FH JOANNEUM

DIPLOMA THESIS

Critical evaluation of an alternative technique for tunnel enlargement and settlement reduction

BMI 2008 Thomas Wechner, BSc

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Critical evaluation of an alternative technique for tunnel enlargement and settlement reduction

University of Applied Sciences
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Construction Management and Engineering

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Declaration:

"I declare that this paper is my own work and was written without literature other than the sources indicated in the bibliography. Information used from the published or unpublished work of others has been acknowledged in the text and has been explicitly referred to in the given list of references. This paper has not been submitted in any form for another degree or diploma at any university or other institute of tertiary education."

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Abstract:

The thesis at hand addresses the redevelopment of an existing tunnel structure in an inner city environment. The application of a newly developed tunnel enlargement method is the focus of this research work. This alternative technique for tunnel enlargement and settlement reduction is elaborated and critically evaluated. An innovative grouting-anchor system is key part of this tunnel enlargement method. The application of this anchoring system enables an injection from the existing tunnel structure in advance in order to stabilize the surrounding subsoil. This results in a homogenization effect in the subsoil. The occurring settlements due to tunnelling are reduced to an acceptable minimum. Furthermore, additional work on the surface becomes unnecessary. A detailed explanation of the application processes for this tunnel method is presented in this thesis. Additionally a critical evaluation of the interplay between applied grouting, tunnelling and occurring settlements is analyzed. Comparing the new tunnel enlargement method with traditional techniques provides further insights on benefits and limitations.

Kurzfassung:

Die Anzahl von Untergrundkonstruktionen im innerstädtischen Bereich nimmt immer mehr zu. Meine Diplomarbeit befasst sich genau mit dieser Thematik. Es handelt sich um die Erneuerung eines 125 Jahre alten Eisenbahntunnels. Die Illustration einer speziell dafür entwickelten Tunnelbaumethodik ist Kernstück dieser Arbeit. Hauptteil dieser Diplomarbeit ist die Erläuterung sowie kritischen Bewertung dieser neuartigen Methodik. Ein neu entwickelter Injektionsanker bildet die Basis dieser alternativen Bauweise. Durch diesen neuartigen Anker kann das umgebende Erdreich vom Bestandstunnel schon vorab stabilisiert und verbessert werden. Ein Homogenisierungseffekt des umliegenden Bodens ist die Folge dieses Vorhabens. Die durch den Tunnelvortrieb auftretenden Setzungen können somit auf ein akzeptables Niveau reduziert werden. Zudem werden zusätzliche Bautätigkeiten an der Oberfläche überflüssig. Eine genaue Darstellung der einzelnen Arbeitsvorgänge ist Kernstück dieser Diplomarbeit. Des Weiteren wird das Zusammenspiel des angewandten Injektionsprozesses, dem Tunnelvortrieb und den auftretenden Setzungen genauestens analysiert und ausgewertet. Ein kritischer Vergleich der herkömmlichen mit der alternativen Tunnelbautechnik hebt die Vorteile der neu entwickelten Methodik hervor.

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1 Introduction

1.1 Motivation

Since the beginning of my academic studies in “Construction Management and Engineering” an increasing interest in the field of heavy civil engineering has became evident. During my time in Germany and the USA as an intern, I developed a particular interest in tunnelling. This was the main reason for choosing this fascinating topic for my diploma thesis. For me it was always important to write a scientific paper focusing on a practical and ongoing matter. The project, I was involved in during my internship in Germany, met those conditions. As a result, I have decided to illustrate and evaluate a newly applied tunnelling technique which will deepen my knowledge regarding tunnelling due to a case study approach.

1.2 Scope and outline of thesis

This thesis deals with the illustration of an innovative tunnelling method for the special application of tunnel enlargement. The research is based on a current case of a tunnel project in an urban area in Germany. The main research subject of this master thesis is the elaboration and critical evaluation of an alternative technique for tunnel enlargement and settlement reduction.

The first concept for this project was based on traditional techniques for tunnel enlargement. Due to difficult sequences of construction, high costs and unsecure results Beton- und Monierbau and Mr. Dr. Ing. M. Baudendistel created an innovative tunnelling technique for this extraordinary challenge. This special method enabled a widening of an existing tunnel without influencing the surface. A new developed grouting-anchor technology was the key part of the entire development. The alternative technique ensured the reduction of settlements to an absolute minimum. Consequently additional construction work on the surface became pointless. Within the introduction an overview about the alternative procedure for the widening of an existing tunnel will be provided. Moreover, continuous comparisons of the primary and alternative concepts are also established in this diploma thesis.

1.3 Research objectives

The objective of the master thesis is the evaluation of the new tunnelling technique for the enlargement of an existing tunnel in urban areas. This includes a detailed description of grouting- and construction sequence of the newly developed tunnelling method. This paper addresses the benefits as well as the methodological procedure of this revolutionary tunnelling technique. Moreover the potential advantages, disadvantages for this unique tunnel method will be highlighted. In this context, key drivers such as time, risks and manpower will be discussed. A strict comparison of the primary and alternative concept is significant for this evaluation.

In addition a critical assessment of occurring settlements and the overall grouting process will be provided. A wide spread interpretation of the interconnection of applied grouting, tunnel excavation, present geology and appearing settlements is the core part of this thesis.

1.4 Structure of study

This master thesis is basically divided into two main sections. There is a theoretical part with a detailed description of the original and alternative tunnelling method as well as an empirical expose including a critical analyses plus interpretation of the tunnelling-, settlement- and grouting process.

In total this thesis contains 10 chapters. The first chapter provides a general introduction regarding my personal motivation and the content of this thesis. In chapter 2, basic aspects about the project are briefly introduced briefly. The primary concept will be described in chapter 3. A short excursus dealing with grouting is exemplified in the upcoming chapter. Chapter 5 presents a detailed illustration of the alternative tunnelling method. In chapter 6 a critical evaluation of the alternative tunnelling concept is worked out. A complete analysis of the applied grouting process including occurring settlements is illustrated in the following chapters. Afterwards an additional excursus focusing on monitoring is provided. Chapter 10 will focuses on economical aspects and will summarizes the outcome of this research.

2 Basic aspects

2.1 Scope of project

The project “Alte Mainzer Tunnel” deals with the redevelopment of a historic railway tunnel in Germany. The “Alte Mainzer Tunnel” is operated by the German Railway Inc. and is one of the key constructions for the traffic link between Mainz, Worms, and Mannheim/Ludwigshafen. Because of the importance for the German railway network, new safety regulations, and the dilapidated structure a redevelopment of the 125 years old railway tunnel was absolutely necessary. The main reason for the construction contract was to enlarge the tunnel cross section while minimizing the occurring settlements.

2.1.1 History

The original “Alte Mainzer Tunnel” with a total length of 1.196 meters (3.923 feet) was finished in 1884 after a construction time of approximately three years. This tunnel was supposedly driven up by the old German “Kernbauweise” and stabilized by a massive stonework arch. In the early 1930's, parts of the tunnel had to be opened because of massive damage on the structure. The remaining tunnels of this engagement were the “Tunnel Mainz Hauptbahnhof” and “Tunnel Mainz Süd”. Due to the rising train traffic, a second railway tunnel was built in 1998. In May 2007, the redevelopment and re-engineering of the “Alte Mainzer Tunnel” started.

2.1.2 Geographical location

Mainz is the capital city of the “Rheinland Pfalz” and is located in the mid-west region of Germany. It is a part of the metropolitan area of Frankfurt – Wiesbaden – Mannheim. Because of the famous neighborhood and history, Mainz became a very significant traffic junction. To get an idea about the geographical location, a map is provided below.

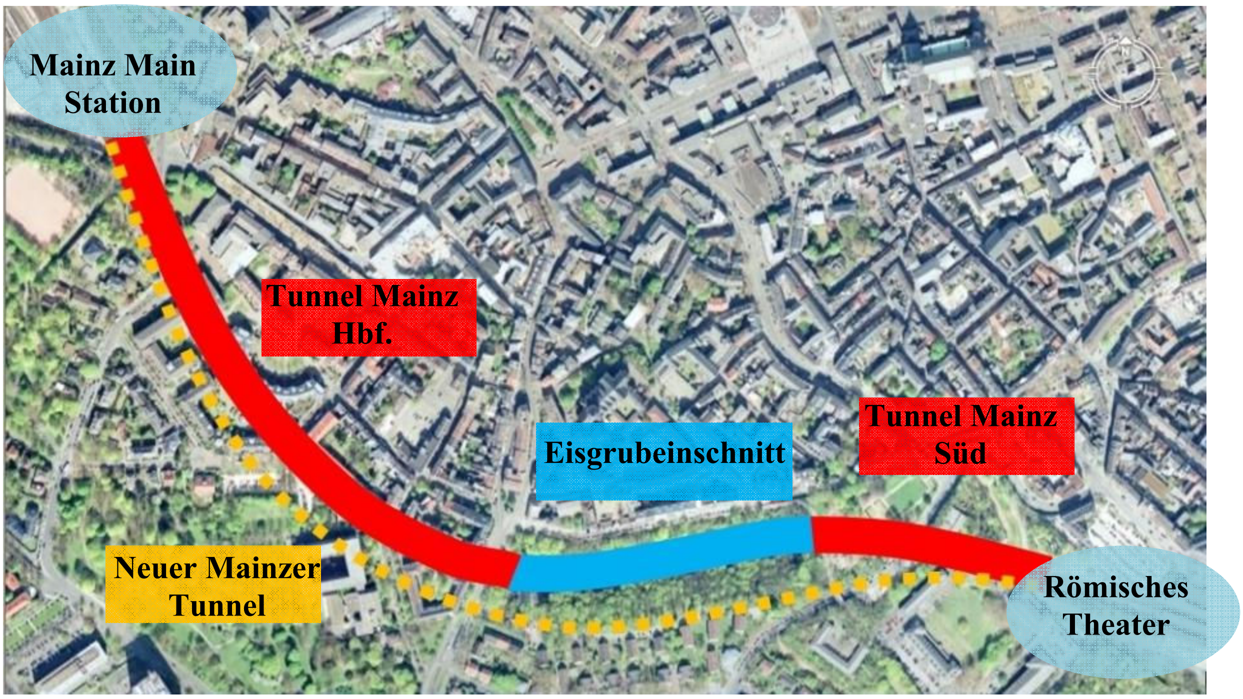


Figure 1: Map of the area (source map: Google- Maps [29])

This map (figure 1) shows the city center of Mainz with the two railway stations, “Mainz Main Station” located in the West, and “Römisches Theater” in the East. As exemplified before, we see the “Alte Mainzer Tunnel” in red and blue coloring and the “Neuer Mainzer Tunnel” in orange. The “Alte Mainzer Tunnel” is subdivided in three building lots. Those are the “Tunnel Mainz Hauptbahnhof” with 656 m (2152 feet), the “Tunnel Mainz Süd” with 238 meter (780 feet), and the uncovered tunnel section “Eisgrubeinschnitt” with 291 meter (954 feet). These tunnels are situated just a few meters beneath several buildings directly in the city center of Mainz. Due to the situation of the tunnels it was a special challenge to re-engineer those tunnels.

2.1.3 Geology

The project area is situated in the so-called “Mainzer basin”. This geological field is mainly defined by heterogenic, cohesive semi firm to firm tertiary subsoil. The main layers consist of a sand, silt, and clay composition. In addition, there are some rock material benches comprised of lime, dolomite-sand, and siltstone. The layers are generally horizontally orientated with a slight lean towards southeast. The ground water level is placed beneath the tunnel structure (Marcher et al. 2007 [12], Meyer et al. 2009 [14]).

The photograph (figure 2) below impressively displays the different layers of rock shining in a wide variety of colors. Furthermore, we can see the influence of the past tunnel advancement can be seen by creating settlements above the existing tunnel lining.

Figure 2: Photography of tunnel face with the different layers (source Beton- und Monierbau)

2.1.4 Boundary conditions

Whether there are or not normal conditions, it is difficult enough to drive up a tunnel, but is not comparable with a tunnel project executed in an urban area. In a city, engineers have to take care of a variety of different factors. One of the main conditions was to integrate the two railway stations “Mainz Hauptbahnhof” and “Römisches Theater” into the alignment. Moreover, the designers had to retain the existing tunnel lots of the “Alte Mainzer Tunnel”. Because of these conditions, we had to deal with a multitude of challenges. The most significant were:

- To enlarge an existing 125 year old tunnel
- To drive a tunnel below build-up area
- To minimize the occurring settlements
- To guarantee safety at all time
- To keep a tight time schedule
- To stay within estimated costs

Advanced tunnelling techniques, innovative procedures, and an excellent team, made it possible to achieve these challenges. In the next chapter those points will be explained in more detail.

2.2 Assessment of tasks

As mentioned before, this special project meets several complex tasks. To get an idea about those challenges, the most important tasks of this project will be pointed out.

2.2.1 Tunnel cross section enlargement

In the course of new safety regulations and improvements on the railroad line in this area, it became essential to modernize the existing “Alte Mainer Tunnel”. To increase capacity of the railroad line, we had to enlarge the distance between the tracks from 3.5 meter, to 4.0 meter. With the change of the superstructure, the wideness of the existing cross-section was affected. Therefore, the cross section of the tunnel had to be enlarged form 42 m² to 74 m².

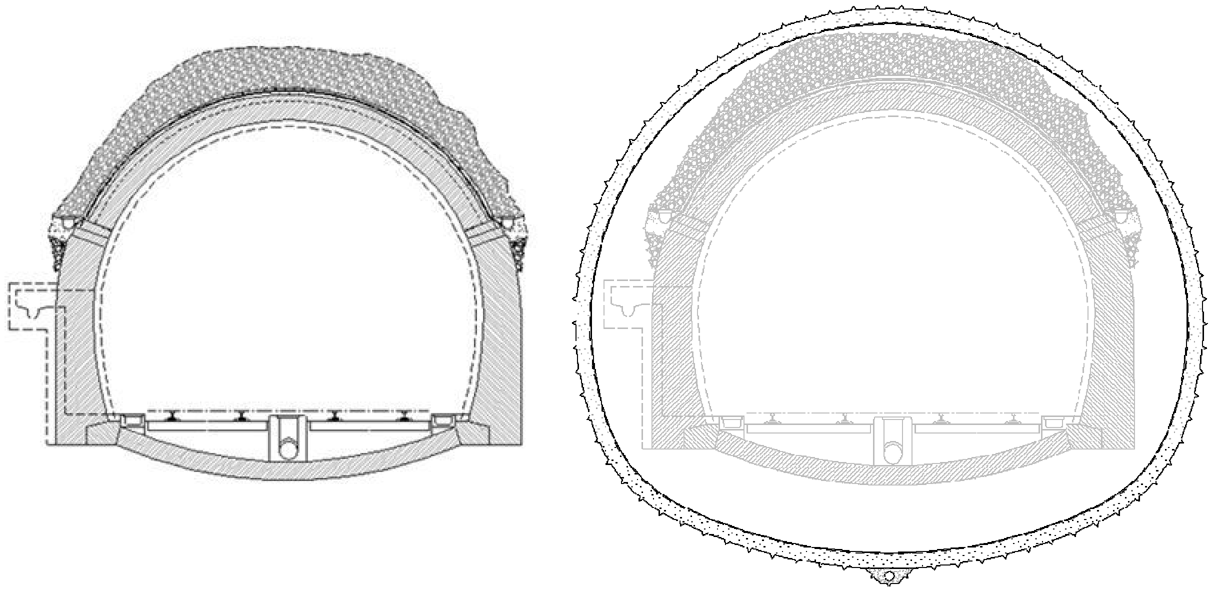


Figure 3: Old and new cross section of the „Alte Mainzer Tunnel“ (source: Beton- und Monierbau)

The two drawings above (figure 3) show the cross section of the old and new “Alte Mainzer Tunnel”. The 125 year old tunnel was built with a massive stonework arch. This tunnel was sealed with bituminous felt against water, and it was equipped with a draining system. Furthermore, the engineers implemented a packing layer above the tunnel crown to stabilize the surrounding rock mass. The average inside diameter was about 10.0 meters. In figure 3, the right side shows the final shotcrete lining after tunnel advancement. The new average inside diameter is about 12.0 meters. The new tunnel was driven by using the “New Austrian Tunnelling Method” (NAMT). Because of the new challenges of the enlargement of an existing tunnel below a build up area, the procedures applying NATM had to be adapted. Furthermore, new anchor technologies had to be invented. An improved grouting system and monitoring program was applied. In the upcoming chapters, these new techniques will be explained in more detail.

2.2.2 Settlements due to tunnel advance

It is always a demanding job to excavate a tunnel in a build up area. The tunnel has to be driven underneath existing buildings with a small cover between the foundations and the crown of the tunnel. All kinds of underground construction activities modify the primary stress conditions in the subsoil and cause diversity settlements.
Depending on the ground loss induced by excavation and the type of soil, the appearance of settlements can be completely different. The cover between the tunnel and the surface is a predominant indicator for occurring settlement on the surface (Bickel 1982 [2]). However, tunnel excavation in a city without adequate cover will affect the serviceability or stability of structures. The size and fosse of settlements as a consequence of mining or tunnelling is mainly dependent on the following factors (Wood 2000 [24]):

- Distance from tunnel crown to surface
- Soil classification
- Soil properties such as angle of friction, hardness, etc.
- Design of the tunnel
- Superficial constructions
- Local water situation
- Type of tunnel excavation (NAMT, TBM, etc.)
- Speed of tunnel advancing
- Active or passive tunnel supporting systems
- Variety of ground treatment measures

Faced with an inner city situation where surface settlements may be crucial, additional support measures may be required such as: Face support, excavation in parts, and structural treatments (stabilization of foundation and ground treatment measures), (Kummerer 2003 [10]).

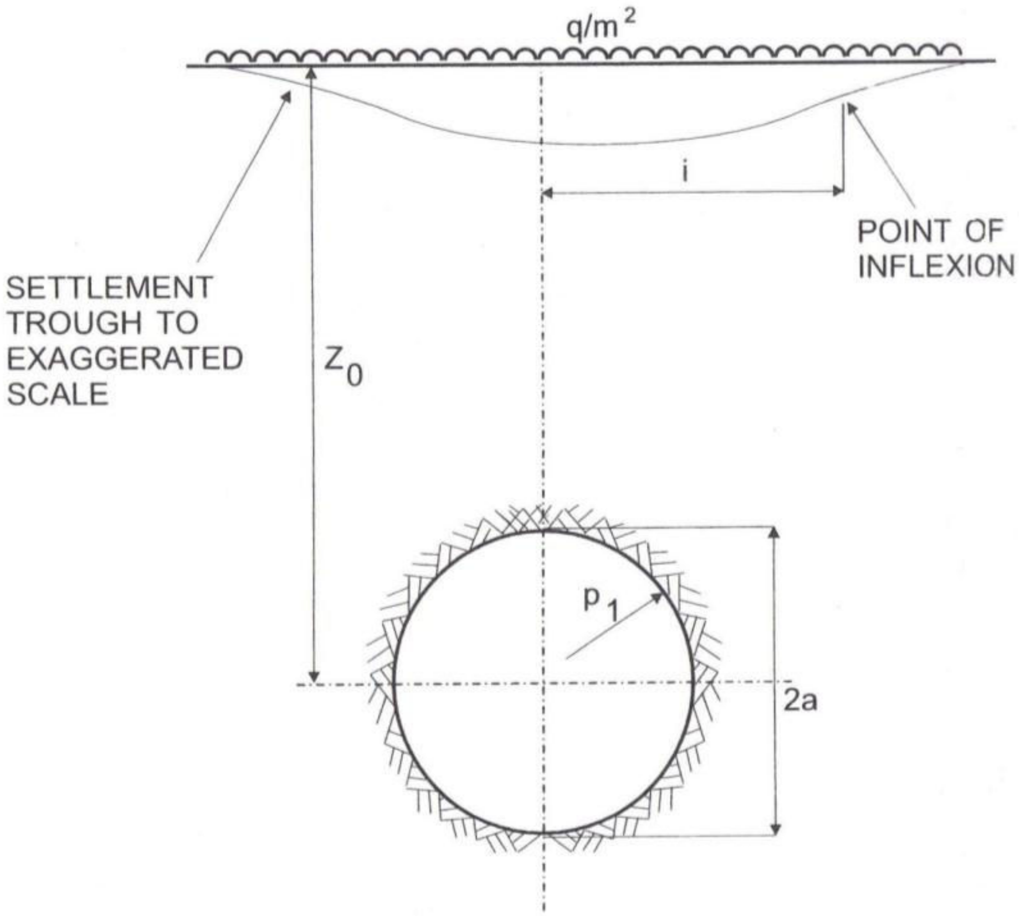


Figure 4: Consequence of tunnelling, settlements (source Wood 2000 [24])

[Z_o] … distance form tunnel crown

[p_1] … radius of tunnel

[2a] … clear height of tunnel

[i] … point of inflexion

The drawing above (figure 4) presented by Muir Wood 2000 [24] shows the basic consideration about settlements due to the tunnel excavation process. Tunnel advancing close to the surface will generate settlements. During the tunnelling process a kind of subsidence cavity will accrue on the surface. The maximum vertical settlement situated directly above the tunnel crown and the points of inflexion are the main indicators of this bended line. Hereby we can qualify that the earth displacement process can influence an expanded area around the tunnel axis. The stronger the subsidence cavity appears the bigger effect it has on existing structures on the surface. Occurring settlements can influence the stability of foundations and consequently the structural safety of buildings. The flow chart below shows a functional diagram dealing with the hazards due to tunnelling in a build-up area. The main goal is to prevent damages from the results of the tunnel advancing process.

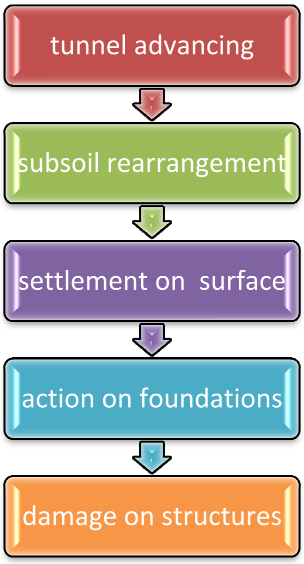


Figure 5: Consequences due to tunnel advancing

If the tunnel will be constructed in an undeveloped area, appearing settlements on the surface will not play a decisive role. The main issue will be the stability of the tunnel itself. As soon as the subsidence cavity is influencing overhead constructions, engineers have to pay attention to occurring movements on the surface. Especially in cities, tunnelling can affect a large amount of buildings (Wood 2000 [24]).

Because of this danger, it is absolute necessary to maintain permissible limits. These guidelines should help to avoid huge damages on structures. Depending on the type of superstructure, buildings can absorb slight movements. However if those deformations become to powerful, the serviceability or stability of structures is at risk. Therefore, the most affected structures were analyzed to get some prescriptive limits. To get those settlements under control, the standardized tunnelling methods will be not adequate enough. Supplementary to sensitive tunnelling advancing, additional arrangements have to be undertaken to minimizing occurring settlements. The detailed techniques and methods due to settlement reduction will be pointed out in the next chapters.

Construction	*Distance to tunnel*		*Maximal allowed settlements [cm]*	
	Vertical	*Horizontal*	*At building*	*In tunnel*
Alexanderturm	16 m	7 m / 30 m	0.8	5.5
Dorint Hotel	13 m	-2 8m / 75 m	1.3	2.7
Kästrich	13 m	5 m / 70 m	1.7	2.2
Drusustraße 1	13 m	13 m / 26 m	1.9	4.4
Am Gautor	14 m	0.1 m / 30 m	1.3	2.3

Table 1: Allowed settlements due to sensitive construction, (source DB Projektbau GmbH et al. 2006 [C])

Table 1 gives a rough outline of sensitive structures located close to the tunnel alignment. In the first column the vertical and horizontal distance between tunnel and mentioned building can be identified. The short distance between the tunnel crown and foundations is remarkable. The left column represents the maximum admissible movement. Needless to say there are much more buildings, streets, and pay grounds influenced by this tunnel project. The map below (figure 6) will exemplify those difficulties more precisely.

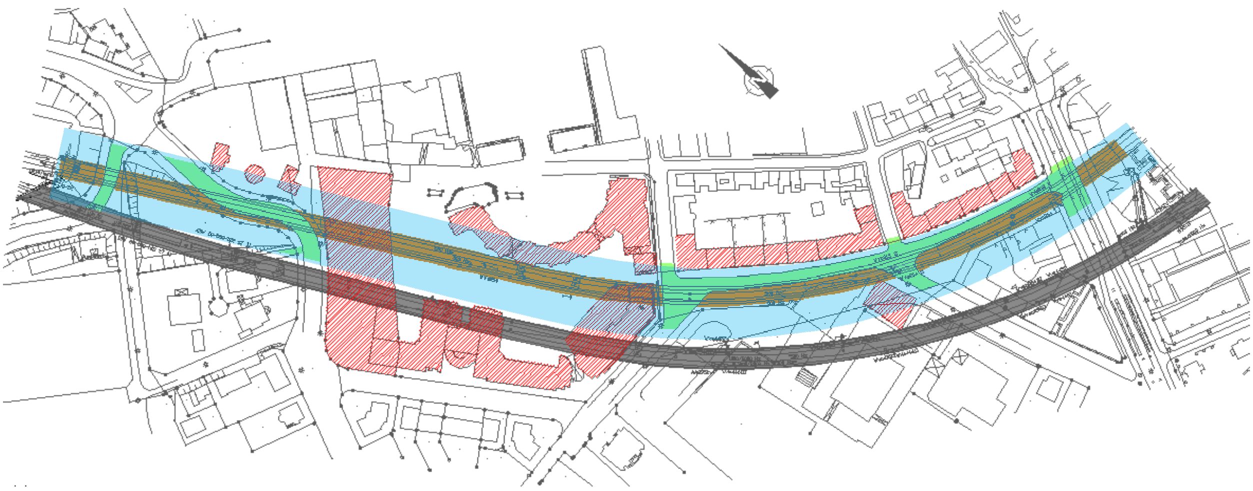


Figure 6: Affected structures in the sphere of influence –main station, (source Beton- und Monierbau)

The two simultaneous running bolted lines represent the "Alte Mainzer Tunnel" in orange and the "Neuer Mainzer Tunnel" in gray. The blue shaded area illustrates the sphere of ground displacement due to tunnel advancing. The subsidence cavity will have a width of approximately 40 meters. The red hatched areas exemplify buildings that were influenced by this project. It was absolutely necessary to maintain all those structures without any damages.

2.2.3 Safety during construction

Tunnelling is risky! Because of the nature of tunnels, mining is connected with a multiplicity of hazards. New tunnelling techniques and safety regulations helps to avoid notable incidents, but hazards can never be excluded in total. According to Bickel 1982 [2] we have the classic health hazards such as gas intrusions, dust, noise, explosion fumes, diesel combustions, moisture, and so on. Those hazards are the direct result of tunnel advancing by the application of drilling, blasting, loading, and mucking. A well designed ventilation and drain system helps to reduce those risks. Air pollution and adverse working conditions are nonlethal risks but can bring out several health hazards and will decrease working efficiency. The main focus is to create a safe and friendly working environment for all employees (Wood 2000 [24]).

Furthermore, we are faced with a variety of notable incidents, which could be a result of incautiousness, slack safety regulations, or a combination of extraordinary circumstance. Inrushes cause the most danger in the field of tunnelling.

> *"Small inrushes can be seen as overexcavation, but major inrushes (cave-ins, or daylight collapses) are catastrophes frequently resulting in high cost, downtimes, and even death". (Kolymabs 2005 [8])*

Unforeseen underground conditions, insufficient monitoring, inadequate planning, or lack of execution can be reasons for disastrous events, especially in tunnel projects with low overlap. Application of state of the art tunnelling methods by an experienced crew on site may reduce the danger of inrushes; however unforeseen hazards can never be totally excluded.

Regarding the project "Alte Mainzer Tunnel", we have a multiplicity of risks. Additional to the danger of daylight collapses in the tunnel, we are also faced with the possibility of damages on structures. The probability of an abrupt inrush is not presumptuous because of the existing structure of the "Alte Mainzer Tunnel". The challenge was to reduce the occurring settlements on the surface and to guarantee the stability of the affected structures. With an extremely strict monitoring program, sophisticated risk management, and several safety regulations, the main health hazards could be eliminated.

2.2.4 Time and cost management

Time and cost have to be mentioned together because they are connected to each other for the society. These two parameters are the main indicators whether a project runs successfully or will end in disaster. Especially in the business of tunnelling unexpected troubles can easily raise the overall project costs or generate immense delays.

The cost distribution for a tunnel project is manifold. First they depend on technical features such as the current rates and ground quality. However there are many more factors influencing the price of a tunnel construction, as started by Kolymabs 2005 [8].

- Project culture (cooperation)
- Laws, standards, etc
- Legal procedures
- Tendering
- Contract
- Risk management

In addition, incalculable parameters like political pressure, corruption, public influence, etc. have to be considered too. Therefore, efficient cost and time management is responsible for the success of the project. The basic task is to develop a realistic time schedule including also the critical path. Moreover we have to update the cost estimations and schedules frequently so that differences can be identified on time. Due to irregularities or difficulties it is now possible to react and solve arising problems on time. The communication and relationship between all the project partners is an important factor for the success of the whole project.

To carry out a project effectively, a wide variety of factors must be taken into account. Management systems and consultants help to achieve the goal.

3 Original Concept

In this chapter the original construction concept as proposed by the client is explained. Basically, it has to be distinguishing between measures in the tunnel and on the surface. According to BEMO 2007 [A], the main construction steps in the tunnel can be summarized in the following operations,

1. Stabilizing packing with grouting
2. Fix existing tunnel with steel arches
3. Advanced actions during tunnelling (Spiling, pipe arches …)
4. Excavation - tunnel enlargement
5. Bolting and producing shotcrete lining
6. Generate temporary invert
7. Final ring closure after finishing entire tunnel

With exception of steps one and two, it was planned to apply conventional tunnelling methods. Thus, surface settlement could not be avoided in total; therefore additional measures on surface were required to meet the strict requirements regarding to settlements on the surface. These further activities would have been:

1. Partial grouting via grouting shafts (Kästrich 49 -61)
2. Local usage of drilling pile wall (gateway tunnel main station)
3. Dig- and cast construction (tunnel south)
4. Wall-reinforcement ("Zitadellenmauer")

All these activities result in massive environmental impacts on the surface. Permanent noise disturbance, dirtiness and restricted areas would have been direct consequents of these operations. These special operations have to be mentioned independently from the tunnel excavation process.

In this paragraph the construction process of the original concept will be explained briefly. Step number one would have stabilized the packing layer to avoid abrupt inrushes. Afterwards a sand stone cut would have been executed and steel arches would have been assembled. To minimize occurring settlements forepoling measures would have been applied. Subsequently the tunnel enlargement procedure could have been executed. Right afterwards the shotcrete lining including bolds would have been established. The final job would have been the accomplishment of the invert excavation and consequently the final ring closure.

In the next few chapters the primary concept will be explained in more detail. Mode of operations and basic consideration of this model will be pointed out. Furthermore in the upcoming chapter fundamental knowledge about tunnelling will be presented. Therefore subject areas such as "New Austrian Tunnelling Method", forepoling techniques and ground bolting will be discussed in more detail within the corresponding topic.

3.1 Stabilizing packing by the application of grouting

For a better understanding, the different steps of procedure are exemplified chronologically. Besides setting up the site arrangement, the stabilization of the hard core was one of the first steps to do. The hard core is a result of the German "Kernbauweise". In former times, before the invention of modern tunnelling techniques, it was common to stabilize the tunnel crown with a kind of hand-set packing.

The hand-set pitching is a composition of tuff, basalt, and limestone with a pore volume of approximately 25 %. Because of these properties, heavy settlements occurred during excavation. To avoid large ground displacements, grouting must be executed.

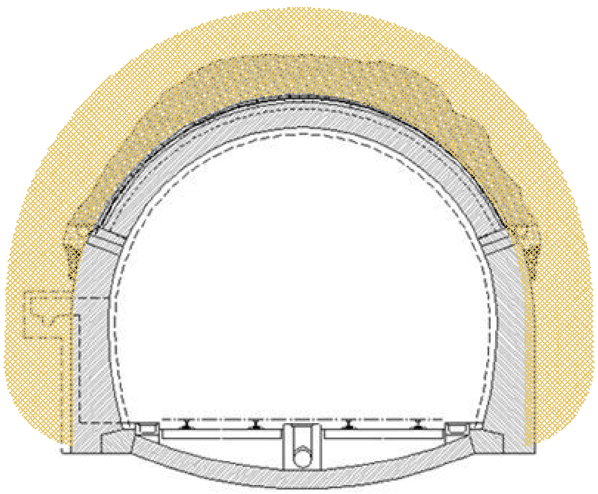


Figure 7: Stabilizing packing by dint of grouting (source Beton- und Monierbau)

Before removing the sandstone-brickwork, the packing had been stabilized by the application of grouting. Drill holes with a size of Ø 42 mm and a length of approximately 2.5 meters had to be implemented. The modular grid was announced by 1.5 x 1.5 meters. The drill had been taken from the existing tunnel. The grouting suspension was a special mixture of cement, water and additive, and was injected in an area of at least 1.5 meters around the existing tunnel construction. The objective was to stabilize the present packing so that settlements could be minimized. This individual operation was scheduled in the bidding documents as well as in the alternative concept. Because grouting is one of the main procedures, a widespread outlook on the function, challenges, applications and advantages of the grouting procedures will be given in chapter 4. The widespread outlook will also include analysis and evaluations referring to quantity and quality.

3.2 Fixing existing tunnel with steel arches

To support the existing tunnel structure during tunnelling, special manufactured steel arches should have been applied. Those structures would have helped to minimize the risk of abrupt inrushes or deformations due to tunnel excavation. The entire structure would have had an extension of circa 16 meter. Eight individual segments with a length of 2 meters would have been established to one construction. The friction-locked connection between existing tunnel lining and steel arches would have been essential. The steel arches would have to be positioned as close as possible at the excavation face of the new tunnel. Step by step the supporting structure would have to follow up the excavation procedure.

3.3 Advanced actions during tunnelling (Forepoling)

Particular circumstances such as sensitive buildings and complex geology, hardly any cover or weak ground conditions make it necessary to implement additional actions to avoid settlements. If the excavated face is unable to stand up even for short time, a pre-driven support is necessary to allow work on the excavation face. The basic idea behind this concept is to drive up the tunnel under the protection of a previously driven canopy. Traditionally, steel sheets or steel rods (spiles) were used. Nowadays, a wide range of forepoling systems are available. Advance actions like spiling or pipe arches help to improve the structural stability of the subsoil. Furthermore, the risk of uncontrolled inrushes will be minimized. According to Kolymabs 2005 [13] the following forepoling techniques have to be mentioned:

- Spiling
- Pipe roof
- Perforex-method
- Grouting
- Soil freezing

Spiling and pipe roofs are designated in the primary concept of the project "Alte Mainzer Tunnel" and will be illustrated on the next page in more detail. As mentioned before grouting will be extensively manifested in chapter 4. Because soil freezing and perforex are not applied in this project, I will not explain these techniques in detail.

3.3.1 Spiling

By drilling a certain type of artificial canopy of spiles into the tunnel face, the primary stand-up time of the face can be extended. The typical materials used are steel rods or pipes, with a length of approximately 4 meter (Bickel 1982 [2]). The distance in circumference direction is about 30 cm. The horizontal angle is limited by 15°. If applicable, exceeded dimensions up to 15 meters can be practicable.

> *"In order for the spiles to act not only as beams (i.e. in longitudinal direction) but also to form a protective arch over the excavated space, the surrounding soil is grouted through the steel pipes or sealed with shotcrete". (Kolymabs 2005 [8])*

Because of the complexity of assembling, spiling is a very time consuming and expensive process.

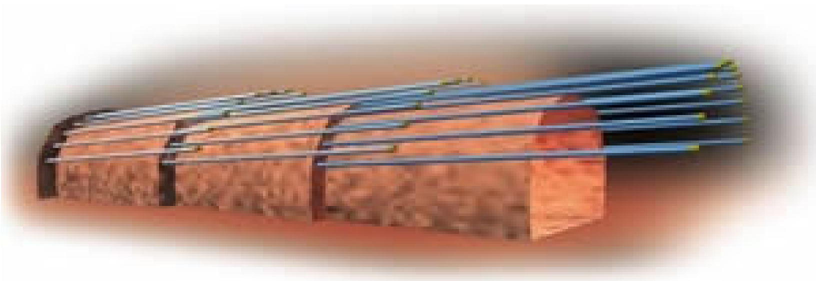


Figure 8: Previous actions, forepoling (American West Drilling Supply 06/20/2009 [25])

3.3.2 Pipe arch

The pipe arch functionality is nearly identical with spiling, however pipe arches provide a significantly higher bearing capacity because of the lager diameter (up to 200 mm) of steel pipes. Common materials are concrete or steel tubes. The main task of pipe arches is to support the tunnel face by acting as a beam. If required, partial grouting can be undertaken due to the hollow steel tubes. In relation to the bidding documents, pipe arches with a total length of approximately 18 meters and a minimum diameter of 100 mm were prescribed. The angle of inclination was limited to 5 °. Pipe arches were scheduled mainly below buildings under risk and in the area of the portals.

3.4 Excavation, tunnel enlargement

Tunnel excavation is one of the key procedures in the process of tunnelling. Almost all working steps and arrangements are aimed to allow smooth tunnel advancing. Over the years multiple excavation technologies have been developed. For nearly any condition or challenge a special excavation method is available. The choice of an adequate excavation technique is mainly based on the geology and local circumstances. Excavation characterizes the processes of detaching rock or rather removing the subsoil.

Basically it has to be differentiated between periodical and continuous excavation. The application of diverse tunnelling techniques is mainly based on geological conditions, local water situation, length of the tunnel, shape of the profile as well as regulations regarding deformations and vibrations. Periodic excavation, also known as "conventional heading" is mainly practicable for short tunnels, variable tunnel profile and difficult geological conditions. TBM's are especially applicable for long tunnel lots, monotonic ground conditions and a steady remaining tunnel profiles.

Referring to the project "Alte Mainzer Tunnel" it was out of question to use the conventional tunnelling technique. The already existing tunnel structure as well as the strict regulations regarding vibrations and settlements, plus the two short tunnel lots made the execution of a TBM nearly impossible. Therefore, the bidding documents dictated to use the "New Austrian Tunnelling Method". Because of the importance of the “New Austrian Tunnelling Method” and the fundamental consideration behind this revolutionary technology, it is indispensable to have additional focus on this tunnelling method.

3.4.1 Excursus: “New Austrian Tunnelling Method - NATM”

In the 1950’s and 60’s a new tunnelling technique called the “New Austrian Tunnelling Method” was developed. NATM was created by a number of Austrian tunnelling engineers [RABCEWICZ, MÜLLER-SALZBURG and PACHER]. This tunnelling technique combines the conventional heading with a multistage of supporting systems. The main part of the “New Austrian Tunnelling Method” is the bearing ring in the surrounding ground, including additional supporting activities. Basically, NATM is a combination of active- and passive support techniques. According to Siding 1989 [20], Kolymabs 2005 [8], the main considerations behind this revolutionary method are:

- Sufficient ground deformations as well as applied anchors help to activate the strength of the surrounding ground. A bearing ring in the surrounding ground is the result of this operation.
- A thin shotcrete lining helps to reduces ground displacements to an acceptable level.
- The deformation of the auxiliary arch has to be monitored continuously. The final inside lining can be executed after a stabilizing trend of occurring deformations.
- Main consideration is to achieve an equilibrium state in the surrounding ground. The reorientation from the primary state of stress to a secondary state of stress is essential.
- Because of these events, a very thin lining is necessary to ensure the stability of the tunnel.

In the past 50 years the “New Austrian Tunnelling Method” has been applied in nearly every field of tunnelling. NATM is especially applicable for tunnel projects with difficult geological conditions. Furthermore, this technology is absolutely useful for underground projects in urban areas. However, the most important issue regarding to the use of NATM is the interaction of Engineer – Geologist – Surveyor. These three professionals are mainly responsible for the success of this tunnelling method.

The specification below will give as a rough overview of the basic steps of the "New Austrian Tunnelling Method" (Sidling 1989 [20]):

1. Full face or partial face excavation
2. Primary shotcrete lining to avoid inrushes
3. Arrange reinforcement steel mesh along shotcrete lining
4. Assemble steel ribs to support surrounding ground
5. Additional shotcrete lining to seal reinforcement
6. Appliance of anchors to activate the bearing ring in the surrounding ground
7. Installation of measuring points to control the stabilizing trend of the time/deformation curve
8. Fabrication final inside lining

The different steps mentioned above will help us to understand the special execution belonging to the project "Alte Mainzer Tunnel". Regarding this project the listed sequences will be dealt with more precisely in the upcoming chapters.

I will close this excursus with the official definition of the "New Austrian Tunnelling Method", published by the Austrian Society of Engineers and Architects [1]:

> "*The New Austrian Tunnelling Method constitutes a method where the surrounding rock or soil formations of a tunnel are integrated into an overall ring-link support structure. Thus the formations will themselves be part of this supporting structure".*

3.4.2 Execution of saw cut on sand stonework

A significant saw cut had to be produced on the existing sand stonework. The slot helped to minimize the negative influence during tunnelling advancing. The main purpose of this operation was to alleviate the removal of the existing sand stonework as well as to avoid deformations in the 125 year old "Alte Mainzer Tunnel" during tunnel excavation. The cut had to have a minimum deepness of 40 cm and had to be executed all around the stonework. The photograph below (figure 9) displays the vehicle with the cutting-machinery during the procedure.

Figure 9, Execute saw cut (source Beton- und Monierbau)

The space between the separate cuttings was defined by 1.0 meter. This is similar to the rate of tunnel advance. By reducing the risk of structural damage in the entire tunnel, cuttings had to be executed near the excavation face. This procedure was a part of the bidding documents as well as the alternative concept. The execution of this operation proceeded very smoothly which provided desirable results.

3.4.3 Crown excavation

Tunnel advancing was the most critical procedure in the project. The main challenge was to avoid vibrations and deformations during the excavation process. To remove the existing sand stonework, along with the surrounding subsoil, excavators including special working tools were used. In particular cases, blasting was allowed.

To guarantee stability during excavation a partial face excavation had been specified. Dividing the face excavation in different sections helps to reduce settlements as well as the risk of abrupt inrushes. It generally implies that small cavities are more stable than large ones. The sketch below (figure 10) shows the most common types of partial face excavation.

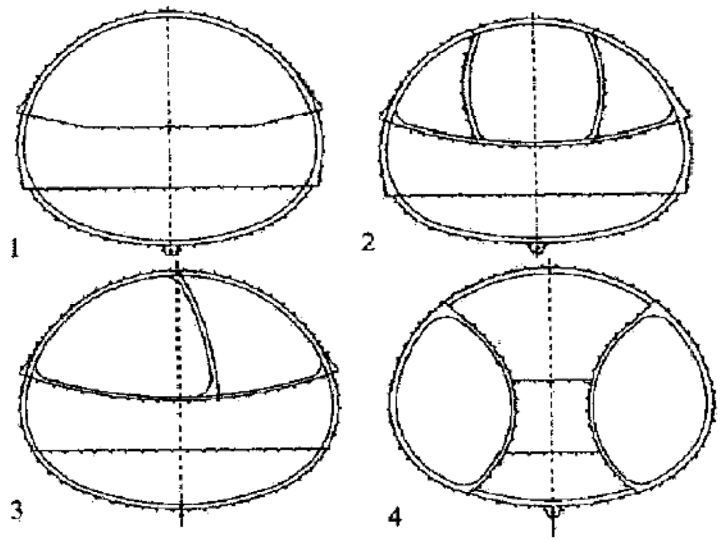


Figure 10: Different type of partial face excavation (source RVS 9.32 2005 [17])

Depending on geology, settlements, and a manifold of circumstances, a division of the excavation face could be necessary. Regarding to the project “Alte Mainzer Tunnel”, a split face excavation was scheduled. Therefore, the tunnel cross section is defined by a crown- and an invert excavation. First of all, the crown area has to be excavated. Afterward the remaining invert has to be removed. The rate of tunnelling advancing was limited to a maximum of one meter per step and approximately four meter per day. The purpose of this prescription was to minimize the influence of occurring settlements on structures and infrastructure constructions on the surface. Additional applied forepoling techniques would have supported this significant aim (DB Projektbau GmbH et al. 2006 [C]).

3.4.4 Shotcrete placing

Right after the crown excavation a thin shotcrete lining must be applied. The main purpose of this operation is to seal the uncovered surface. The primary layer helps to reduce ground displacement and creates a safe work environment for all further actions. Shotcrete belongs to the group of passive supporting systems. Those supporting techniques get activated by sufficient ground deformation based on the redistribution of stress (Bickel 1982 [2]).

3.4.5 Assembling steel ribs included reinforcement steel mesh

Installation of steel ribs and reinforcement of steel mesh is a practicable aid to increase the strength of the applied shotcrete lining. The design is mainly based on issues like rock pressure, deformations, and safety matters.

Regarding the project "Alte Mainzer Tunnel" it was dictated to use pre-curved GI 120 steel ribs. The distance between the separate segments was limited to 1.0 meter. To enforce the stability of the external lining, reinforcement steel mesh was applied. The combination of these three components (shotcrete, steel mesh, and steel ribs) is essential to create a resistant exterior lining. These passive support systems were included in both, the primary and the alternative tunnelling concept. Dimensions are outlined in the further chapter, "Alternative tunnel concept".

3.4.6 Ground bolting, anchor– activating bearing ring

Ground bolting is a complex activity and includes a wide range of different technologies. The right choice of the most adequate anchor method depends greatly on the surrounding geology. According to Lee 2006 [11] weak rock type requires much more specified technologies.

However, improving the stiffness and strength of the subsoil is main duty of these applications. All activities that upgrade the quality of the surrounding rock are appropriate to the category of active supporting systems. Furthermore, rock reinforcement is essential to activate the bearing ring in the adjacent subsoil. Referring to (Schuller 2009 [18]) examples for these devices are

- Anchors
- Bolts
- Nails
- Dowel

Each of these gadgets deserves their own area of application. Regarding to our project in Germany, grout anchors were indicated in the bidding documents. These kinds of anchors achieve their usability by improving the surrounding subsoil due to cement grouting. The primary concept prescribes the disposal of grout anchors with a diameter of 32 mm and a length of about 4.0 meter. Because of the complexity and importance of active supporting technologies, an extensive excursus in the upcoming chapter is provided.

3.4.7 Generate temporary invert

Because of weak ground conditions and strict limits regarding of the settlements, the primary concept dictated the implementation of a temporary invert. This intermediate step would avoid significant ground displacements until the final ring closure is finished. The temporary invert would have been categorized as an external lining construction, without the usage of steel ribs. The drawing below (figure 11) represents the crown excavation, as well as shotcrete lining including the temporary invert.

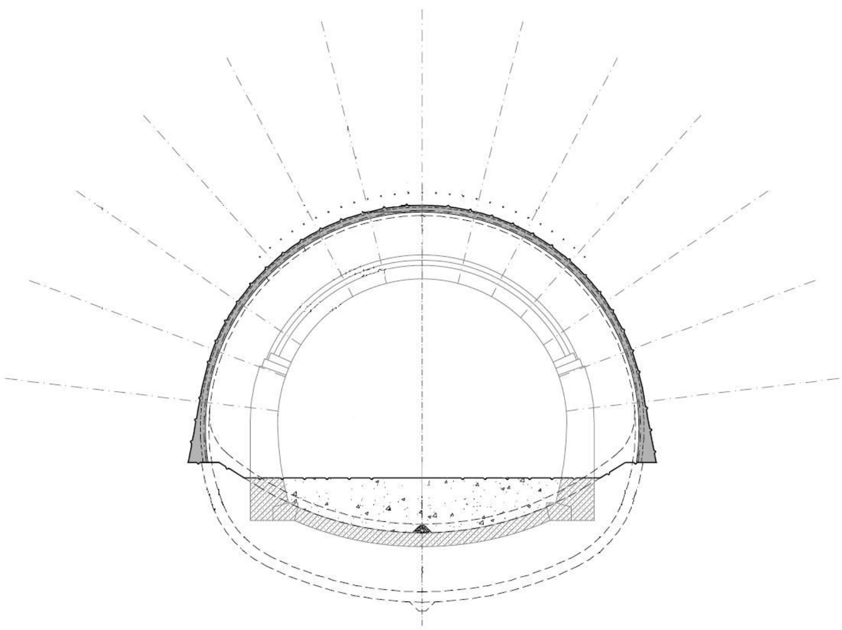


Figure 11, temporarily invert construction (source Beton- und Monierbau)

The temporary invert should have been installed right after the crown excavation. To minimize significant ground deformations the temporary invert would have to be constructed within 24 hour. The rate of advance would have taken place in 2 meter steps. For traffic transposing during this work of sequence, a temporary work plane would have to be built.

3.5 Final ring closure

The final ring closure is an essential procedure. After finishing the external tunnel lining, the entire cross section started to act as one piece. The mostly circular or elliptical shape of the tunnel cross section helps to support this event. Particular attention has to be played to complex connection joins. It is important to establish a force-locked connection between the single parts of the external lining. However, the final ring closure is essential to produce an equilibrium state in the surrounding ground.

In comparison with the project “Alte Mainzer Tunnel” and the original bidding documents, a partial excavation including a temporary invert was tendered. Regarding to these specifications, it was prescribed to complete the crown excavation and the temporary invert first. After the entire tunnel was excavated, the final ring closure could have been finished. The usual thickness of the shotcrete lining should be between 30 and 40 cm, mainly dependent on the geology and applied supporting technologies.

3.6 Final concrete lining

After the completion of the external shotcrete lining, the inner concrete lining has to be constructed. The inner concrete lining has to be mentioned as an independent construction. A connection of the external and internal linings should be avoided. Deformations on the external lining have been died away long before work on the internal construction can take place. To allow slight movements, a “Geotextile” has been installed between both linings.

An additional PVC membrane helps to seal the tunnel construction against occurring water influences. The internal lining is a heavy construction with an average thickness of at least 40 cm. Steel reinforcement such as rebar or steel mesh will guarantee the stability of this massive construction. The design of the internal concrete lining is mainly dependent on further use of the tunnel.

3.7 *Additional on surface measures*

The primary concept of the project “Alte Mainzer Tunnel” included additional arrangements to minimize settlements on the surface. Because of tunnel advancing ground displacement will take place. This event will generate settlements on the surface. Movements affect the stability of structures. To minimize ground displacements, tunnel advancements have been executed very carefully. However, the primary tunnelling concept was unable to avoid settlements in total. Due to this fact, additional arrangements were tendered to reduce the occurring settlements.

3.7.1 Partial grouting via grouting shafts (Compensation grouting)

Grouting is an excellent technique to compensate settlements due to tunnelling excavation. The original bidding documents dictated the application of grouting via grouting shaft on the surface. Grouting allows engineers to modify the properties of the subsoil. However the drawing below (figure 12) will outline the basic consideration behind this technique.

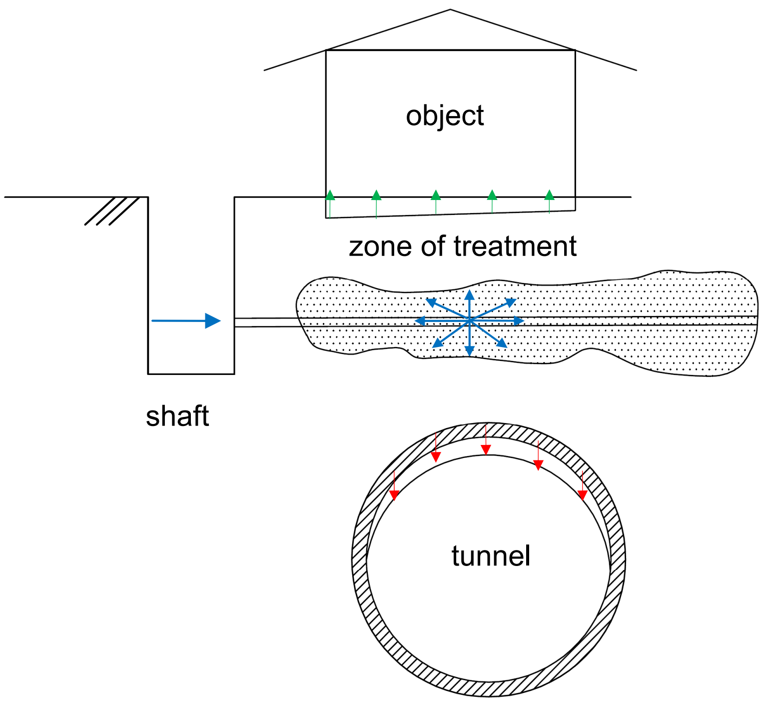


Figure 12, grouting via shaft, after Kummerer 2003 [10]

This method is a very effective way to control occurring settlement on the surface. The previous sketch (figure 12) illustrates the operation mode of grouting via shafts on the surface. The red arrow represents ground displacement due to tunnelling advancing. To avoid significant movements on the surface, the subsoil between the tunnel and the structure would have to be injected. Amount and composite is essential to achieve a satisfactory result. The suspension contains mainly cement, water and bentonite. Because of the complexity of grouting and applications, a wide board outlook in the following excursus will be provided.

3.7.2 Local usage of drilled pile wall

The application of pile walls is an additional technique to avoid defective movements on foundations. These artificial walls have to be situated between the tunnel construction and the buildings at risk. The main purpose of this method is to separate buildings from the tunnel. As a result of this operation, occurring settlements are unable to influence the adjacent building. The sketch below (figure 13) shows the basic function of this method.

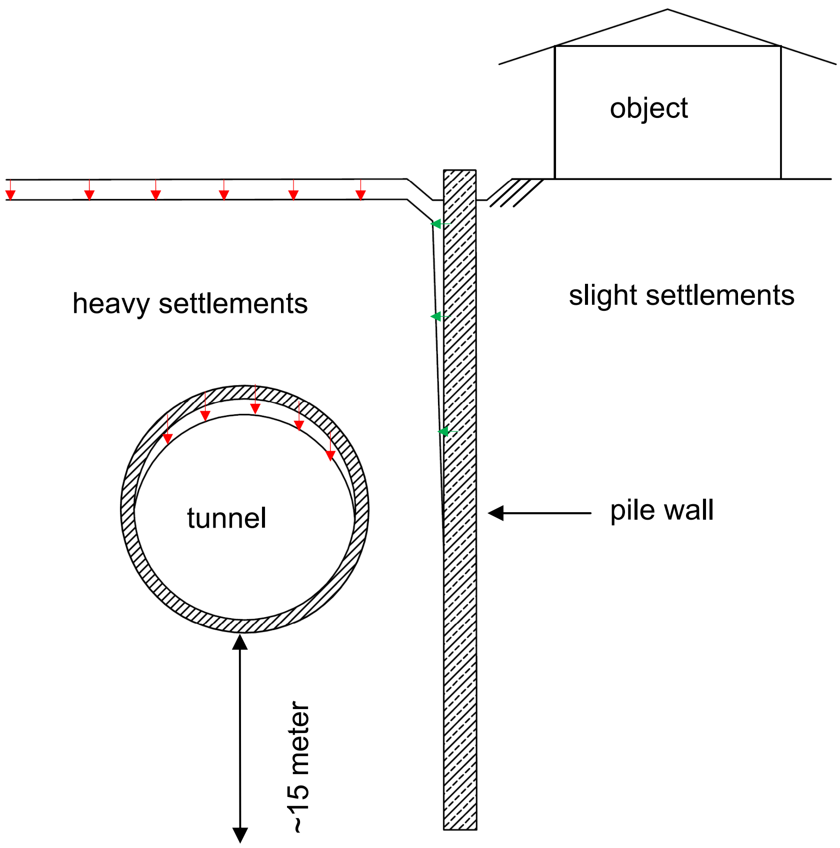


Figure 13, installation of pile wall to reduce settlements

Regarding to the original bidding documents a drilled pile wall (pile-diameter of 1.2 meters) was tendered. To ensure the stability of this construction, the drilled pile wall should have been founded underneath the tunnel invert. The main disadvantage of this method is the massive interference on the surface. Because of advanced techniques belonging to the alternative tunnelling concept, the usage of pile wall became dispensable.

3.7.3 Dig-and-cast construction method

This is a totally different technique to excavate a tunnel without adequate cover. In the region of the so called “Zitadellenmauer” – building lot, “Alte Mainzer Tunnel south,” it was inevitable to drive up the new tunnel in a dig-and-cast construction method. This special tunnel technique allows engineers to construct tunnels close to ground level. According to Megaw 1982 [13] the main steps are:

- Trench excavation
- Construction of the reinforcement concrete cast
- Trench backfill
- Awaiting of the hardening of reinforcement concrete slab
- Tunnel advancing beneath the protection of the artificial canopy

Certainly there are many more sequences of work included. But the specification above will give a brief overview about this special tunnelling technique. The main disadvantage of this method is the amount of space needed on the surface. In reference to our project, an approximately 20 by 15 meter large cast was poured. The minimum thickness was limited by 45 cm (Deutsche Bahn 2006 [B]). The dig-and-cast construction was part of the original and the alternative bidding documents.

3.7.4 Wall-reinforcement (Zitadellenmauer)

Moreover, it was necessary to stabilize the historical “Zitadellenmauer” with grout anchors during the tunnelling excavation. Those activities helped to protect this unique construction form cracks and further damages. However, “grouting” and “anchors” are the keywords for the excursus provided on the next page.

4 Excursus grouting

The first experiments with grouting dates back more than 200 years. Over the years, different grouting techniques and materials have been developed. Nowadays grouting is an essential part of heavy civil engineering.

> "*Grouting is broadly defined as the placement of a pumpable material which will subsequently set or gel in pre-existing natural or artificial openings (permeation grouting) or in openings created by the grouting process (displacement or replacement grouting.*" (Byle et al. 1995 [4])

To seal or improve the strength and stiffness of the rock or subsoil is the main purpose of grouting (Kummerer 2003 [10]). Nowadays, a wide range of diverse grouting techniques are common. Grouting is categorically divided in the following classes:

- Compaction grouting
- Permeation grouting
- Jet grouting
- Fracture grouting
- Soil mixing

Each of these grouting methods belongs to a particular field of application and requires special equipment. The main area of application is the support of tunnel activities, settlement remediation, groundwater control, underpinning, embankment stabilization etc. The choice of the most adequate grouting technique is mainly biased on the local ground conditions as well as the purpose of application. A wide range of different grouting materials are available. The basic components are water, cement, and additional chemicals or additives if required. Chemicals are useful to change the characteristic of the suspension. Depending on the geological conditions, the injection pressure and the grouting mixture are capable for variation (Byle et al. 1995 [4]).

Additionally, it has to be mentioned that monitoring is an indispensable part of the grouting process. It is absolutely necessary to control the amount, pressure, and occurring ground displacements in the surrounding subsoil.

Regarding the project “Alte Mainzer Tunnel” a special grouting concept was implemented. This alternative program was developed to fulfill the following objectives.

- Stabilization of the backfill
- Compensation of occurring settlements on the surface
- Sealing of water bearing layers
- Significant improvement of present ground conditions

The combinations of these four targets were essential for the adaptability and the success of the alternative tunnelling method. However, to reach the specification, a combination of different grouting technologies was used. Mainly permeation- and fracture grouting was applied.

Permeation grouting:

According to Byle et al. 1995 [4] the main purpose of permeation grouting is to fill soil pores and/or rock fissures. This grouting method operates without causing relevant movements or fracturing of the rock or subsoil. The replacement of water and/or air of clefts and voids in the rock are the main function of this grouting technology. The injection of the grout fluid has to be monitored at all time to avoid fracturing in the grouted soil mass. Pressure has to be chosen to serve these specifications. The sketch below (figure 14) represents the basic function of permeation grouting.

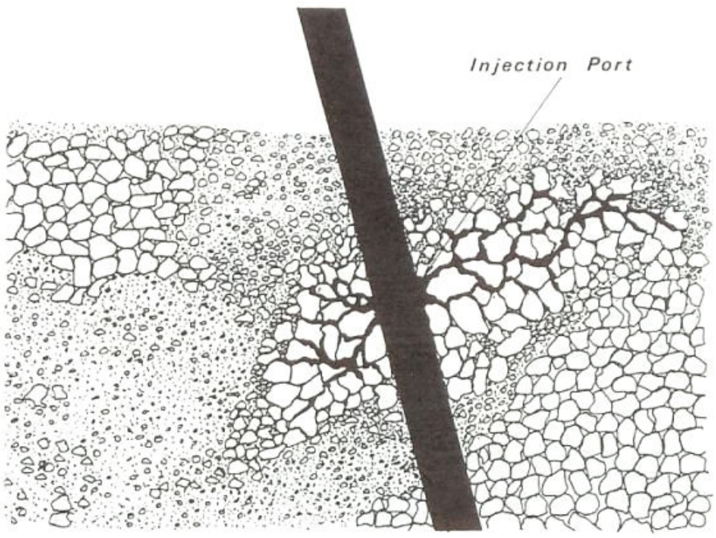


Figure 14, systematic sketch of permeation grouting, after Houlsby 1990 [7]

Permeation grouting works with a very low level of pressure. Concrete grout is penetrating out from the injection port in spaces between large pieces of sand or gravel. Grouting material is not able to flow in voids of finer materials. However, to reach a higher level of penetration fracture grouting has to be applied.

Fracture grouting:

Regarding *(Byle et al. 1995 [4]) h*igh grout pressure has to be used to fracture the subsoil at the point of injection. Significant ground movements could be a result of this operation. Special permission will be necessary to execute this method. Fracture grouting dramatically improves the stiffness and strength of the soil. Additionally, this method is absolutely useful to compensate settlements, as well as for lifting of foundations.

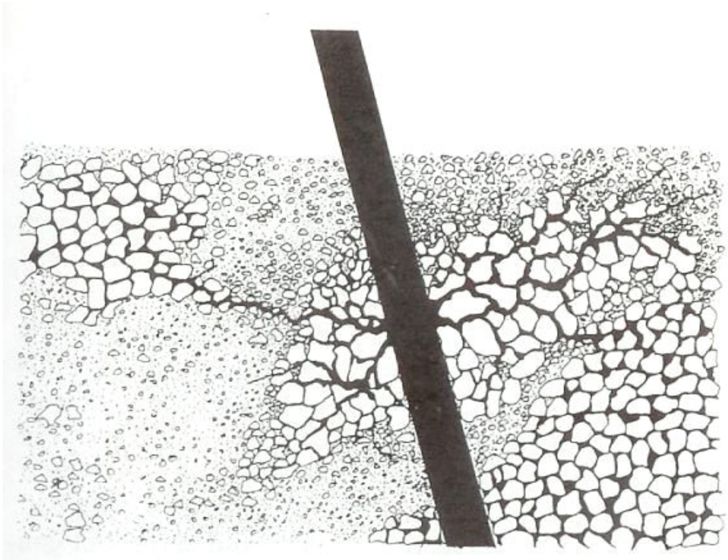


Figure 15, Fracture grouting, after Houlsby 1990 [7]

In comparison to permeation grouting, the level of penetration is much higher. Cement grout is spread out all over the grain structure. The fracture process generates heavy deformations in the subsoil. Because of this fact, there is a limited field of application. Furthermore, the rate of penetration is additionally based on the composite of the grouting material. The supplementary of chemicals or additive will change the viscosity, setting speed etc. of the grouting suspension. The right mixing proportion is essential to execute grouting successfully. Regarding the project “Alte Mainzer Tunnel” a cement based grouting mixture was prescribed.

4.1 Grouting pipes and grouting anchors

Nowadays, a wide range of different grouting pipes and anchors are available. The function of grouting anchors and grouting pipes will be worked out in this excursus. In this chapter, I will provide essential information to get along with the alternative grouting concept. Belonging to the mode of operation, we have to differentiate between filling-pips, grout lances and grouting anchors. However, the main purpose of those devices is the injection of grouting fluid.

4.1.1 Filling-pipes

This is likely the simplest way to execute grouting. Everything starts with the grout hole drilling process. Depending on the hardness of subsoil, different drilling methods have to be used. After removing the drill rods, a simple PVC pipe has to be installed into the clear bore hole. Before starting with the grouting process, the gap between the pipe and the drill hole has to be sealed. The PVC pipe is a simple tube with a few openings to relieve the grouting fluid. The drawing beneath (figure 16) shows a simple cross section of filling pipes applied at the project “Alte Mainzer Tunnel”.

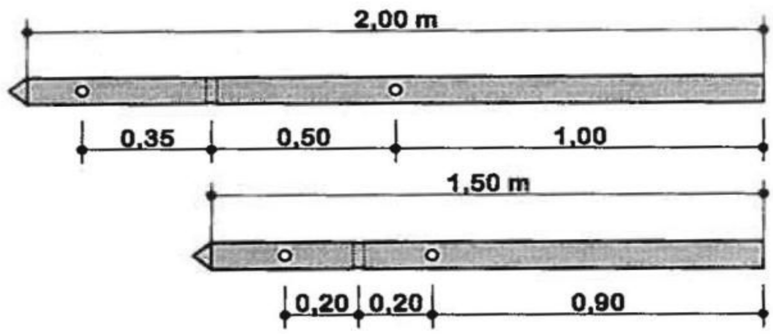


Figure 16, filling pipes, source BEMO-Injektionskonzept 2007 [17]

This technique was used to stabilize the packing layer. The usage of simple filling pipes without any manchettes or packers is quite limited. A high pore volume as well as a short grout hole is absolutely necessary to guarantee an adequate penetration in the adjacent subsoil. As mentioned, this simple filling technique was used to grout the packing layer. The hand-set pitching has a pore volume of approximately 25 % and is a composition of tuff, basalt and lime stone. The length of the grout hole was limited to 2.5 meter.

4.1.2 TAMs (Tubes-à-manchette)

A more specific and advanced grouting technique is established as TAM's (Tubes-à-manchette). This special grouting method allows engineers to grout the adjacent rock or soil much more precisely and controlled. The grouting pipe has openings in regular intervals. Those openings are covered with a rubber sleeve. The rubber sleeve has to protect the port. To insulate particular parts of the grout hole a double-packer come into action. The sketch below (figure 17) presented by Houlsby 1990 [7] demonstrated the basic functions of this grouting technology.

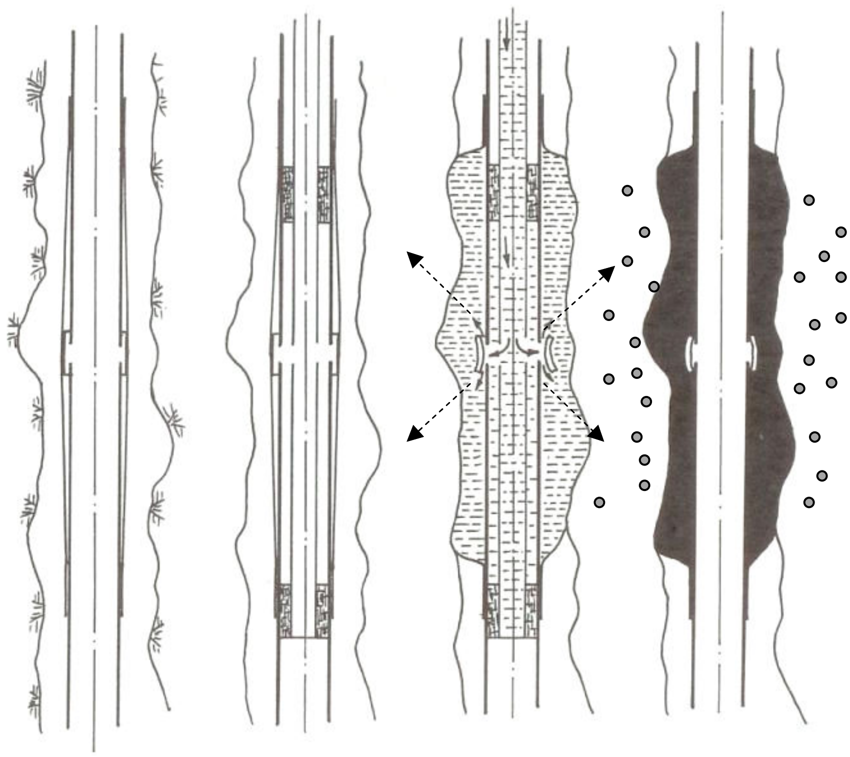


Figure 17, TAM grouting operations, after Houlsby 1990 [18]

After completion of the drilling procedure the four main grouting steps are:

1. Placing of the grout tube (TAM)
2. Positioning of grout supply tube with double packer
3. Cement grouting process
4. Removing the double packer and hardening process

This specific operation has to be reprised for all additional openings over the entire grouting tube. Quantity and grout pressure have to be monitored at all time. Regarding the alternative concept this grouting technology has been used to improve the stiffness and strength of the subsoil. The grouting tubes had a length of 3.0 or 5.0 meter. Three openings were placed each meter. By applying this grouting method a significant part of the artificial bearing ring could be constructed.

4.1.3 Grout anchor (IBO-Anchor)

This special device combines two techniques. On the one hand, grout anchors operate like a usual anchor, and on the other hand, they are used for the grouting process. IBO-anchors are especially applicable for poor ground conditions. Therefore grout anchors are a very practicable method to improve the strength and stiffness of rock or soil. The sequences of work are basically quite simple.

1. The boring process
2. The grouting operation
3. Anchor activation

In this case it has to be mentioned that the entire IBO-anchor acts at first as a boring rod then as a grouting pipe and at last as an anchor. The drawing below (figure 18) illustrates the most important parts of this anchor type.

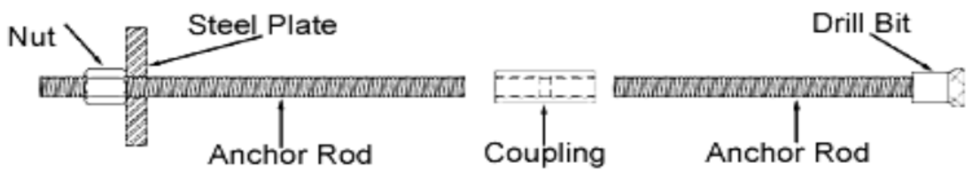


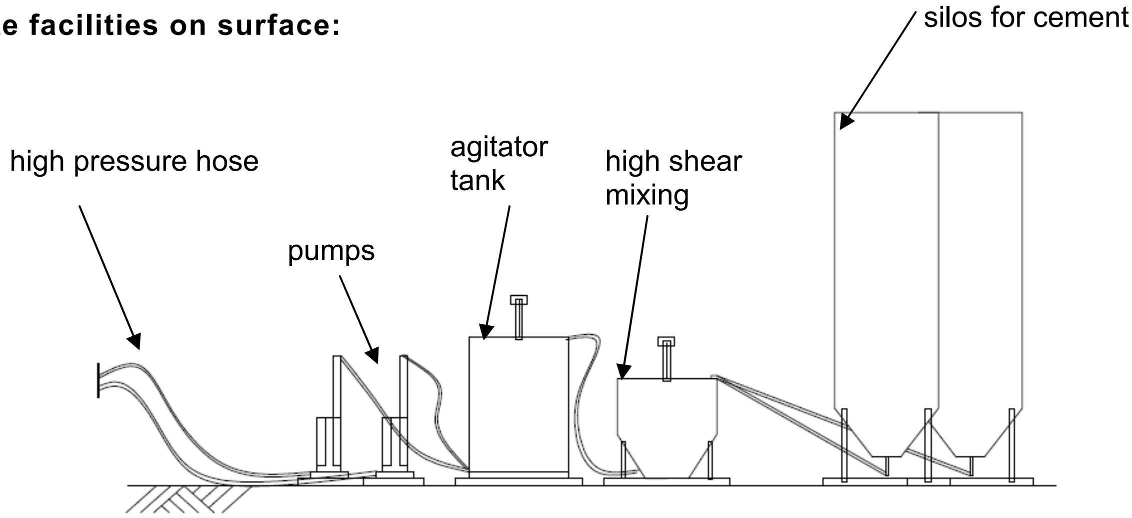
Figure 18, IBO-anchor (Cooperation-Group 10/03/2009 [26])

However, nowadays grout anchors are frequently used in collaboration with the "New Austrian Tunnelling Method". Regarding the alternative concept IBO-anchors, with a total length of 9.0 meter were used. Reinforcement and stabilization of the external bearing ring was the main duty of this supporting method. Because of the tunnel enlargement process, a modified version of the IBO-anchors was applied. The mode of operation for this new developed anchor technique will be worked out in the upcoming chapter.

4.1.4 Site facilities

In this chapter, a short overview of required equipment will be provided. Depending on the type of grouting operation as well as different requirements the side arrangement will vary slightly. Grouting is quite a complicated process. Therefore, a high variety of different tools and devices are necessary.

Site facilities on surface:



Site facilities in existing tunnel:

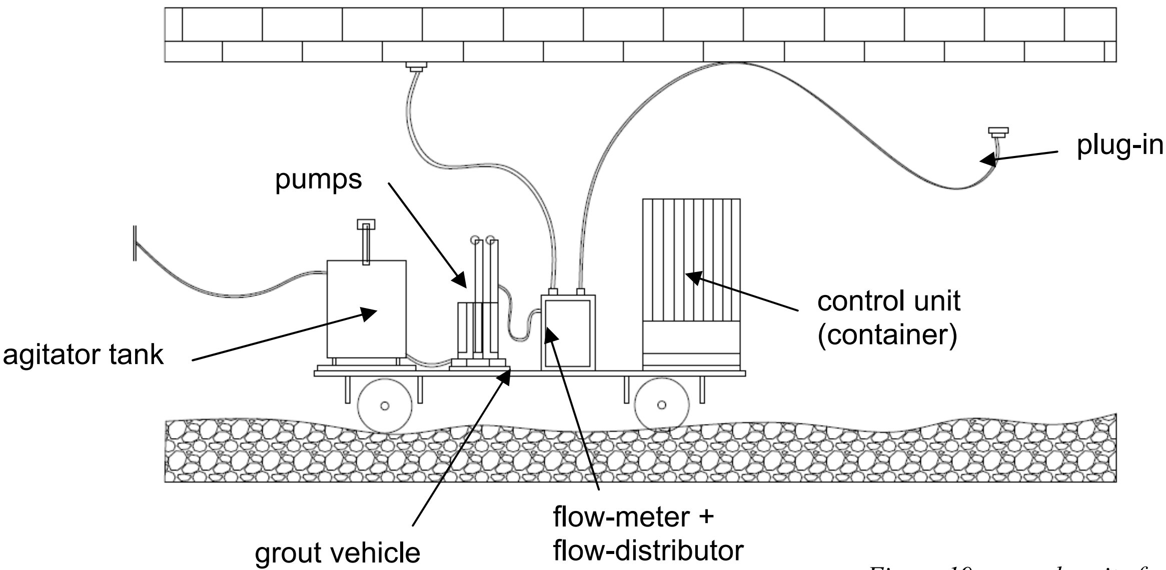


Figure 19, exemplar site facilities

This site arrangement is similar to the equipment used in the “Alte Mainzer Tunnel” project. In total, 4 grouting vehicles were positioned in the tunnel. At peak times, 16 different plugs were in use. Analysis and critical evaluation of the entire grouting process, including quantity, time and occurring settlements will be addressed in further chapters.

5 Alternative concept

The redevelopment of the “Alte Mainzer Tunnel” was interconnected with a wide range of challenges. Most of these special circumstances have been announced in the primary concept. Complex tunnelling techniques and extensive ground treatment methods have been tendered in the original bidding documents. High construction costs, an extended construction time as well as significant environmental impacts would have been a consequence of the execution of the primary tunnelling concept.

Because of these unacceptable terms an alternative concept was developed. The main objective of this new tunnelling idea was to reduce the individual tunnelling operations. Furthermore occurring settlements due to tunnel advance could have been reduced to an absolute minimum. An extensive grouting program was a key procedure of the entire tunnel project. The stabilization- and homogenization of the adjacent subsoil was the primary result of this operation. In combination with applied anchor techniques an artificial barrel-vault was created. With the help of this vault, a safe, continuous and controlled tunnel excavation was secured. Due to the homogenization process in the subsoil, a reduction to one particular tunnelling method was possible. The increased stiffness and stability of the adjacent bearing ring helped to reduce the application of forepoling measures. Furthermore, most treatments on the surface became needless. According to BEMO 2007 [A] the alternative tunnelling concept is structured as followed:

1. Stabilizing of packing
2. Grouting operation via IBO-Anchors plus temporary activation of anchors
3. Additional grouting operation via TAM’s
4. Execution of saw cut
5. Excavation – tunnel enlargement
6. Installation of shotcrete lining including reactivation of IBO-Anchor

The upcoming chapter will emphasize the different sequences of work in full detail, with a particular focus on the grouting- and tunnel enlargement procedures. Unfortunately, in spite of this innovative concept not all activities on the surface could have been terminated in total. Two out of four operations on the surface, we already studied in the original concept, are still required. Those are the “dig- and cast construction” in the area of the gateway tunnel south and the wall-reinforcement activity in the section "Zitadellenmauer". Those overhead-works were explained in the previous chapters in full detail, and a new explanation is not necessary. The main objective is to provide a complete overview of the alternative tunnelling concept, especially emphasized on the scope of tunnelling!

5.1 Grouting process

The grouting process was one of the major operations of the entire project. This particular process was subdivided into three different assignments. Each of these operations was essential to guarantee the success of the tunnel enlargement plan. The applied grouting techniques as well as their particular specifications are illustrated in the following chapters.

5.1.1 Stabilizing packing layer by use of grouting – step 1

The stabilization of the hand-set pitching was one of the first operations which had to be undertaken. Because this particular operation has been elaborated on in the primary concept before, some additional important information becomes necessary. The modular gird was assessed by 1.5 meters x 1.5 meters. Each second grouting row was relocated by approximately 0.75 meter. The lengths of the filling pips were limited by 2.0 meter. Three grouting openings were assumed per injection pipe. A cement based grouting mixture with a water/cement ratio of 0.9 was used.

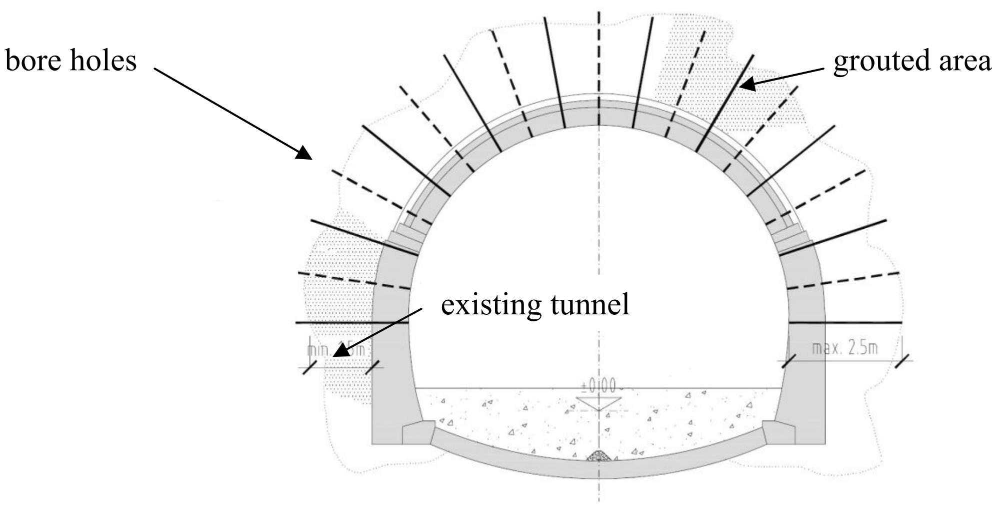


Figure 20, Stabilizing of packing by dint of grouting (source Beton- und Monierbau)

The grouting pressure was announced by 3.0 bars plus frictional los plus elevation. Slight changes because of varieties in the geology conditions were allowed. The speed of pumping was limited by 10 liter per minute. During the entire grouting process a total amount of 3776 m³ of cement suspension had been injected. By stabilizing the hand-set pitching, significant settlement could have been avoided. A complex monitoring program had been enforced to control grouting pressure, ground displacement and occurring settlements.

5.1.2 Grouting via IBO-anchors – step 2

The creation of a sustainable bearing ring was main task of this particular grouting – anchoring process. Basic consideration of the "New Austrian Tunnelling Method" is the integration of the adjacent rock/subsoil in the overall supporting system. To enable this process the ground conditions have to meet some specific requirements. A certain stability and strength of the surrounding subsoil is a prerequisite to enforce this method. Grouting was used to increase the strength and stiffness of the local ground conditions up to a sufficient level. The better the improvement of the subsoil, fewer settlements occur due to tunnelling advancing. The main objective of this grouting process was to fill all cracks and voids to avoid potential settlements. Idealized tunnelling advancing was executed under favor of an artificial barrel-vault. The establishment of this synthetic vault was essential to perform the alternative tunnelling concept.

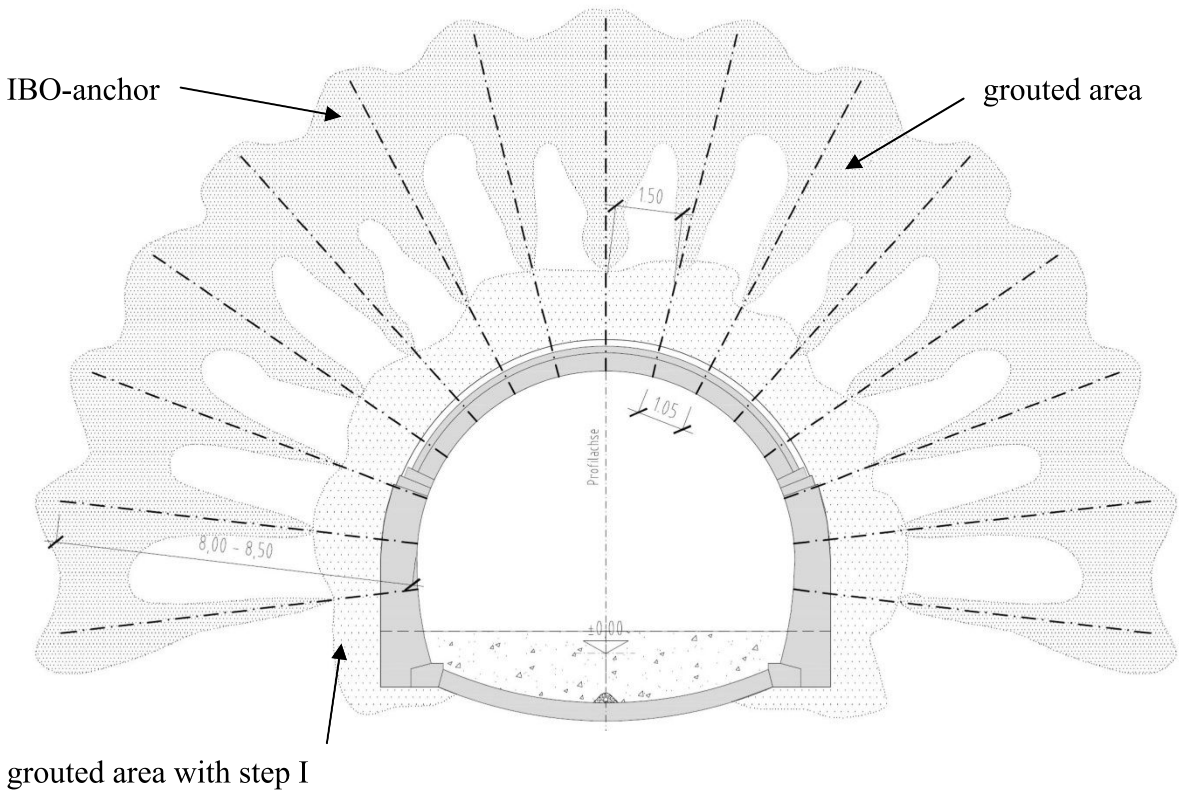


Figure 21, grouting via IBO-anchor (source Beton- und Monierbau)

The tunnel cross section above (figure 21) represents the outcome of this complex grouting process. A huge barrel-shaped vault with high stability and strength was created. 15 IBO-anchor ensured an adequate penetration of the entire area. With each meter in the longitudinal direction, a new grouting row was assembled. The primary length of those anchors was between 8.0 up to 8.5 meters. After the tunnel enlargement procedure the total length of IBO-anchors was reduced by approximately 1.5 meters. For this purpose a special screw-coupling was designed. Function and specification of this new developed anchor technology will be worked out in the next chapter “tunnel enlargement”.

The grouting process was executed in series - row by row. A mainly cement based grouting material was used. To increase the penetration of the grouting fluid additives had been used. The water/cement ratio was specified by the factor 0.5. Grouting pressure was limited by 3.0 bars plus frictional losses plus elevation. In the case of a pressure increase, the grouting process had to be stopped to avoid the risk of uncontrolled ground displacements. Pumping speed varied between 2.0 up to 6.0 liter per minute. Depending on local ground conditions the quantity of grouting had been varied significantly. A total amount of approximately 10.209 m³ of cement fluid had been grouted in this procedure. Each fifth anchor was checked for a required load-bearing capacity of at least 20 KN (BEMO, Injektionskonzept 2007 [D]).

Figure 22, grouting process (source Beton- und Monierbau)

The posted image (figure 22) will gives a rough idea about the complexity of the entire grouting process. During the grouting operation the whole tunnel was packed with a variety of diverse equipment. On the left side we can identify the grouting vehicle including the monitoring container. In the background an anchor boring machine in duty is visible. Additionally we will register the different rows of grout-inlets as well as IBO-anchors.

5.1.3 Grouting via TAM's – step 3

Grouting via TAM's (Tubes-à-manchette) was one of the final operations of the entire grouting procedure. TAM's were assembled either with a length of 3.0 or 5.0 meters. These lances were situated precisely among the applied grouting anchors. The main objective of this special grouting procedure was to fill the remaining space between the IBO-anchors. For this purpose grouting tubes with a variety of outlets, including double-packers, had been used. TAM's are especially practicable for this field of application. The area between the existing tunnel lining and the hand-set pitching was not grouted in this particular operation. The drawing below will indicate this issue. Furthermore, now we can identify the artificial barrel-vault.

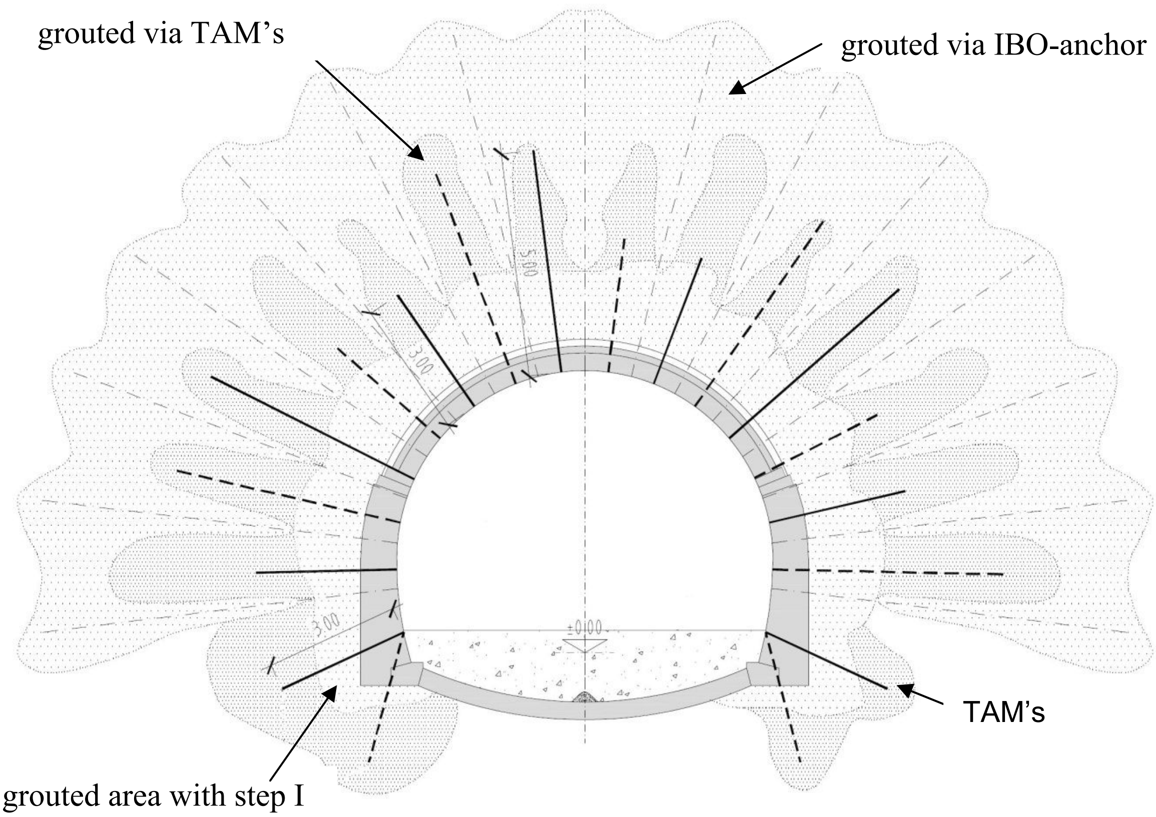


Figure 23, grouting via TAM's (source Beton- und Monierbau)

To achieve additional penetration, grouting pressure was fixed by 5 bars plus frictional los plus elevation. Depending on occurring ground conditions pumping speed varied between 1.0 and 5.0 liter per minute. The grouting process was executed progressively. In this particular operation 569 m³ of concrete suspension was used.

For the entire project more than 12.440 m³ of suspension fluid were grouted. Figure number 24 on the upcoming page represents the schema of the whole grouting operation. As mentioned before the grid of the IBO-anchor was defined 1.0 by 1.0 meter. The grouting pipes had an all over distance of 1.5 by 1.5 meters and TAM's were applied in an interval of roughly 2.0 by 2.0 meters. In summation the entire grouting process was a complete success. All main objectives like stabilization, as well as reduction of occurring settlements were achieved.

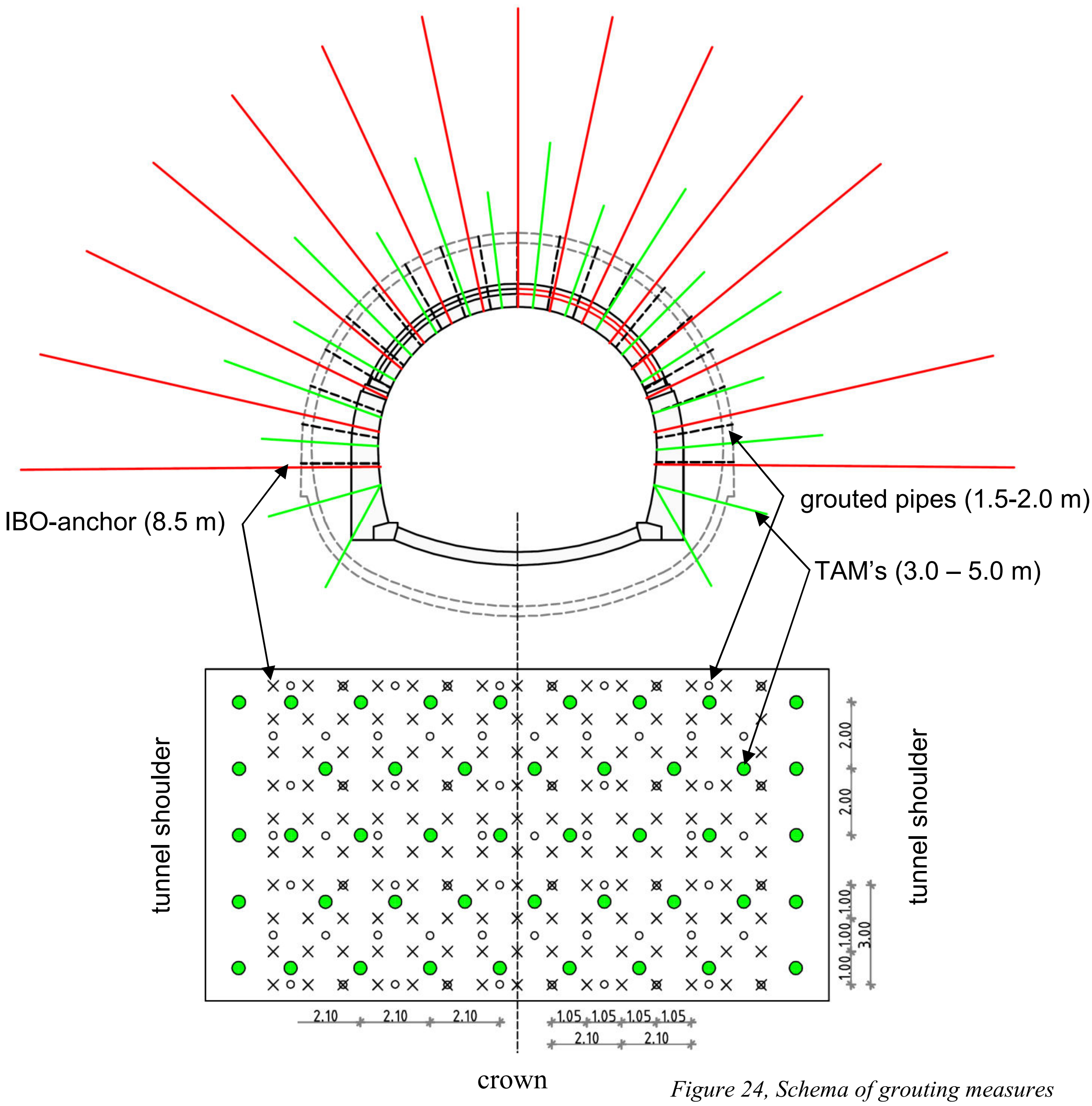


Figure 24, Schema of grouting measures

5.2 Execute saw cut on sand stonework

To separate the existing sand stonework a slight slot had to be produced. This individual operation was part of the original and alternative concept and has been explained in full detail in the previous chapter. However, assembling of steel arches was not part of the alternative concept. The improved ground conditions as well the assembled IBO-anchor made this time-consuming undertaking unnecessary.

5.3 Crown excavation – tunnel enlargement

Nowadays a wide range of different tunnelling methods are available. Unfortunately none of these techniques was perfectly suitable for this special undertaking. The application of established tunnelling techniques would have been interconnected with a complex and expensive tunnel advancing program. A slow, inefficient tunnel excavation would have been a consequence of the original tunnelling concept. Additional occurring settlements due to tunnel advancing could have been avoided in total. Because of these significant drawbacks, an absolutely new tunnelling method fitting unique requirements was developed by BEMO (Beton- und Monierbau) and Mr. Dr. Ing. M. Baudendistel. Core piece of this revolutionary development was a specially designed IBO-anchor-coupling. This in turn enables the disassembly of anchors on a new length. Because of this development the new tunnelling method became reasonable.

This special tunnelling technique is closely connected with the universally known “New Austrian Tunnelling Method”. Basic features and considerations are quite similar. The new developed method aids and rearranges particular procedures. Those slight changes are a result of the tunnel enlargement process. Listed below, the new developed operation cycles are mentioned.

- Phase 1 – Disassembling of the anchor steel-plate of existing IBO-anchor
- Phase 2 – Excavation, tunnel enlargement
- Phase 3 – Shotcrete, steel arches and steel mesh
- Phase 4 – Reactivation of IBO-anchor

Excepting the special affair of the IBO-anchor disassembly and reactivation process, all other tunnelling operations are widely common. The installation, grouting and activation procedure of the IBO-anchor was already a part of the grouting operation. In this context the grouting- and the tunnel enlargement process have to be mentioned together. Just the combination of these two particular techniques enabled the success of the newly designed tunnelling method. In the following chapters the main four working steps are explained in more detail, as presented in the "Tunnel enlargement concept" provided by BEMO 2007 [A].

5.3.1 Phase 1 – partial disassembling of the anchor

The image (figure 25) below shows the initial situation of the tunnel enlargement cycle. On the right side of the drawing we can identify the old tunnel lining with the implemented IBO-anchors. The left side shows the final tunnel lining after the tunnel enlargement process. First step was to disassemble the already installed IBO-anchors upon a special length. For this purpose the anchor steel-plate had to be detached. Sequentially the front anchor rod was removed. One advanced placed anchor-coupling situated directly behind the new tunnel lining made this operation possible. Tunnel advancing in its all subsequent operations were executed in one meter steps!

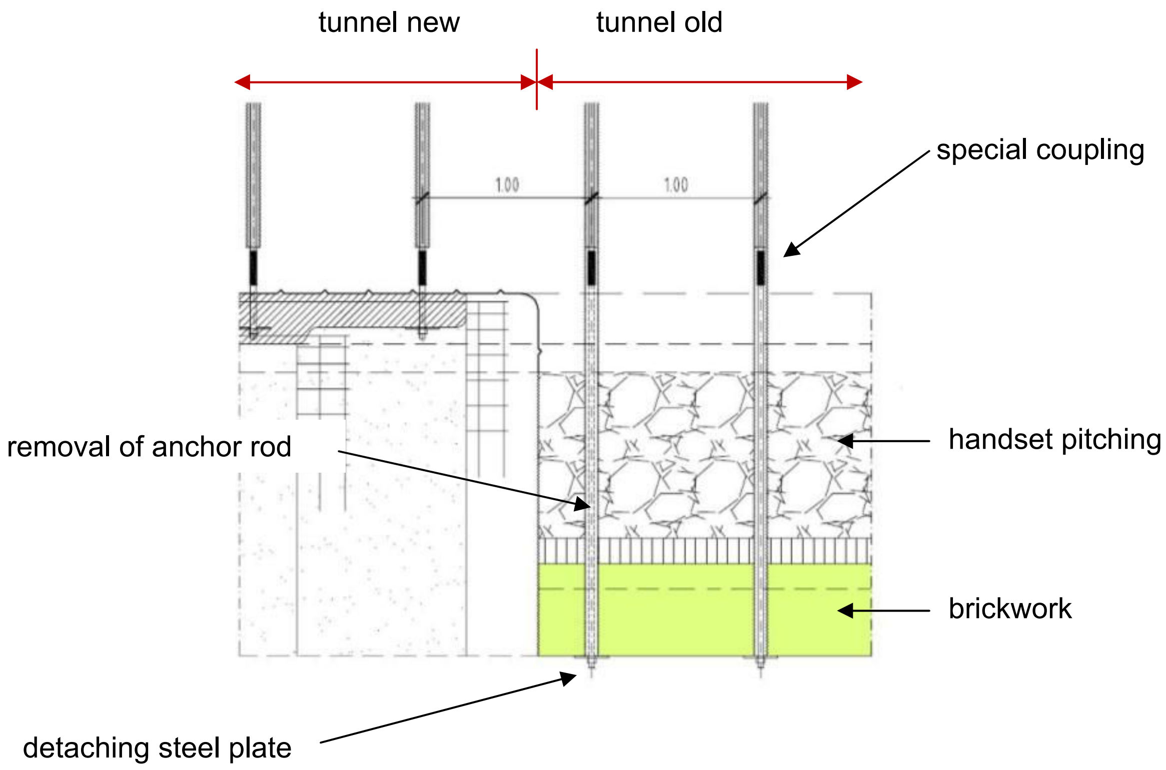


Figure 25, tunnel enlargement – Phase 1, tunnel cross section (source Beton- und Monierbau)

5.3.2 Phase 2 – Excavation, tunnel enlargement

Phase number two addresses the excavation process itself. Main assessment of this procedure was to detach the existing sand stonework including removal of the surrounding subsoil. For this purpose excavators with special work tools were used. In particular excavators with hammers-, gripper- and shovel work-tools had been utilized. The main challenge was to avoid vibrations and deformations during the entire excavation process. Therefore tunnel advancing had to be executed very sensitively. Any unwanted ground displacements would result in unexpected settlements. Well educated and experienced labors were indispensable for the success of this delicate procedure.

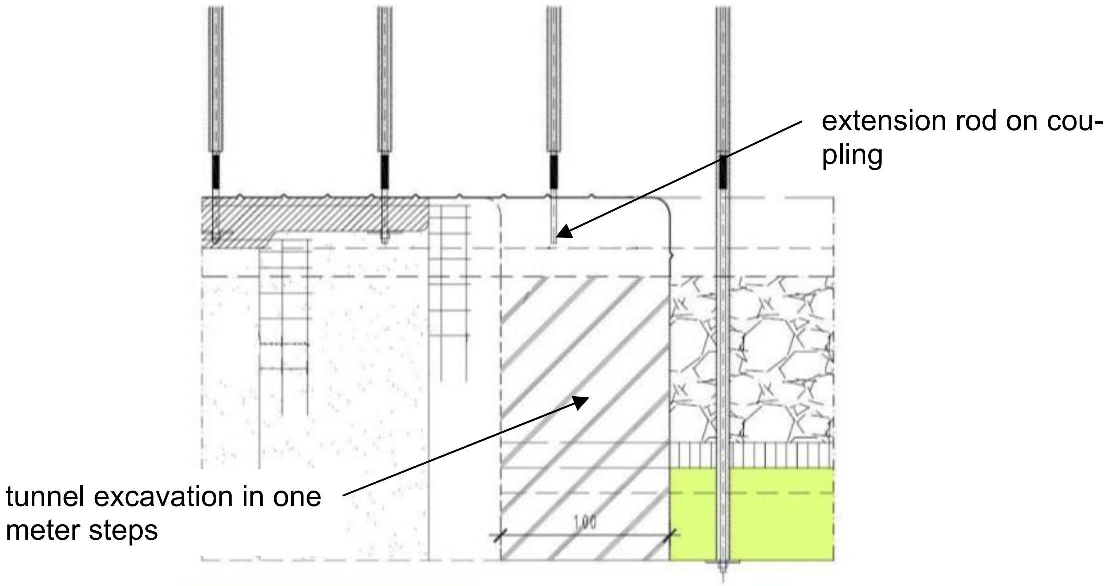


Figure 26, tunnel enlargement – Phase 2, tunnel cross section (source Beton- und Monierbau)

Right after the tunnel excavation process an extension rod (length of 0.5 meter) had to be screwed on the existing anchor coupling. This extension was necessary to reactivate the IBO-anchor after applying the first shotcrete sealing.

Figure 27, tunnel enlargement – Phase 2, photography (source Beton- und Monierbau 2007)

The photography above (figure 27) represents the tunnel face right after the crown excavation. We can easily identify the red shining sandstone work with the adjacent subsoil. Additionally the 15 separate rows of IBO-anchor can be recognized.

5.3.3 Phase 3 – Shotcrete, steel arches and steel mesh

To minimize significant settlements the uncovered surface had to be sealed as soon as possible. The first thin shotcrete lining helps to reduce the danger of abrupt in-rushes and creates a safe work environment for all further operations. Right after the primary sealing process a layer of steel mesh (Q 257, Q 377) was assembled. To increase the stability of the external shotcrete lining, each meter a massive steel arch was installed. The first layer of shotcrete had to have a thickness of approximately 20 cm to guarantee the stability of the preliminarily construction. In this context the final shotcrete with one additional layer of steel mesh for the provisos cycles was finished. A total thickness of at least 30 cm was assigned for the complete shotcrete lining.

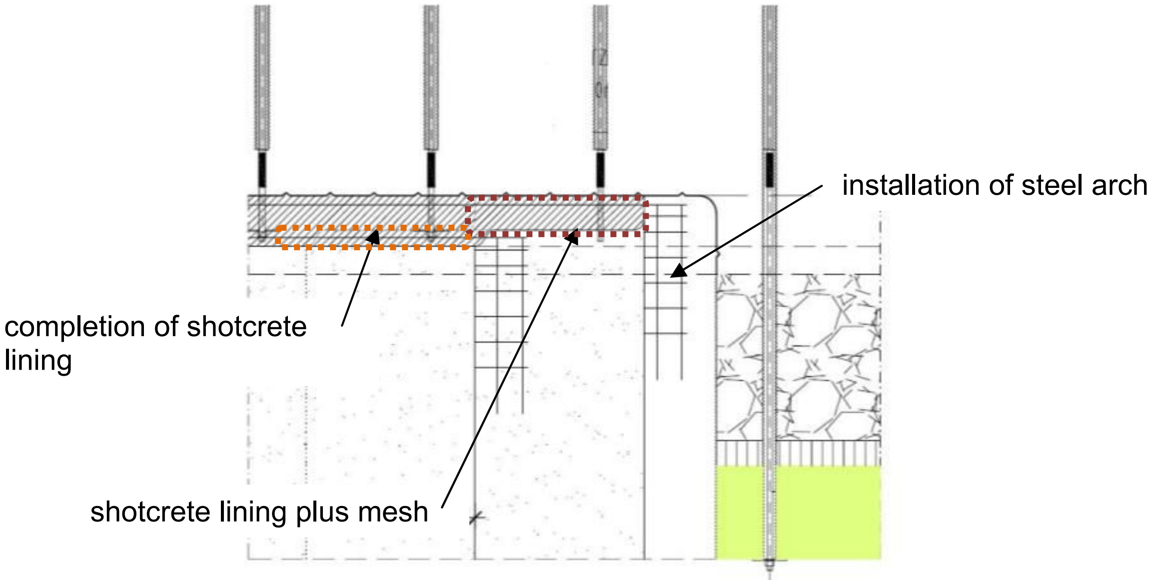


Figure 28, tunnel enlargement – Phase 3, tunnel cross section (source Beton- und Monierbau)

5.3.4 Phase 4 – Reactivation of IBO-anchor

The reactivation of the IBO-anchor was the final procedure of the entire tunnel enlargement cycle. For this intention an additional steel plate and a nut had to be installed on the remaining anchor rod. After stressing the IBO-anchor the reactivation process was completed. This particular process was essential to re-enforce the load-bearing capacity of the surrounding bearing ring in the subsoil and thus achieve an equilibrium state in the adjacent ground. After the completion of this individual process, the tunnel enlargement cycle will start over again. The drawing (figure 29) below represents the final IBO-anchor reactivation process in more detail.

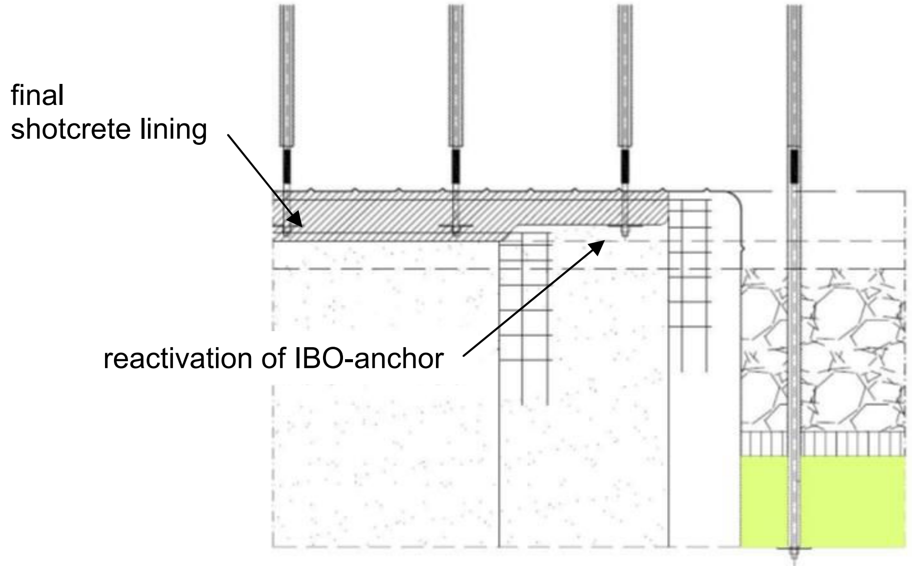


Figure 29, tunnel enlargement – Phase 4, tunnel cross section (source Beton- und Monierbau)

To secure the face temporarily, spiles were used. The length of the spiles was limited by 4.0 meters. Distance between the single spiles was specified by 30 cm. In the longitudinal direction the spiling distance was defined by 1 meter. Approximately 37 units of spiles were used per single tunnel meter (figure 30).

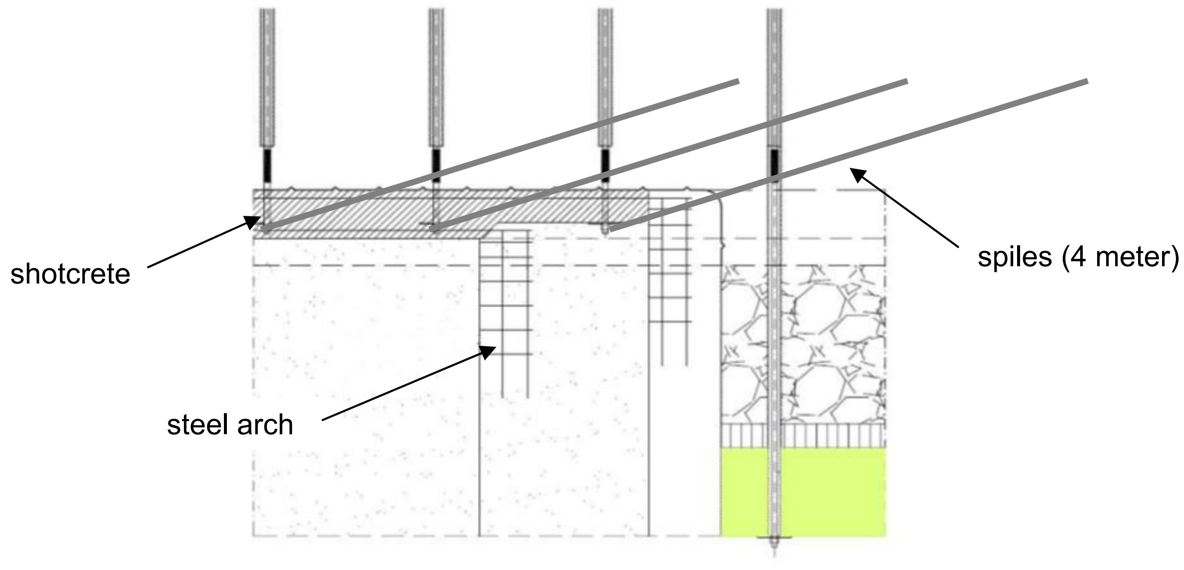


Figure 30, tunnel enlargement with the use of spiles (source Beton- und Monierbau)

5.4 Invert excavation – ring closure

The invert excavation is one of the final procedures to complete the external tunnel lining. After finishing the entire shotcrete lining the tunnel cross section starts to act as one piece. Consequently an equilibrium state in the surrounding ground will be achieved. Regarding to the accomplished project (Alte Mainzer Tunnel) the overall invert excavation was performed without the installation of a temporary invert. The extensive grouting procedure eliminated this particular undertaking. However the invert excavation procedure included a great variation of individual steps. In the listing below a rough overview about these activities is provided:

1. Demolishing existing tunnel invert plus removal of adjacent subsoil
2. Installation of water drainage
3. Shotcrete sealing for uncovered surface
4. Assembling steel mesh
5. First shotcrete layer, thickness 20 cm
6. Additional layer of steel mesh
7. Completion of shotcrete layer (nominal thickness 30 cm)
8. Repeat the steps 1-7,for a length of 10 - 20 meter
9. Integration of working level

Those particular operations are similar to established tunnelling excavation methods. Because of this fact a special explanations of these activities will be not necessary. The “Austrian tunnelling codex” defines this particular tunnelling advancing procedure as “Class I excavation”. Regarding to the project “Alte Mainzer Tunnel” it was essential to carry out the final ring closure instantaneously. Basically, it can be said, the faster the entire tunnel cross section is completed, the less the risk of settlements. As mentioned before settlement reduction is one of the main objectives of the alternative tunnelling method.

The rate of advance was limited to two meter. In total the shotcrete linings had to have a minimum thickness of 30 cm. Two layers of steel mesh (Q 257) were assembled to guarantee an adequate stability of the shotcrete lining. The installation of additional steel arches was not necessary. Right after the construction of the tunnel invert an artificial working level was assembled. In the next pictures the invert excavation procedure in more detail (figure 31) is presented.

Figure 31, invert excavation (source Beton- und Monierbau)

The ending will feature a drawing presenting the entire tunnel enlargement process. On the left presents the tunnel cross section is presented whereas at the right side the longitudinal section is shown. In particular the grouted area is displayed in green. The artificial bearing ring is easily noticeable. Furthermore the dimensions of the tunnel enlargement excavation can be identified.

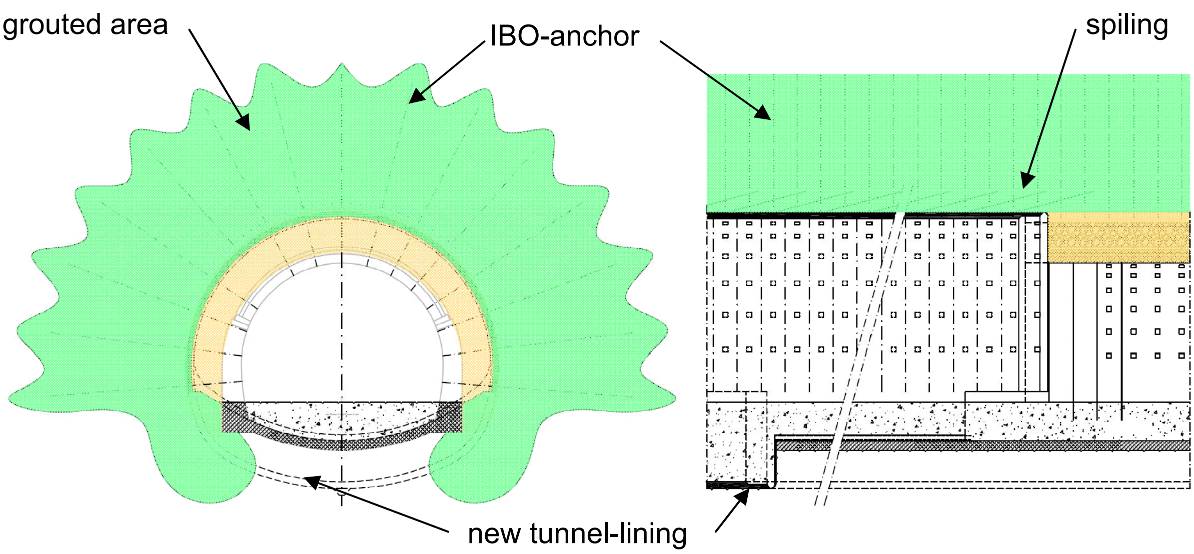


Figure 32, overview grouting- and tunnelling activities (source Beton- und Monierbau)

As a conclusion it has to be mentioned that the entire tunnel enlargement procedure was a complete success. The upcoming chapter will point out this circumstance in more detail.

5.5 Concrete lining

The fabrication of the concrete lining is the very last operation in the entire tunnel procedure. After the completion of this particular operation, interior-professionals will assume control of all further procedures. Depending on the intentioned purpose the tunnel has to be equipped with special features.

However, the construction of the internal concrete lining is a complex and labor-intensive undertaking. The concrete lining is mainly separated from the external shotcrete lining. All movements and deformations in the external lining have to be removed. A “Geotextile” assembled between both linings will allow slight movements.

Figure 33, concrete lining (source Beton- und Monierbau)

The image above represents the internal tunnel lining during construction. In particular we can recognize the invert reinforcement. A thickness of at least 45 cm was accomplished. The internal lining was poured in individual blocks of a length of 10 meters. Different sections are indispensable to avoid cracks in the entire construction. After an adequate curing-time, interior installation can take place.

6 Quality of execution - critical evaluation

In the presented chapters I provided a detailed elaboration of different tunnelling methods. At the very beginning the delicate circumstances of the project “Alte Mainzer Tunnel” were addressed. In this context we got an overview about the special challenges of the entire tunnelling enlargement undertaking. Right after this excursus an extensive illustration of the primary tunnelling concept was outlined. This digression should help us to understand the main considerations of the alternative tunnelling concept much better. As final step the alternative tunnelling concept in full detail was presented. All steps have been explained in their particular characteristics. In the next chapter a critical evaluation of the alternative tunnelling concept is given.

The main objective of the following elaboration will be to point out the special excellences of the new tunnelling method. For this purpose we have to compare the primary- and the alternative concept. An objective and fair discussion of all important matters is required. This evaluation will be mainly focused on technical issues like: Soil mechanics, individual operations and minimizing of risks. Economical matters like time, manpower and so forth will be discussed in a separate chapter later on.

6.1 Regarding to soil mechanic issues

Design and accomplishment of a tunnelling project is mainly based on local ground conditions. Nowadays a wide range of different tunnelling techniques are available. Each of these methods is good for a special area of application. Regarding to the project “Alte Mainzer Tunnel” additional circumstances had to be taken in to account. The fact that this unique project had to be executed at low depth below a built up area required a complex tunnelling concept.

Both concepts answered these challenges differently. The ordinary concept was mainly based on a combination of diverse tunnelling methods. Every particular problem was solved with a separate technique. In contrast, the alternative concept was designed to harmonize the entire tunnelling procedure. The basic requirement for this undertaking was a complex grouting operation. This fundamental consideration contained a multitude of benefits.

6.1.1 Reduction of settlements

One of the major aims of the entire project was the reduction of occurring settlements due to tunnel advancing. The prescribed limits were very strict to avoid damages on structures at all times. Both methods were designed to minimize settlements to an absolute minimum. A wide range of different techniques was used to reduce settlements in the primary concept. In the alternative concept, an extensive grouting program in combination with a new tunnelling method ensured a perfect minimization of settlements. In comparison with the primary concept, settlements were offset much better in the alternative concept. This particular circumstance will be pointed out in the following table.

Construction	***Primary concept***		***Alternative concept***	
	At building	*In tunnel*	*At building*	*In tunnel*
Alexanderturm	0.8	5.5	-1.5	3.0
Dorint Hotel	1.3	2.7	0.5	2.5
Kästrich	1.7	2.2	0.7	2.4
Drususstraße 1	1.9	4.4	1.7	1.8
Germanikusstraße 2	1.3	2.3	0.2	2.1
Bastion Martin	0.8	5.5	0.3	1.8
Am Gautor	1.3	2.3	0.4	1.4

Table 2, comparison settlement – different concepts[1]

The table (table 2) provides a list of sensitive buildings in the area influenced by the tunnel project. On the left side we can recognize the prescribed limits for the primary concept. On the right side the resulting settlements of the alternative tunnelling methods are listed. This elaboration illustrates very impressively the numerical difference of both concepts.

Movements near sensitive constructions were reduced to an absolute minimum. Settlements located on the tunnel crown were harmonized to an acceptable level. This special circumstance is a direct result of the extensive grouting process. The entire grouting procedure was mainly developed to compensate for occurring settlements due to tunnel excavation. Fortunately, the grouting procedure included some additional benefits. A short illustration of those will be provided in the upcoming chapters.

[1] These values are representing an average measurement; it's a particular area not single point!

6.1.2 Significant improvement of local ground conditions

The significant improvement of local ground conditions was a main advantage of the alternative concept. One of the results of the extensive grouting process was the harmonization process of the entire subsoil. Simultaneously the stiffness and strength of the adjacent subsoil were extensively increased. This special circumstance was essential to apply the newly developed tunnelling method. The harmonization of the local ground conditions was important to reduce the various sequences provided in the original bidding documents. Just one standardized tunnel advancing class was executed in the alternative concept. Furthermore it was possible to excavate the new tunnel construction under favor of an artificial barrel vault. A much more efficient and economical tunnel advancing was the main outcome of the alternative grouting program.

6.1.3 Sealing of water bearing layers

Another benefit of the overall grouting procedure was the water-sealing effect of the injection process. Grouting is not only applicable to improve specific properties of the ground or compensate occurring settlements, it can also be used to seal water bearing layers. This is a really important fact, having a dry construction site makes tunnelling much simpler. Ground water control is usually an expensive and laborious undertaking. Thanks to a concentrate grouting program most of the water bearing layers could be sealed in total. Additional measures to reduce water inflow became unnecessary in the alternative concept.

6.1.4 Better response to ground conditions

The overall grouting process contained one more specific advantage. As mentioned previously, monitoring is an important component of the entire grouting procedure. An important part of the monitoring program is the observation of settlements in interconnection with recording time, quantity and injection pressure of the grouting operation. The interpretation of these parameters allows an exact outlook of the present ground conditions. A much better response to the upcoming subsoil is possible. Therefore engineers are able to react to variations in ground conditions much more effectively.

6.2 Regarding individual operations

A multitude of individual operations are required to excavate a tunnel. The selection of the most adequate tunnelling technique is mainly based on local circumstances and geology conditions. Nowadays tunnels can be constructed in nearly every ground condition. Basically it is just a question of time and costs. Regarding the project “Alte Mainzer Tunnel” two different concepts werre worked out to realize this unique tunnel project. Both considerations pursued an individual strategy.

6.2.1 Comparison of both methods

The primary concept is mainly based on a variation of individual operations. For each special situation a certain tunnelling method was scheduled. A multitude of different operations and constructions would have been the consequence of this consideration. In the alternative concept an absolutely new strategy was applied. An extensive grouting procedure was used to harmonize the present ground conditions. This particular circumstance allowed the reduction of the amount of different operations significantly. To simplify this idea a comparison of the primary- and alternative concept is worked.

For this purpose the entire tunnelling procedure is split up into three sub parts. This is to differentiate between operations on surface, advanced actions and the actual tunnelling process. The left side of the chart represents the original concept and the right side illustrates the alternative concept. The main objective of the alternative proposal was to minimize construction activities on the surface. Construction works in an urban area are always connected with a wide range of different restrictions and high construction costs. Beside the “dig-and-cast construction” all additional operations could be skipped in the alternative concept.

To realize the reduction of individual operations, a complex grouting program was implemented. This particular operation was much more time consuming and more complex in comparison with the original proposal. The only operation which could be eliminated that belonged to the original bidding document was the steel arches assembling process. All further procedures in this particular group were identical.

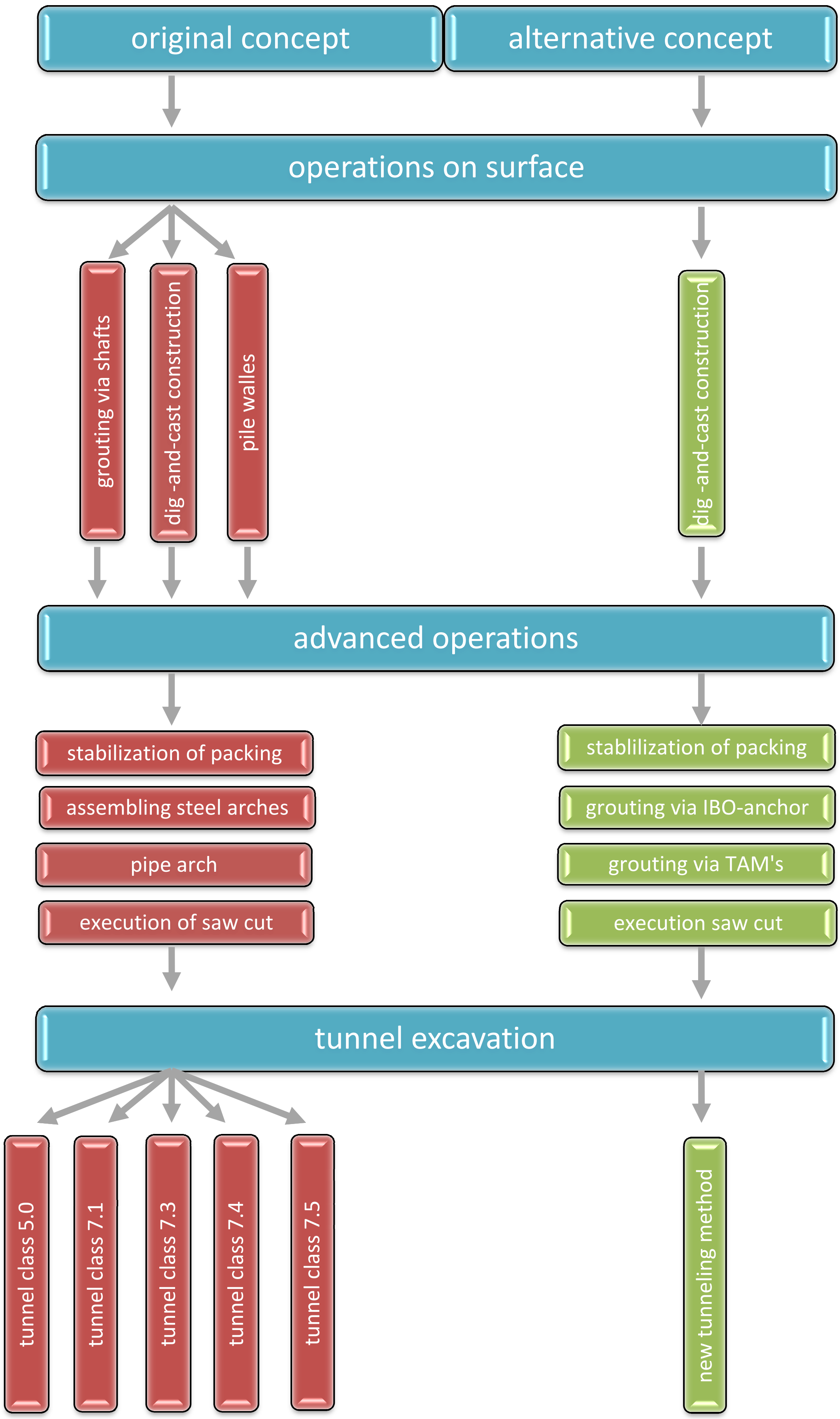


Figure 34, comparison of the primary- and alternative concept

An additional positive effect of the extensive grouting process is recognizable in the last group. In the primary concept five different tunnelling techniques were projected. Each method has its own specification and would have required special equipment and knowledge. An execution of such a variety of different tunnelling methods implicates a lengthy and expensive construction process. In the alternative concept a specially designed tunnel method was applied. The entire tunnel advancing was executed by the use of one unique tunnelling method. A speedy and economic construction process was achieved.

6.3 Minimizing risk

Tunnelling is consequently interconnected with many risks. The minimization of risks has to be the main objective of any tunnelling project. Without any doubt the geological conditions are one of the main risks in the area of tunnelling. Most troubles are a direct result of unexpected or suddenly changing soil conditions. With the execution of the alternative tunnel concept several risks were eliminated or reduced. The improvement of the strength and stiffness of the surrounding ground helped to minimize the most dangerous hazards. In this context the risk of:

- Significant settlements
- Unexpected inrushes
- Abrupt water inflows
- Damages on structures
- Connection of different operations
- Unforeseen ground conditions

were reduced to an absolute minimum. In general, no tunnelling method is perfect and disqualifies all hazards. A certain amount of risk is always present. However, the application of the alternative concept helped to minimize the present exposure to an absolute minimum.

To put it in a nutshell, it can be mentioned that the advantages of the new tunnelling method are predominant. The alternative concept is not only more efficient in the sense of time and costs but also much safer.

7 Emphasis on grouting

A critical evaluation of the entire grouting procedure is a main part of this master thesis. In this particular chapter a multitude of charts is provided, visualizing the quantities of the undertaken grouting process. An explicit study of these figures will help us to analyze the grouting procedure in more detail. Firstly, the specific amount of grouting fluid for each separate operation is outlined. For this purpose a subdivision of the grouting process becomes necessary. Afterwards a critical interpretation of the grouting trend is presented. An extensive discussion of all influencing factors is an additional part of this chapter. For more transparency, the entire grouting process is divided into the two existing building lots.

7.1 Visualization – Tunnel Main station

Basically, we have to differentiate between three different grouting activities. As mentioned previously, grouting was executed in application of IBO-anchors, TAM's and filling pipes. Each of those grouting techniques created an individual grouting course. The chart below illustrates the entire grouting procedure. For this purpose, the quantities of all three different grouting operations have been counted together.

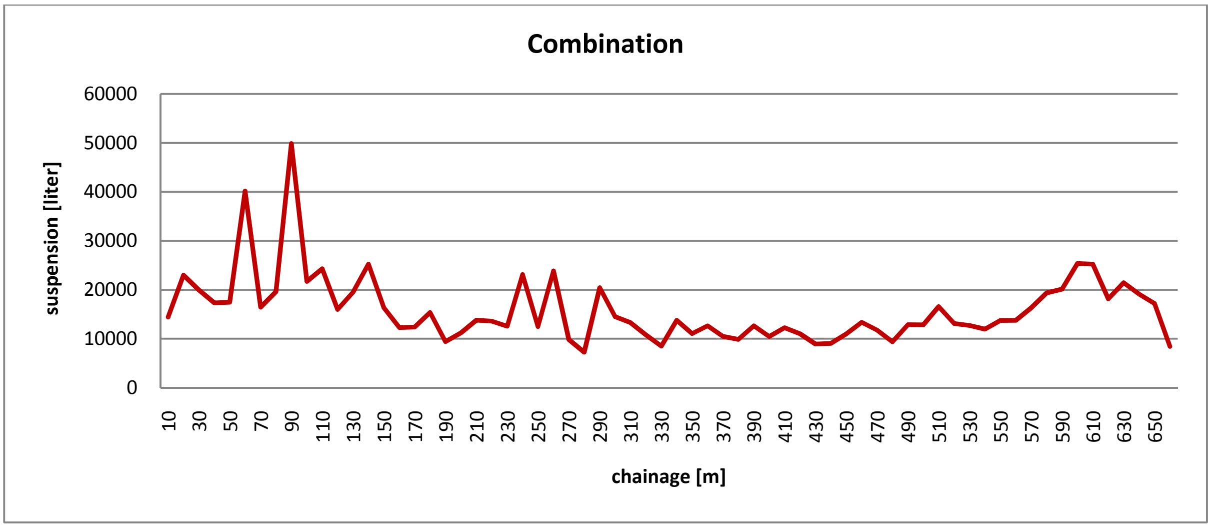


Chart 1, total grouting activity

In total more than 9.506 m³ of cement suspension were grouted. At an average approximately 14.6 m³ of grouting fluid was used per single tunnel meter. A variety of different circumstances had influenced the course of this undertaking. In an ideal situation of harmonized conditions a constant trend would be expected. To enable a correct interpretation of the entire grouting process we have to study the individual grouting operations in more detail. For this purpose an additional chart presenting the different grouting activities is worked out. Furthermore, a rough overview of the proportions of the single operations themselves is given.

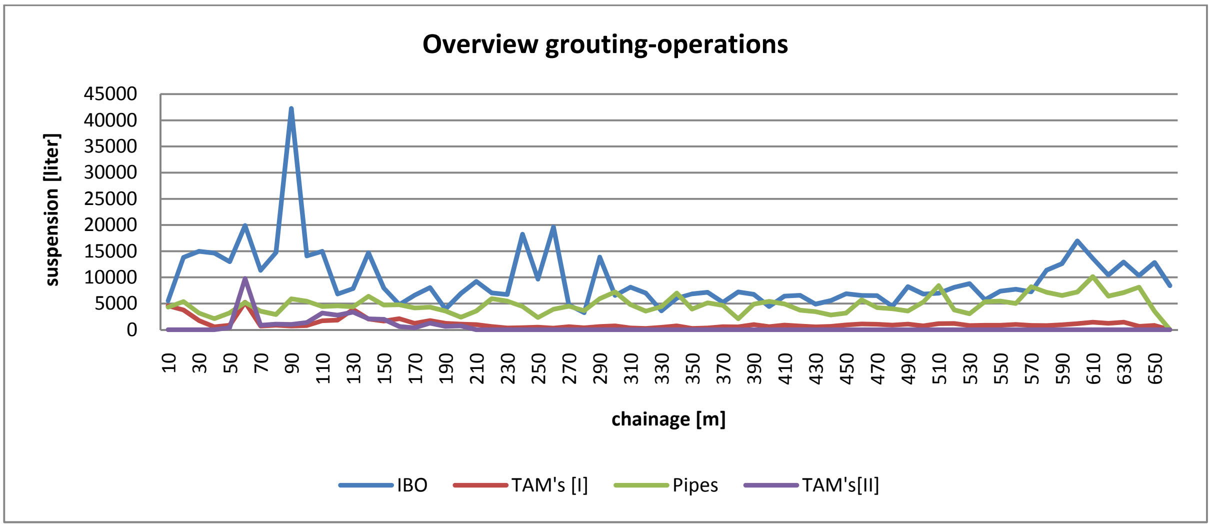


Chart 2, grouting quantity – overview

As we can recognize the amount of grouting fluid varies significantly. Each individual operation represents a different grouting course. According to this chart the most material was grouted by the use of IBO-anchors. The fulfilling procedure of the hand-set-pitching required also a considerable amount of cement suspension. Just a minor amount of grouting fluid was injected by the use of TAM's. This special technique was mainly used to upgrade special areas of the adjacent subsoil. However, an exact analysis of the different distribution will be provided in an upcoming chapter.

7.2 Critical evaluation – Main Station

In this particular chapter the individual trends of the grouting procedure are analyzed. There is a special focus on extreme changes in the overall grouting process. Issues like geology, constructions, water and so on will be discussed in full detail. The main objective will be to identify interrelations of diverse circumstances. Moreover the different quantities of the grouting operations will be interpreted.

7.2.1 IBO-anchor

This was one of the major grouting operations. Overall more than 6328 m³ of cement suspension was fulfilled. The cement suspension was grouted through 15 different anchors per segment, each segment having a length of 1.0 meter. In average about 0.65 m³ of grouting material was injected through a single IBO-anchor. In average, approximately 9.74 m³ of grouting material per single tunnel meter was fulfilled. The illustration below (chart 3) represents the grouting trend of this particular operation in more detail.

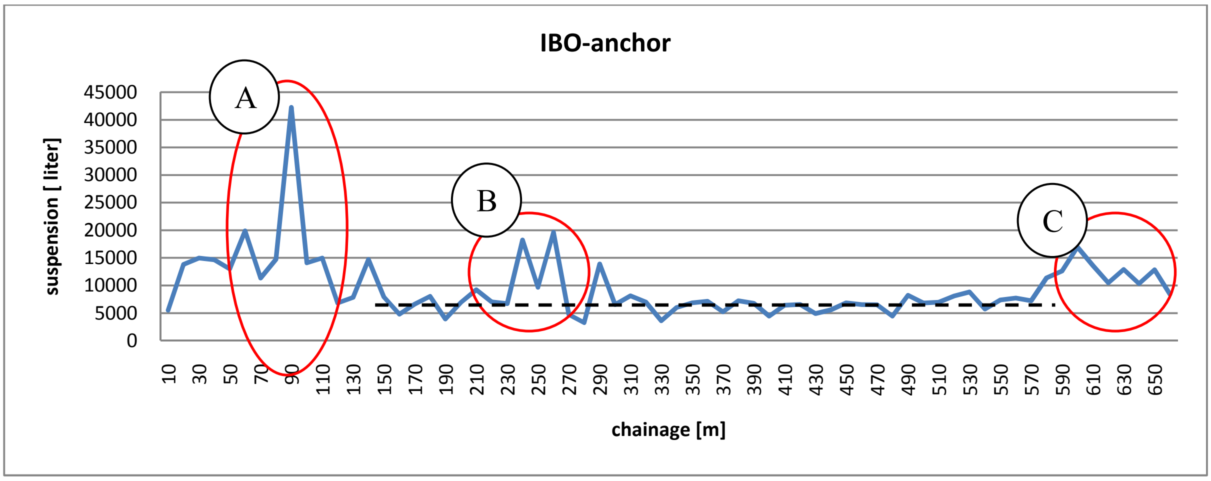


Chart 3, grouting quantity – IBO-anchor

Basically, we can identify three major outlines in the entire chart. Between those irregularities an almost constant trend is noticeable. This area is marked with a dashed line. At a guess the average amount of grouting material in this specific field was around 6 m³ per tunnel meter, much less in comparison with the total average. In this particular area ground conditions and covering were nearly steady.

Regarding to section “A” a significant increase is noticeable. A massive water bearing layer was detected in this specific area. Grouting was used to dry up this particular area. For this purpose a much higher amount of grouting fluid became necessary. To figure out the penetration of the surrounding subsoil a test section had been implemented in area “B” previously. This tunnel section was highly applicable for a test run – no structures on the surface were present. In section “C” the overall ground condition changed and an increased amount of cement suspension was required to achieve the requested penetration. The entire grouting procedure was accomplished in less than 9 months of work.

7.2.2 Filling Pipes

The main purpose of this special grouting operation was the stabilization of the packing layer. Filling pipes were used for this scope. In total around 2523 m³ of grouting material were fulfilled. At an average approximately 3.8 m³ of grouting fluid were used per single tunnel meter. The chart below (chart 4) represents the amount of used cement suspension.

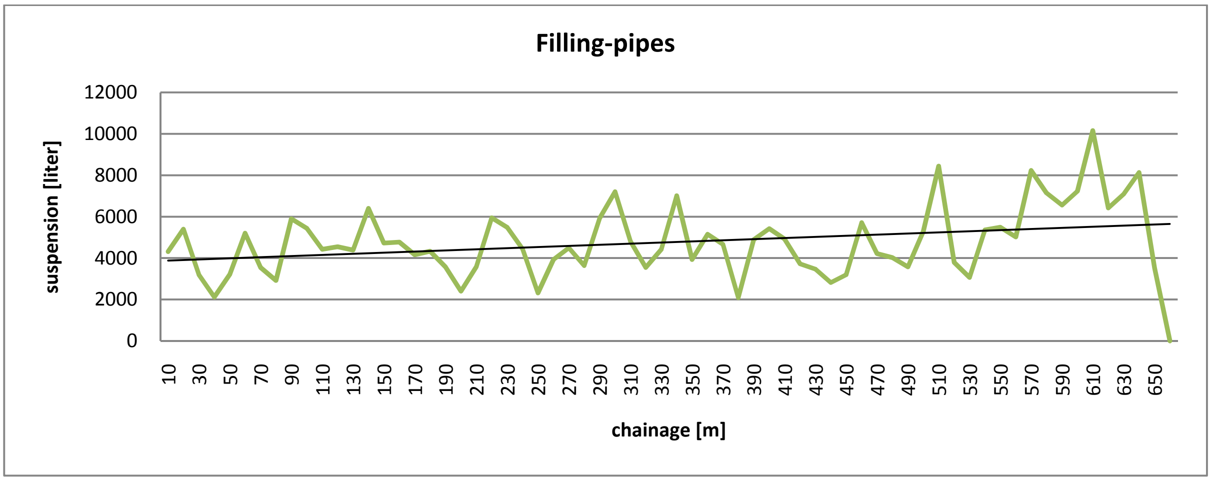


Chart 4, grouting quantity – filling pipes

In this particular operation an almost constant trend is recognizable. No significant outlines are present. The supplementary added trend line confirms this statement. This special grouting operation was exclusively used to fulfill the packing layer. As a whole, the hand-set pitching was throughout homogeneous and constantly thick. Because of this circumstance an almost consistent grouting process was accomplished. Furthermore, the connectivity between used grouting material and present soil conditions can be easily identified.

7.2.3 TAM's

TAM's had been used to complete the entire grouting procedure. The main function of this special grouting procedure was to fulfill all remaining cavities. For this purpose, a precise grouting execution was essential. Minor amounts of grouting fluid were used for this scope. Approximately 655 m³ of cement suspension was grouted. Primarily, this grouting operation was executed in two different sequences [TAM's 1 and TAM's 2]. Both grouting undertakings are illustrated in two different charts (Chart 5, 6). Operation 1 was executed simultaneously with all other grouting processes. The second operation was performed after a certain time frame. Because of unsatisfactory results the second sequence [TAM'S] was eliminated after a short period of time. Regarding the trend of the grouting process we can identify two major outlines at the very beginning of the trend. The reason for these increases was an insufficiently fulfilled water bearing layer. Excluding some irregularities at the beginning the entire grouting procedure runs constantly. In average around 1.0 m³ of concrete suspension was grouted per tunnel meter. The secondary operation exactly follows the trend of the primary grouting procedure (TAM's I).

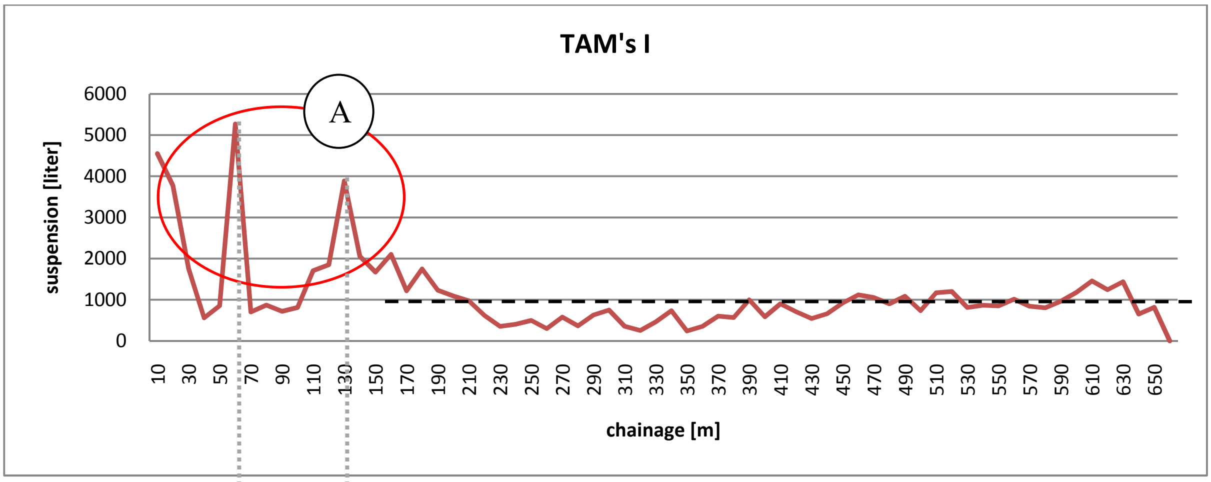


Chart 5, grouting quantity – TAM's I

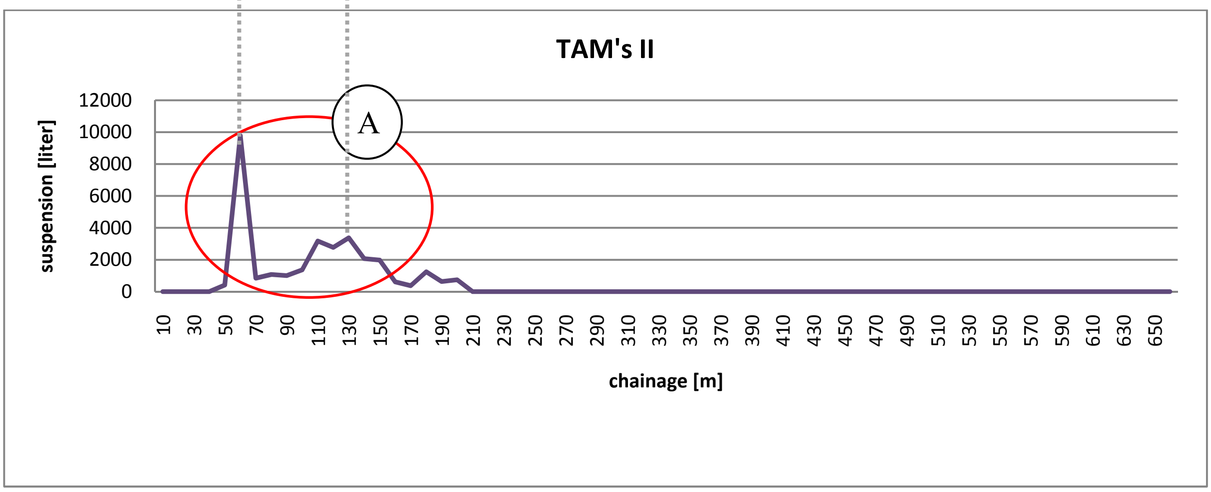


Chart 6, grouting quantity – TAM's II

After a detailed reflection of the entire grouting process the overall trend is absolutely traceable. All individual outlines were a special result of certain circumstances. Beside these irregularities, a consistent grouting process is visible.

7.3 Visualization – tunnel south

The evaluation of the grouting trends for the "tunnel south" is much trickier. On the one hand the length of this particular lot is shorter and on the other hand the terrain is more rugged. However a critical analysis of the grouting procedure is absolutely necessary to co-check the interpretation in the first case. Furthermore some comparative values will be an additional outcome of this investigation. The structure of the analysis will be similar compared to the fist case. Below we can identify the total amount of used cement suspension for this construction lot (chart 7).

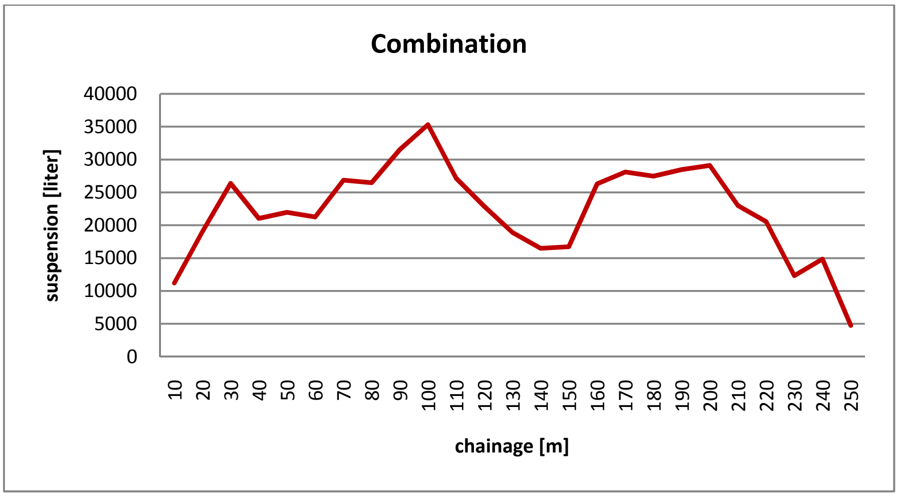


Chart 7, total grouting activity – tunnel south

Overall more than 5.204 m³ of grouting fluid was fulfilled. At an average approximately 20.8 m³ of cement suspension was used per single tunnel meter. This is 30 % more grouting material compared to the previous tunnel lot. For further interpretations we have to split up the entire grouting procedure in its individual operations.

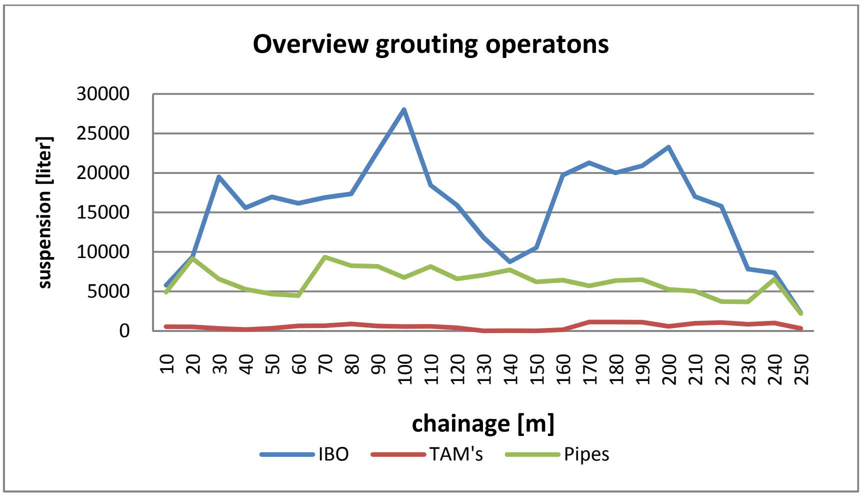


Chart 8, grouting quantity - overview

Again three different grouting operations can be identified. The amount of grouting fluid varies significantly. IBO-anchors were used to fulfill the majority of the cement suspension. To stabilize the packing layer a notable amount of grouting material was used. Minor quantities of grouting fluid were injected by TAM's. However, in the following chapters there is a separate focus on each individual operation. Furthermore reasons for the increased demand of grouting fluid are analyzed.

7.3.1 IBO-anchor

Due to the utilization of IBO-anchors almost the majority of grouting fluid was fulfilled. In total more than 3.881 m³ of cement suspension was used. Per single tunnel meter approximately 16.31 m³ of material was injected. Generally, it has to be mentioned that the penetration of the surrounding subsoil was much higher. The chart provided below (chart 9) illustrates the grouting process in more detail.

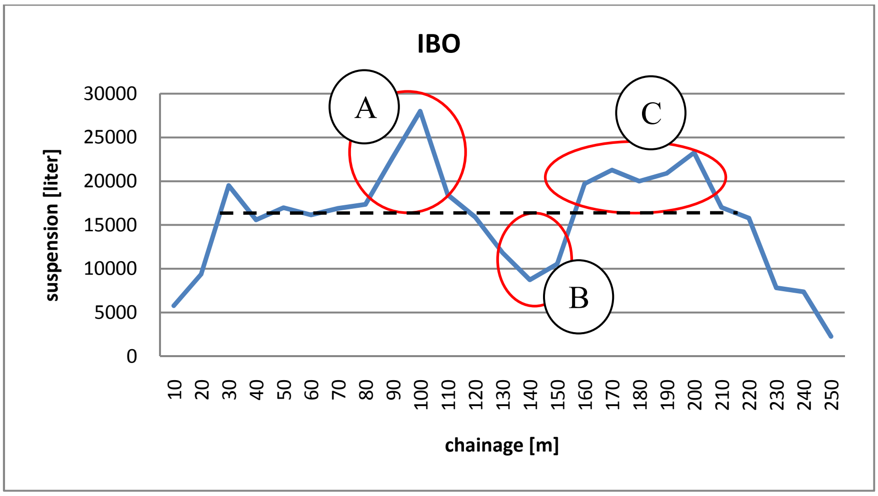


Chart 9, grouting quantity – IBO-anchor (south)

In this particular case it is quite difficult to identify a constant trend. Too many influencing factors were present, especially for this short tunnel slot. For a changeless grouting process conditions have to be similar for certain distances. However, we recognize three significant outlines. Belonging to section "A" a remarkable increase is noticeable. In this unique area it was hardly possible to reach the required grouting pressure. Therefore a much higher amount of cement suspension was fulfilled to guarantee an adequate penetration. Because of a crossing street (Windmühlenstraße) in the area of section "B" a limited grouting program was accomplished. Just a reduced number of anchors were injected. Responding to section “C” a considerable amount of cement suspension was flowing into an unknown corridor system.

7.3.2 Filling pipes

The stabilization of the hand-set-pitching was the main objective of this particular operation. However, more than 1253 m³ of grouting material was injected in total. In average approximately 5.26 m³ of cement suspension was fulfilled. Below we can see the grouting trend more precisely (chart 10).

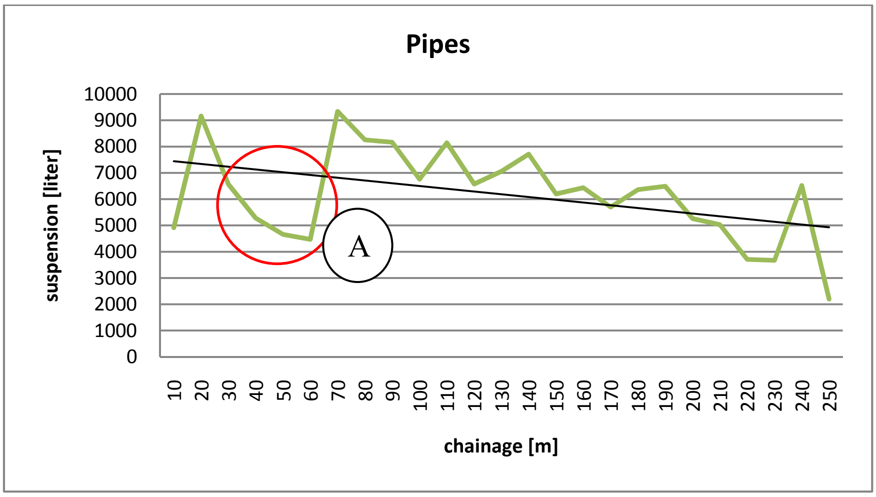


Chart 10, grouting quantity – filling pipes (south)

Basically we can identify a constant trend. For this case similar statements undertaken in the chapter 7.2.2 are applicable. The amount of grouting fluid is varying slightly. Excepting in section “A” a significant bump is visible. In this special area an increased amount of lime rock and sand very close to the existing tunnel lining were present.

7.3.3 TAM’s

TAM’s were used to accomplish the overall grouting procedure. In total less than 71 m³ of cement suspension were injected. The average per tunnel meter was about 0.3 m. Because of the penetration effect produced by advanced grouting activity, the subsoil was not able to absorb huge quantities of suspension anymore. Just cracks were fulfilled. This amount is too marginal to issue a profession statement about the overall grouting trend. Generally it can be mentioned that this particular grouting operation runs quite constantly.

7.4 *Further analysis*

In this selective chapter I like to focus on some special characteristics of the grouting procedure. In the forgoing elaborations we got a wide overview about the entire grouting undertaking. Current trends, quantities as well as special situations were discussed in full detail. To allow more insight into the entire grouting procedure, an additional analysis will be undertaken. Furthermore, the different quantities of the overall grouting procedure will be compared.

7.4.1 Detailed reflection

Grouting is a very complex undertaking. A manifold of different tools and technologies have to be applied. Every grouting operation has its specific characteristics. In this paragraph most significant are worked out. For this purpose a more detailed chart is illustrated below (chart 11).

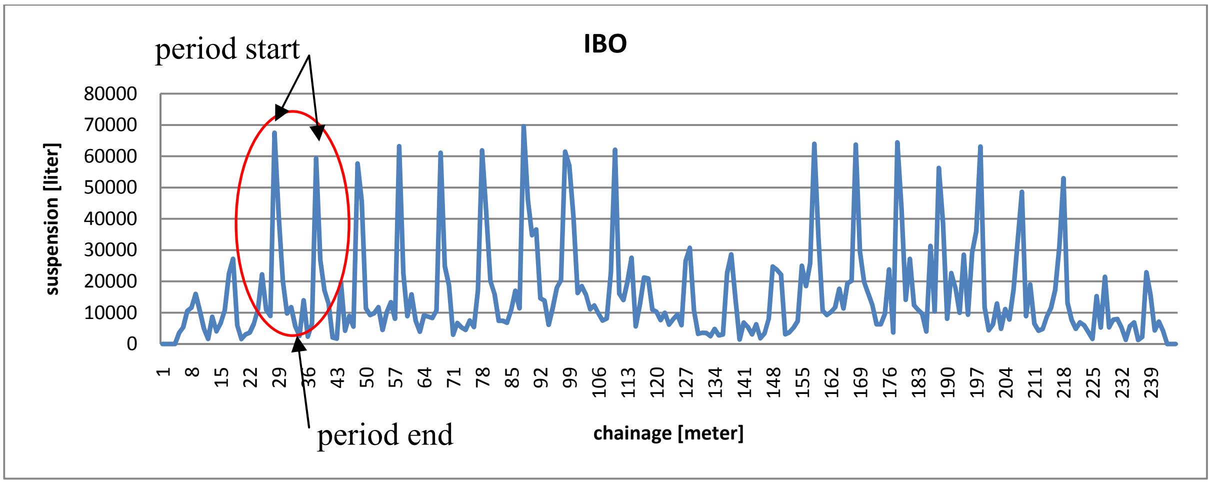


Chart 11, grouting quantity – detailed reflection

This specific chart above represents the particular grouting amounts per single tunnel meter. The charts displayed in the past were simplified to identify the overall grouting-trend much more easily. However, in the chart above we can recognize the exact grouting-trend. Remarkable are the periodic outlines placed ever 10 meter. The background of these anomalies is quite simple. To avoid circulations during the grouting procedure, the execution was not continuous. A periodical interval of about 10 meter was applied. For example the tunnel tunnel meter 30 and 40 was firstly grouted until the required pressure was achieved. Afterwards the grouting operation was continued with tunnel meter 31 and 39 and so forth. Because of the penetration-effect a much lower amount of cement fluid could have been grouted at the end of each period. This is the reason of the periodic trend of the overall grouting procedure. Execution of this unique technique avoided circulation in total.

7.4.2 Quantities

To conclude, I would like to present a clear-arranged comparison. The specific distribution of grouting fluid is illustrated in the charts below (chart 12).

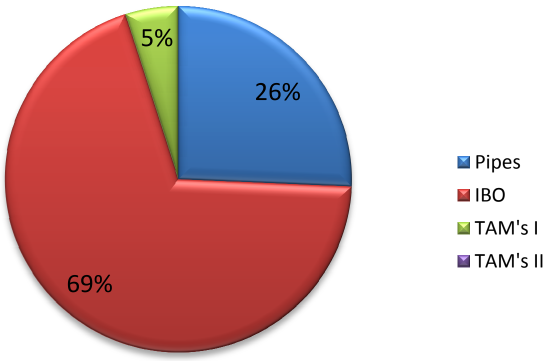


Chart 12, comparison - different operations

On average more than 69 % of cement suspension was grouted via IBO-anchor. Filling pipes were used for about 26 %. Just a minor quantity of grouting fluid had been injected by way of TAM's. The chart provided below represents an additional aspect.

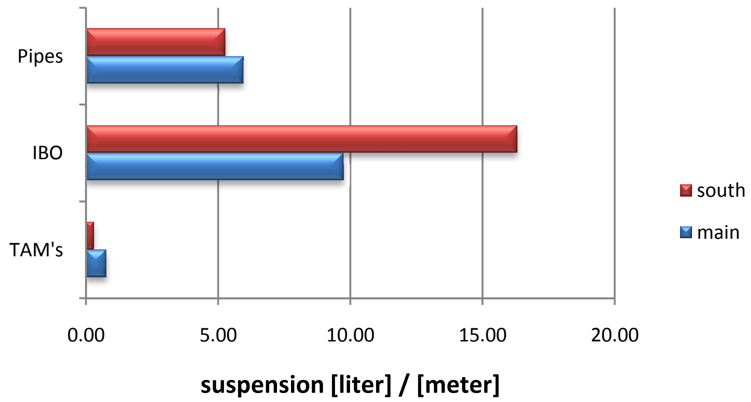


Chart 13, comparison – suspension quantity/meter

This special chart illustrates the average amount of grouting fluid per single tunnel meter (chart 13). The extended use of IBO-anchors in building lot "tunnel south" is readily identifiable.

8 Critical evaluation - settlements

Controlling and monitoring of occurring settlements due to tunnel excavation is a demanding job. Engineers have to pay full attention to this special issue. Any kind of underground construction activities will modify the primary stress-status in the surrounding subsoil. An unavoidable change of the equilibrium state will consequently causes diverse settlements. The intensity of appearing movement is mainly dependent on ground loss induced by excavation, type and attitude of soil and cover between tunnel crown and surface. Uncontrolled settlements will consequently affect the stability and serviceability of structures. Basically the term “settlement” is defined as: (see also Kummerer 2003 [10], Wood 2000 [24])

“A sinking down or subsidence (of structure, loose earth, etc)” (Oxford 1933 [15])

Regarding the project “Alte Mainzer Tunnel” we have to upgrade this specific definition. In this sense we have to differentiate between two different types of displacements:

- Positive movements due to the grouting process (heave)
- Negative movements due to tunnelling excavation (subsidence)

The alternative concept included a complex grouting program. This extensive grouting procedure produced heave on the surface. Followed by the tunnel advancing process negative settlements were generated. In the upcoming chapter both types of displacements are elaborated in full detail. Especially the interconnection of both movements will be precisely analyzed. Furthermore, influencing factors like, quantity of grouting fluid, present terrain, and geology will be evaluated. Finally, an accurate look of occurring movements on the tunnel crown is provided.

The main objective of these comprehensive analyses is the visualization of the elevation- and subsidence procedure. In particular, the compensation effect of the undertaken grouting procedure is pointed out. Moreover we will be able to recognize the homogenization-effect of this particular operation.

8.1 *Analysis – main station*

The upcoming evaluation will be divided into the two existing building lots. Firstly, a chart representing the heave, as a direct result of the extensive grouting process is presented. This will be continued with an additional chart displaying the negative settlements due to tunnelling excavation. Finally, a critical look at occurring movement located on the tunnel crown is given.

8.1.1 Heave - due to grouting

Grouting was one of the most important parts of the alternative tunnelling concept. Basically, grouting was implemented to homogenize and upgrade the quantity of the surrounding subsoil as well as reducing and offsetting occurring settlements due to tunnel advancing. Heaves are a primary result of this operation.

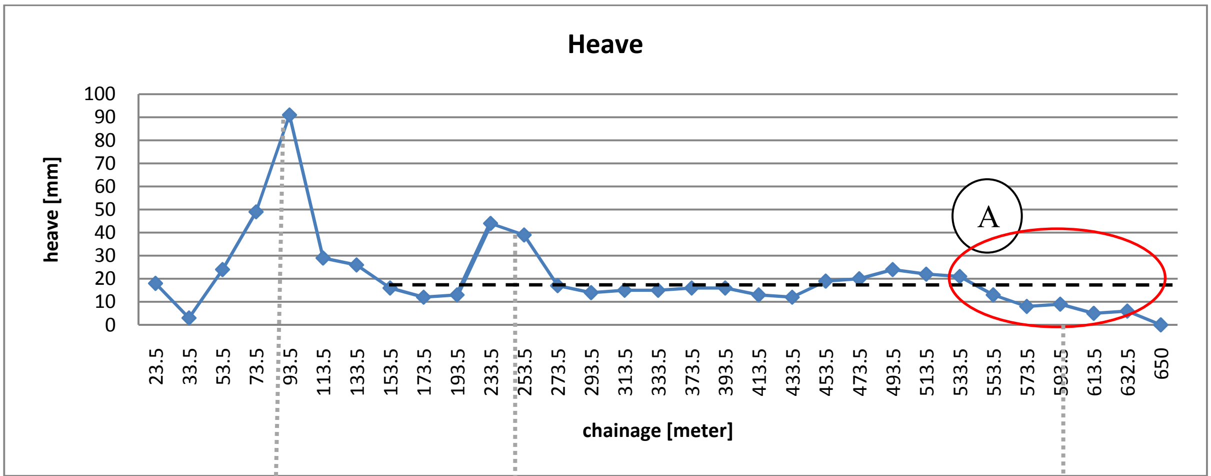


Chart 14, heave – main station

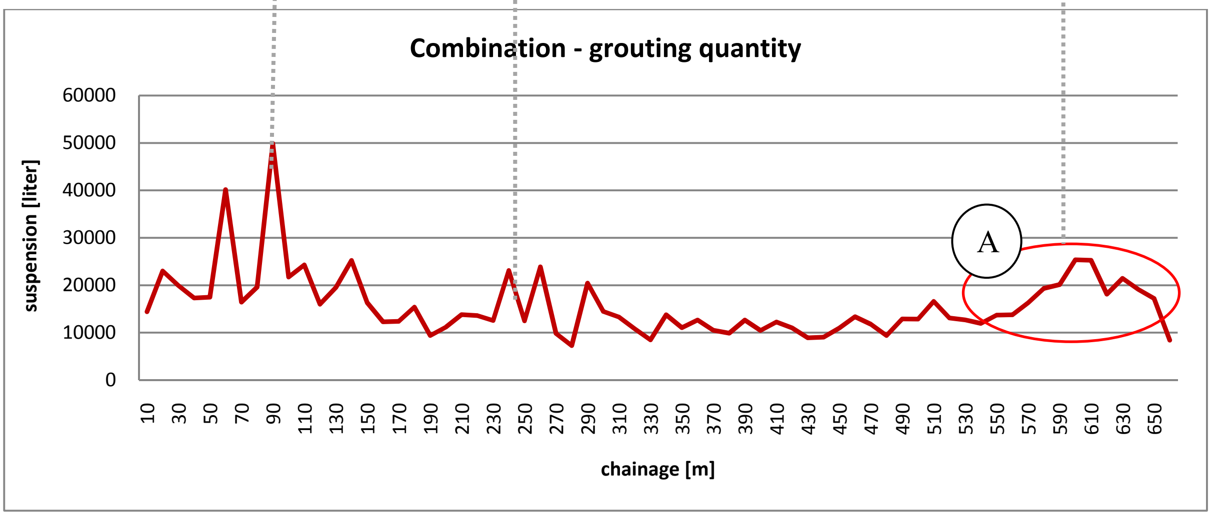


Chart 15, total grouting activity

The chart number 14 indicates the entire heave-trend. These positive elevations were measured directly above the tunnel axis on the surface. Excepting two massive outlines the overall trend was quite constant. On average a median elevation of approximately 18 mm had been produced. By a strict comparison of both charts in regards to heave and grouted quantity a direct connectivity can be identified. The overall trend of both charts is almost equal. Furthermore grouting fluctuations were almost balanced by the continuous behavior of the ground.

In section “A” we can recognize a diverse trend on both charts. As mentioned before in this specific area ground conditions changed. In this particular area the porosity of the subsoil was higher comparing to the previous sections. A much higher amount of grouting fluid was necessary to reach the required grouting pressure. In spite of an extended grouting program an inadequate penetration was achieved. This instance is visible by a lower lifting-effect in this particular section. The remarkable large heave at tunnel chainage 80-100 and 230-260 was without effecting consequence. In this special area no construction had been present. All artificial elevations due to the grouting procedure were within the prescribed limits.

8.1.2 Settlements due to tunnel advancing

Right after the accomplishing of the grouting procedure, the tunnel excavation process started. Driving-up a tunnel beneath a build-up area is an enormous challenge. Any kinds of uncontrolled ground displacements will inevitably influence the stability of adjacent constructions. However, it is nearly impossible to avoid occurring settlements in total. The main objective of the alternative concept was to reduce ground movements to an acceptable level. Tunnel advancing without adequate cover will generate settlements on the surface. A so called “settlement trough” will appear on the surface as a direct consequence of this activity.

> “The volume of the settlement trough is typically equal to the volume of ground lost in the tunnel” (Bickel 1982 [2])

Because of this inter-relationship it was absolutely necessary to avoid any kind of unnecessary ground displacement during the tunnel advancing process. The extensive grouting procedure in combination with the newly developed tunnel technique minimized this danger. Certainly settlements can also be a reason of vibrations, impulsive loadings, groundwater lowering and so on. Regarding to these factors the magnitude of occurring settlements is mainly dependent on modulus of elasticity, composition of different layers and the load-bearing capacity of the ground (Urban M et al. 11/12/2009 [27]).

However the application of the alternative concept avoided significant settlements by upgrading the quality of the adjacent subsoil. Furthermore it was possible to compensate for occurring settlements with artificial elevations.

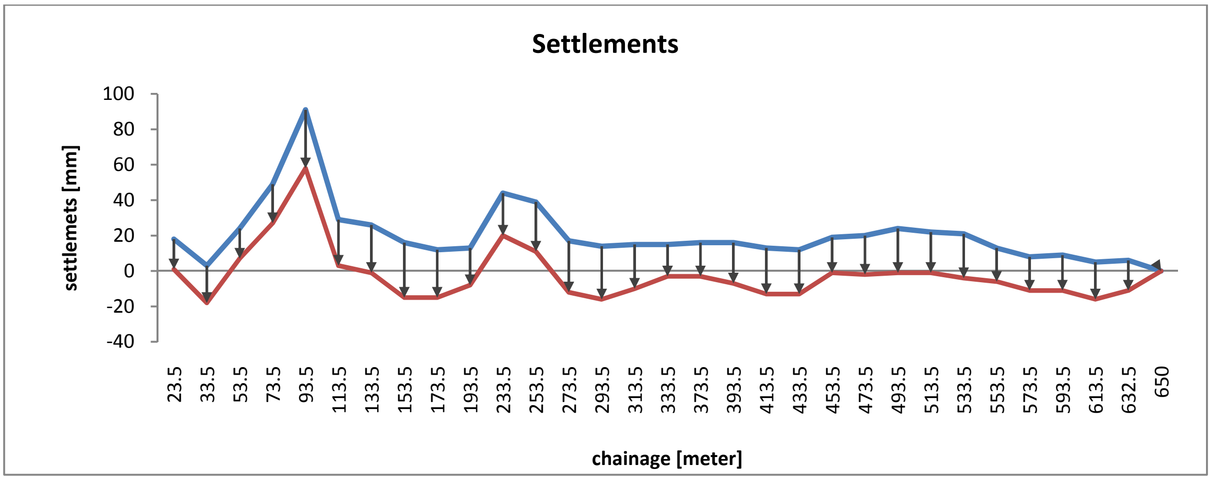


Chart 16, settlements, main station

The chart above presents the occurring displacements due to the tunnelling excavation process (chart 16). Displayed in blue we can recognize the positive elevations. The black arrows indicate the subsidence-effect as a direct result of tunnel advancing. Marked in red we will identify the final settlements after accomplishing the entire tunnel project. In average the value of negative settlements was between 15 and 25 mm. Because of the homogenization-effect as a result of the grouting process, settlements developed a continuous trend. Furthermore the interrelation between elevation- and the subsidence process is easily noticeable. In total, occurring settlements were offset by the grouting procedure. Just a few small negative outlines are identifiable. As mentioned before the terrain is nearly constantly even. The two positive outlines are situated between clear areas. Therefore, no damage took place. However, the alternative concept enabled a controlled devolution of occurring ground movements.

8.1.3 Occurring movements on tunnel crown

The initial situation of all settlements is ground movements before, during and after the tunnel excavation process. In this sense we have to differentiate between running ahead- and subsequent settlements. Subsequent movements take place between and after the tunnel advancing procedure. Running ahead settlements are a main consequence of the three-dimensional stress-redistribution in the ground, caused by the excavation.

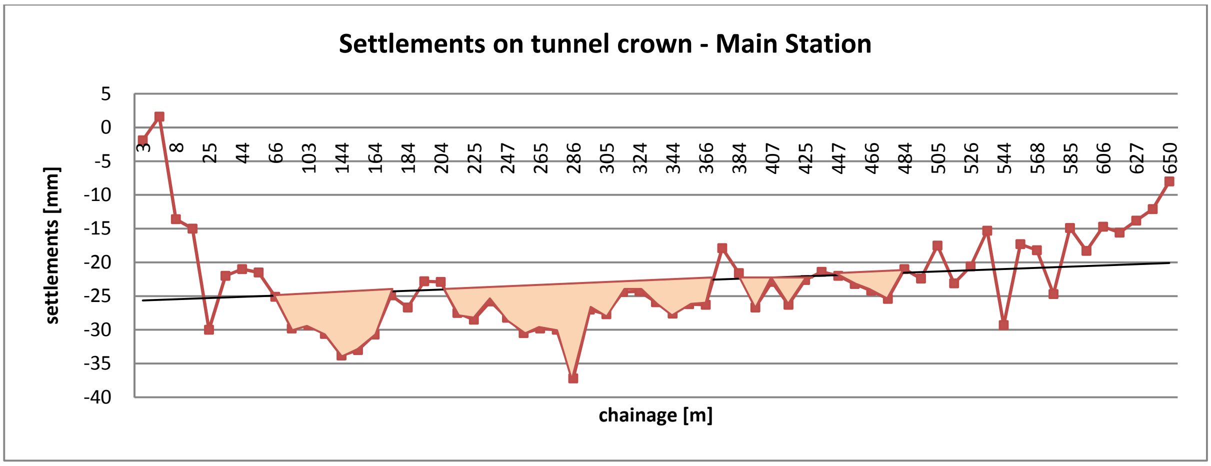


Chart 17, settlement on tunnel crown – main station

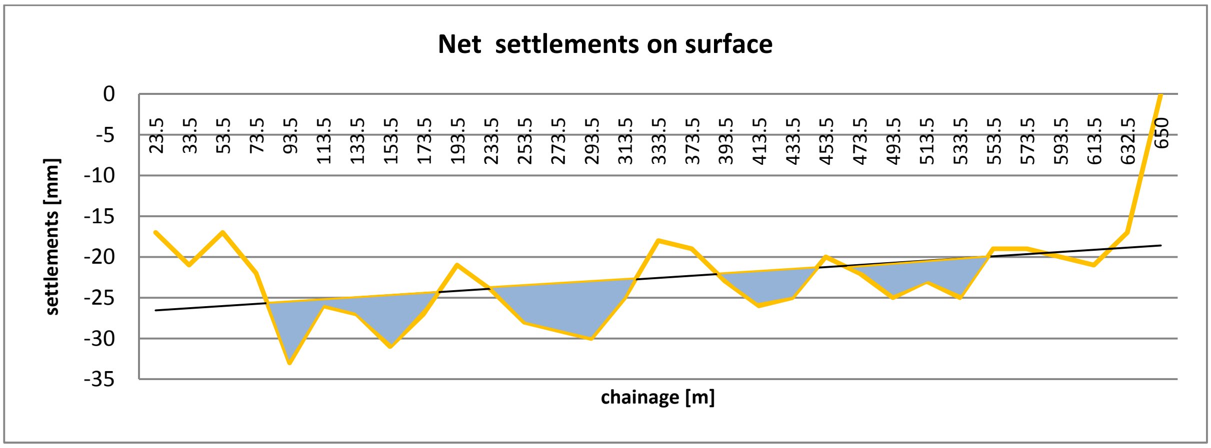


Chart 18, net subsidence on the surface

However, chart number 17 will indicates subsequent settlements measured on the tunnel crown. Chart number 18 illustrates the net subsidence on the surface. This special value was displayed with black arrows in chart 16. Generally, it has to be mentioned that a common tunnel monitoring program comprises a three dimensional record of at least five different points around the entire tunnel cross section. In chapter 9 a detailed explanation of this essential undertaking is presented. Because of the significance of vertical settlements located directly on the tunnel crown those will be presented in more detail. As we can recognize the overall trend is quite constant. In average a negative subsidence of about 25 mm can be noticed. This specific value fits perfectly with the basic consideration of ground displacement in the tunnel and appearing settlements on the surface. An exact evaluation of both charts (17, 18) will demonstrate this connectivity more precisely. The overall trend of occurring settlements on the surface is equal to the developed trend of settlements on the tunnel crown. Both types of ground movements demonstrate the same main characteristics.

8.1.4 Multiple combinations

In this special paragraph I am going to combine diverse charts we have analyzed in advance. The main objective of this final comparison is to provide an overall review of the interrelation of present terrain, quantity of grouting suspension and occurring settlements. Especially in the field of tunnelling, all different operations are strictly interconnected together. In this sense it is absolutely necessary to have an additional emphasis on the interaction of single events. However, the upcoming arrangement (figure 37) comprises the following components:

- longitudinal section
- overview grouting quantities
- settlements on surface
- settlements on the tunnel crown

These four elements are the most important components to evaluate the entire tunnel enlargement procedure. In this context the interrelation of terrain, amount of grouting fluid and occurring settlements are easily recognizable. The added dotted lines should help compare the different trends. Therefore, it is possible to identify characteristic trends in all three charts. This composition is primarily used to provide an overview of the different events. To sum up, the entire tunnel enlargement process was a complete success. As mentioned in several charts, occurring settlements due to tunnel excavation were minimized to an absolute limit. Moreover, the alternative concept was safer, more time efficient and much more economical.

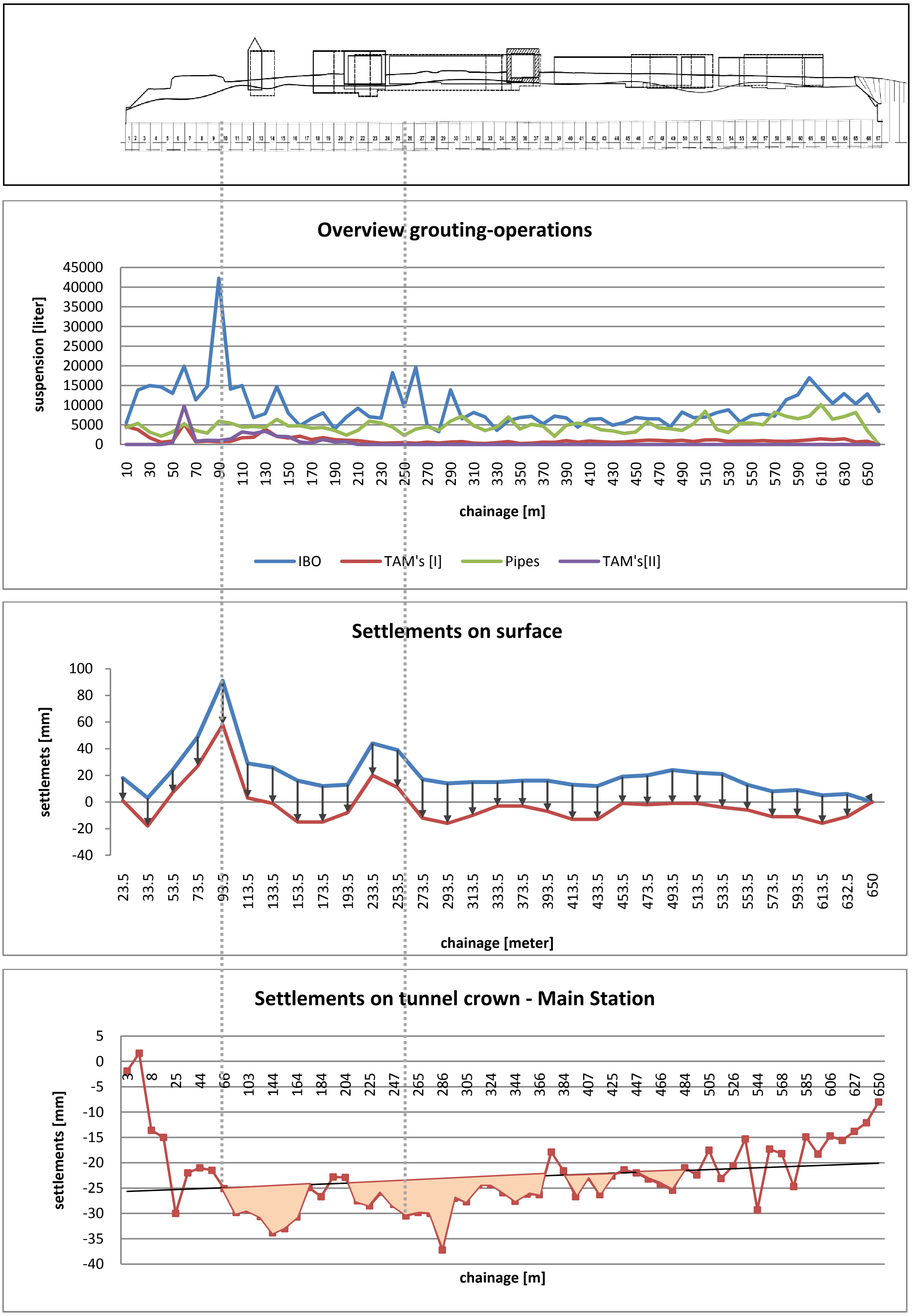


Figure 35, multiple combinations – main station

8.2 Analysis – tunnel south

In the following chapter occurring settlements belonging the building lot “tunnel south” are analyzed. This additional critical evaluation is absolutely necessary to provide a complete elaboration about the entire tunnel enlargement procedure. Furthermore, we are able to double-check the established interpretation regarding the first case. The basic structure of this additional evaluation will be similar in comparison with the previous analysis.

8.2.1 Elevation - due to grouting

For this particular procedure the same considerations and assumptions are valid as mentioned in the foregoing case. Heave has been a direct and intended result of the complex grouting procedure. Because of the shortness of this tunnel section in combination with rugged terrain an overall trend is hardly identifiable.

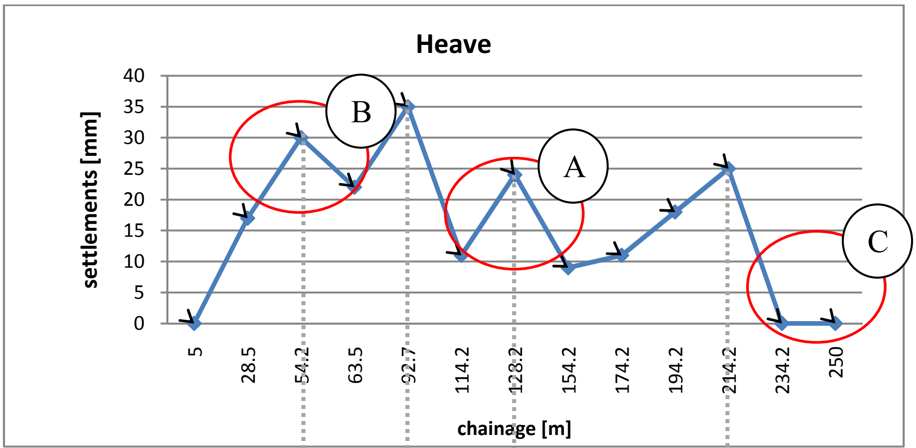


Chart 19, heave– tunnel south

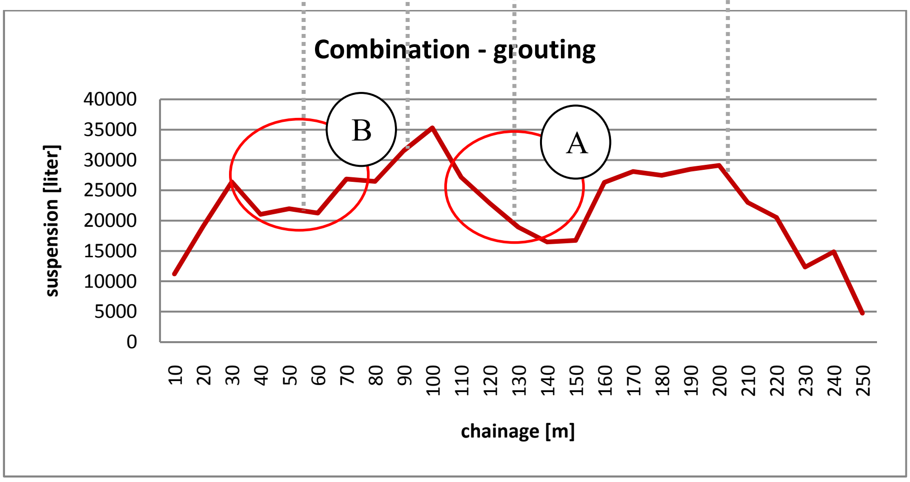


Chart 20, combination - tunnel south

However, a direct connectivity of occurring settlements and disposed grouting fluid is definitely noticeable. Both trends are almost equal. Basically, we can identify four huge outlines. Two of them are directly located in a field of an increased amount of grouting suspension. Except in section “A” and in section “B”, this interconnection is not recognizable. A road placed just a few meters above the tunnel crown is the main reason for this abnormal trend in section “A”. In this particular case, already a small amount of grouting fluid can effect significant elevations. Because of the minor cover it is nearly impossible to identify the actual reason. Nevertheless, these movements did not have any consequences, because the entire street was closed during construction. Regarding the abnormality in section “B”, no traceable reasons are identifiable. A more consolidated ground was probably present. In section “C” no heaves had been recorded. In this specific area the tunnel was driven up with the so called “dig and cast” technique.

Because of the short tunnel length as well as an exaggerated visualization - occurring settlements appear more intense than they really are. However, on average the occurring elevations are quite constant.

8.2.2 Negative settlements due to tunnel advancing

Subsidence was a straight result of the tunnel excavation process. In average the value of negative settlements was between 10 mm and 18 mm. Those minimal quantities verify the success of the entire grouting procedure. The chart provided below indicates this fact in more detail. Generally a quite constant trend is recognizable. The space between the blue and the red lines indicates the value of subsidence due to tunnelling advancing.

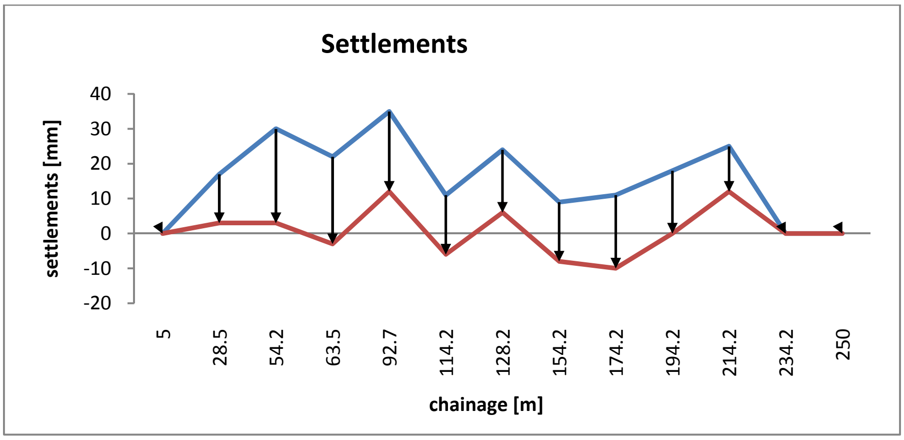


Chart 21, settlements – tunnel south

In review, marked in blue we can identify the maximum heave and in red the final settlements after the accomplishment of the entire tunnel. Basically, the equal assumptions and considerations worked out in chapter 8.1.2 are absolutely valid. Almost all subsidence was compensated due to the extensive grouting process. The main objective to homogenize occurring movements was achieved.

8.2.3 Occurring movements on tunnel crown

In this particular chapter occurring settlements measured directly on the tunnel crown are analyzed. For a considerable evaluation I will compare settlements on the tunnel crown displayed in chart 22 with present movements recorded on the surface illustrated in chart 23. The overall trend of both charts is quite similar. Basically, we can identify one massive outline located between tunnel meter 110 and 140. As mentioned before in this special area a narrow street is located.

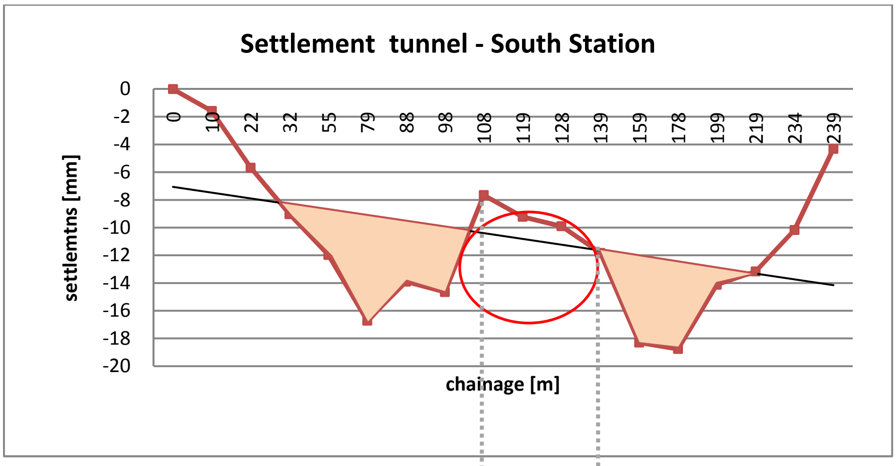


Chart 22, settlements on tunnel crown – tunnel south

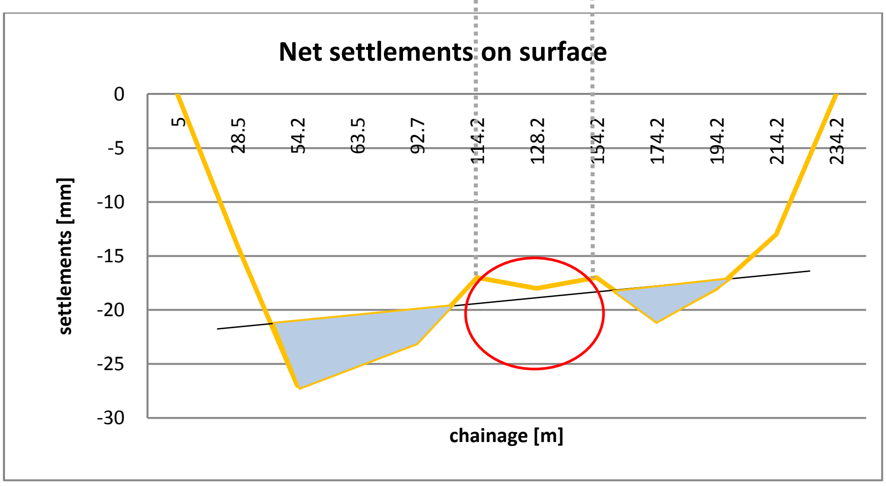


Chart 23, net subsidence on the surface – tunnel south

The main reason for this positive anomaly was the short distance between tunnel crown and surface. Generally, settlements located near the surface are primarily influenced by the following factors (Wood 2000 [24)]:

- Distance between tunnel axis and surface
- Local ground conditions
- Tunnel excavation method
- Overlaying loads
- Shape and dimension of the tunnel profile

Disregarding point one all influencing factors remain constant during the tunnel excavation process. Therefore, we can identify the irregular terrain as the ultimate cause. However, the basic consideration behind this reaction is quite simple. The lesser the distance between the tunnel crown and surface, the smaller is the stage of stress in the tunnel, and this interrelation mainly affects the amount of occurring settlements. Concluding the overall trend of produced settlements in the tunnel and on the surface was quite similar. The present variation displayed in the charts ahead was a direct result of the abrupt changing terrain. Nevertheless, all present settlements were within the required limits.

8.2.4 Multiple combination

In this particular chapter an additional comparison of different charts is provided. The main objective of this elaboration is to provide an overview of essential events in the tunnel enlargement procedure. Basically, the same statements and conclusions are valid as mentioned in chapter 8.1.4.

The influence of the uneven terrain belonging to occurring settlements and grouting quantity is especially well recognizable. This particular circumstance is well notable in the section of tunnel meter 120 -150 where a street is crossing the tunnel alignment. A significant change in the overall trend in all three chars is visible. However, this elaboration shall help to understand the complex interrelations in the field of tunnelling

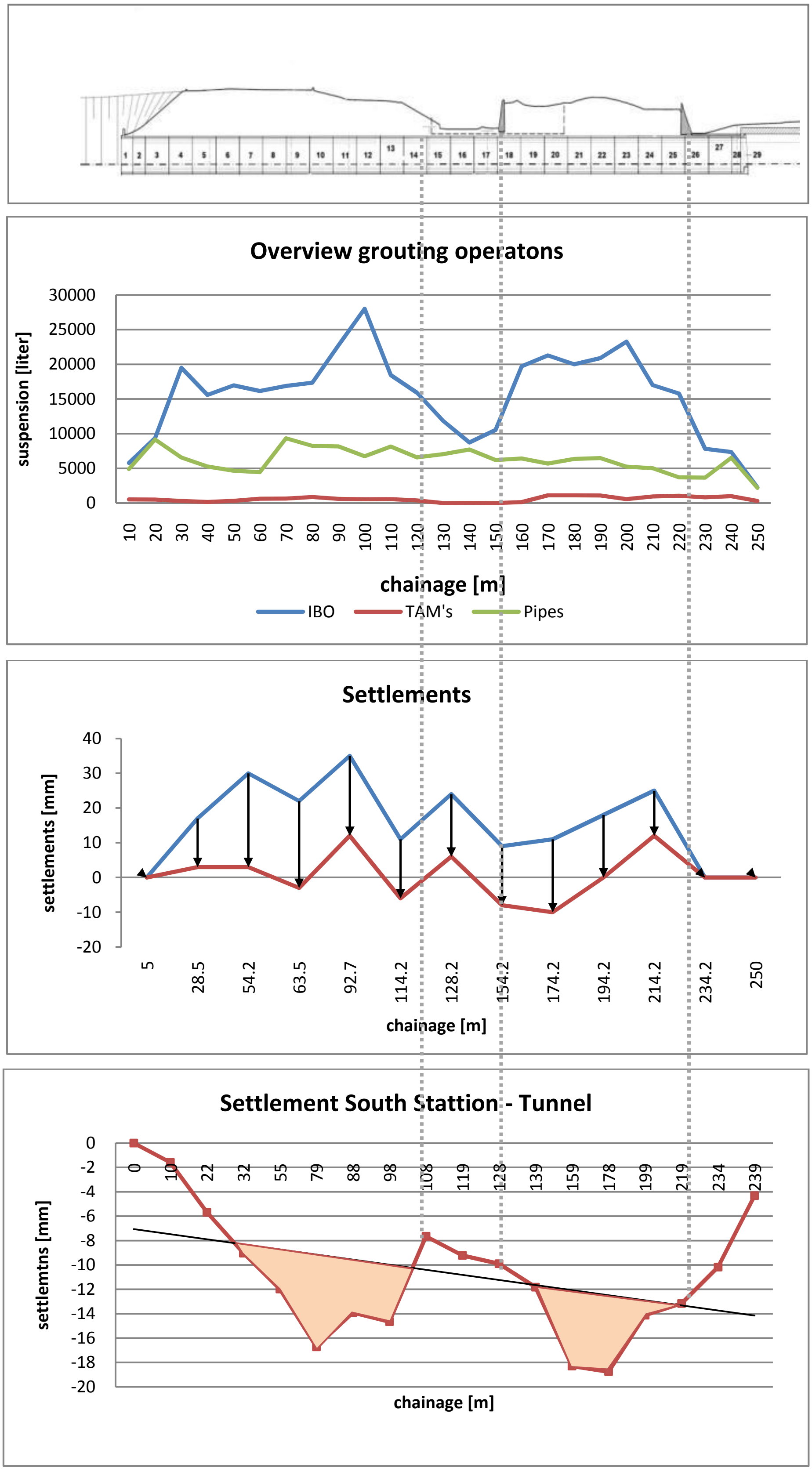


Figure 36, multi combination – tunnel south

9 Excursus monitoring

Monitoring is an essential part of the entire tunnelling procedure. Primarily, the implementation of a complex monitoring program enables the success of modern tunnel excavation techniques such as “NATM” or “TBM’s. However, monitoring takes place during the tunnel advancing process. Certainly, some of these investigations have to start before and end after the tunnel excavation phase. Monitoring is the act of observing movements or stress while keeping a record on it (Princeton University 11/18/2009 [28]). The main objectives of monitoring are:

- Verification of design
- Verifying and upgrading geologic models
- Advise against sudden damages
- Detailed adjustment of sequences of construction

In this context, monitoring observes basically three main values: movements (absolute or convergences), occurring stress and present forces. However, nowadays a wide range of different measuring devices are available. The most common devices are theodolite, leveling apparatus, extensometers and inclinometers, measurement bolts and manometers. A comprehensive monitoring program includes measurement on the surface and in the tunnel.

Regarding the project “Alte Mainzer Tunnel” monitoring was a key-procedure of the entire tunnel enlargement concept. Especially in urban areas, observations of occurring settlements and ground displacements play a decisive role. All kinds of uncontrolled and unpredictable events represent an unaccountable potential of risk. Due to these circumstances, an extensive monitoring program was implemented. Continuous measurements were taken daily.

In the following chapter the monitoring process is explained in more detail. To make this excursus more comprehensible and interesting I am going to work out this matter by the implementation of a case study. Because of the complexity of this special topic it will be impossible to analyze all different parts of the overall monitoring program. A selected assortment is therefore provided in the following chapters.

9.1 Case study (Chainage 513.5 – main station)

In this excursus the settlement procedure is elaborated more precisely. For this purpose, just one single tunnel meter will be analyzed in full detail. Furthermore, an extensive elaboration of applied monitoring techniques will be provided. I am going to start with a specific interpretation of negative settlements and heave placed on the surface. Afterwards I am going to continue with occurring settlements in the tunnel. This exposition includes absolute and relative movements. Finally, I will provide a slight overview of additional monitoring devices.

9.1.1 Levelling – monitoring on the surface

The terrain above a tunnel construction-site has to be observed frequently. For this purpose levelling is the most adequate technique. The main objective of this investigation is to monitor the settlement trough due to tunnel advancing. Furthermore, present elevations as a result of grouting can be measured. Technical devises such as theodolite and leveling apparatus are appropriate. Chart number 37 indicates the entire elevation and subsidence process elaborated for one particular point on the surface located directly above the tunnel axis.

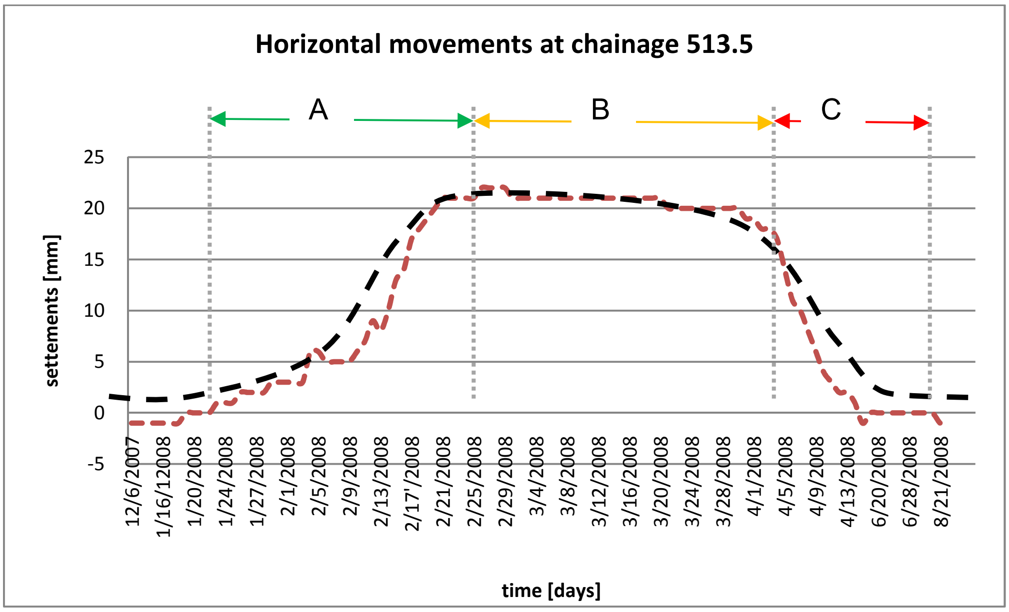


Figure 37, time-distance diagram

A time-distance diagram is an excellent instrument to display occurring settlements due to tunnel excavation or applied grouting process. For this purpose we have to split up the overall trend into three sections. Section “A” displays heave as a direct result of the extensive grouting process. A maximum elevation of 20 mm was reached. The time frame between grouting- and excavation is indicated in section “B”. The downswing trend during this period is a result of consolidation and already started influences of the upcoming excavation process. Section “C” displays negative settlements due to tunnelling advancing. As we can recognize, present settlements were occurring relatively quickly. However, the illustration in chart number 39 displays the ideal situation. All negative settlements were compensated for by the foregoing grouting procedure.

9.1.2 Heave (cross section - surface)

A critical evaluation of a settlement trough comprises a multitude of important information. The dispersion and dimension of occurring settlements is perhaps the most relevant output. However, we will focus on heave as a direct result of the extensive grouting procedure. The chart below will illustrate this activity more precisely (chart 24).

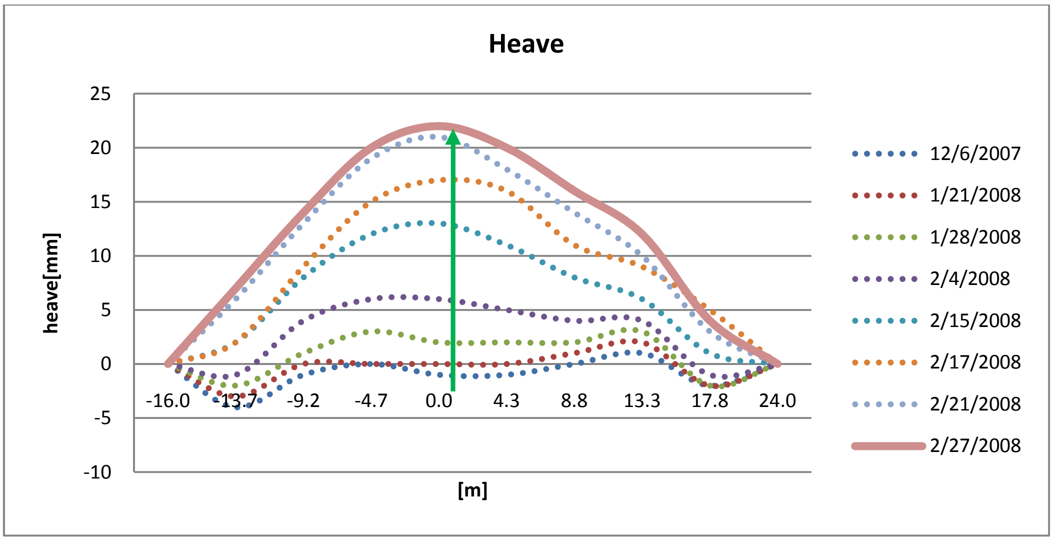


Chart 24, heave trough

Directly above the tunnel axis the highest elevations are present. The further away from the center, the smaller the heave is. A cross-section of almost 40 meters is influenced by the extensive grouting procedure. The different lines indicate the gradual lifting process. Basically, we can identify these curves as an inverse settlement trough.

9.1.3 Settlements (cross section - surface)

Negative settlements were a consequence of the tunnel enlargement procedure. Chart number 25 below displays this procedure in more detail

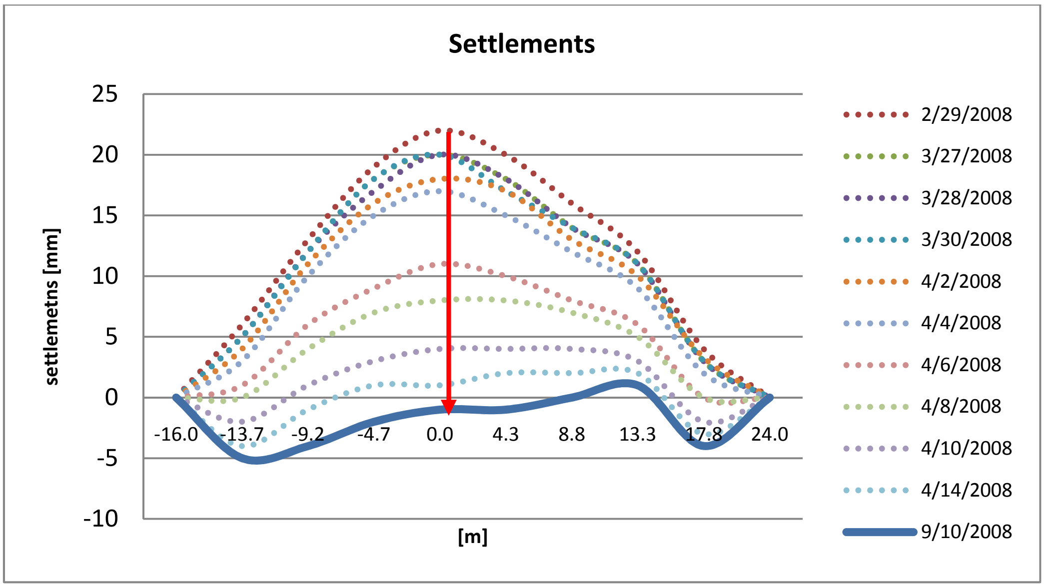


Chart 25, settlement trough

The largest settlements are located exactly above the tunnel axis. Just like the lifting process, the intensity of occurring subsidence is decreasing as the distance from the center increases. After achieving a state of equilibrium in the subsoil the settlement process is completed. This illustration displays the perfect situation. All occurring negative settlements have been compensated for by the implementation of a sophisticated grouting program. The exact date of tunnel excavation at this stage was the 5th. of April 2008.

9.1.4 Absolute movements in tunnel

Right after the tunnel advancing procedure a comprehensive monitoring program has to be implemented. The main objective of this additional undertaking is to observe and record occurring settlements in the tunnel. Therefore, a manifold of different values can be measured. Regarding the project “Alte Mainzer Tunnel” five diverse measuring points all along the tunnel cross section had been installed. The distance between the single stations was approximately 10 meters. A theodolite was mainly used to survey those points. In this sense all points were measured three-dimensionally. Therefore, a vertical-, a lateral and longitudinal deformation was recorded. Without a doubt, the vertical deformation is the most meaningful value in this project. Because of the importance of vertical settlements this topic is dealt with in more detail. The next chart number 26 displays these values.

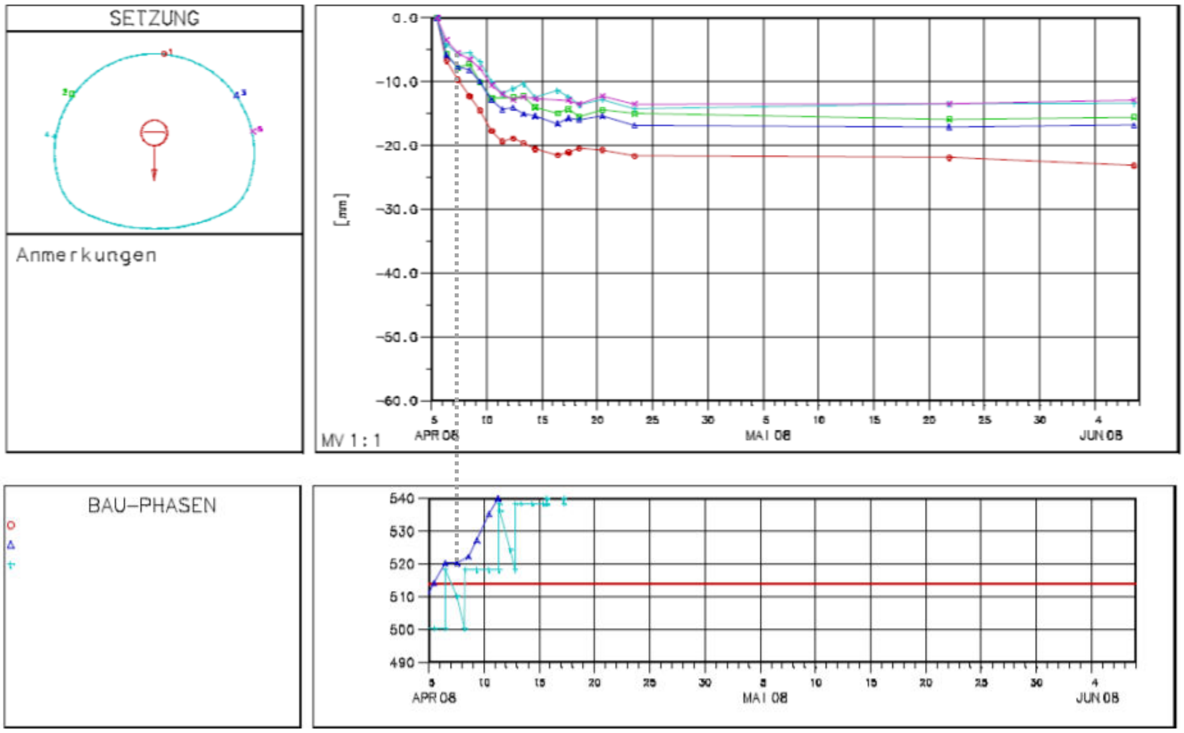


Chart 26, time-distance diagram, absolute vertical settlements, source Beton- und Monierbau

The charts above demonstrate the overall trend of vertical settlements in interconnection with the time. In the lower chart the different construction operations are displayed. Approximately after one month a stabilized trend is recognizable. As expected the most significant settlements are located directly on the tunnel crown. A maximal deformation of 20 mm had been achieved. Especially in the area of the bench, the subsequent invert excavation is noticeable. The additional added dotted line helps to indicate a slight change in the overall trend. Occurring deformations in longitudinal and lateral direction were beneath 0.5 mm.

9.1.5 Convergence (tunnel) – relative movements

Convergence is the relative deformation between two different points. For monitoring convergences theodolite or and extensometer are the most practical instruments. Back in the past invar wires or steel tapes had been used. The observation of relative movements is an essential part of the entire monitoring program. Convergences are necessary to get an insight into the soil structure interaction. In the following chart recorded convergence is displayed.

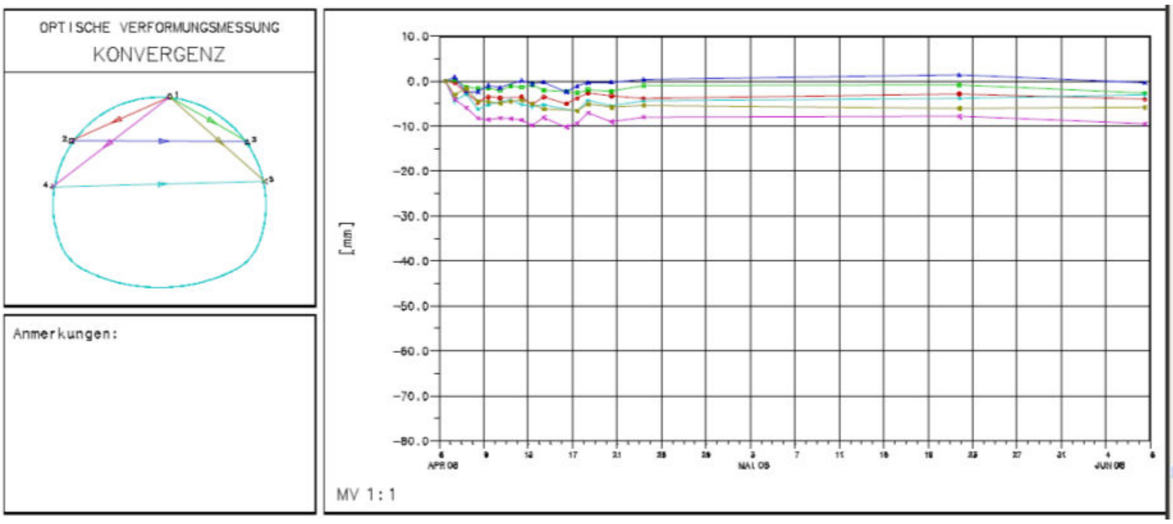


Chart 27, time-distance diagram convergence – chainage 514.0, source Beton- und Monierbau

In chart number 27 we can recognize convergence measured right after the tunnel advancing procedure. Because of the extensive grouting program significant deformations was avoided. In average the diameter was compressed by 5 mm. After a few days a stabilized trend is recognizable. Compared to other projects, this value is insignificant.

9.2 Additional devices

In this paragraph a slight overview of special monitoring devices is given. To guarantee a comprehensive monitoring program a multitude of different measurement tools have to be implemented. In this sense we already got in touch with theodolite and leveler. For measuring the change of inclination - inclinometers are appropriate. Extensometers are used to monitor appearing convergences in the surrounding subsoil. To observe stress or forces measurement bolt and manometers have to be installed. Furthermore slide micrometer, deflectometer and so forth are practicable instruments to observe occurring deformations.

The implementation of an extensive and complex monitoring program enables management of the grouting operations as well as the tunnel enlargement process without any notable trouble.

10 Economical aspects– project management

In this final chapter, the focus will be on economic- and management aspects with regard to the alternative tunnelling method. The main purpose of this additional elaboration is to complete the overall analysis worked out in this master thesis. Key drivers such as time, costs and required manpower will be evaluated precisely. For better comprehensibility the grouting- and the tunnel advancing procedures are analyzed separately. This session will be closed with a brief critical discussion.

The economical aspects of a tunnel project are absolutely essential. A reasonable disposal of resources in combination with an efficient tunnel advancing method ensures the economic success of a tunnel project. Certainly there are a manifold of different factors influencing this ambition. However, a professional project management team is a prerequisite to run a project successfully (Pequignot 1963 [16]).

10.1 Grouting procedure

Grouting was one of the most expensive and time-consuming procedures of the entire tunnel project. Nevertheless, the implementation of this particular process was absolutely required to guarantee the success of the entire tunnel enlargement undertaking. In the following subchapters this particular process with regard to economic aspects is analyzed in more detail.

10.1.1 Time & economic aspects

First of all the main focus will be on aspects such as time- and economics. Those two factors are the most important values to evaluate the efficiency of a particular procedure. However, the entire grouting process started at the 10th of July and was finished around June 15. Thus, the total duration was a bit more than 11 months. Except for three weeks over Christmas and 5 days on Easter the entire grouting process was executed without any interruptions. On average, every day more than 45.624 liters of grouting suspension was injected. That's a total of 14.554 m³ for the entire grouting procedure

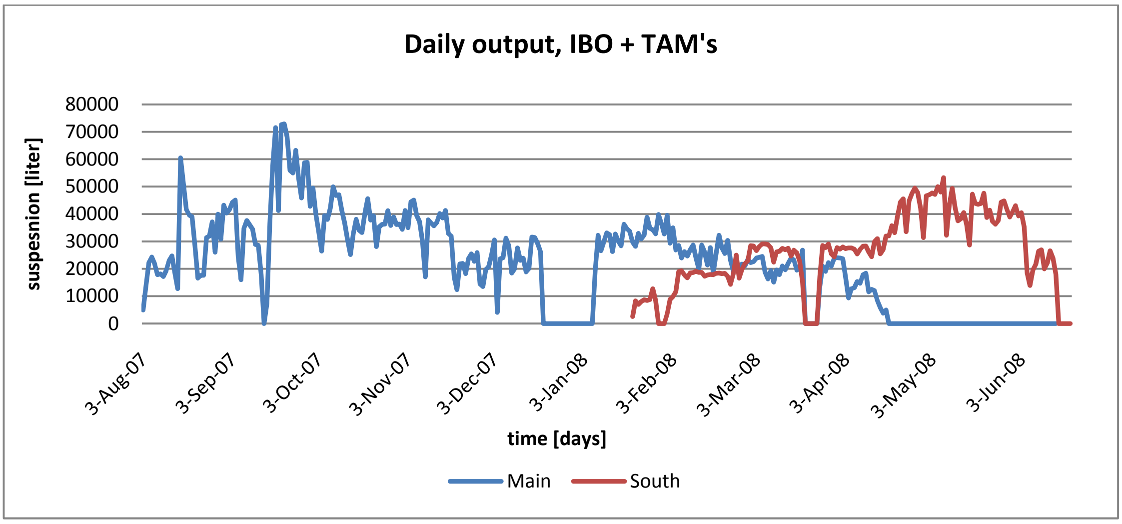


Chart 28, daily output, IBO + TAM's

Chart number 28 indicates the daily output of the entire grouting process. Unfortunately, exact dates of the stabilization procedure due to filling pipes are unavailable. But anyway, the chart added above provides a good exposition of the overall grouting trend. An almost constant trend is recognizable. In this sense I like to point out the almost smooth change between construction lot "main station" and "tunnel south". This complicated transfer was executed without decreasing the average daily output.

10.1.2 Required equipment

To accomplish the grouting process as fast as possible a huge contingent of different equipment was required. The specified side arrangement, used for the project "Alte Mainzer Tunnel" is listed below:

- Grouting vehicle (4 units)
- Lift truck (1 units)
- Lifting platform (4 units)
- Drilling jumbo (1 unit)
- Mixing plant (1 unit)
- Shop (1 unit)

A detailed description of the grouting vehicles as well as the mixing plant was already exemplified in chapter 4.1.4. At peak time, 16 different plugs ins were used. As we recognize, an immense amount of diverse side equipment was used.

10.1.3 Manpower

Grouting is a labor-intensive procedure. To arrange, control, maintain and support this operation a multitude of manpower is required. The table number 3 illustrates this fact in more detail.

Action / Position	Pump [man]	Packer [man]	Mixer [man]	Operating device [man]	Cleaning packer [man]	Drilling [man]	Sum [man]
Vehicle 1	2	3	-	-	-	-	5
Vehicle 2	1	2	-	-	-	-	3
Vehicle 3	2	2	-	-	-	-	4
Vehicle 4	1	2	-	-	-	-	3
Mixing plant	-	-	2	-	-	-	2
Lift truck	-	-	-	1	-	-	1
Lifting platform	-	-	-	1	-	-	1
Drilling jumbo	-	-	-	-	-	4	4
Shop	-	-	-	-	2	-	2
Sum	6	9	2	2	2	4	25

Table 3, organization of manpower

The horizontal axis describes the different actions belonging to the grouting procedure. In the left-most column we can identify the appropriate workstations. In total 25 labors were required to execute the grouting procedure. In conclusion it is worth mentioning that the entire grouting procedure took place without any noticeable incidents. All prescribed limits and regulations were fulfilled. By application of the alternative grouting procedure a much more efficient and safer tunnel advancing procedure was achieved to.

10.2 Tunnel advancing

The tunnel advancing process was mainly influenced by the newly developed tunnel excavation method. Regarding execution, expenditure of time and need of manpower, the alternative tunnelling technique is almost comparable with tunnel class 1. The rate of advance is mainly dependent on the length of the tunnel, present geotechnical conditions, used tunnelling methods, design and professionalism of the entire team. However relatively adequate speed of tunnel advancing was reached, especially by consideration of the demanding circumstances. Now all the positive effects of the extensive grouting procedure became noticeable. Matters such as time, manpower and site arrangement will be discussed in the next subchapter.

10.2.1 Time & economic aspects

Driving up a tunnel is quite a time consuming procedure. A manifold of different factors influence the daily rate of advance. Basically, the more homogeneous and stabile the surrounding subsoil, the more efficient and faster the tunnel advancing process. To increase those properties was the main purpose of the extensive grouting procedure.

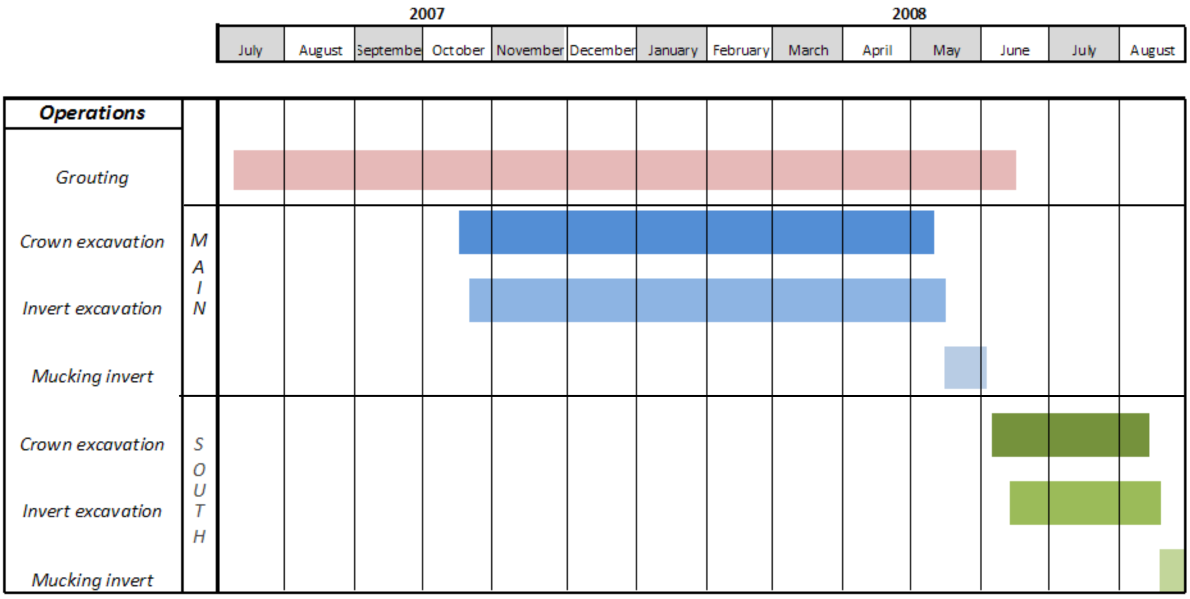


Figure 38, time schedule – main operations

Chart number 40 illustrates the main construction sequences including the appropriate duration. The time schedule is highly simplified to provide a good overview. In red we can identify the entire grouting procedure for both tunnel lots. Tunnel excavation “main station” started on 17th October 2007 and was finished around the second of June 2008. Thus, the total duration was about eight and a half months. The rate of advance was in average 3.13 meters per day. For building lot “tunnel south”, tunnel advancing started at the 6th of June 2008 and was finished by the end of August 2008. The total duration accordingly was less than three months. On average 2.94 meters was excavated per single day. Those excellent values are the direct result of the alternative tunnelling method. Application of the original concept would have been more time consuming. This was among other things one of the main reason to execute the alternative tunnelling concept.

10.2.2 Required equipment

The application of the new developed tunnelling method did not increase the usual demand of required tunnelling equipment. In this sense, excavators, mechanized drilling vehicles, muckers, trucks, wheeling loader and so forth were used. No special device was necessary to execute the newly developed tunnelling technique.

10.2.3 Manpower

The automation reduced the need of employees dramatically. Nowadays labors are mainly used to operate and maintain equipment, control diverse operation or manage the construction site. However, no process could be executed without the presence of human people. During the entire construction time the amount of required manpower on the site varied significantly. It was mainly dependent on the work progress. On the single tunnel excavation process around 16 labors worked in two different shifts. Additionally ten people were employed to maintain and repair diverse tools. Around ten more employees were responsible to manage and run the entire construction site. In total including the workers of the grouting procedure more than 99 people had been employed on peak time.

10.3 Final critical discussion

In the previous chapter we discussed issues such as time, used equipment and required manpower. Basically, we could recognize that the overall grouting procedure was a time- and material consuming undertaking. This special operation was just in combination with the newly developed tunnelling method, an absolutely reasonable step. The implementation of the extensive grouting program reduced not only the number of different tunnel support devices, but also increases the quality of the surrounding ground immensely.

To summarize it was risky to apply a new untested tunnelling method, but the advantages of this new revolutionary technique have overcome all doubts. This fact is especially outstanding regarding occurring settlements, safety aspects and economic use of time.

11 Summary and conclusion

In this diploma thesis a detailed description of a tunnelling project in a built up area has been presented. The foundation of this research was a tunnel project executed in Germany. The core part was the illustration of an alternative tunnelling method for the redevelopment of an existing tunnel structure. Furthermore detailed analyses and critical evaluation of the grouting-, tunnelling- and settlement procedure were worked out.

The first goal of this diploma-thesis was to highlight the manifold challenges of an intra-urban tunnel construction. Afterwards conventional tunnelling techniques were described. On the background of this, an absolute new and revolutionary tunnel method was illustrated in detail. A discussion identified the assets and drawbacks of this innovative technology. To confirm these statements, selected operations were investigated to get an idea about the interconnection of grouting, tunnelling and occurring settlements. A critical assessment of economical aspects was represented at the end of this diploma thesis.

The main objective of this paper was to introduce the reader into an innovative tunnel technique. Furthermore the exact analysis of the entire grouting procedure was essential to identify the complicated interaction between grouting – eaves and tunnelling – settlements. The strict comparison of both concepts reflected the benefits of the new tunnelling method. Therefore, it turned out that the alternative technique was not only more effective facing time and costs issues but also the risk of uncontrolled ground displacements was reduced to an absolute minimum.

This diploma thesis at hand should be a guideline for further tunnel redevelopment projects in urban area with close similar conditions.

12 References

12.1 List of illustrations

12.2 List of tables

12.3 List of charts

12.4 List of literature

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Drawings

AMT-A-E-06-02-200-06	Geology – longitudinal section
AMT-A-A-06-25-002-01	Excavation and supporting
AMT-A-A-06-25-004-01	Grouting and forepoling
AMT-H-A-06-02-001-00	Longitudinal section (main station)
AMT-S-B-06-00-002-04	Longitudinal section (tunnel south)
AMT-H-A-06-09-001-01	Characteristics of settlements
AMT-A-A-06-08-002-02	Grouting concept
AMT-A-A-06-25-001-01	Excavation class 1