Collapse of the historical archive of the city of Cologne due to underground construction – Damage analysis and conclusions for quality assurance and risk management in geotechnical engineering

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ABSTRACT: In the field of geotechnical engineering, risks that materialise can have a significant impact on the serviceability and stability of a geotechnical structure, as well as its construction timeline. Therefore, risk control and mitigation measures should cover all stages of ground investigation, geotechnical interpretation, design and construction. These aspects are explored and reflected on the collapse of the Historical Archive of the city of Cologne as an example. The collapse of the Historical Archive of the city of Cologne and adjacent buildings occurred in March 2009 during the construction of the new North-South metro line. This incident caused significant damage to the city of Cologne, but also affected the underground construction sector in general. With a total damage sum of around 1.3 billion euros, it stands as the most severe accident on a German construction site to date. The investigation of the damage evidence was a technically challenging task that lasted more than twelve years. It involved numerous steps, including the construction of a 34 m deep investigation shaft. Based on these experiences the consequences for the independent checking of design and execution, for the quality assurance of underground works and their supervision, but also the need for a risk prevention based on communication and partnership between all parties involved in the construction process is reflected.

1 INTRODUCTION

Dealing with uncertainties and risks is an omnipresent task in structural and geotechnical engineering. Therefore, for the design and execution of geo- technical structures an appropriate consideration of uncertainties and risks is essential for all engineering stages - from soil investigation, field and laboratory testing, specification of a subsoil model and evaluation of soil/ rock properties to calculation with adequate empirical, analytical or numerical models, as well as for execution and supervision. The motivation to elaborate risk management and assessment is first and foremost the avoidance of danger to people and property but unquestionably also the elimination of financial and societal consequences of a severe failure like the collapse of the historical archive in Cologne (Fig. 1) considered as exceptionally case study in the following.

Risks that materialise can have a significant impact on the serviceability and stability of a geotechnical structure, as well as its construction timeline. Additionally, these risks can potentially affect the surrounding environment. Those risks arise not alone from variable and complex characteristics of the subsoil and groundwater, as well as from design and modelling of the soil-structure interaction, but also from execution process.

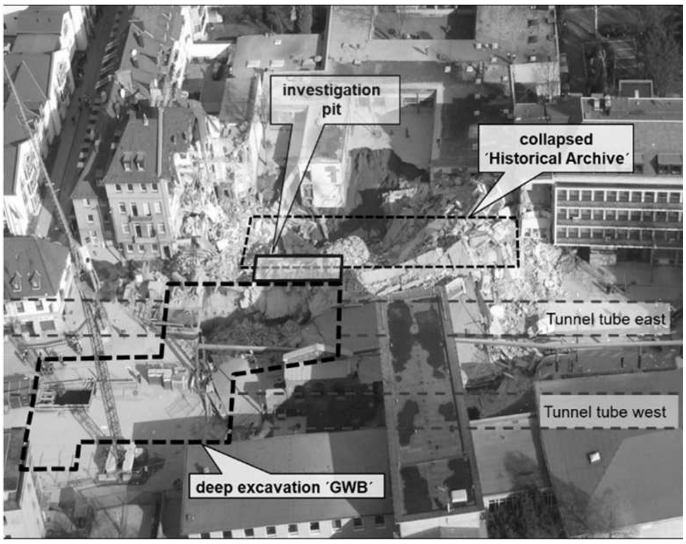


Figure 1. Aerial view of the collapsed Historical Archive and neighbouring residential buildings on Cologne's Waidmarkt immediately after the accident on March 3rd, 2009.

Sowers (1993) investigated the impact of human factors on uncertainty in geotechnical engineering by performing a comprehensive analysis of over 500 case studies of reported civil engineering failures.

The author identifies three main causes of failure: absence, ignorance, and rejection of current technologies. Absence of knowledge or current technology denotes the cause of 12 % of failures. This includes lack of data, i.e. for example the magnitude of a 1,000-year return period extreme weather event. It is argued that "blindly" relying on an estimation, based on the observed time period is ignorance or rejection. Ignorance is encountered by Sowers often in shape of a "know-it-all" attitude of engineers, who are often not properly qualified or experienced enough for specialized and complex problems. This cause is linked to 33 % of failures. Over 55 % of failures are classified in the rejection category, which includes several different aspects. The major ones that lead to rejection are faulty communications, pressures on the engineer like time, economical or ecological constraints. Thus, 88 % of failures can be appointed to human error. Some of the proposed mitigating measures are persisting engineering education, recognition of limitations and "resisting the unbalanced pressures that thwart good engineering" (Sowers 1993).

Hence, geotechnical risk management must identify various sources of risk and conduct risk analyses to assess the probability and consequences of undesirable events. Risk control and mitigation measures should cover all stages of ground investigation, geotechnical interpretation, design and construction.

These aspects are explored and reflected on the collapse of the Historical Archive of the city of Cologne during the construction of the new North- South metro line as a dramatic case study. The investigation of the damage evidence was technically a very challenging task that lasted more than twelve years. The concept for the investigations as well as the identified cause for the damage will be presented. Based on these experience consequences for the independent checking of design and execution, for the quality assurance of underground works and their supervision, but also the need for a risk prevention based on communication and partnership between all parties involved in the construction process is reflected.

2 CASE STUDY: COLLAPSE OF THE HISTORICAL ARCHIVE IN COLOGNE

On March 3rd, 2009 the Historical Archive of the City of Cologne, Germany, and adjacent residential buildings collapsed (Figs 1, 3 & 13). These buildings were located at the square ´Waidmarkt´ in the immediate neighbourhood to the deep excavation.

´GWB´ which was part of the construction work for a new 4.3 km long north-south underground line in Cologne. At the time of the accident the final excavation level had just been reached around 26.6 m below ground level. The collapse was a dramatic loss for Cologne's urban society but has also a severe impact on other underground and infrastructure construction activities. With a damage amount evaluated to around 1.3 billion euros it was the most serious accident on a German construction site to date (Moormann & Effenberger 2024).

a) Before collapse

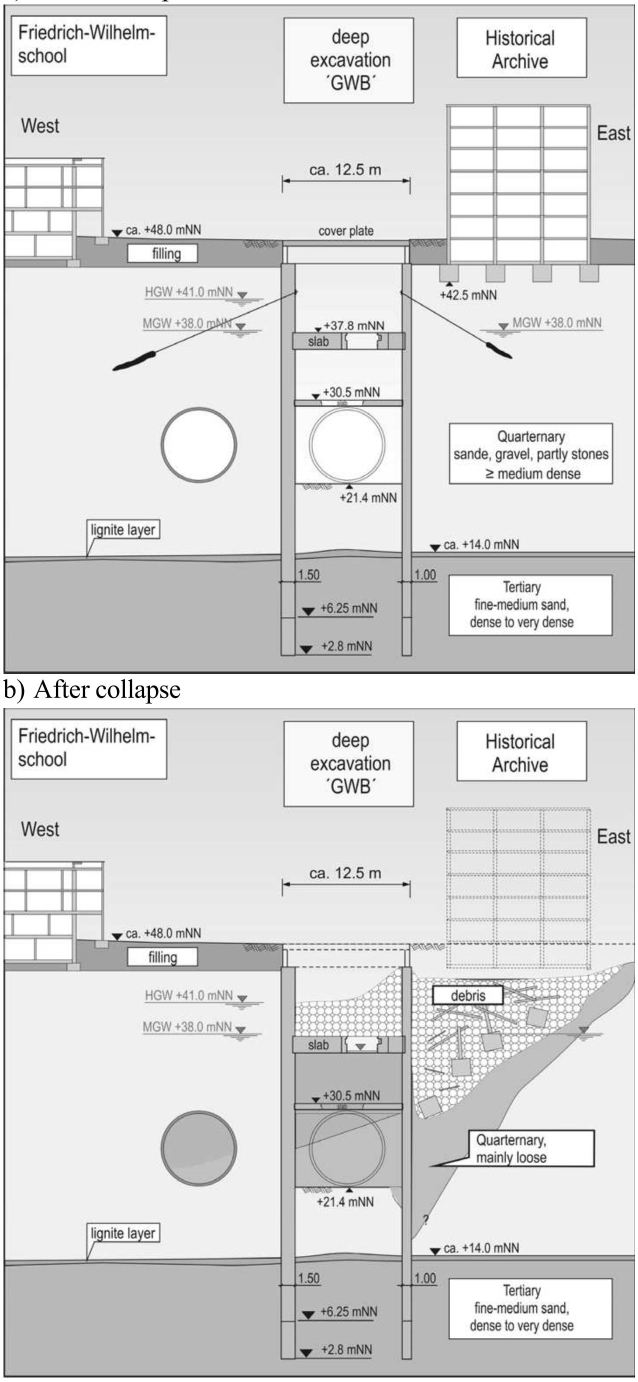


Figure 2. East-west section through the deep excavation ´GWB´ with neighbouring buildings and subsoil situation (position of section corresponds to section 1-1 in Fig. 3).

After phases of immediate stabilisation, salvage and an initial survey, the cause of the damage was clearly clarified through a technically highly demanding investigation of evidence lasting more than twelve years, during which, among others, a 34 m deep inspection shaft was executed in direct neighbourhood to the potentially damaged diaphragm wall of the deep excavation ´GWB´. As the measures for the conservation of evidence and for the investigation of the cause of damage were concluded and based on that a settlement between employer and construction joint venture was reached in 2020, it is possible to report on the measures and the identified cause of damage.

2.1 *Deep excavation ´GWB´*

The excavation pit ´GWB´ was constructed with diaphragm walls with wall thicknesses of 1.0 m and 1.5 m. With regard to the stabilisation against hydraulic ground failure the diaphragm walls were embedded up to 45 m below ground level, i.e. a lower wall edge of 2.8 m above sea level (a.s.l.) in the corner areas and 6.25 m a.s.l. on the long sides of the walls considering the higher hydraulic gradients resulting from the spatial inflow at the corners of the excavation (Aulbach & Ziegler 2013). The retaining walls were anchored in the upper part and braced by two reinforced concrete slabs constructed during excavation at 10.0 m (37.8 m a.s.l.) and 17.3 m (30.5 m a.s.l.) below ground level (Fig. 2a).

The dewatering in the ´GWB´ pit was carried out via wells arranged in the footprint of the excavation pit and filtered in the quaternary and/or tertiary, which led to a lowering of the free groundwater level in the quaternary and a (partial) relaxation of the tertiary aquifer. Within the diaphragm wall enclosure the groundwater level in the quaternary layers was lowered by open dewatering.

Overall, the realised excavation corresponds to the in the past often successfully realized concept of a "tertiary excavation pit" with water-pressure- retaining walls embedded into the tertiary in conjunction with an internal tertiary dewatering system to relieve the hydraulic head in the Tertiary below the excavation bottom. The relief of the tertiary hydraulic head is essential to ensure the hydraulic stability of the excavation base and to minimise upward flows in the earth resistance area of the retaining walls.

2.2 *Subsoil conditions*

The subsoil conditions at the ´Waidmarkt´ site are illustrated for an east-west section in Figure 2. Below street level and up to 6 m thick fillings Pleistocene terrace deposits (Quaternary) down to a depth of around 14 m a.s.l. which consist of terrace gravels and sands of the Rhine of varying grain size and composition, into which cohesive, slightly silty secondary sediments and isolated cohesive layers of decimetre thickness can be incorporated in some areas.

Separated from the terrace body by a thin layer of tertiary fine sand, the surface of an Oligocene lignite layer is reached at approx. 14.0 m a.s.l. which was explored in predominantly continuous thicknesses of 0.7 m to 1.8 m, but is also exposed locally.

The lignite is underlain by tertiary dense to very dense fine-medium sands which were exposed as a largely uniform layer with a thickness of approx. 48 m down to a depth of -35 m a.s.l. Due to their high uniformity ($C_U \leq 2$) and their mica content, the water-filled tertiary sands can be easily hydraulically mobilised what must be considered for dewatering, drilling works etc.

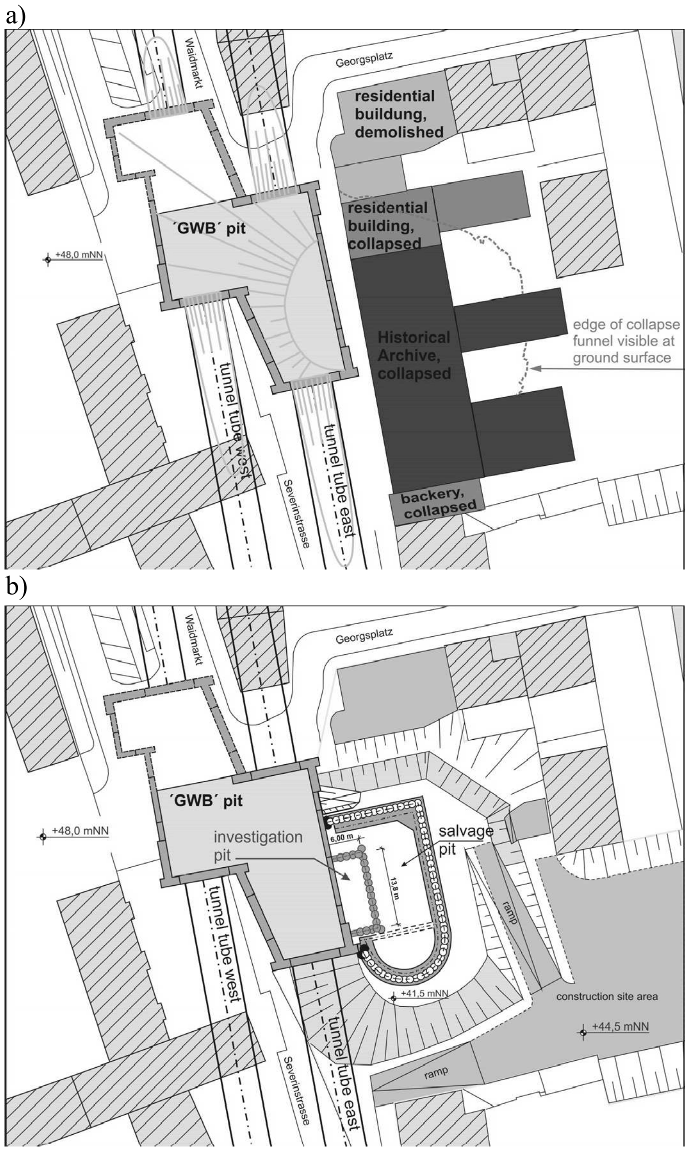


Figure 3. Site plan of the deep excavation ´GWB´ at ´Waidmarkt´ square in Cologne, a) at the time of the collapse with existing buildings and upper edge of the failure funnel, b) with salvage pit and investigation pit after the accident during salvage and preservation of evidence.

Concerning the groundwater situation, two aquifers have to be considered, a quaternary and a tertiary aquifer. The local hydrogeological conditions at the ´Waidmarkt´ square are strongly influenced by the river Rhine and its water levels, both in terms of groundwater levels and the direction of groundwater flow. The groundwater levels in the Quaternary follow the water levels of the Rhine, which is located approx. 400 m east from ´Waidmarkt´, with a slight attenuation and generally fluctuate between approx.

36.5 and 40 m a.s.l.; at high tide whereat water levels of 41.5 m a.s.l. and more are reached in exceptional cases. The groundwater levels in the tertiary aquifer are at around 36 to 39 m a.s.l. and also follow the changes in the Rhine level with slight attenuation.

2.3 *Execution of the deep excavation ´GWB´*

The diaphragm wall was already constructed in 2005 using the conventional two-phase method. As joint system lost flat steel profiles were used which had a smooth surface on the side of the subsequent panel. When excavating the neighbouring panel, the tool used for cleaning the joint and removing concrete that has flowed in behind the joint profiles was therefore not guided by the joint construction. In fact, the cleaning of the diaphragm wall joints resp. stop ends was only partially successful, so that in the course of the excavation leaks occurred in several places at the joints, which required sealing measures to stop local water inflow.

An analysis of the execution records of the diaphragm wall carried out after the accident shows that obstacles were encountered during the production of panels #10 and #11 (Fig. 4) of the eastern diaphragm wall. During the construction of bite #10.3, obstacles were encountered at a depth of approx. 25 m (21.8-22.8 m a.s.l.) which made the use of a chisel necessary. The problems were even more severe during the following construction of the neighbouring panel #11, which was planned as a 3.4 m wide single bite closing panel being the last panel to be executed for the whole ´GWB´ pit. Massive obstructions were encountered in this panel at a depth of approx. 23 m (23.2-22.8 m a.s.l.), which caused a damage to the grab shells used. This obstruction could not be removed even with the use of chisels. In consequence, the grab shell was changed from 3.4 m to 2.8 m wide and the excavation of panel #11 was continued to the final level. An evaluation of the recorded concrete consumption shows a lower additional consumption for panel #11 compared to the theoretical concrete consumption than for the other panels. It was not possible to precisely analyse the increase or decrease in concrete consumption over the height due to the small number of measuring points; however, a decrease in concrete consumption up to the height of the obstacles encountered is recognisable.

With regard to the quality assurance and records of the diaphragm wall construction, further anomalies were identified, e.g. identical logs of the verticality measurements of panels #5 and #11 as well as missing acceptance records of the reinforcement cages and indications of missing shear reinforcement which had to be added on site in the course of coupling the reinforcement cage sections over the open trench.

After excavation of the ´GWB´ pit to the lower edge of the cover plate (Fig. 2a) and construction of the cover plate at street level, excavation was interrupted for tunnelling with TBMs passing in 2007 the non-excavated pit during the shield drive for the construction of the eastern and western tunnel tubes, before further excavation below the cover plate was continued applying a top/down method in 2008.

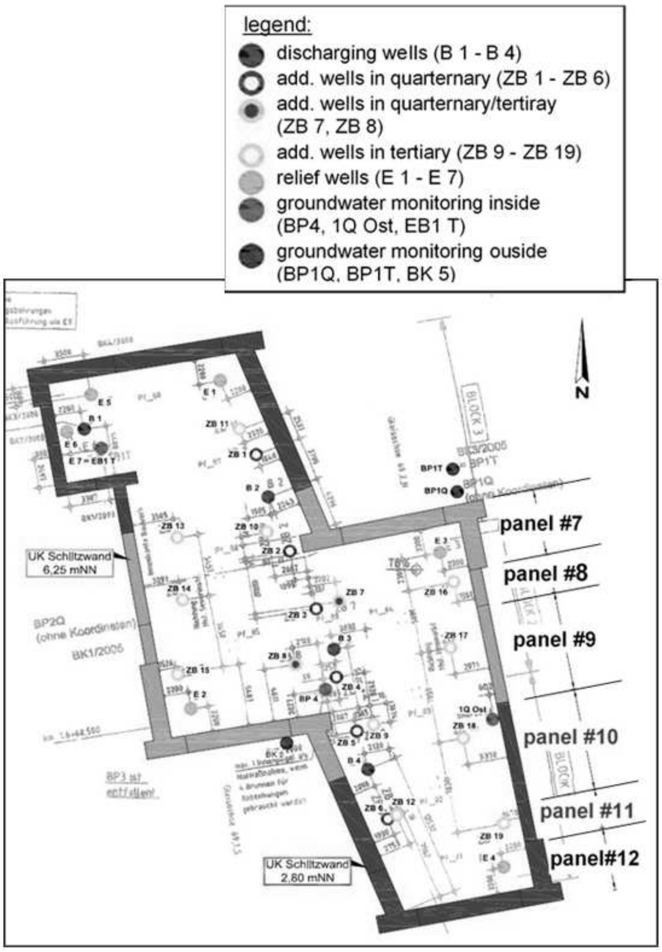


Figure 4. Ground plan of the excavation pit ´GWB´ with diaphragm wall panels and groundwater discharching and relief wells; status before collapse in March 2009.

Parallel to the further excavation, dewatering was carried out in the excavation pit, initially with four discharging wells (B1 to B4) and four relief wells (E1 to E4) connecting the tertiary with the quaternary aquifers (Fig. 4). As it was not possible to achieve with these wells a groundwater drawdown correspon- ding to the excavation progress and, in particular, the necessary relief of the hydraulic head in the tertiary aquifer three further discharging wells and a total of 19 additional wells were successively installed (Fig. 4). The recorded water extraction rates show that despite the roughly constant water level differences between the outside and inside water levels over a longer period of time, a significant increase in the extraction rate from around 115 l/s (corresponding to 414 m^3/h) to around 180 l/s (648 m^3/h) and a maximum of >200 l/s (720 m^3/h) was recorded at the beginning of December 2008 in connection with the commissioning of additional wells. These pumping rates were significantly higher than the expected water extraction rates. At the time of the accident in March 2009, the ´GWB´ pit had largely been excavated to the final excavation level: while the reinforcement of the floor slab had already been laid on the clean layer in the western section, the excavation of the last 0.3 m for the construction of the final subgrade was carried out in the eastern section, starting from the rough subgrade. At midday on March 3rd, 2009, work began on the construction of a pump sump for water collection below the planned final excavation level in order to control water ingress from the diaphragm wall in the area of the joint between panels #10 and #11 (position of panels marked in Fig. 4).

2.4 *Collapse of March 3rd, 2009*

On March 3rd, 2009, at 13:58 pm, an accident occurred in the deep excavation ´GWB´ during which about 5,000 m³ of sand and gravel flowed into the excavation pit, causing the collapse of the adjacent ´Historical Archive´ of the City of Cologne, a massive 7-storey reinforced concrete skeleton building, immediately adjacent to the excavation pit to the east, as well as of parts of the adjacent multi-storey residential buildings on both sides (Figs. 1, 3a). The spread foundation of the Historical Archive, consisting of single and strip foundations founded in the quaternary sands and gravels, sank into the ground (Fig. 2b); foundations were later recovered from a depth of up to 20 m below ground level. This sudden "loss of foundation" caused the building to tilt towards the street, then to completely collapse, thereby partly falling into the excavation pit, breaking through its covering (Figs. 1, 5). The soil inflow at the lowest level of the excavation pit resulted in the formation of a cone of debris up to 7 m high consisting of quaternary sands and gravels, the foothills of which reached into the four tunnel tubes (Fig. 3a) and whose greatest height was directly in front of the eastern diaphragm wall (Figs. 2b and 3b). Although the workers fleeing from the final excavation level of the ´GWB´ pit who had noticed a rapidly increasing water and then soil ingress during final excavation and construction of the pump sump in front of the eastern diaphragm wall, warned the visitors to the Historical Archive and the residents of the neighbouring residential buildings of the impending accident at the proverbial last minute, two young residents tragically died in the subsequent collapse of the residential buildings. At that moment, around 30 linear kilometres of archives from 1,200 years of Cologne´s city and regional history, the "city's memory" that has grown over the centuries, seemed to have been destroyed within seconds and lost forever.

2.5 *Immediate stabilisation measures*

On the evening of March 3rd and on March 4th, 2009, initial inspections of the damaged area and immediate measures to stabilise the excavation were carried out by placing around 1,600 m³ of concrete on the base of the excavation (´ballast concrete´) via the northern staircase and on March 8th, 2009, an inspection of the tunnel tubes was carried out in order to decide on further safety measures to avert danger.

Figure 5. Salvaging the archives from the rubble of the collapsed Historical Archive at Waidmarkt, looking west with the eastern diaphragm wall of the ´GWB´ pit.

This was followed by the demolition of the neighbouring residential buildings being at risk of collapse. In addition, a comprehensive monitoring programme was installed for the excavation pit and on the existing buildings and continuously adapted in order to detect any further risk to stability at an early stage.

In an initial salvage phase, the fire brigade and the Governmental disaster relief organization carefully removed the huge cone of rubble and debris under the protection of a temporary lightweight hall erected over the excavation pit (Fig. 5) and handed over the archive material that came to light to archivists and many volunteers.

In the east of the ´GWB´ pit, in the area of the collapse funnel recognisable here by its tearing edge (see Fig. 3a), the debris from the historical archive was removed to just above the mean groundwater level, i.e. around 9 m below street level. In this way, by September 2009, 85 % of the archive material had already been recovered, albeit mostly severely damaged. The recovered relics were initially stored temporarily in almost 20 asylum archives throughout Germany. Damp archive materials were partially freeze-dried to prevent mould growth.

2.6 *Deep excavation for salvage*

After salvaging the rubble and archival material down to the mean groundwater level (38 m a.s.l.), investigations carried out up to that point revealed that further rubble from the Historical Archive had ´slipped´ down to a depth of around 20 m below ground level (28 m a.s.l.) in a comparatively narrow collapse funnel.

For the City of Cologne, the obligation towards its own historical heritage and to the various lenders of archive items made it necessary to take all reasonable measures to salvage these archival materials buried below the groundwater level, so that a so-called ´salvage excavation pit´ was planned and realised for this purpose.

Figure 6. Salvage pit (in the foreground) in front of the eastern diaphragm wall of the ´GWB´ pit.

Based on a conceptual study, the excavation pit was constructed in the form shown in Figures 6 and 7 with ground plan dimensions of around 16.5 m by max. 30 m and a rounded section (´apse´) in the south, as a particularly large amount of archival material was suspected here. The excavation pit thus enclosed significant areas of the explored excavation funnel. The construction pit was secured on three sides by a secant bored pile wall (pile diameter D = 1.2 m, pile length 29.5 m) and braced against the eastern diaphragm wall by a circumferential reinforced concrete beam with three tubular steel struts and a reinforced concrete strut which were pre-stressed by hydraulic presses.

An additional 24 micro-piles which together with the bored pile wall formed a type of pile-trestle construction were installed at the eastern wall of the salvage pit in order to transfer the strut forces into the ground with minimal deformation. The horizontal loads were thus transferred from the west side of the ´GWB´ pit via the concrete slabs and the damaged eastern diaphragm wall into the salvage pit. The connection of the bored pile walls to the diaphragm wall of the ´GWB´ pit was realized with ground freezing after an initial stabilisation using foam injections proved to be insufficient. The rubble and archives were excavated under water. Possible horizontal displacements of the eastern diaphragm wall of the ´GWB´ pit at the level of the upper concrete slabs had to be limited to 2 mm at maximum. Construction of the salvage pit began in spring 2010.

a)

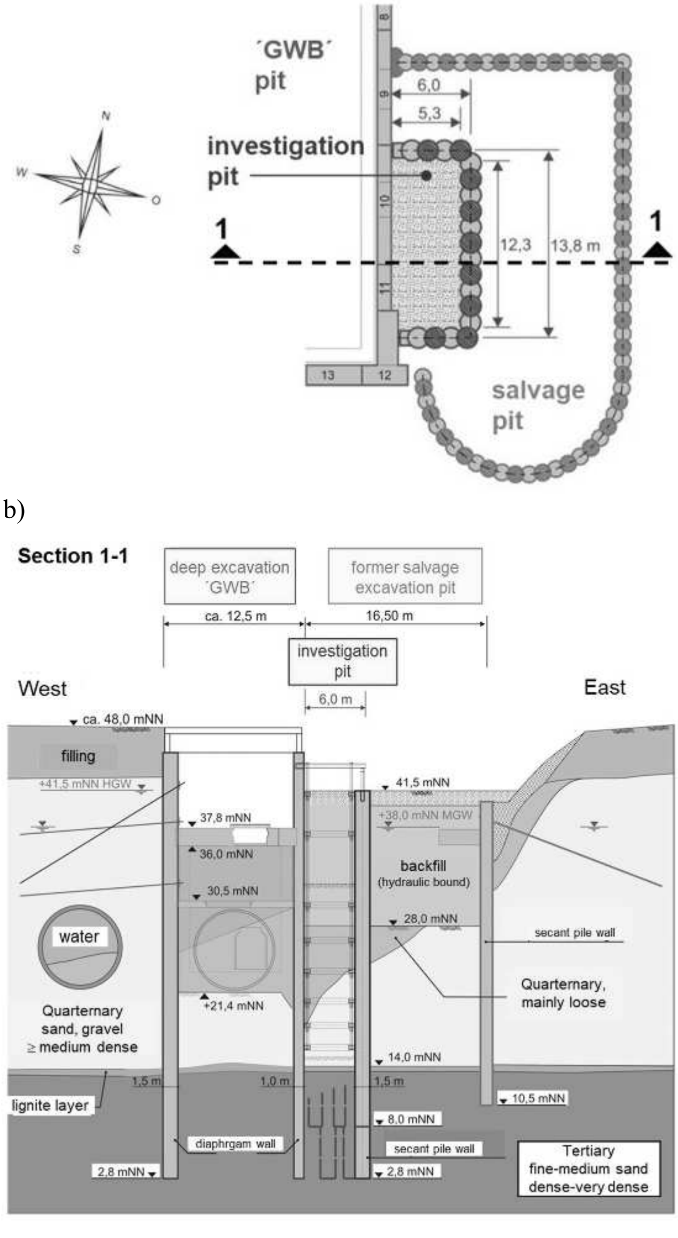


Figure 7. Salvage pit and inspection pit to the east of the ´GWB´ pit: a) ground plan, b) cross-section 1-1.

Due to some difficulties in the construction process and due to unexpectedly large and difficult to salvage foundation bodies weighing up to 30 t, the salvage of the archival material was completed just in summer 2011. The area covered with archival material ended above the predicted depth of 28 m a.s.l. Nevertheless, excavation was carried out to this depth and the remaining debris in the excavation pit was removed to ensure a clear construction area for the subsequent investigation pit. This work and the subsequent collection of evidence within the salvage pit by the court-appointed expert and the experts from the public prosecutor's office lasted until spring 2012, after which the salvage pit was backfilled with a flowable, hydraulically bound material and the temporary struts were removed. During this process, a prestressed reinforced concrete structure was installed in the salvage pit at the level of the upper concrete slab of the ´GWB´ pit to provide low- deformation support for the eastern diaphragm wall, taking into account the requirements of the subsequent inspection pit (Fig. 10).

2.7 *Investigation of the cause of damage*

The clarification of the cause of the damage was the subject of technically extremely demanding and extensive investigations, which - interrupted by construction measures to create the necessary boundary conditions for the preservation of evidence - lasted from 2009 to 2020. In addition to the investigations by the public prosecutor's office in Cologne, evidence on the cause and avoidability of the collapse was collected in an independent preservation of evidence procedure initiated by the owner immediately after the accident. Prof. Dr.-Ing. H.-G. Kempfert, Hamburg, was appointed by the Cologne Regional Court as geotechnical expert in the independent evidence proceedings.

From the outset, two possible scenarios were analysed in parallel with regard to the cause of the collapse of the ´Historical Archive´ building:

- "Suspected area of diaphragm wall quality" with horizontal soil ingress, for example through a void area in the diaphragm wall;
- "Suspected area of vent formation" with vertical soil ingress into the excavation pit through its base, for example through breakthroughs in the lignite layer.

2.7.1 *Indirect investigations*

Immediately after the collapse subsoil investigations were carried out to clarify the subsoil conditions and to examine the stability of the excavation pit and of the surrounding buildings including several public secondary schools. These investigations already formed a dense grid, which was supplemented with further investigations by the expert in the court evidence from 2009 to the beginning of 2010.

Further investigation campaigns followed, including investigations requested by the parties involved in the preservation of evidence process. The scope of the exploration finally realised (Fig. 8), including a total of 113 core drillings, 260 heavy dynamic probing tests (DPH), 186 borehole dynamic probing tests (BDP) and 18 cone penetration tests (CPT), was so intensive that further condensation of the grid was no longer technically reasonable, particularly in the vicinity of the eastern diaphragm wall. In addition, extensive laboratory tests were carried out also. These investigations made it possible to identify the centre of the damage to a tightly confined area in the vicinity of panel #11 in the eastern part of the diaphragm wall of the ´GBW´ pit. The core drillings being modified to monitoring wells were used by the court-appointed expert to investigate the integrity of the eastern diaphragm wall of the ´GWB´ excavation pit by applying indirect methods. In particular, seismic cross-hole tomography was successfully used to check the presence, quality and integrity of the diaphragm wall panels. The planned geometric embedment of the diaphragm wall panels could be verified, but at the same time, in the area of the joint between the adjacent panels #10 and #11 at a depth of approx. 16 m to 23 m a.s.l., i.e. between the final excavation level down to the quaternary base, significantly reduced local wave velocities were clearly recognisable identifying anomalies (Fig. 9).

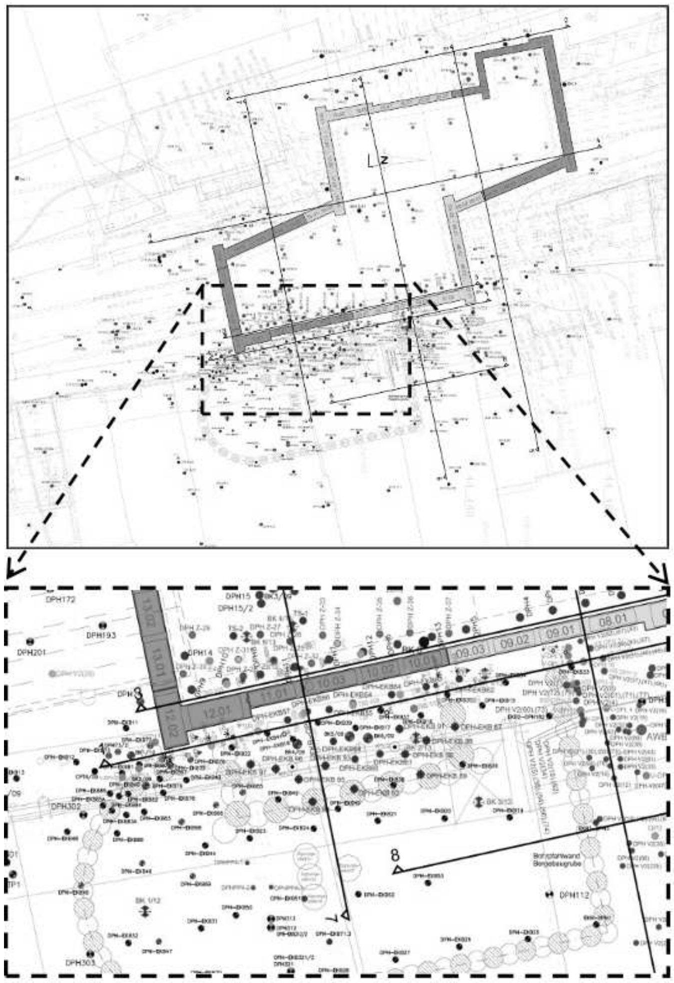


Figure 8. Ground plan: Soil investigation focusing on the south-eastern corner of the ´GWB´ pit.

Supplementary thermographic investigations in the form of fibre-optical temperature measurements in combination with the heating method (heat pulse method) showed clear and significant temperature anomalies in the groundwater flow and thus clear indications of hydraulic pathways in the area of the joint between the diaphragm wall panels #10 and #11 in a depth range of approx. 13 m to 20 m a.s.l. (Fig. 9). However, there were no indications for a vertical flow around the base of the diaphragm wall.

In accordance with the anomalies identified during the construction of diaphragm wall panel #11 (see section 2.3), the results of the investigation gave rise to the suspicion that the accident was probably due to one - or possibly several - defects in the joint area of the eastern diaphragm wall, in particular in the joint area between panels #10 and #11 at a level between the final excavation level and the lignite layer (Fig. 9), while a hydraulic ground failure was largely ruled out as the cause of the failure and an erosion ground failure due to a thin vent appeared unlikely even as a (co-) cause of the damage event (Sieler et al. 2012).

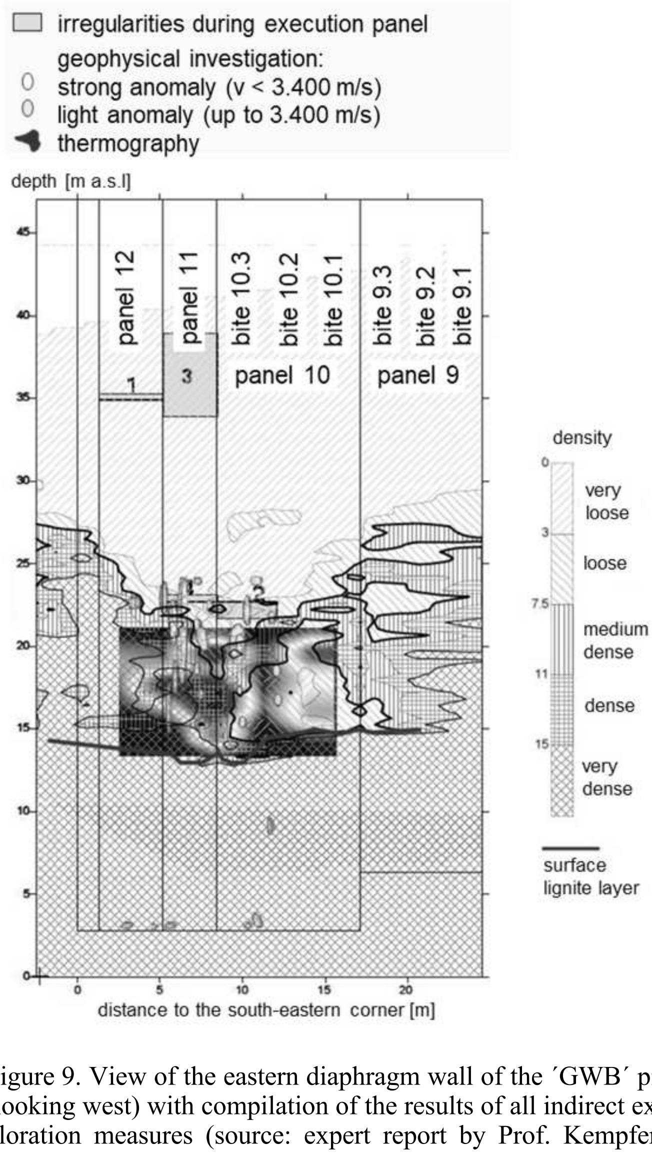


Figure 9. View of the eastern diaphragm wall of the ´GWB´ pit (looking west) with compilation of the results of all indirect exploration measures (source: expert report by Prof. Kempfert (2011-2020), modified).

2.7.2 *Investigation pit: Concept*

While the numerous indirect investigations had already provided reliable indications of the cause of the damage related to "Suspected area of diaphragm wall quality", a direct visual inspection of the suspected areas was required to dispel the last possible doubts regarding the cause of the damage.

In this regard, the construction of an inspection pit inside the ´GWB´ pit (as part of the recovery of the excavation pit) and the construction of an external excavation pit were discussed as alternatives. After the decision on the recovery concept was delayed, the Cologne Regional Court ordered the construction of an external investigation pit in December 2010 in accordance with the specifications of the court- appointed expert.

This investigation pit, located in the centre of the collapse funnel in front of the diaphragm wall panels #10, #11 and #12 of ´GWB´ pit, had comparatively small ground plan dimensions of around 6.0 m x 13.8 m (axial dimensions) or 5.3 m x 12.3 m (clear internal dimensions, see Figs. 3b and 7) and was intended to allow inspection of both the diaphragm wall and - layer by layer - the subsoil conditions down to the surface of the lignite layer, which was expected at 14.0 m to 14.8 m a.s.l. in the construction area of the investigation pit, i.e. at a depth of 34 m below street level resp. 27.5 m below working level.

The investigation pit was designed for underwater excavation and inspection by divers. In a second stage, it was considered as a supplementary option, and this was also taken into account in the planning and design of the pit, to deballast the inspection pit using compressed air. However, the use of compressed air was considered optional and made dependent on the findings obtained during the underwater exploration.

The design of the investigation pit is reported in detail in Moormann et al. (2014). The main elements are presented hereinafter.

2.7.3 *Investigation pit: Retaining wall*

The investigation pit enclosure was constructed on three sides as a secant bored pile wall with large diameter bored piles (D = 1.50 m) (Figs. 7 and 10). The pile base level was initially planned uniformly at 2.8 m a.s.l., corresponding to the depth of the diaphragm wall of the ´GWB´ pit. The planned pile length was therefore almost 40 m. The piles had to be executed fully cased while maintaining a water load inside the casing to be controlled depending on the quaternary groundwater level and a sufficient advanced penetration of the casing below borehole level in order to minimise construction-related loosening, particularly with regard to the sensible evidence situation.

Under the special requirements, test piles were initially executed in order to test suitability of the execution process. Despite the use of a powerful rotary drilling rig (´BG 40´), the first test pile could unexpectedly not be drilled down to its final depth at the end of 2012, as after drilling through the lignite layer it was not possible to drive the casing into the tertiary sands with the required forward penetration. As a result of the execution of further test piles, various optimisation approaches were identified, in particular a reduction in the statically required embedment depth of the secondary piles by 5.2 m to 8.0 m a.s.l. (see Fig. 7), the use of a separate hydraulic unit (PowerPack) for the casing oscillator (Leffer 2000), with which the casing could be torqued independently of the excavation process and kept in continuous oscillation, as well as soil replacement ahead of the actual pile drilling (backfilling with 0/32 mm gravel sand) in the area of the hydraulically bound backfill material of the ´salvage pit´ (28.5 m to 41 m a.s.l.), with which the influence of abrasion in the binder-stabilised sands of the backfill could be minimised. In addition, a method called ´gravel shuttling´ was developed to reduce casing friction: After the lignite layer had been passed with the casing, the borehole was backfilled with gravel (8/16 mm) to a height of approx. 3 m, the casing was then initially pulled back to 0.5 m below the gravel filling level and the drilling process was then continued with advance casing to the final depth.

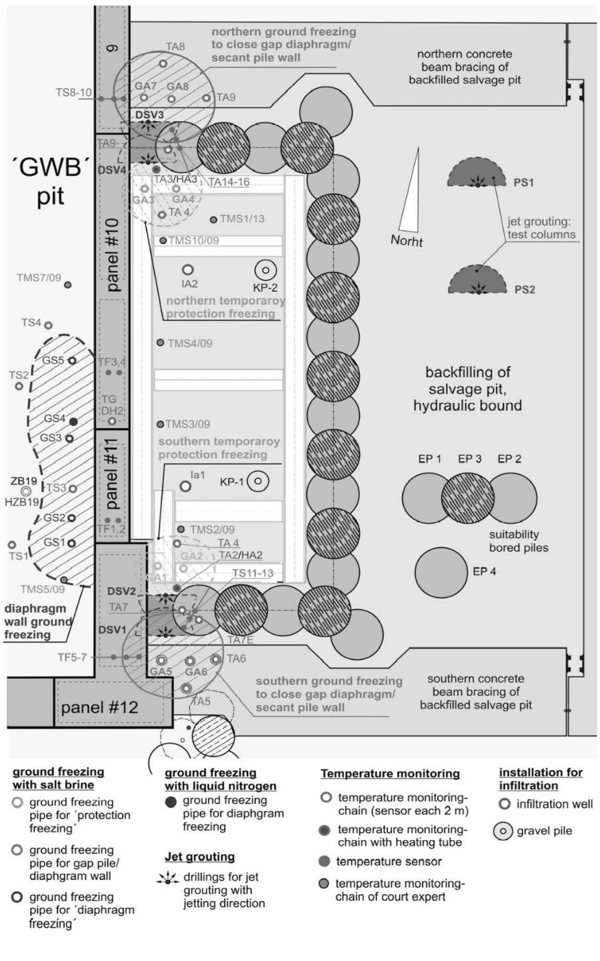


Figure 10. Ground plan of the investigation pit with secant bored pile wall and connecting construction to the diaphragm wall of the ´GWB´ pit plus ground freezing for the diaphragm wall.

A multi-stage construction was chosen for the mechanical and hydraulically sealed connection of the secant pile wall of the inspection pit to the diaphragm wall of the ´GWB´ pit with jet grouting as the main element (Fig. 10). As a preliminary step, a temporary ´protection freezing´ was realised inside the inspection pit. Under its protection, it was possible to grout the soil body, which would later be in contact with the free groundwater in the connection area, using the jet grouting method without having to worry about any impact on the soil situation inside the inspection pit. As a fall-back level and to seal the gap below the excavation level, a further ground freezing, the so-called ´connection freezing´, was realized on the outer side of the gap and operated for the construction period. The shielding and connection freezing were both carried out using the salt brine freezing method.

2.7.4 *Investigation pit: Inner bracing system*

The investigation pit was braced by steel bracing frames in a total of eight levels (Figs. 10 and 11). This bracing solution ensured that the eastern diaphragm wall of the ´GWB´ pit was supported almost over its entire surface, thus ensuring that the earth pressure effects on the diaphragm wall from the east remained as unchanged as possible and were distributed almost evenly, so that overall the boundary conditions of the stable initial situation of the ´GWB´ pit were not significantly changed and at the same time the diaphragm wall could be safely supported even in the event of larger defects. Due to the cramped conditions in the investigation pit and the fact that the bracing had to be installed under water, a concept was developed in which the pre-assembled steel frames for all eight bracing levels were lifted into the investigation pit after an initial excavation phase (35.4 m a.s.l.) and then lowered as a 'package' following the excavation using hydraulic devices, whereby the topmost frames were successively fixed in place (Fig. 11). The dead weight of the prefabricated, horizontally telescopable frames made of sectional steel was between 17.5 t and 27.5 t per bracing layer.

2.7.5 *Investigation pit: Freezing of the eastern diaphragm wall*

To stabilise the diaphragm wall joints, a frozen ground body was arranged on the inside of the ´GWB´ pit, i.e. to the west of the eastern diaphragm wall, within the soil volume deposited in this area ('cone of debris') in the course of the accident and in the quaternary sands and gravels between the former final excavation level in the ´GWB´ pit (21.8 m a.s.l.) and the lignite layer in the area of the two diaphragm wall joints of panels #10 and #11 and of panels #11 and #12 to be inspected (Figs. 10 and 11). This so-called 'diaphragm wall freezing' served to stabilise the soil in the diaphragm wall joints as well as the soil behind them and at the same time to hydraulically seal possible defects in the diaphragm wall, whereby the planning of this freezing measure was based on an assumed defect geometry.

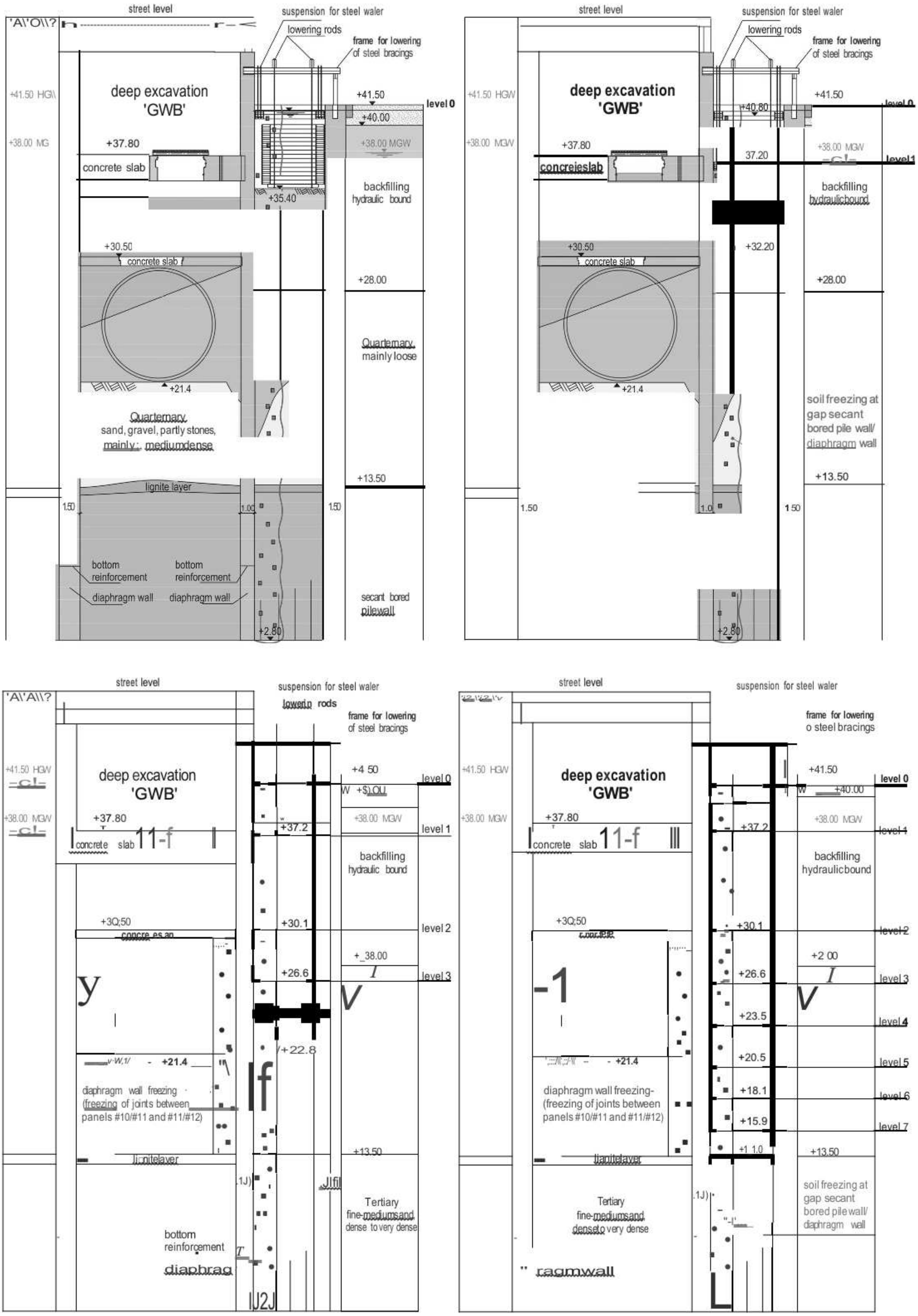


Figure 11. Construction sequence of the inspection pit (west-east section, selected stages).

Four brine freezing pipes (GS1 to GS3 and GS5) and a nitrogen lance (GS4) were installed for the diaphragm wall freezing (Fig. 10), whereby the latter could be used to generate increased heat extraction locally and in defined depth sections that could be varied by moving the feed pipes if the exploration work required this, for example when faults were encountered, which was almost always the case during the execution. The freezing area extended from approx. +28 m a.s.l., i.e. the surface of the debris cone reaching just below the lower concrete slab bracing, to the surface of the lignite at approx. 14.0 m a.s.l., so that this frozen soil body had a height of approx. 14 m.

2.7.6 *Investigation pit: Underwater excavation*

The excavation of the investigation pit was carried out under water and, due to the dimensions of the ground plan and the multi-layer bracing, in very confined conditions using a suction pump. The suction pump, which was suspended from an excavator and lowered into the working areas defined by the bracing frames, was guided underwater at the current excavation level by a diver of the court- appointed expert.

The excavation was carried out in layers of 0.50 m increments from the relevant level of 28 m a.s.l. to the surface of the lignite layer at approx. 14.0 m a.s.l. In the vicinity of the diaphragm wall, the excavation was carried out particularly carefully, if necessary by manually loosening and conveying the soil to the suction pump. Holding points were provided at several levels to secure the diaphragm wall and the base of the excavation pit. The mixture conveyed by the suction pump was channelled through a desanding/separation system to separate the soil material from the process water. The excavated material was laid out field by field, addressed in terms of engineering geology and geotechnics and anthropogenic finds which were of particular importance with regard to the demarcation of the collapse funnel and which were identified (e.g. with regard to their possible origin from the historical archives) and mapped. Furthermore, extensive soil mechanical and mineralogical analyses were regularly carried out on soil samples taken.

Particular challenges for the securing and exploration of evidence arose when diaphragm wall defects and their filling were encountered, as a joint filling frozen by the aforementioned ´diaphragm wall freezing´ gradually thaws in direct contact with the 'free' water of the inspection pit and therefore only has a very limited ´service life´. This service life, which defined the time window available to the expert divers for the collection of evidence and for the installation of appropriate mechanical protection, depended on the respective boundary conditions (geometry, water temperature, etc.). Temporary (air-filled pressure cushions) and permanent mechanical securing systems (including mortar-filled ´Bullflex´ cushions and securing plates) had to be developed with which defects could be sealed after the preservation of evidence. After the installation of a suitable cavity-filling mechanical system, stationary conditions were again established with regard to the freezing, also depending on the boundary conditions. The concept had to be further developed in the detected open void area (see section 2.7.8) and additional horizontal freezing lances and protection by steel tubes had to be installed underwater in layers in the void area what proved to be time-consuming.

a)

b)

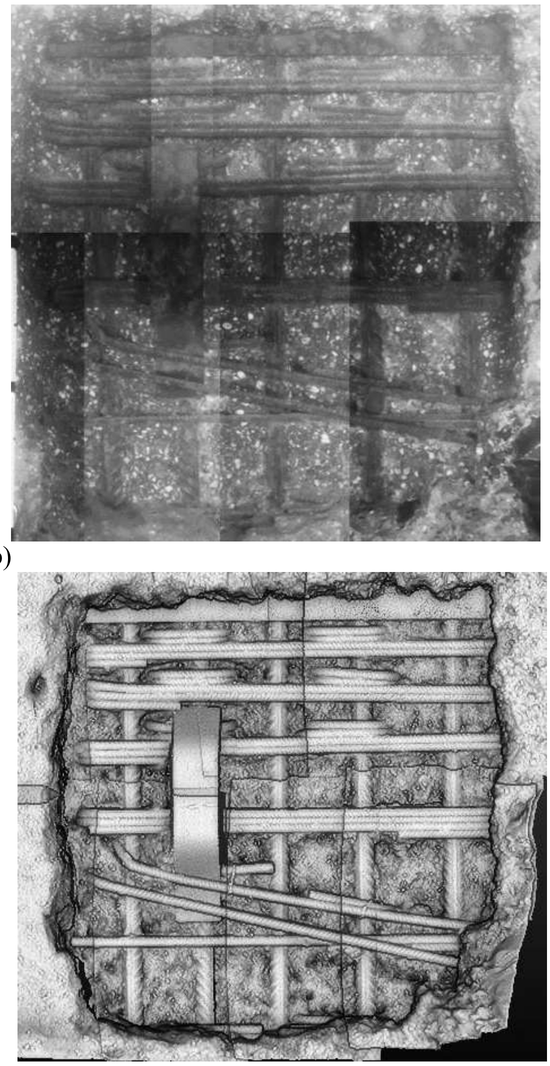


Figure 12. Exemplary image of a reinforcement window in the diaphragm wall panel #10.1, a) photographic, b) with underwater laser scan.

The excavation and exploration of evidence in the inspection pit began in January 2014 and was completed in July 2020 with the excavation of the surface of the lignite. All of the work had to be carried out by divers at increasingly great depths, which was a key boundary condition.

2.7.7 *Collection of evidence: Approach*

During the successive excavation of the investigation pit, not only the detailed documentation of the excavated soil material was carried out as described, but also a comprehensive survey of the diaphragm wall surface. The underwater recording consisted of several elements that were applied in each 0.5 m excavation step: In addition to an initial video recording by the diver´s helmet camera, a) a recording with a high-resolution video, b) a recording with an underwater laser scanner and c) a manual-electronic measurement of the geometry of the diaphragm wall qsurface (only in the case of anomalies) were carried out geometrically referenced by a guide construction. In addition, the diaphragm wall surface was recorded with a sonar device.

As a result of these recordings, the expert and his divers were able to provide a complete graphic-visual and photogrammetric documentation of the diaphragm wall surface down to a depth of 34 m below street level in outstanding quality. The underwater laser scanner obtained from the United States proved to be particularly efficient (Fig. 12).

The area of the joints between panels #10 and #11 as well as between panels #11 and #12 was examined with particular care. When joint fillings and defects were encountered, the joint or void material was completely collected in special trays and the joint/ defect geometry was documented using the afore- mentioned methods and with the additional use of smaller GoPro cameras for the interior and flanks of the joints/defects.

In selected sub-areas, in particular in the overlapping area of the reinforcement cages of the diaphragm wall panels "reinforcement windows" were exposed in order to check the position and dimensions of the reinforcement cages and the possible absence of reinforcing bars (Fig. 12).

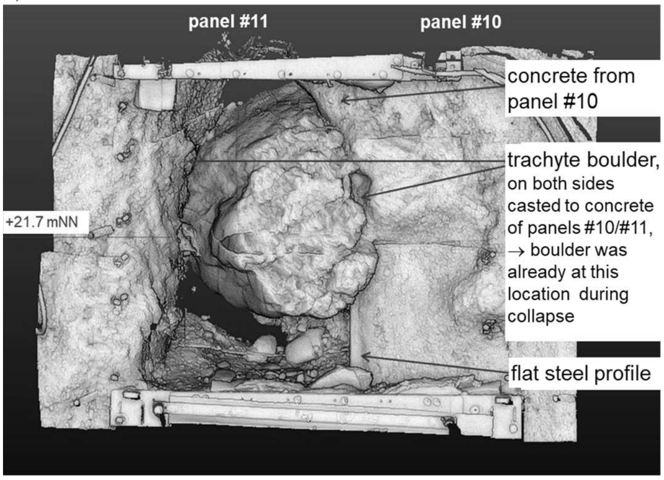
2.7.8 *Collection of evidence: Findings*

In the course of the exploration of evidence carried out in this way, in the area of the joint between panels #10 and #11, from a depth of approx. 25.2 m a.s.l. on, concrete increasing in width by depth was detected, which extended from panel #10 into panel #11 (Fig. 14) and reached a width of around 600 mm at a depth of approx. 23.0 m a.s.l.

A large natural boulder was encountered beneath this concrete from panel #10 at a depth of 22.1-21.4 m a.s.l. and thus directly at or below the final excavation level in the ´GWB´ excavation pit to the south of the panels #10/#11 joint, i.e. in the cross-sectional area of panel #11 (Figs. 13a and 14).

The trachyte boulder with a diameter of around 600 mm and a length of around 1.20 m was first extensively documented in situ. It was then divided into two half-shells with the help of guided overcut horizontal drillings, which were carried out with an underwater drilling template approximately in the centre of the block, and recovered from the joint using anchors. In dry conditions, the boulder was reassembled and examined (Fig. 13b). Traces of the teeth of diaphragm wall grabs were found on both the northern and southern sides of the boulder; traces from the reinforcement cage of panel #11 were also found on the southern side. These traces prove that the natural boulder was already in the position encountered during the exploration of the evidence when panel #11 was executed (Fig. 15). In conjunction with the triangularly growing concrete from panel #10 found above it, it can be concluded that the natural boulder was encountered in the course of the execution of panel #10 and was displaced into the ground section of the later panel #11 during the attempt to salvage it, without the salvage being successful (Fig. 15). During the construction of panel #11 the boulder was then not removed from under the overlying concrete; after the change to the 2.4 m wide grab shells, the teeth of the diaphragm wall grab merely "scraped" along the natural boulder (Fig. 15).

a)



b)

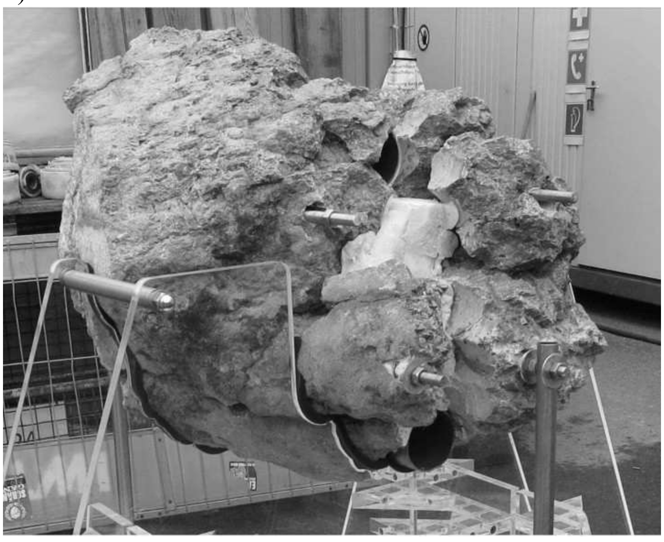


Figure 13. Natural boulder (trachyte) from the joint between panels #10 and #11, a) underwater laser scan in situ, b) recovered and assembled block (basis: Kempfert (2011-2022), modified).

Under the trachyte boulder, a continuously open void up to 600 mm wide and filled with quaternary material was encountered in the further excavation over the depth, which, although only explored up to the surface of the lignite, is expected to be in fact open to the lower edge of the diaphragm wall.

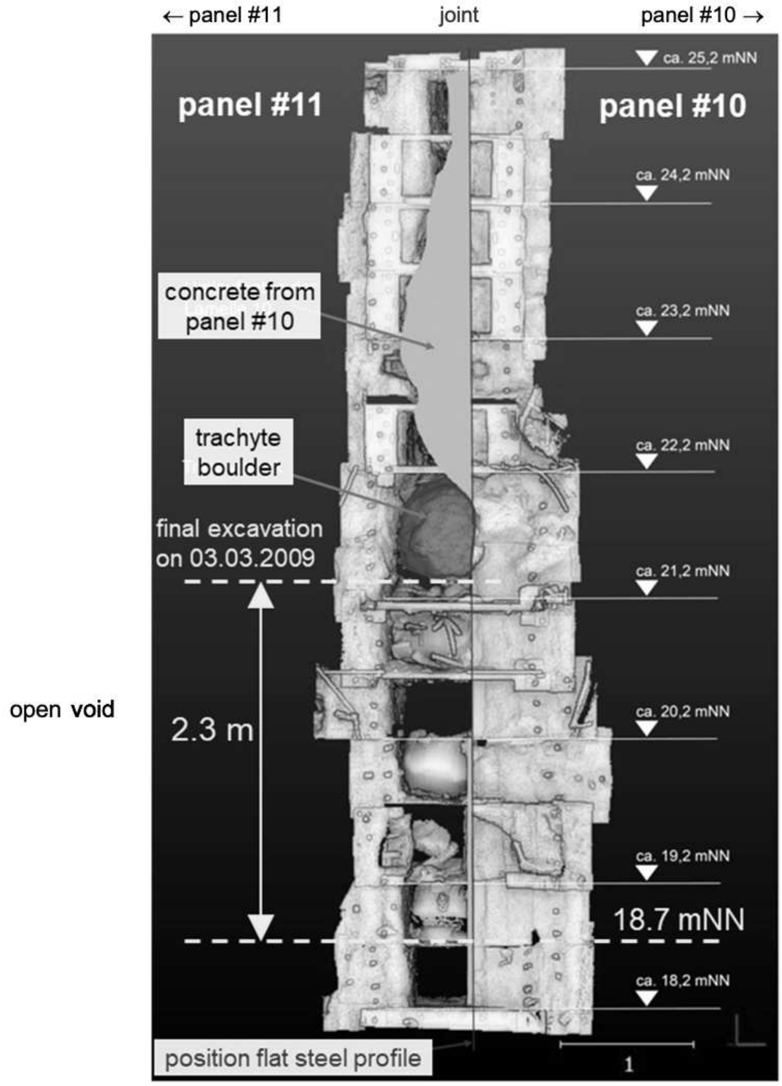


Figure 14. Compiled visualisation of the explored situation in the joint area of the diaphragm wall panels #10/#11 (evaluation of the underwater laser scans based on Kempfert (2011-2022)).

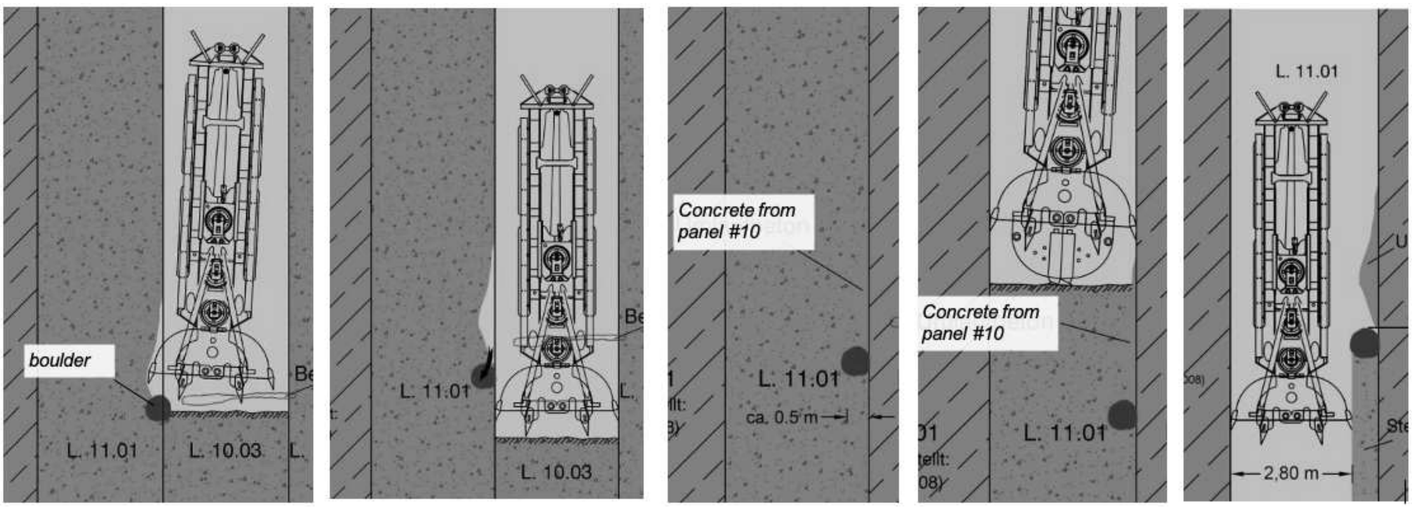


Figure 15. Construction sequence of the panels #10 and #11 of the eastern diaphragm wall with the natural boulder (trachyte, marked in red) encountered during execution of both panels.

Based on the distribution of anthropogenic findings, colour changes of the in-situ soil material and other indicators such as the erosion/ presence of the filter cake in the joint surfaces, it was possible to identify and to prove that the base of the "moving" masses (collapse funnel) in the void lies at a level of around 18.7 m a.s.l. In consequence it can be concluded that the area of the void through which around 5,000 m^3 of quaternary material flowed in the course of the accident is only around 2.3 m high and about 600 mm wide and therefore has an area of only approx. 1.5 m^2 in total (see Fig. 14).

Based on an independent evaluation of the laser scan images taken by the expert Prof. Kempfert and his divers in the inspection pit, Figure 14 shows the area around the joint between panels #10 and #11 with the "open" void area filled with quaternary sands and gravels from 21.7 m a.s.l. downwards, the trachyte boulder above it and the triangle shaped concrete that flowed in behind the flat steel profile (stop end) when panel #10 was poured and which was not removed in the course of the excavation of panel #11.

At the time the damage occurred on March 3rd, 2009, the excavation level in the ´GWB´ pit in front of panels #10 and #11 was at around 22.0 m a.s.l.; the planned final excavation level would have been 21.7 m a.s.l.

The discovery of the natural boulder in the northern cross area of panel #11 and the open void below it, filled with quaternary material and 450 mm to 640 mm wide in the further course, as well as the successful demarcation of that part of the void area that was passed by the granular-fluid mixture during the accident, provide a clear and forensic clarification of the cause of the damage. Despite this the layer-by- layer excavation and exploration of evidence in the inspection pit was continued down to the depth of the surface of the lignite layer at approx. 14.0 m a.s.l.

In a final step, the lignite was also exposed in sections using a specially manufactured excavation box using the caisson method in order to verify that the lignite layer in the ground plan of the inspection pit was intact and without defects. This additional proof was provided in 2020. This meant that the thesis of a suspected area of "vent formation" with a vertical material entry through the base of excavation could be definitively and legally ruled out in the sense of a ´counter-evidence´.

The results of the very demanding investigation of evidence were documented by Prof Kempfert in several expert reports (Kempfert 2011-2020).

2.7.9 *Cause of the collapse*

As a result of the highly complex preservation of evidence procedure and investigations it was possible to clarify the cause of the damage clearly and beyond doubt. As a result of the investigations carried out from 2009 to 2020, the accident on March 3rd, 2009 can be attributed solely, i.e. mono-causally, to a defect that remained in the joint area between two panels during the construction of the diaphragm wall. In the area of the joint between the panels #10 and #11 an approximately 600 mm wide void was found below approx. 21.7 m a.s.l., i.e. at about the level of the final excavation of the ´GWB´ pit downwards. This defect results from the fact that the existing soil material in this area had not been excavated and replaced by concrete during the construction of diaphragm panel #11. A triangular wedge of concrete, which protruded into the cross area of panel #11 (Figs. 14 and 15), had not been removed in the course of the excavation of panel #11 and was therefore the initial of this defect. The triangle-shaped concrete originates from previous execution of adjacent panel #10: during excavation of this panel the trachyte boulder was hit in the southern outer edge of the panel´s cross section and trials to catch and remove the boulder create a void in the area of the adjacent panel #11 which was poured by concrete which flowed behind the flat steel profile that was used as joint resp. stop end element (Fig. 15).

As a result of the challenging investigation of the evidence, it was proven that during the accident on March 3rd, 2009 around 5,000 m^3 of quaternary material flowed through the void in the depth section between 21.2 m a.s.l. and about 18.7 m a.s.l., which led to the collapse of the historical archive, literally as the ground was removed from under the foundations. It can be assumed that this void in panel #11 continues below the section through which the granular-fluid mixture flow passed to the lower edge of the diaphragm wall.

The cause of the damage can therefore be traced back to an execution issue respectively to the fact that suitable countermeasures were not taken in response to the difficulties encountered during the execution of panel #11 of the diaphragm wall in 2005. The obstacles encountered during excavation of this panel and the failure to remove these obstacles, finally the change of the grab shells from 3.40 m to 2.80 m wide for excavation of the 3.4 m wide, single bite panel #11 were an unambiguous evidence that the panel #11 was not executed in a regular way and that from the depth where the grab shells were changed most probably a 600 mm wide void filled with quaternary sand and gravels was left.

Technically, it would have been possible to reliably seal the remaining defect in panel #11, for example with one or two columns executed using the jet grouting method.

Against the background of these results of the investigation of the evidence, the City of Cologne and the construction JV, which still assumed an alternative course of events, reached an out-of-court agreement in a moderated procedure to settle the financial loss incurred by the City of Cologne and concluded finally on a settlement in June 2020. According to this settlement the construction JV paid 600 million euros in damages to the City of Cologne and committed themselves to reconstruct the damaged ′GWB′ excavation pit and to finalize this structure at its own expense and under its own responsibility.

Currently it is expected that the very challenging reconstruction activities will last until about 2032, what means that it will have taken nearly 25 years from the occurrence of the damage to its removal and to the moment the first metro train will have run through the ′GWB′ underground structure at the ′Waidmarkt.

3 CONLUSIONS

3.1 *Dealing with serious damage cases*

The accident at the deep excavation pit for the ′GWB′ structure at ′Waidmarkt′ in Cologne on March 3rd, 2009 was a dramatic case of damage with far- reaching consequences for the city of Cologne, in particular due to the collapse of the adjacent historical archive, for the north-south metro project and local residents, but also for all those involved in the project. Contrary to the expectations of many of those involved, the cause of the damage was clearly and unequivocally clarified in an unprecedented process of preserving evidence in terms of complexity, technical challenges and scope, but also in terms of duration and effort. All of the independently obtained evidence from the indirect and direct investigations form a complete and consistent overall picture. The only cause was a 0.6 m wide void in a diaphragm wall panel located just at resp. below the excavation pit′s final excavation level, which was a consequence of an execution error. The fact that it was possible to identify and document this mono-causal cause of damage in an extremely challenging environment in such a clear and qualified manner, and thus in a way that would stand up in court, is first and foremost the merit of the court-appointed expert witness, Prof. Dr H.-G. Kempfert and his team, who led the evidence proceedings through all the technical difficulties with great commitment and professional expertise.

The technical challenges that arose during the underwater preservation of evidence in an up to 34 m deep excavation pit next to a damaged diaphragm wall was a daily companion for all those involved in the realisation and creation of the structural condition for the investigation over years. New solutions and prototype-like concepts had to be developed, tested and implemented for many tasks relating to the preservation of evidence and the realisation of the construction work. The successful realisation of the investigation of the evidence and the clear clarification of the cause of the damage were the prerequisites for ending the evidentiary proceedings with an out-of-court settlement between the parties involved, thus avoiding a lengthy legal dispute.

Nevertheless, the fact that more than 15 years have passed since the damage occurred should be motivation for further considerations regarding the prevention and handling of (major) damage cases in ground engineering.

The example of the Waidmarkt accident shows that it is often not possible to quickly clarify the cause of the damage, as extensive and time-consuming investigations of the subsoil situation and the structural conditions, which are initially not accessible to direct inspection, especially in underground construction, are required. Promising approaches for alternative concepts for dealing with damage events and for accelerating following procedures e.g. by combining measures for investigation and reconstruction are documented in international context for other major damages, such as the Nicoll Highway Collapse in Singapore (Whittle & Davies 2006).

3.2 *Risk prevention and mitigation*

Risk prevention and risk mitigation are even more important tasks than dealing with damage cases as these are the only tools to avoid collapses and damages.

Based on experiences from damages, consequences for the independent checking of design and execution, for the quality assurance of underground works and their supervision, but also the need for a risk prevention based on communication and partnership between all parties involved in the construction process needs to be discussed and implemented especially but not solely for major geotechnical projects.

Besides measures and approaches for risk management and assessment during design, as discussed in section 1 of the present paper the successful realisation of geotechnical structures in engineering practice requests the following additional measures especially related to checking and quality assurance:

- An independent structural and geotechnical checking is essential and must include both,
  - the checking of the design and all verifications and
  - the supervision and monitoring of the execution.
- For all stages of soil investigation, design, execution, checking and supervision geotechnical expertise and experience is required; therefore, it is mandatory to involve an independent geotechnical checking engineer at least for structures of the Geotechnical Category 3 according to EN 1997-1.
- The (independent) supervision of execution of special geotechnical works like e.g. piling, diaphragm walls, ground improvement and injections has to be carried out by qualified and experienced experts on site.
- A risk prevention in partnership needs to be established and practiced in all phases of planning and

realisation. In this context a regular communication on technical level between client, contractors, designers and the independent checking engineer is essential. Such a regular communication, e.g. organisationally to be implemented by jour fixes, allows also to identify and discuss any irregularities and anomalies occurred during execution.

All of the above measures are relevant and needs to be established but especially a regular technical communication between all parties is considered to be an essential tool for risk prevention and mitigation during the execution.

In this regard the presented case study of the collapse of the ´Historical Archive´ at the Waidmarkt in the city of Cologne is an example where irregularities during execution of the diaphragm wall were observed and documented but were subsequently not pursued further neither internally inside the construction companies nor in communication with the owner´s independent supervision and by the owner itself. As discussed inn section 1 of this paper human factors have been identified as main cause for failure on site and one of the major impacts are faulty communications as well as pressures on the involved people like time, economical or ecological constraints. In this regard, an open-minded communication focused on technical aspects and a partnership-based approach are considered to be effective mitigating measures for risks in geotechnical engineering and execution.

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