MASTERING LARGE-SCALE GEOTECHNICAL CHALLENGES

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SAMMANFATTNING

Detta dokument förklarar med hjälp av exempel hur man hanterar stora geotekniska utmaningar i två stora infrastrukturprojekt i Tyskland: den femte slusskammaren i Kielkanalen i Brunsbüttel och tunnelbaneprojektet U5 Öst Lot 1 i Hamburg. Det ger också en bild av hållbarhetsaspekterna i båda projekten.

Byggandet av den femte slusskammaren i Brunsbüttel är ett av de mest betydande vattenbyggnadsprojekten i Tyskland just nu. Det har utvecklats av kunden Wasser- und Schifffahrtsamt Brunsbüttel (WSA) (Generaldirektoratet för vattenvägar och sjöfart) och har designats och byggts av Wayss & Freytag Ingenieurbau AG. Syftet är att säkerställa långsiktig driftsäkerhet och kapacitet för Kielkanalen (Nord-Ostsee-Kanal, NOK), en viktig sjöfartsled som förbinder Elbe med Östersjön. NOK är världens mest trafikerade konstgjorda sjöfartsled och används för nationella och internationella godstransporter. Den utgör ett effektivt och miljömässigt fördelaktigt alternativ till Skagen-rutten. Att upprätthålla dess prestanda är därför avgörande för både nationella och europeiska transportkorridors motståndskraft.

Denna artikel behandlar grundläggningen av den inre huvuddelen av den femte slusskammaren. Utmaningar med avseende på deformationstoleranser och stora skillnader i vattenhöjd har lett till en innovativ och ekonomisk lösning med dubbla användningsområden för borrade pålar, som först fungerar som lyftskydd för betongplattor under vatten och i slutskedet som grundpålar.

Projektet U5 Öst är den första byggfasen av Hamburgs nya helautomatiska tunnelbanelinje (GoA 4), som bildar en öst-västlig axel med hög kapacitet som ska förbättra kollektivtrafikförbindelserna i staden avsevärt. Den cirka 6 km långa sträckan omfattar fem framtida stationer och förbinder stadsdelarna City Nord, Alsterdorf, Ohlsdorf Süd, Barmbek Nord, Steilshoop och Bramfeld. Som en av de mest infrastrukturintensiva delarna av det övergripande U5-programmet kombinerar den västra ingångsdelen – betecknad U5 East, Lot 1 – komplexa geotekniska, strukturella och logistiska utmaningar i en tät innerstadsmiljö. U5 East, Lot 1 byggs av ”HOCHBAHN U5 Projekt GmbH” som agerar som kund och byggkonsortiet bestående av Wayss & Freytag Ingenieurbau AG och Ed. Züblin AG.

Detta projekt – en nationell referenspunkt för hållbar infrastruktur – står inför utmanande krav på miljömässig hållbarhet. Denna artikel presenterar en innovativ metod för design och konstruktion av grundvattenfönster i slitsväggar för att återupprätta grundvattenflödet som avbrutits av bygggropar inbäddade i moränlera.

SUMMARY

This document clarifies on examples how to master large scale geotechnical challenges in two major infrastructure projects in Germany: the 5th lock chamber of the Kiel canal in Brunsbüttel and the U5 East Lot 1 subway project in Hamburg. It also gives an impression of the sustainability aspects in both projects.

The construction of the fifth lock chamber at Brunsbüttel represents one of the most significant current hydraulic engineering projects in Germany, developed by the client “Wasser- und Schifffahrtsamt Brunsbüttel (WSA)” (General Directorate for Waterways and Shipping) and designed and constructed by Wayss & Freytag Ingenieurbau AG. Its objective is to ensure the long-term operational reliability and capacity of the Kiel Canal (Nord-Ostsee-Kanal, NOK), a key maritime waterway linking the Elbe with the Baltic Sea. As the world’s busiest artificial shipping route, the NOK serves national and international cargo transport and provides an efficient, environmentally advantageous alternative to the Skagen route. Maintaining its performance is therefore essential for the resilience of both national and European transport corridors.

This paper deals with the foundation of the inner head of the fifth sea lock chamber. Challenges with respect to deformation tolerances and high water head differences, lead to an innovative and economic dual use bored pile solution acting first as uplift protection for underwater concrete slabs and in final stage as foundation piles.

The U5 East project represents the first construction phase of Hamburg’s new fully automated underground line (GoA 4), forming a high capacity east–west axis intended to significantly improve public transport connectivity across the city. The approximately 6 km long section includes five future stations and links the districts of City Nord, Alsterdorf, Ohlsdorf Süd, Barmbek Nord, Steilshoop and Bramfeld. As one of the most infrastructure intensive components of the overall U5 programme, the western entrance section - designated U5 East, Lot 1 - combines complex geotechnical, structural and logistical challenges within a dense inner city environment. U5 East, Lot 1 is built by “HOCHBAHN U5 Projekt GmbH” acting as the client and the construction joint venture consisting of Wayss & Freytag Ingenieurbau AG and Ed. Züblin AG.

This project - a national benchmark for sustainable infrastructure delivery - faces challenging environmental sustainability requirements. This paper introduces an innovative approach for design and construction of groundwater windows in diaphragm walls to reestablish groundwater flow disconnected by construction pit walls embedded in moraine clay formation.

1 CONSTRUCTION OF THE FIFTH SEA LOCK BRUNSBÜTTEL

1.1 General Overview

The Brunsbüttel lock complex comprises two double-lock systems, consisting of the Old Lock in the south and the Large Lock in the north. The Large Lock, in continuous operation since 1914, now exhibits substantial structural, mechanical, and electromechanical deterioration. Extensive rehabilitation measures are indispensable but cannot be executed without maintaining reliable lock availability for shipping. For this reason, the construction of an additional, fifth lock chamber as a replacement and supplementary structure was initiated to safeguard the operational continuity of the site during future rehabilitation works.

The new lock chamber is being constructed on the lock island between the two existing lock systems and will function as a full sea lock between the Elbe and the Kiel Canal. It comprises an Elbe-side outer head, an inland-side inner head, and a lock chamber approximately 360 m in length. The chamber width is aligned with that of the existing Large Lock to enable operational synergies - most notably the interchangeability of sliding gates - and to enhance both operational safety and long-term economic efficiency.

From an engineering perspective, the project is dominated by hydraulic engineering and special civil engineering works. Large-scale excavation pits must be constructed within the tidal range of the Elbe, requiring robust temporary works and foundation systems. These include extensive sheet pile walls with back-anchoring, deep-founded structural components, and jet-grouted elements for anchoring and soil improvement. The suitability of the jet grouting system was verified through preliminary performance tests and formally approved by the supervisory authorities.

A critical component of the hydraulic design is the construction of the lock bed and the associated bed protections on both the Elbe and inland sides. These measures ensure overall structural stability and provide effective protection against hydraulic erosion resulting from flow patterns, tidal dynamics, and lock operations. In the outer harbours, additional bank protection and guide structures are being built to guarantee safe vessel approach and departure under tidal influence.

The project further encompasses flood protection installations, operational traffic and maintenance areas, supply and disposal infrastructure, and the full mechanical and electrical outfitting of the lock heads, including steel hydraulic structures, drive systems, control systems, and electrical equipment. All construction activities are being carried out while the existing lock facilities remain in continuous operation, requiring meticulous coordination with respect to water level dynamics, shipping management, and construction sequencing.

By adding a modern, high-capacity lock chamber, the project establishes a technically robust and operationally resilient foundation for the Brunsbüttel lock site. It ensures the long-term performance of the Kiel Canal and thus reinforces a vital element of the European maritime transport network.

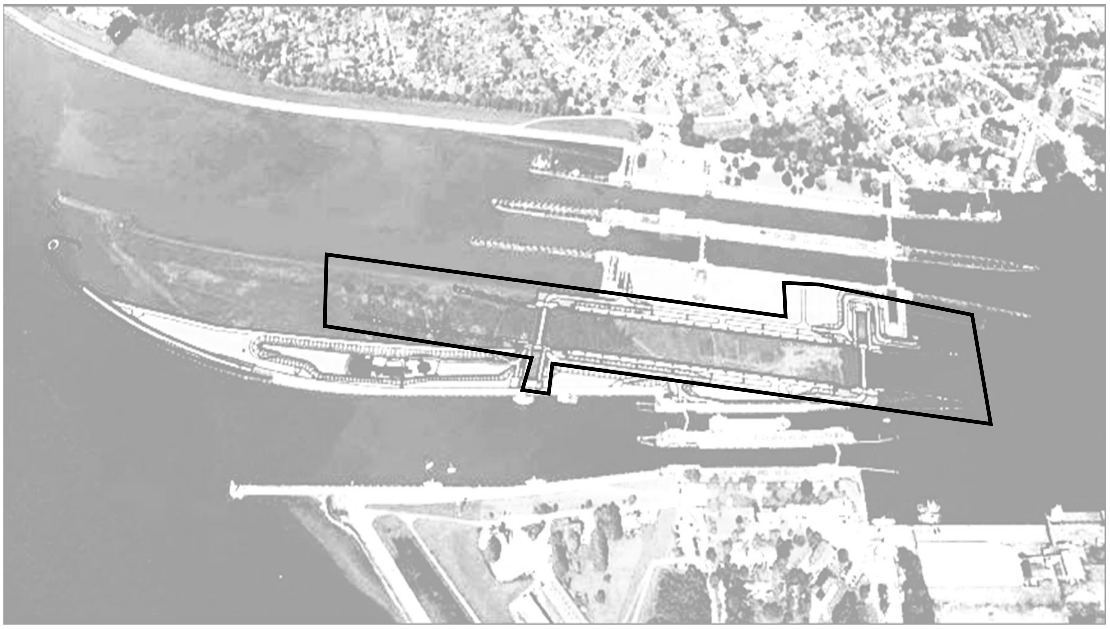

Figure 1. Visualisation of the 5^th^ lock chamber located between the Old Chambers in the south and the Large Chambers in the north.

1.2 Objectives

Considering a maximum water level difference of 7.2 m and challenging tolerances for maximum differential deformations of 4.0 cm between the bottom (-16.9 m b.s.l.) and the top (+6.5 m b.s.l.) of the lock head, the inner lock head have to be founded on bored piles.

As the construction had to be grounded below sea level, three construction pits (see figure 2) had to be built. A combined sheet pile wall is being used to enclose the excavation pits. Onshore, this will be suspended in a single-phase diaphragm wall during the first construction phase. The excavation is executed with the aid of temporary fill at +3.00 m above sea level. Where construction using the diaphragm wall method is not possible, the sheet piles are installed from a jack up platform using partly pre-piped drillings. The bases of the supporting planks will be poured over a length of 3.00 m. The remaining borehole is to be filled with 2/32 gravel up to the harbour floor. In the annular space of the jacking boreholes for the support piles and the replacement boreholes for the intermediate panels, a sealed horizon at a height of -20.00 mNHN to -19.00 mNHN is created using bentonite pellets.

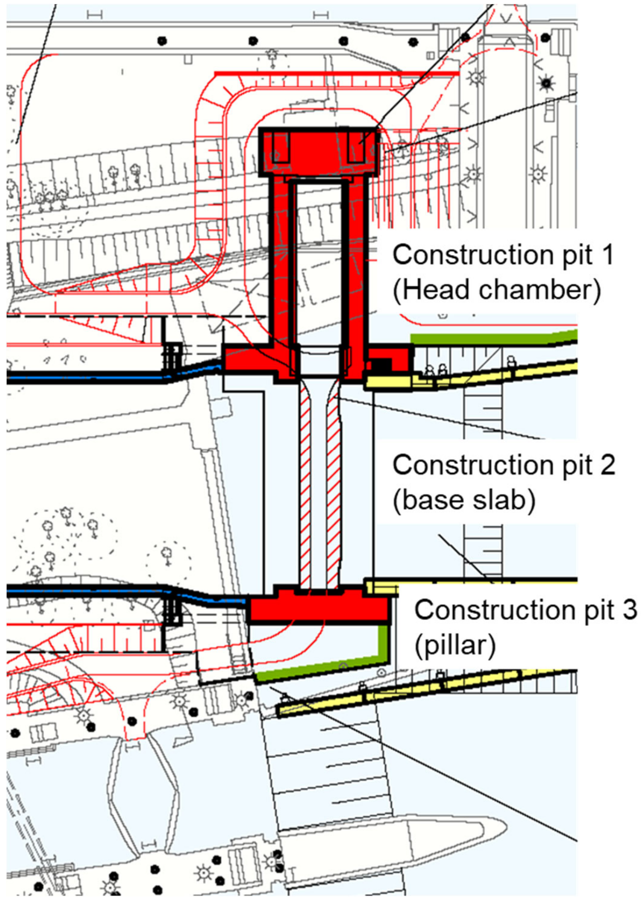

Figure 2. Overview of the fifth sea lock chamber in Brunsbüttel, Germany

As the bottom of the construction pits are grounded in a sand layer, the pits are sealed by underwater concrete slabs. To avoid additional micropiles for uplift protection, the bored piles were designed as tension and pressure piles. The detail of the pile head acting as a tensile connection between the bored pile and the underwater concrete slab will be presented in the following.

1.3 Ground conditions

The geotechnical parameters are shown in table 1. At the top of the harbour floor (-10.5 m b.s.l.), silt and mud is located which has no special geotechnical characteristics. The ground between -10.5 and -22.0 m b.s.l. comprises of unconsolidated clay. Underneath, to a depth of – 33.0 m b.s.l. sand and gravel formation with very high bulk density is to be found resting on stiff moraine clay. The foundation level consists of very dense sand and gravel.

Table 1. Geotechnical Parameters

Soil layer	Depth of layer base [m.b.s]	Specific Weight [kN/m³]	Friction angle [°]	Cohesion [kN/m²]	Constrained modulus ES,k [MN/m²]	K_f-value
Silt	-10.5	-	-	-	-	-
Clay	-22.0	17.0/ 7.0	30	3	5	$1x10^{-7}$
Sand & gravel	-33.0	18.5/ 10.5	35	0	50	$1x10^{-3}$
Moraine clay	-41.0	22.0/ 12.0	25	20	80	$1x10^{-8}$
Sand & gravel	-	19.0/ 11.0	37.5	0	100	$1x10^{-3}$

The parameters of shaft friction and the tip resistance used for the design of the bored piles are shown in table 2.

Table 2. Parameters of shaft friction and tip resistance for bored piles

	Clay	Sand			Moraine clay
	weak	Low bulk density	Middle bulk density	High/ very high bulk density	stiff
Shaft friction qs,k [kN/m²]	8	20	60	120	55
Tip resistance $q_{b,k}$ [kN/m²]	-	-	2000	4000	1200

1.4 Technical solution

The bored piles are driven from a jack up platform. While the upper part of the drilling (water, silt and clay) of the foundation and buoyancy piles are pre-piped, the non-piped part of the lower bore hole is supported by bentonite slurry. The cast-in-place piles have an outer diameter of D = 1.30 m. The required drilling runs down to a depth of -46 m b.s.l.. Construction takes place before the excavation of the construction pit and the installation of the underwater concrete slab. The piles are poured approximately 1.0 m above the upper level of the underwater concrete slab (top of pile -18.95 m b.s.l.). As the upper end of the longitudinal reinforcement of the piles is fitted with couplers, it can be extended after the excavation pit has been drained. Hence, the reinforcement can be connected to the solid structure.

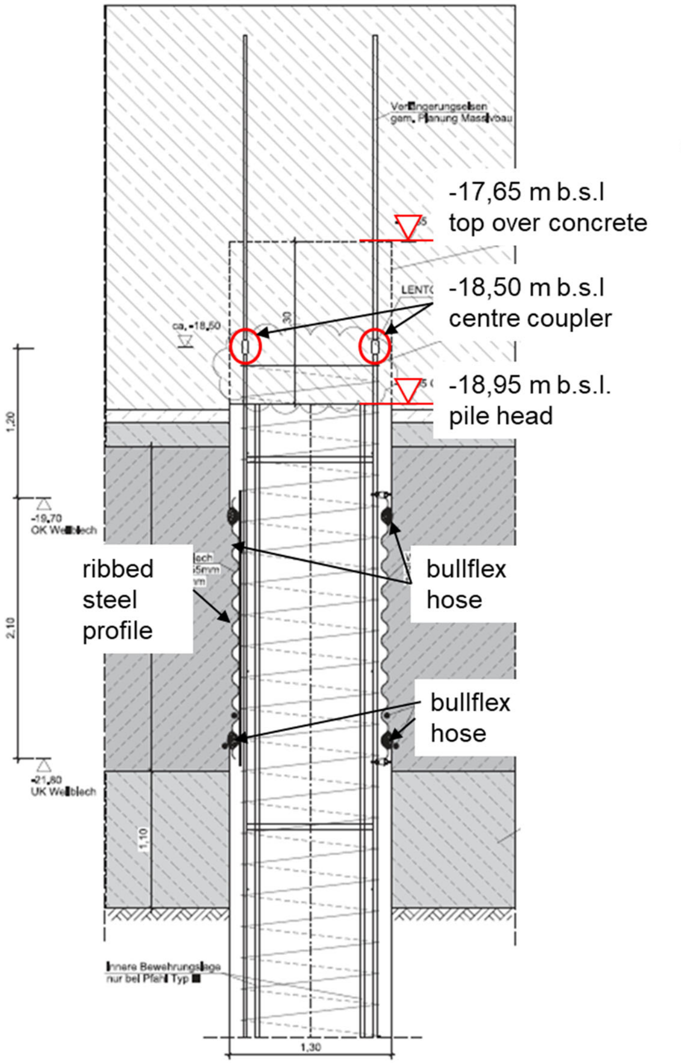

Figure 3. pile head detail of the tensile connection between the bored pile and the under water concrete slab.

At the upper part of the reinforcement cage, a circular ribbed profile (corrugated profile 200x55 mm, or similar) is connected at the correct height using wire rope clamps. The outer diameter of the ripped profile equates to 125 cm. Bullflex hoses are connected to the upper and lower edges of the corrugated profile to prevent concrete flow and to reduce the effort of later cleaning by divers (see figure 3). After the reinforcement cages have been placed in the bentonite-supported borehole, the Bullflex hoses are grouted with cement paste (with a mixture similar to that used for grout anchors or jet grouting piles) so that the annular space between the corrugated pipe and the edge of the borehole is sealed. The pile is then poured using the tremie method. During the pouring, the ribbed profile is protected from beeing covered with concrete by the outer casing and the Bullflex hoses. After the hardening process of the concrete and finalisation of the construction pit wall, the pits are excavated down to the planned excavation pit base at -23.00 m b.s.l.. Finally, divers remove the concrete and bentonite residues from the ribbed profile and clean the entire shaft using high-pressure water jets.

The general pile grids were adjusted for simplified excavation so that the largest possible number of piles are located under the axes of the bracing. This results in a pile grid with axial distances in longitudinal direction between 3.30 and 4.12 m and in transverse direction between 3.18 and 5.01 m

The exact layout is shown as an example for excavation pit 1 in the ground plan in figure 4. The tolerance of the axis deviation of the buoyancy piles is set to +/-10 cm.

The design calculations are performed in accordance with EC 7 (DIN EN 1997-1) for the limit states STR, GEO-2, and UPL. The factors of safety are taken from EAB 2012 (DGGT, 2012), EB 79, Appendix 6, Tables 6.1 and 6.2 and Appendix 7, Table 7.3 (for reinforced concrete components) and DIN 1054, Tables A 2.1 and A 2.3.

For design calculations a water table at +3.5 m a.s.l. is considered, while the bottom of the underwater concrete slab is at -22.0 m b.s.l. resulting in a water head of 25.5 m. This boundary conditions result in a designed tension load of $F_{t,d}$ = 3.211 kN to be captured by the ribbed steel profile, transmitting the tension load from underwater concrete slab into the pile head.

Considering vertical tolerances for the setting of the reinforcement cages of ±20 cm, the total height of the ribbed profile is reduced from 2.1 m to the required effective height of 1.9 m and the thickness of the underwater concrete slab to 2.6m.

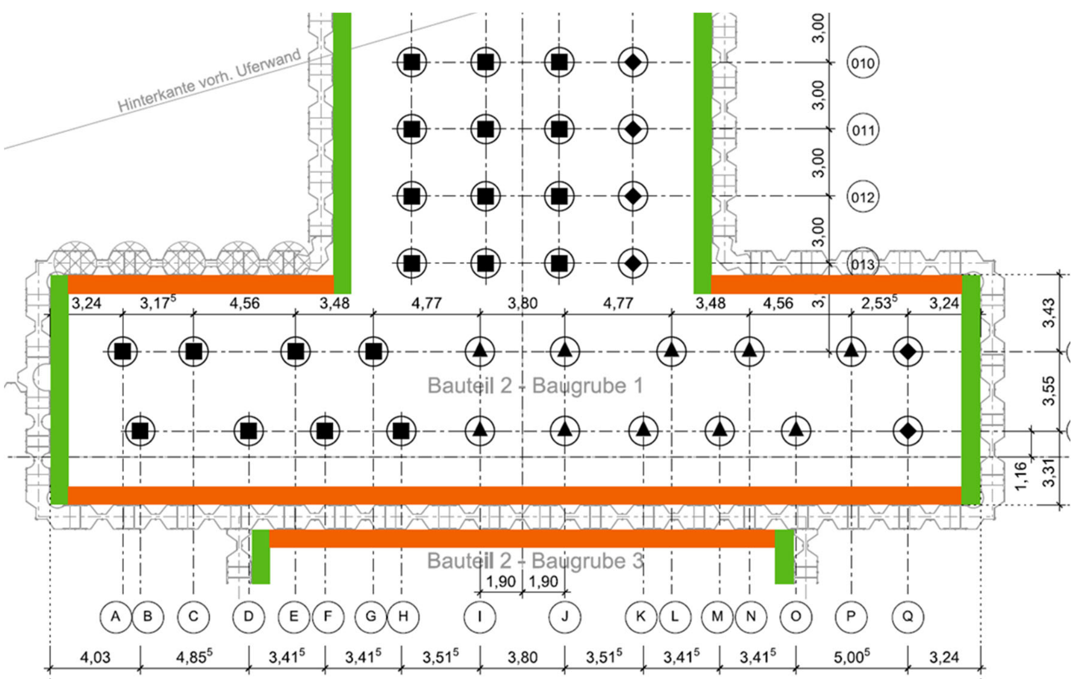

Figure 4. Pile grid of construction pit 1.

1.5 Sustainability approach

Ecological sustainability is a central aspect of the construction of the fifth lock chamber in Brunsbüttel. A key issue is the protection of soil and water. Around 1.7 million cubic metres of soil, consisting mainly of clay and silt, are being excavated on the lock island. Instead of relying on extensive road transport, this material is transported by water to a soil storage site at Dyhrrsenmoor, which significantly reduces transport distances and associated emissions. As construction takes place in the immediate vicinity of the Kiel Canal water system, particular importance is attached to safeguarding water quality and controlling erosion. This is achieved, among other measures, through the careful use of construction techniques such as sheet piling and jet grouting, which are designed to minimise vibrations and thus reduce impacts on the surrounding environment.

Closely linked to this is the protection of flora, fauna and soil life. The planning approval documents and the information letters published by the General Directorate for Waterways and Shipping address species protection and ecological compensation measures in detail. Where construction activities interfere with natural habitats, compensation areas are designated and ecological monitoring is carried out, as required under planning approval law. These measures relate in particular to the protection of inland and shoreline areas of the canal as well as neighbouring wetlands, which are sensitive ecosystems within the project area.

Flood protection and climate adaptation also play an important role. The fifth lock chamber is not an isolated structure but part of a wider system that contributes to strengthening coastal defences. Flood protection concepts have been coordinated with the construction project so that the lock infrastructure continues to function reliably even under conditions of rising sea levels or during storm surges, thereby addressing long-term climate risks.

Economic sustainability is reflected both in the construction process and in long-term operation. The new lock chamber makes it possible to carry out essential repairs to the existing locks without the need for months-long closures. From an economic perspective, this is more sustainable than repeated emergency repairs that disrupt shipping and require disproportionate effort. The new chamber has the same width as the existing large lock chambers, allowing gates and technical components to be used interchangeably. This standardisation reduces storage requirements and maintenance costs over the life cycle of the facility. The planned service life of at least 100 years further underlines the focus on long-term resource efficiency and value retention.

Logistics and emission reduction are also important elements of economic sustainability. The predominant use of waterways for transporting materials and heavy equipment significantly lowers CO_2 emissions per tonne-kilometre compared with road transport by lorry. In addition, maintaining the continuous availability of the locks during construction ensures that the Kiel Canal remains an efficient shipping route. This has an indirect but relevant climate benefit, as it avoids detours around

Denmark and thus reduces overall greenhouse gas emissions in maritime freight transport.

Social and organisational sustainability is addressed through transparency, communication and safety. The Waterways and Shipping Administration regularly publishes information letters that document construction progress as well as environmental and safety-related aspects of the project. This ongoing public communication increases transparency and allows local stakeholders and the wider public to follow developments and understand the rationale behind construction decisions. Occupational and operational safety is another core concern. On a large construction site of this scale, low-vibration construction methods and comprehensive risk minimisation measures are applied to prevent damage to neighbouring structures. These measures serve not only to protect construction workers but also to limit impacts on the environment, for example on aquatic organisms in the canal.

In summary, the construction of the fifth lock chamber in Brunsbüttel is characterised by a broad understanding of sustainability. Ecological considerations focus on the protection of soil, water and ecosystems, economic sustainability is pursued through durable, efficient infrastructure and low-emission logistics, and social sustainability is supported by transparency and high safety standards. Together, these aspects aim to limit environmental impacts while ensuring the long-term performance and resilience of the Kiel Canal as a key transport artery.

2 CONSTRUCTION OF U5 EAST LOT 1, HAMBURG

2.1 General Overview

The U5 project is extending approximately 24 km across Hamburg from east to west see Figure 5). Upon commissioning in 2040, the line is expected to carry around 270,000 passengers daily.

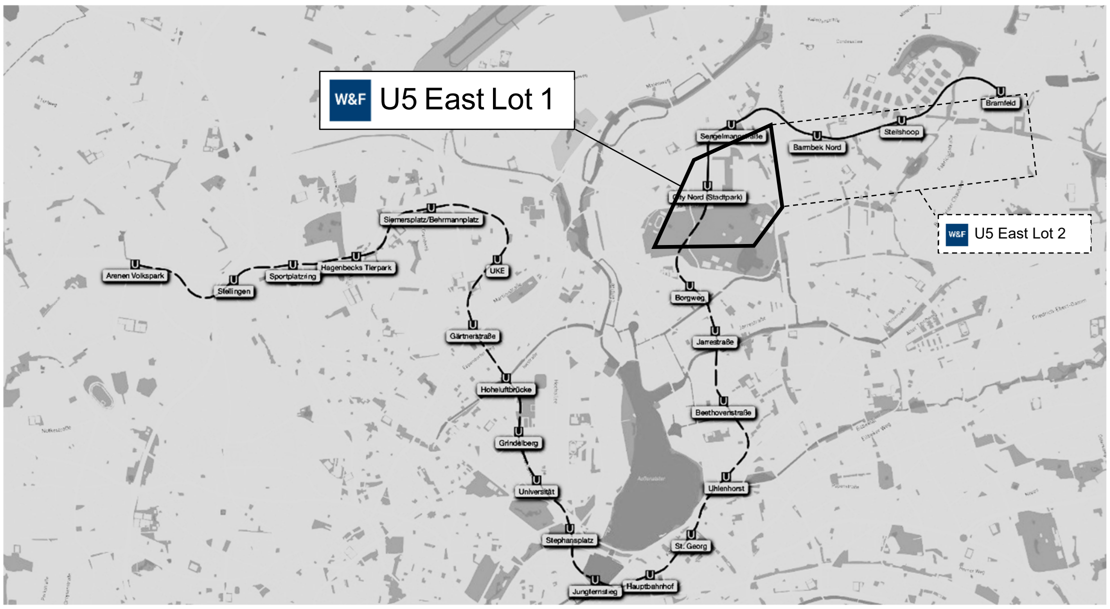

Figure 5.
Overview of the Hamburg U5 line and the location of the U5 East Lot 1 & Lot 2; (Hamburger Hochbahn AG, 2021)

Lot 1 extends from the new City Nord station to the area east of Sengelmannstraße and is divided into two sub-lots. Lot 1.1 comprises the underground City Nord station, including an upstream turning and storage facility and associated emergency exit structures. Lot 1.2 encompasses the Sengelmannstraße transport node, where extensive underground and above-ground structures converge: the conversion of the existing U1 station under live operation, new bridge structures over Sengelmannstraße, a grade-separated flyover for the U1/U5 crossing, and adjacent tunnel and trough sections. Parts of the construction take place between the operational tracks of the U1 and the DB freight bypass line, requiring temporary auxiliary bridges and tightly coordinated track possession windows.

The construction works are dominated by open-cut methods employing large-diameter diaphragm walls, bored pile walls, and locally sheet pile and beam-pile

walls. Due to high groundwater levels and the proximity to sensitive urban assets, many excavations are designed as watertight pits with vertical sealing into the regionally significant moraine clay layer. Horizontal sealing by underwater concrete slabs is used selectively depending on local permeability and uplift conditions.

Excavation support is provided by single or multi-level bracing systems and back-anchoring. The confined construction sites require detailed groundwater management concepts, including temporary dewatering, water treatment systems and measures for recreation and maintaining groundwater flow in the final state, particularly within the listed City Nord ensemble.

The City Nord station is constructed entirely in open troughs with single lengths of approximately 250 m. Special requirements arise from the protection and temporary support of several existing pedestrian bridges and from heritage constraints within the listed urban quarter. In the Sengelmannstraße area, geotechnical complexity is amplified by multiple overlapping structures, narrow construction corridors, adjacent operational rail traffic and the presence of significant utilities, including a 110 kV overhead line.

The permanent structures of Lot 1 are designed as water-impermeable reinforced concrete frame constructions. Additional components include angular retaining walls, vibration-reducing track support slabs with under-ballast mats, and extensive noise barriers. Excavation, logistics and interface coordination represent essential elements of the project, with several major works proceeding in parallel and under stringent spatial and operational constraints.

Overall, U5 East Lot 1 exemplifies modern urban underground construction under highly demanding boundary conditions, combining special civil engineering, geotechnical design, structural shell construction, groundwater engineering and complex construction sequencing within an environment that remains in continuous operation.

Beyond its mobility benefits, HOCHBAHN aims to position the project as a national benchmark for sustainable infrastructure delivery. To achieve this, a comprehensive greenhouse-gas (GHG) reduction strategy has been established, built around a continuously updated GHG roadmap that guides planning, procurement, and construction.

2.2 Objectives

The diaphragm walls acting as the outer perimeter of the construction pits are almost embedded in the tertiary moraine clay layer (Mergel). For construction logistics and safety reasons, the alignment is divided into several troughs. Hence, the natural groundwater flow is cut off from west to east, causing the groundwater level to rise on the west side of the tunnel. To prevent this, the water is pumped out using wells during construction time. Once the tunnel is finished, the original natural groundwater flow is reestablished by installing “groundwater windows” approximately in distances of 50 m along the alignment in the western and eastern diaphragm wall panels in a depth below tunnel floor.

In the eastern part of this project, the groundwater barrier is located at a greater depth, so that these diaphragm wall construction pits are sealed at the bottom by underwater concrete slabs. For economic and ecological reasons, the buoyancy control of the underwater concrete slabs, originally planned with micropiles, was completely eliminated by means of an adapted construction planning during the construction phase. In the excavation pits with a clear width of less than 7.0 m, this was achieved exclusively by clamping the underwater concrete floor into the diaphragm walls. In areas with larger clear widths of up to approximately 15.5 m, diaphragm wall barrettes arranged in the middle of the construction pit, and whose heads were structurally integrated into the slab, had to be used additionally to secure the buoyancy.

In the following, the structural implementation of the innovative technical realisation of "groundwater windows" is described.

2.3 Ground conditions

The ground surface considered in design calculations is at +14.0 m a.s.l.. The geotechnical parameters are shown in table 3. Below ground level, we find fillings. Down to -12.0 m b.s.l., the ground comprises of alternating layers of stiff moraine clay and middle dense sand layers. The foundation level consists of semi-solid and solid moraine clay.

Table 3. Geotechnical Parameters

Soil layer	Depth of layer base [m.b.s]	Specific Weight [kN/m³]	Friction angle [°]	Cohesion [kN/m²]	Constrained modulus ES,k [MN/m²]
Filling	+10.0	18/ 10	30	0	30
Alternating **moraine clay (stiff)** and **sand** (middle dense) layers	-12.0	22/ 12 19/11	30 35	10 0	50 60
Moraine clay (semi-solid & solid)	-	22/ 12	30	10	80

For the design of the diaphragm walls a shaft friction of 60 kN/m² and a tip resistance of 3.000 kN/m² has been considered.

2.4 Technical solution "groundwater window"

To reestablish groundwater flow after completion of construction works, in approximately 50 m distance, groundwater windows have to be installed into the already hardened diaphragm walls (thickness 1.2 m) opposite on both sides of the construction pit (see figure 6).

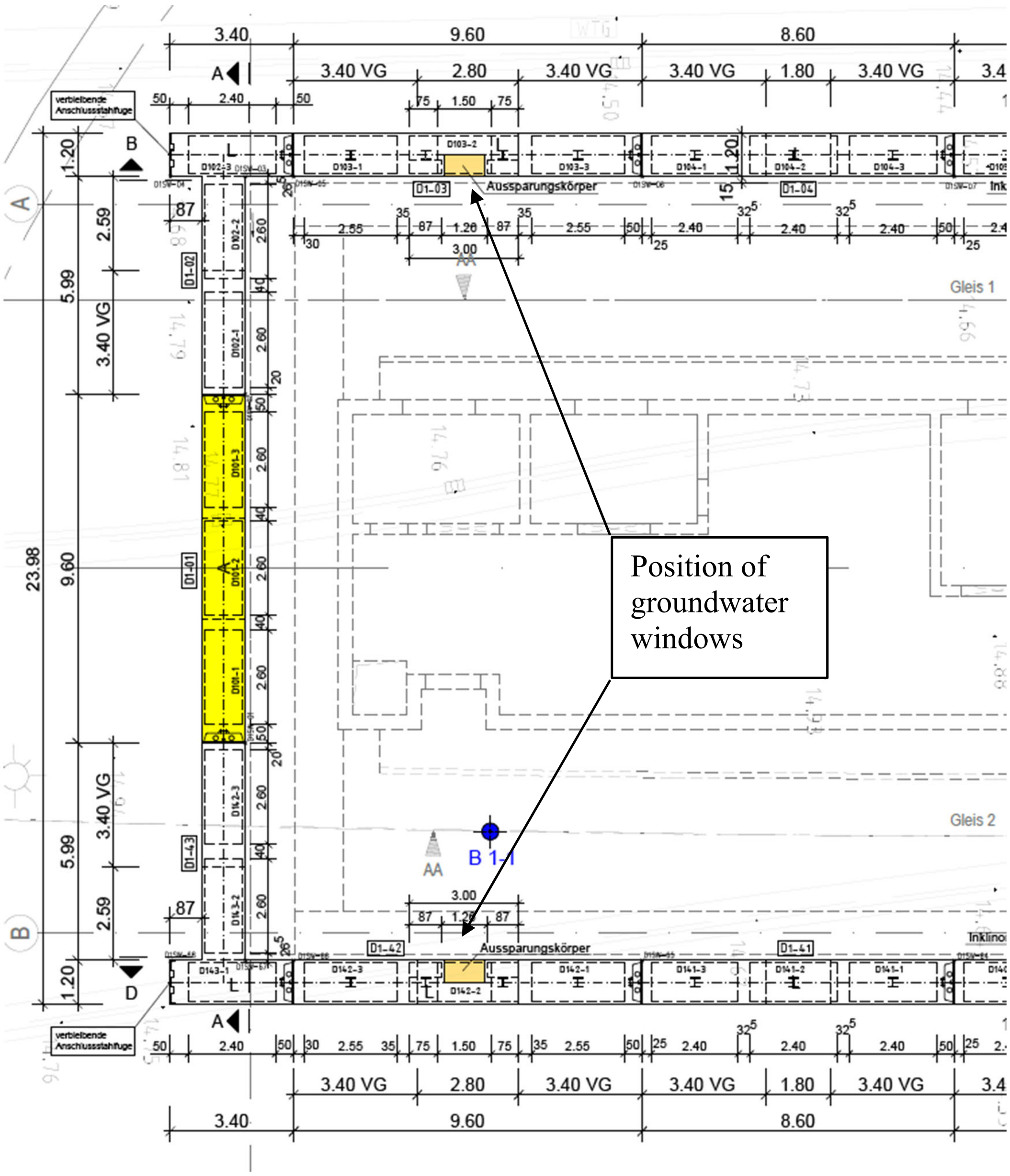

Figure 6. Ground plan of the D-wall construction pit showing the position of groundwater windows.

The top of the groundwater windows - having a width and a height of 1.0 metre - are positioned one metre below the bottom of the tunnel slab. Therefore, the complete cross section of the diaphragm walls has to be cored with a diameter of 1.2 m down to a depth of approximately 18.0 m below ground level.

To simplify the core drillings, the regular diaphragm wall cross-section of the upper 20.0 m is designed and constructed unreinforced. Therefore, the required longitudinal reinforcement is shifted over a width of 1.3 m from the centre part to the reinforced edge areas of the diaphragm wall panel (see figure 7).

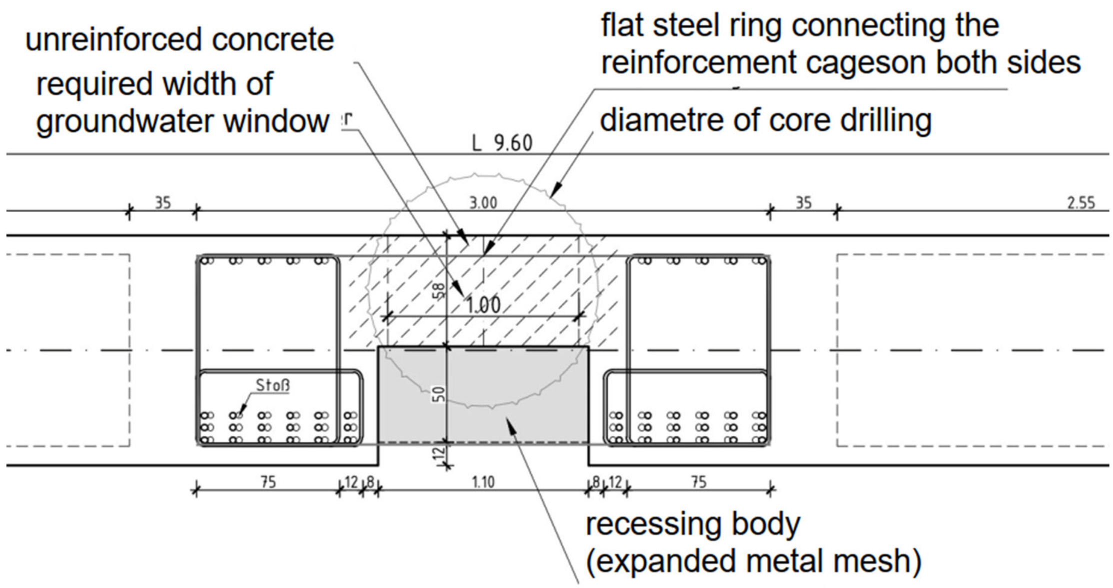

Figure 7. The solid reinforcement cages located on both side of the unreinforced part of the diaphragm wall.

To prevent the future tunnel structure from being damaged by the later executed core drillings and to facilitate drilling, the diaphragm wall cross-section was also reduced to a thickness of only 60 cm in the upper part. For this purpose, an expanded metal grid acting as a recess form was installed between the reinforcement cages. The two reinforcement cages and the recess body are connected to each other via flat steel rings to form a single reinforcement cage. The stresses inside the unreinforced concrete beam resulting from the earth and water pressures acting on the diaphragm wall are transferred to the left and right reinforced part of D-wall panel by formation of a pressure arch in the unreinforced area (see figure 8).

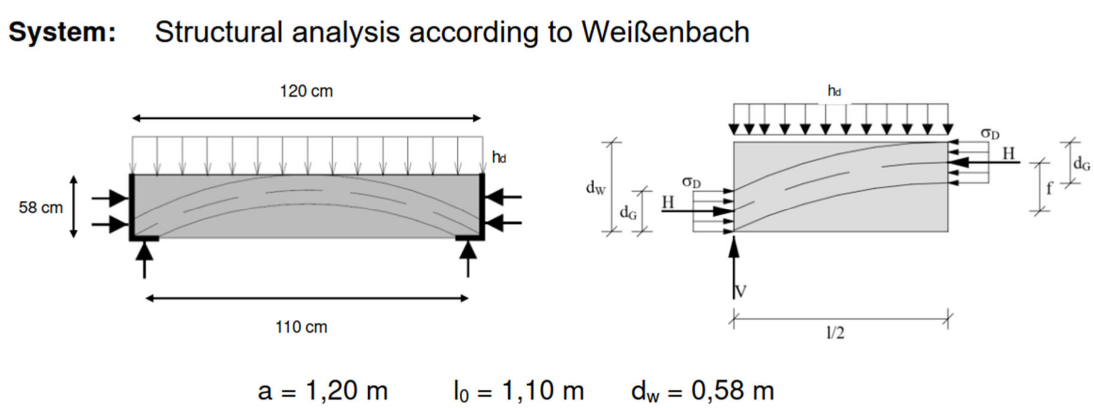

Figure 8. Stresses acting on the unreinforced concrete are transmitted by compression arch.

To reestablish the groundwater flow, filter material has to be installed in a trench below the bottom of the tunnel (see figure 9) after finalization of the construction pit excavation. After demolishing the diaphragm wall by pre-cased core drillings, the holes must be refilled with sand having a k_f-value of 1x10-4 m/s. As the water conductivity through two opposite diaphragm wall panels on western and eastern side of the construction pit is reestablished, groundwater flow is recreated.

The core drillings are done as pre-cased drillings using a 120 ton drilling rig stabilized by surcharge water overload with water head above ground water level.

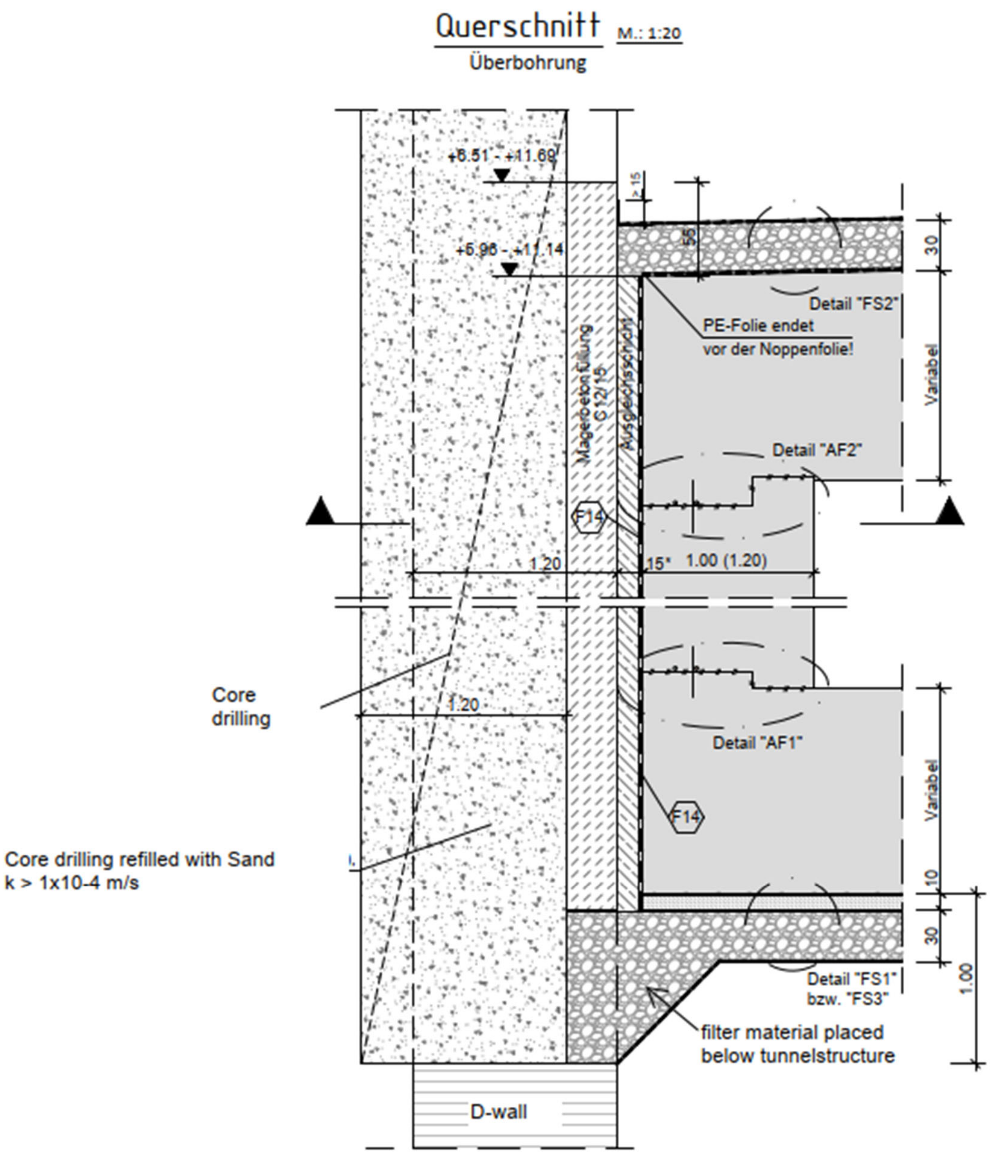

Figure 9. Cross section of the groundwater window.

2.5 Sustainability approach within the U5 project

As per the sustainability report 2023 (Gschösser, 2023), the U5 project is Germany's largest current underground railway development, spanning roughly 24 km across Hamburg and projected to transport around 270,000 passengers daily upon opening in 2040. Beyond its mobility benefits, HOCHBAHN aims to position the project as a national benchmark for sustainable infrastructure delivery. To achieve this, a comprehensive greenhouse-gas (GHG) reduction strategy has been established, built around a continuously updated GHG roadmap that guides planning, procurement, and construction.

Because underground rail construction involves high material and energy demands—particularly in reinforced concrete structures, steel production, and geotechnical works—sustainability has been embedded as a core project objective. The GHG roadmap (Begemann et al., 2022) enables systematic identification, quantification, and implementation of emission-reduction measures. Its methodology follows DIN EN ISO 14040 and DIN EN 17472, assessing life-cycle stages from raw material extraction to manufacturing, transport, construction (A1–A5), use-phase carbonation (B1), and end-of-life (C1–C3), including module D credits. Data primarily stems from Ökobaudat (Germany's federal database for sustainability/life-cycle evaluations of buildings), supplemented by environmental product declarations (EPD) and manufacturer information. Two scenarios are evaluated: a baseline scenario based on conventional practices and a target scenario incorporating optimized designs, low-carbon materials, innovative methods, and assumed future industrial decarbonization.

The 2022 roadmap (Begemann et al., 2022) identified reinforced concrete, steel construction, and special civil engineering as the main GHG hotspots. Reduction potentials of up to 88% were found through material-efficient design, low-clinker cements (CEM II/C, CEM III), reinforcement steel with higher recycled content, electric arc furnace (EAF)-produced steel using renewable energy, and optimized construction logistics powered by green electricity. Anticipated industrial advances—particularly Carbon Capture, Utilisation, and Storage (CCUS) technologies expected by 2035—were also included. Overall, emissions for the extended shell could be reduced from approximately 2.74 million t CO_2e to about 847,000 t CO_2e, representing a reduction potential of roughly 70%.

The 2023 roadmap update (Begemann et al., 2023) marks a shift from theoretical potential to measures already embedded in construction practice. New contractual requirements mandate the use of low-GHG concrete and reinforcement steel in the first U5 East construction lots. Achieved steel emissions have already fallen to around 500 kg CO_2e/t, with 400 kg CO_2e/t targeted for 2024/2025. Updated construction schedules, refined planning data, reduced structural volumes in the U5 Mitte 1000 package, and revised material quantities further increased accuracy. The updated target scenario projects total emissions of roughly 841,000 t CO_2e, maintaining a 69–70% reduction relative to the baseline (Figure 10).

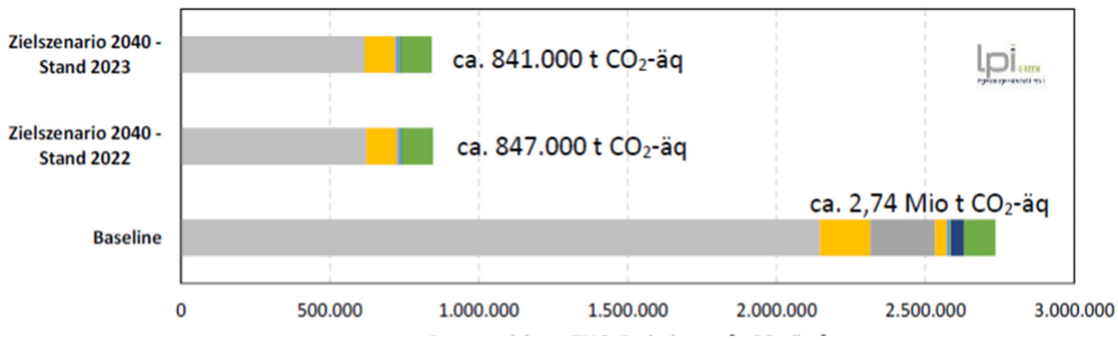

Figure 10. Forecasted GHG emission [t-CO_2 equivalent]
Comparative overview of greenhouse gas potential in the baseline scenario as of 2022 and in the target scenario as of 2022 and 2023 for the extended shell construction; Begemann, et al. (2023)

An external annual review by the University of Innsbruck (Geschösser, 2023) confirms the roadmap's methodological robustness and its character as a dynamic management tool rather than a static assessment. The review highlights HOCHBAHN's pioneering integration of future technological developments and its role in stimulating low-carbon innovation in the construction materials market. Practical experience from early construction is already feeding back into planning, strengthening evidence-based optimization.

Looking ahead, future roadmap updates will incorporate real construction emission data from U5 East, further expand the use of low-GHG materials and technologies, and transfer successful approaches to subsequent project phases. The assessment scope will be broadened to include technical building equipment and station design. GHG considerations will also be embedded more deeply into project risk management. While full climate neutrality cannot be achieved through construction methods alone, HOCHBAHN aims to minimize emissions as far as technically feasible and compensate unavoidable residual emissions through appropriate offsetting strategies.

3 CONCLUSION

The purpose of this paper is to present the technical experience gained during the execution of the projects "Fifth Sea Lock Brunsbüttel" and "U5 East Lot 1" in Hamburg, with a focus on innovative engineering solutions developed under demanding geotechnical and environmental conditions. One key contribution is the design and realisation of bored pile heads functioning simultaneously as foundation elements and uplift-controlling structures for underwater concrete slabs, thereby eliminating the need for additional micropiles. The detailed construction method enables the safe transfer of tensile forces exceeding 3,000 kN into the bored piles, ensuring both structural reliability and construction efficiency.

A further contribution is the development of an innovative approach for designing and constructing groundwater windows in diaphragm walls. These windows allow the natural groundwater flow to be re-established following completion of deep excavation works in dense urban environments, thereby mitigating long-term hydrogeological impacts. Together, these solutions demonstrate how targeted engineering innovations can meet the environmental requirements of modern infrastructure projects—by reducing CO_2 emissions through material optimisation and by minimising adverse effects on natural groundwater regimes.

Overall, the approaches described offer practical, resource-efficient alternatives for future complex civil engineering projects, combining structural performance with sustainable construction practices.

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