flood events, one radio logger was installed in an upstream well adjacent to the excavation pit so groundwater levels could be monitored online constantly. The other loggers were installed to the north and west downstream of the remediation wells. Groundwater levels in the radio logger were logged at 2hr-intervals, while the other loggers recorded data at 4hr-intervals. Data of the latter were read once a month and checked at regular intervals by dip measurements with an electric contact gauge.

3.5.2 Monitoring of chemical composition

To monitor the effects of soil and groundwater remediation on groundwater, a total of 15 groundwater monitoring wells onsite and offsite plus two remediation wells and the outlet of the remediation plant were sampled regularly. Regular groundwater monitoring began in November 2021 and is still ongoing. For the first two months, groundwater sampling was performed on a biweekly basis to monitor initial conditions. The provide an overall picture of groundwater contamination, groundwater wells were divided into three groups: 1 well upstream, 6 wells in the excavation and soil remediation area, 2 remediation wells directly downstream of the soil remediation area, 4 wells downstream of the remediation wells and 4 wells at a greater distance downstream of the study area. The latter ones were sampled on a quarterly basis. With the exception of the remediation wells, the groundwater monitoring focused on existing groundwater monitoring wells. The newly installed remediation wells (DN125, PVC) have a depth of 16 m. The majority of existing groundwater monitoring wells have a diameter of DN50 (PVC). Only one well further downstream of the study area has a diameter of DN80. Most wells have a depth of approx. 13-14 m. Only two wells within the soil remediation area reach a depth of approx. 21 m. Groundwater samples were taken with either a submersible pump (Grundfos MP1) or a scoop if conditions did not allow for a submersible pump. The samples at the remediation wells and the outlet of the remediation plant were taken as tap samples close to the remediation plant. The pumping rate was usually set to 10 l/min. During pumping, the pumped water was continuously monitored regarding the pH value, electrical conductivity, redox potential, temperature and oxygen in addition to sediment content and colour. Groundwater samples were taken after reaching constant conditions regarding the aforementioned parameters, which usually occurred after approx. 20 min.

Groundwater samples were taken at a depth of approx. 10 m bgl to be able to sample at consistent depths independent of seasonal changes and to still sample the upper part of the aquifer with the highest cyanide concentrations.

All groundwater samples were analysed for total cyanides (CN_{tot}) according to ISO 14403-2:2012 (continuous flow analysis), total petroleum hydrocarbons (TPH; ISO 9377-2:2000 using solvent extraction and gas chromatography) and polycyclic aromatic hydrocarbons (PAH; ISO 17993:2002 using HPLC with fluorescence detection after liquid-liquid extraction) including naphthalene. Selected wells within the excavation area and downstream of the remediation wells were also analysed for easily released cyanides (ISO 14403-2:2012, continuous flow analysis). In addition, aromatic hydrocarbons (BTEX; DIN 38407-43:2014-10 using gas chromatography and mass spectrometry in headspace samples) and phenols (ISO 14402:1999, flow analysis) were analysed in selected wells within the excavation area and the outlet of the remediation plant.

As the soil excavation progressed, groundwater monitoring wells were shortened at regular intervals and finally removed. Consequently, the selected wells for BTEX and phenol analyses changed throughout the course of the project.

4 RESULTS AND DISCUSSION

4.1 Soil removal and soil remediation

To validate the success of soil remediation, the soil excavation pit was divided into 15 different sections from which mixed soil samples (validation samples) were taken from the soil surface once the final excavation depth was reached and subsequently analyzed for CN_{tot}, CN_{free}, PAH and TPH in soil and leachate, respectively. Each validation sample represents an excavation area of approx. 300 m² depending on conditions on site (i.e. progress of soil removal, homogenous soil, excavation depth). In areas that had previously been contaminated to greater depths, sampled sections were typically smaller to better locate and remediate a contamination hotspot, if necessary. If target remediation values were exceeded in a validation sample, the respective section had to be excavated to greater depths depending on the magnitude of detected concentrations. In case of low exceedances, the soil was excavated until reaching the groundwater surface. That way no additional geotechnical measures to provide stability were required. A validation sample from the bottom of the smaller, deeper excavation pit in the center of the contamination was taken by the excavator and sampled from the excavator shovel. However, the reliability of this sample is limited due to the mixing of sediments from different depths during the excavation work underwater. In total, validation samples of each section complied with the target remediation values.

4.2 Groundwater data

CN_{tot} concentrations in both remediation wells have varied between concentrations below the target remediation value and approx. 0.1 mg/l with one outlier of 0.35 µg/l in January 2022. Since September 2022, CN_{tot} concentrations in both remediation wells have been below the target remediation value. From January 2022 to December 2022, a total of approx. 4.5 kg CN_{tot} have been removed from groundwater by P&T remediation.

A maximum CN_{tot} concentrations of about 1.5 mg/l CN_{tot} was detected in groundwater monitoring wells within the soil excavation area (see Fig. 5). However, as the excavation progressed, these wells were damaged and removed so the amount of available data for each well differs. CN_{tot} concentrations varied strongly between different wells and sampling events. In general, CN_{tot} concentrations have been decreasing since the beginning of groundwater monitoring in November 2021 (see Fig. 6). The abstraction of groundwater for remediation upstream of the displayed wells did not result in an immediate and apparent decrease of CN_{tot} concentrations but rather a slow decline, which does not appear to be influenced by the groundwater level. However, since September 2022, all of the remediation wells and downstream groundwater monitoring wells complied with the target remediation value for CN_{tot}.

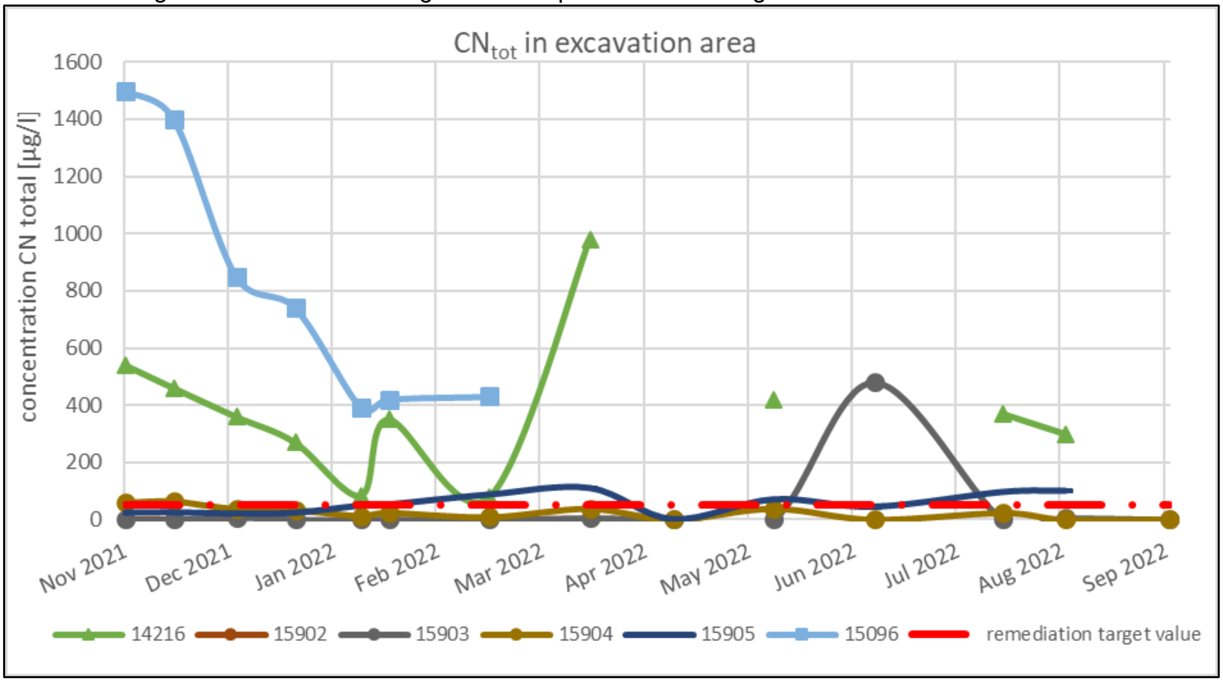

Figure 5. *Cyanide concentration in groundwater of groundwater monitoring wells in excavation area*

CN_{free} were only detected in two groundwater monitoring wells within the excavation area that generally showed elevated CN_{tot} concentrations. CN_{free} concentrations ranged between 0.008 mg/l and 0.06 mg/l. TPH concentrations were detected occasionally in several wells within the excavation area, the remediation wells and downstream wells but did not appear to be related to specific events or locations. TPH concentrations ranged between 0.1 mg/l and 0.7 mg/l. PAH concentrations ranged between 0.02 mg/l and 1.53 mg/l and were mostly detected in groundwater monitoring wells within the excavation area. No phenols or BTEX above the remediation target values have been detected during any of the sampling events. Since September/October 2022, no target remediation values for any of the target contaminants have been detected.

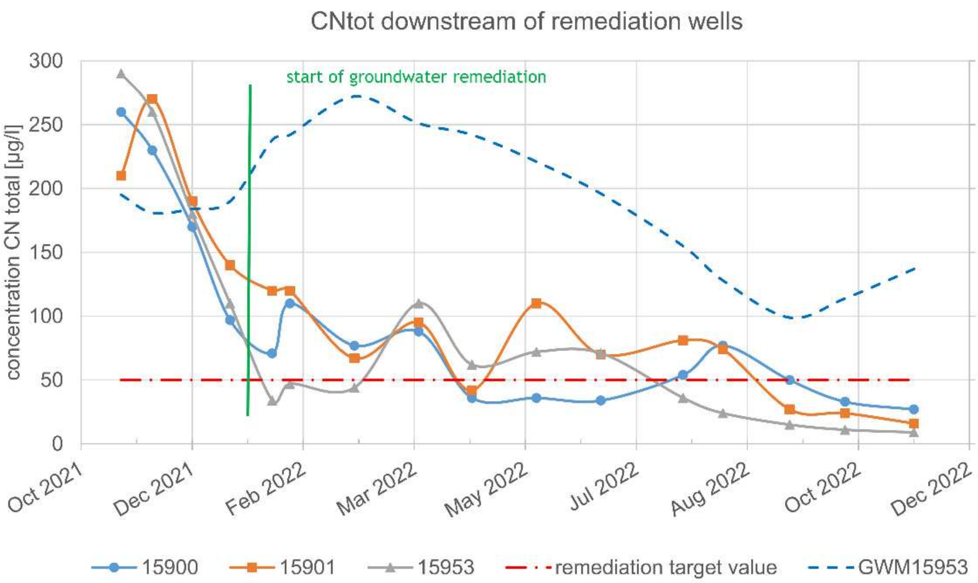

Figure 6. *Cyanide concentration in groundwater of downstream groundwater monitoring wells*

5 CONCLUSIONS

Geotechnical and environmental remediation work has been carried out in a metropolitan area in Germany polluted mainly with cyanides. Geotechnical excavation and design works have been performed to secure the ground. The soil within the pit was fully excavated until the design depth of 7.9 m was reached. Remains of the former coal gasification plant included an underground tar pit, which contained a viscose mixture of tar (mainly PAH) and debris so extra precautions were required during removal to avoid contaminant transport and health issues for workers. To prevent further migration of contaminants from the site, two remediation wells were installed downstream of the excavation area to abstract and remediate groundwater in a groundwater remediation plant before discharging the remediated water into the public sewer system. To monitor the effects of soil and groundwater remediation on groundwater, a total of 15 groundwater monitoring wells onsite and offsite plus two remediation wells and the outlet of the remediation plant were sampled regularly and the groundwater monitoring is still ongoing. Until November 2022, the cyanide contamination in soil was successfully remediated while cyanide concentrations in groundwater have decreased to concentrations nearing or complying with the target remediation values.

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