

TBM rescue projects using shafts and ground freezing

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Abstract

In recent years tunnel boring machines (TBM) got stuck in the ground unable to continue driving due to different failures. In all those projects the lost TBMs could be rescued via already existing or newly built shafts or deep pits and the application of ground freezing. Rescue shafts were designed and built, usually using diaphragm walls up to a depth of 100 m below surface. All rescue shafts had to be built in partly disturbed soil conditions due to the occurred TBM failure and under enormous time pressure.

Clients always retained CDM to provide consulting and design works as well as the required lab testing on frozen soil samples. Most of the projects were carried out by the construction companies BAUER (shafts and freeze pipe drillings) and Deilmann-Haniel Shaft Sinking GmbH (freezing equipment and monitoring).

This paper presents two projects in Istanbul (Turkey) and Cairo (Egypt), both examples for the same rescue concept the lost TBMs. But for each project the shaft conditions and the freezing lay-out as well as the freezing method had to be adapted to the actual in-situ conditions. Both, brine freezing and LN₂ (liquid nitrogen) freezing were performed. Different soil and groundwater conditions, different shaft and TBM dimensions as well as the kind of the TBM failure governed the finally chosen soil freezing design.

The paper describes all phases of those TBM recoveries, from the failure, the results of the pre- and final design and the lab tests as well as the experience made during shaft sinking, drilling works, soil freezing and construction works to the successful finish of each project.

Keywords: TBM, shaft, ground freezing, lab testing

1. Introduction

As developments in tunnel boring machines (TBMs) are being made and pushed into more and more difficult ground, the number of machines getting stuck is increasing. Until a few years ago, these machines were rescued via a diaphragm wall as deep as 100 meters in combination with supportive measures like e. g. vertical jet grouting (also up to 100 meters deep), still with the risk of unexpected leaking during opening of the shaft wall. Sometimes, compressed air was used to open the shaft walls for recovery of the TBM.

Recently, ground freezing was successfully applied in Europe and the Middle East for the rescue of stuck TBMs. In Istanbul (Turkey) a TBM had just finished its planned drive arriving in the jet grouted dense block at the reception shaft, but at the start of the diaphragm wall cutting it appeared that the dense block was leaking. When the attempt to seal the leakage with additional grouting measures failed, ground freezing with liquid nitrogen was successfully applied for freeing the TBM. The freeze pipes were horizontally drilled from the shaft creating a frozen soil cylinder allowing the diaphragm wall to be cut open and the TBM advance into the receiving shaft.

During the construction of the Cairo Metro Line one of the segmental liners failed during tunnel construction. Inflow of water and soil flooded the TBM resulting in a sink-hole at the ground surface. A rescue shaft was installed directly in front of the TBM with diaphragm walls extending about 100 meters to a low permeable layer. Brine freezing was used with horizontal freeze pipes drilled from the shaft to envelope the TBM and extended to the failed segmental lining. From within the frozen soil ring cylinder the tunnel debris was removed, liner segments replaced and the TBM rescued.

The presented cases show that stuck TBMs can be rescued safely, even under extremely difficult conditions. The advantage of ground freezing is that the required water cut-off and soil stabilization can be adapted to the situation as needed with measures conducted from the shaft close to the machine. Works can be executed safely under atmospheric conditions without any restrictions to the workers.

2. Marmaray Project, Istanbul Turkey

The Marmaray Project in Istanbul is one of the largest transport projects in the world. Around 2.5 billion Euros are being invested in a railway tunnel under the Bosphorus Strait and in the modernization of suburban transport routes along the sea from Halkalı to Gebze. The project includes four new underground stations and a 13.6 kilometre long tunnel sub-crossing the centre of Istanbul and the Bosphorus Strait connecting Europe and Asia.

Part of the earthquake resistant tunnel with a depth of 56 metres (m) below sea level was constructed using the shield tunnelling method. The deep excavation for the underground station Üsküdar secured by diaphragm walls was also used as reception shaft for the TBM drive. Immediately prior to the entering of one of the TBMs (TBM 5), leakages were detected in the jet grouted sealing block and at the opening of the diaphragm wall, considerable amounts of water and soil were flowing into the shaft. The first attempt to seal the leakages with additional grouting measures conducted from the reception shaft failed. Figure 1 shows the location of the Üsküdar underground station.



Figure 1: Üsküdar underground station – reception shaft

Bauer and CDM developed and designed an alternative solution using ground freezing. To get a watertight connection between the shield of the TBM shield with a diameter of 7.93 m and the diaphragm wall, horizontal freeze pipes were drilled from inside the shaft against the water pressure. As ground freezing was only needed for short term purposes liquid nitrogen freezing was applied. Thermal design calculations were done to prove that the freeze pipe layout was sufficient to achieve the required sealing and also to determine the liquid nitrogen consumption. Figure 2a presents the freeze pipe layout and the results of the thermal FE calculations.

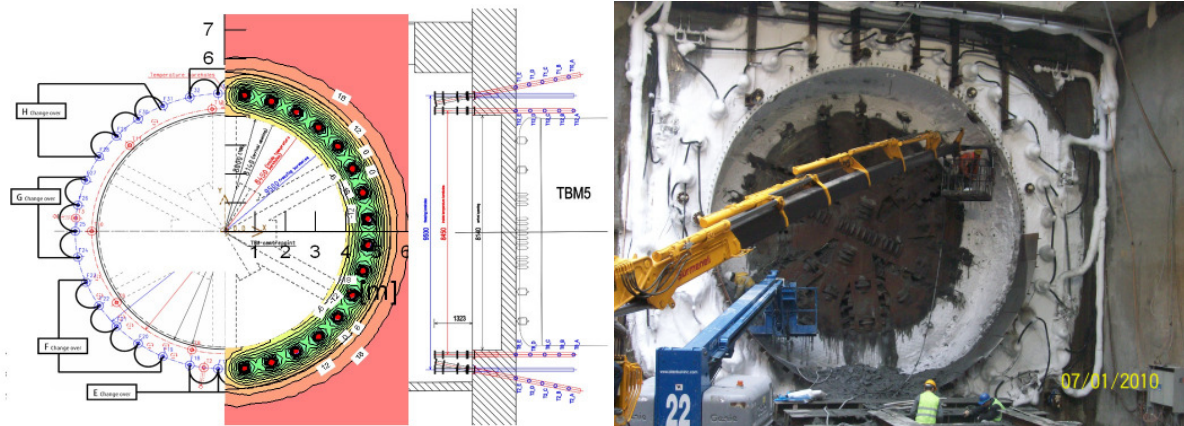


Figure 2a: Freeze pipe layout and thermal calculation results

Figure 2b: Opened diaphragm wall prior to bulkhead installation

The ground freezing layout includes the following:

- 33 freeze pipes with a length of approx. 3.5 m and a spacing of 0.9 m
- 12 temperature measurement pipes with 5 thermocouples each
- 5 thermocouples inside the TBM
- monitoring of face pressure

Due to the short freeze pipe length of approx. 3.5 m the pipes were connected in line regularly changing the flow direction to ensure a homogeneous development of the frozen soil. The following break-in sequences were used to recover the machine.

- Initial ground freezing phase to seal against the water pressure
- Cut of diaphragm wall, installation of a steel bulkhead, space between bulkhead and TBM filled with slurry
- Stop of freezing operation, after partial thawing moving of TBM towards the bulkhead
- Installation of segment ring while cutting wheel is in the diaphragm wall
- Second ground freezing phase
- Removal of bulkhead and installation of final rubber sealing
- Stop of freezing and recovering of TBM after thawing

In Figure 2b the opened diaphragm wall during the first freezing phase prior to the bulkhead installation is shown. As additional measures dry ice bags were used cooling the TBM chamber to reduce the heat source introduced by the TBM.

The TBM was finally safely recovered (as shown in Figure 3) even under extremely difficult, inhomogeneous ground conditions, which were disturbed by the previous different grouting measures/phases.



Figure 3: Rescued tunnel boring machine

3. Greater Cairo Metro Line 3, Cairo Egypt

The Greater Cairo Metro Line 3 is part of the overall improvement of the Cairo public transportation system. The construction of Line 3 has been split in three phases and started in 2008. The tunnel consists of a single-tube double-track, mainly constructed using tunnel boring machine (TBM) drives. The underground stations are being built in advance of the related TBM tunnelling. During the 4.3 km long TBM mixshield drive (diameter 9.43 m) of the 1st phase one of the segmental liners failed. Inflow of water and soil flooded the TBM resulting in a sinkhole at the ground surface. This failure happened in El Gaish Street between the underground stations Bab El Shareya and El Gaish.

After evaluation of different options considering jet grouting, ground freezing and mixed solutions using both techniques, finally the construction of a shaft directly in front of the TBM and horizontal ground freezing was chosen to rescue the machine. Two rings of drill holes, with the holes tapering towards each other, were necessary for this. These holes were drilled from a previously constructed rescue shaft.

The rescue shaft was constructed in a distance of approx. 2 to 3 meters from the stuck TBM. The shaft with an inner diameter of 18 m consisted of 1.2 m thick and 100 m deep diaphragm walls installed with a Bauer trench cutter BC 40, penetrating into a low permeable clay layer for water cut-off. The final excavation level was approx. 40 m below ground surface. A total of 24 cuts had to be constructed for the wall (12 primary and 12 secondary cuts) with a width of 2.5 m. Figure 4 shows the BAUER diaphragm wall cutter at the construction site in the inner city of Cairo before its deployment. The shaft was constructed within approx. 4 weeks.



Figure 4: Site impressions of the rescue shaft before the start and after finish of construction

In contrast to the Marmaray project, in Cairo the frozen soil not only served as sealing but also as a structural element. The frozen soil ring extended from the shaft towards the already installed and stable segmental lining behind the failure and had to bear the loads from the soil and the water. A vertical cross-section of the rescue shaft, the stuck TBM and the planned frozen soil body with a length of approx. 25 m is presented in Figure 5. The depth of the tunnel axis is at depth of approx. 30 m and the groundwater level at approx. 2.5 m below ground surface.

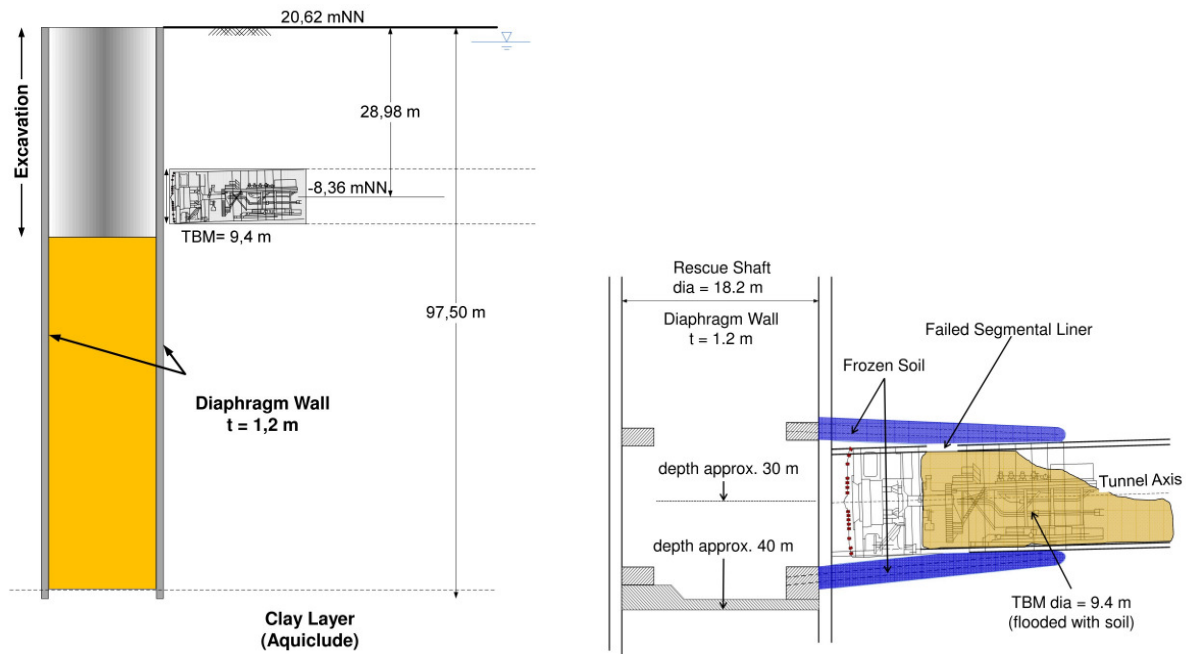


Figure 5: Rescue shaft and structural frozen soil body

The ice body to be produced had to have both a sealing and a structural function. As far as the structural function was concerned, the design provided for a gap with a width of 2.1 m (distance between the TBM and first stable tubing ring) to be spanned. It was assumed that this stable arch had to be effective in this area for three months.

As the frozen soil body served as structural element structural calculations were required to design the frozen soil thickness. The undisturbed soil in the failure area consisted of poorly graded fine to medium sands. But due to the failure and the soil movement into the TBM the governing area had to be considered being extremely disturbed. For the thermal and structural design a simplified model was applied taking into consideration the following areas in the ground:

- disturbed soil area
- intermediate area
- undisturbed area

The related model is shown in Figure 6.

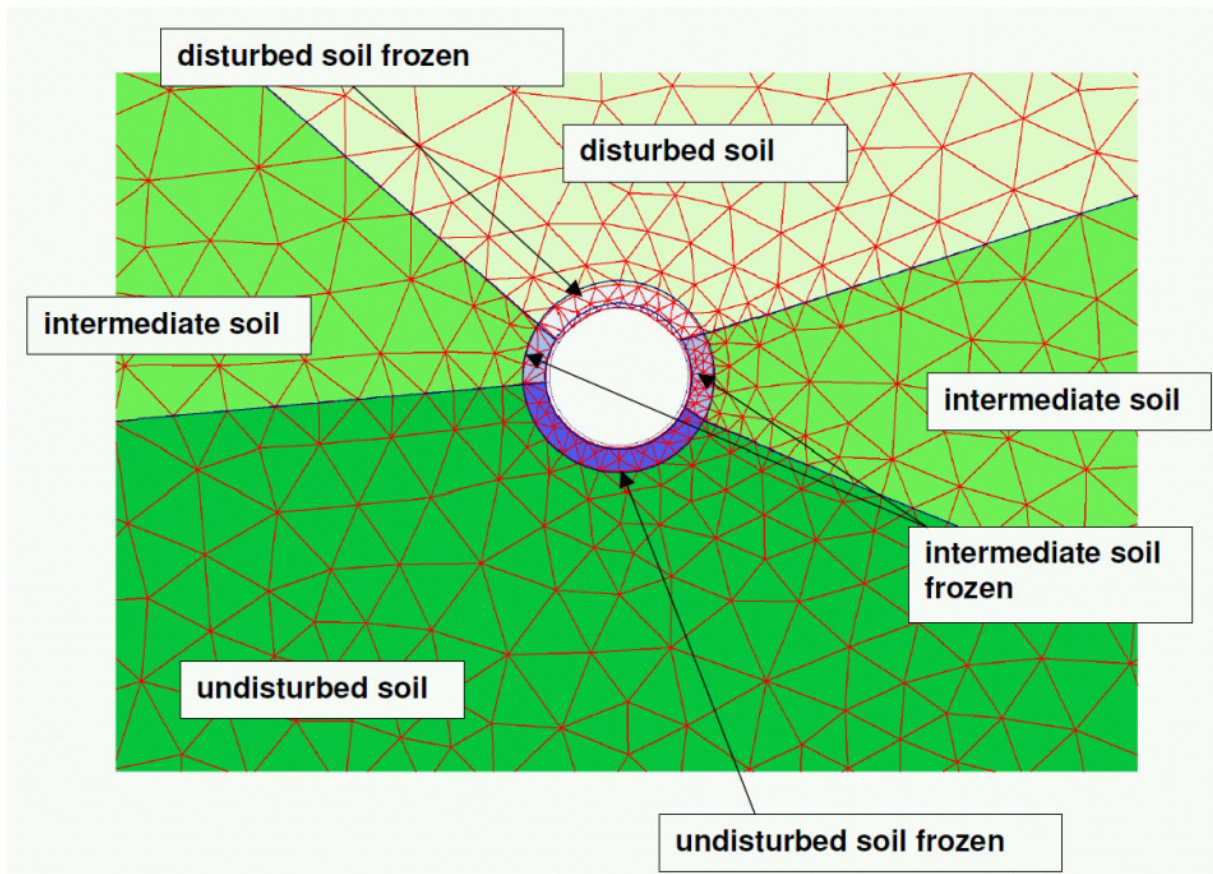


Figure 6: FE model considering different soil conditions around the TBM

Due to the time constraints the ground freezing design (thermal and structural) was initially performed using estimated frozen soil design parameter. This was only possible based on the extensive experience from design and frozen lab testing of other ground freezing projects. Nevertheless, it was mandatory to verify the estimated values by extensive special laboratory tests on frozen soil samples during the design phase of the further rescue measures. Original soil material was used to prepare remoulded specimen considering the three soil conditions (disturbed, undisturbed and intermediate). Detailed investigations were conducted in CDM's geotechnical and freeze laboratory in Bochum, Germany.

Table 1 summarises the assumed characteristic soil values for the structural calculations. The results of the design calculation showed that a frozen soil thickness of not less than $t = 1.5$ m related to a soil temperature of $T = -10$ °C (average over thickness) is sufficient. To achieve a short initial freezing time and the highest possible level of safety the freeze pipes layout consisted on two circular rows of freeze pipes with a spacing ranging between 0.88 and 1.25 meters between the pipes. The smaller freeze pipe spacing was used in the upper part of the disturbed soil area. Brine freezing was chosen considering the long freezing operation of approx. 10 month being estimated for the rescue of the TBM and the rehabilitation measures of the tunnel tube.

Soil layer	E	ν	ϕ	c	γ_{sat}	Permissible σ_D
	[MN/m ²]	[-]	[°]	[kN/m ²]	[kN/m ³]	[kN/m ²]
Disturbed unfrozen	10	0.3	22	0	18	
Disturbed frozen	100	0.3	22	280	18	1,000
Intermediate unfrozen	20	0.33	27	0	19.5	
Intermediate frozen	250	0.33	27	490	19.5	1,750
Undisturbed unfrozen	30	0.35	22	0	21	
Undisturbed frozen	330	0.35	22	550	21	2,000

- E Modulus of elasticity
- ν Poisson ratio
- ϕ Inner angle of friction
- c Cohesion
- γ_{sat} Specific gravity of the saturated soil
- σ Unconfined compressive stress

Table 1: Summary of soil parameters for frozen and unfrozen soil (average temperature of the frozen soil T = -10°C)

The following figure 7 shows that the spacing between the freeze lances had to be closer in the disturbed areas than in the undisturbed areas in order to complete the initial freezing phase successfully within 28 days.

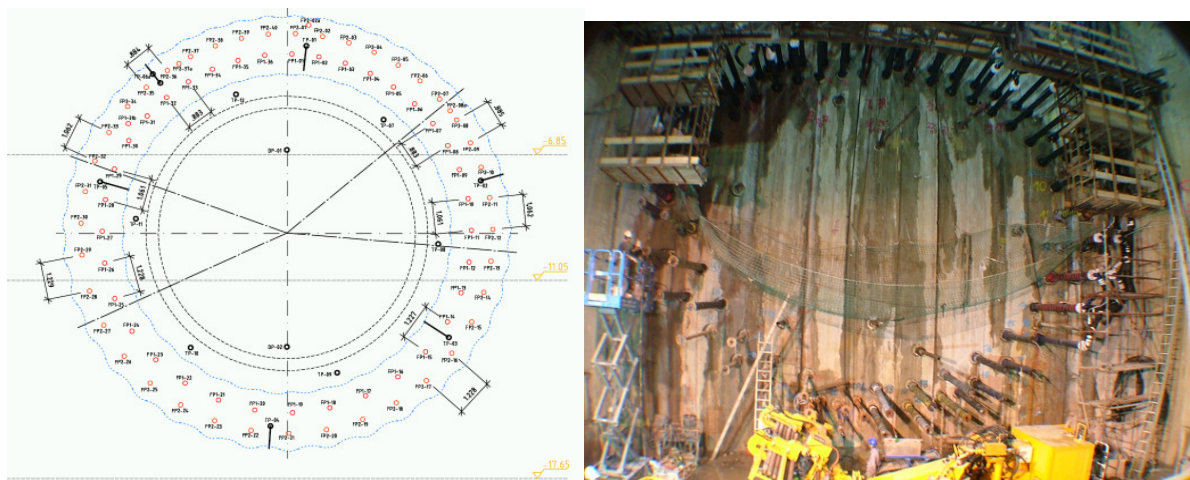


Figure 7: Drilling pattern in planned and executed position

The freeze pipe and freeze body layout included the following:

- Frozen soil thickness of not less than 1.5 m related to an average temperature of $-10\text{ }^{\circ}\text{C}$ or colder
- Frozen soil length approx. 25 m
- 2 circular rows of freeze pipes with a total number of 76, spacing from 0.88 to 1.25 m
- 12 temperature measurement pipes drilled from the shaft
- 3 temperature measurement pipes drilled from surface

The freezing equipment was installed and operated by Deilmann Haniel Shaft Sinking. Since it was expected that ground freezing would have to be maintained for more than ten months, it was decided to use calcium chloride (brine freezing).

According to the thermal FE calculation, a total refrigerating capacity of 376 kW/h would be adequate for the initial freezing phase of about 30 days. Four refrigerating machines with a refrigerating capacity of 94 kW/h each were installed for this (see figure 8).



Figure 8: The four freeze plants for the Metro Cairo project

Figure 9 presents the opened diaphragm wall with the TBM cutter wheel. Finally, the TBM was rescued and the broken tunnel lining was repaired safely under atmospheric conditions without any safety issues. In Figure 10 an aerial view of the area with the recovery of the cutting wheel is shown.



Figure 9: Opened diaphragm wall



Figure 10: Aerial view with recovery of cutting wheel

4. Conclusion

Recovery actions of buried tunnel boring machines using ground freezing were successfully carried out in the cities of Istanbul and Cairo from the end of 2009 until the beginning of 2011. For drilling and installation of the required freeze bodies shafts protected with up to 100 m deep diaphragm sealing walls were conducted. Since the tunnel boring machines were to be enveloped in an ice body to enable repair of the tunnel behind it and recovery of the TBM, holes for freeze pipes and temperature measurements with a length up to 28 m had to be constructed. Different freezing phases were designed to ensure a safe recovery of the tunnel boring machines under difficult conditions in underground areas with unknown soil conditions.