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# Mechanized Tunneling in Soft Soils: Choice of Excavation Mode and Application of Soil-Conditioning Additives in Glacial Deposits

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ABSTRACT

The history of the formation of the alpine region is affected by the activities of the glaciers, which have a strong influence on underground works in this area. Mechanized tunneling must adapt to the presence of sound and altered rock, as well as to inhomogeneous soil layers that range from permeable gravel to soft clay sediments along the same tunnel. This article focuses on past experiences with tunnel-boring machines (TBMs) in Switzerland, and specifically on the aspects of soil conditioning during a passage through inhomogeneous soft soils. Most tunnels in the past were drilled using the slurry mode (SM), in which the application of different additives was mainly limited to difficult zones of high permeability and stoppages for tool change and modification. For drillings with the less common earth pressure balanced mode (EPBM), continuous foam conditioning and the additional use of polymer and bentonite have proven to be successful. The use of conditioning additives led to new challenges during separation of the slurries (for SM) and disposal of the excavated soil (for EPBM). If the disposal of chemically treated soft soil material from the earth pressure balanced (EPB) drive in a manner that is compliant with environmental legislation is considered early on in the design and evaluation of the excavation mode, the EPBM can be beneficial for tunnels bored in glacial deposits.



## 1. Introduction

Two main operation modes exist for mechanized tunnel excavations above and below the groundwater table in soft soils. If operated in slurry mode (SM), the tunnel face is supported with the help of a bentonite slurry; if operated with the earth pressure balanced mode (EPBM), the excavated soil is used directly to transfer the stabilizing pressure to the face. The development of slurry shields began in Japan in the 1970s; this method was then relatively soon and frequently used in Europe [1]. The first shield supported with earth pressure was applied in 1974 in Japan. After several subsequent projects in Asia, this technology arrived in Europe in the early 1980s. Due to the potential of this method, the development of this technology was strongly pushed forward. The resulting development and application of chemical soil conditioners (e.g., foams and polymers), which are injected during the excavation process, allowed the continuous expansion of the application limits.

At present, many tunnels in the alpine region are still being bored with slurry support. This usage goes against the global trend; over 90% of tunnel-boring machines (TBMs) produced for excavations in soft ground worldwide are constructed as EPBM machines [2]. In general, TBM designs tend to focus on optimizing the combination of different excavation modes on the same TBM [3]. Dual-mode or multi-mode TBMs can change their operation mode between open mode and closed mode within minutes or seconds [4]. In fact, a combination of SM and EPBM and the ability to switch between these two modes can be installed on the same machine.

This paper reviews past experiences with mechanically bored tunnels with large diameters in loose ground in Switzerland, with a special focus on soil-conditioning aspects. All the projects discussed here have the following common attributes: Their geological conditions were inhomogeneous; and soil layers with different grain-size distributions, which were outside of the original optimum operation ranges of the excavation methods, were predominant. The effects of the chemicals that were used for unique earth pressure balanced (EPB) drives with a large diameter in Switzerland are specifically highlighted, allowing some conclusions to be drawn for further projects in comparable soil conditions.

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## 2. Background

### 2.1. Key aspects of soil conditioning

With respect to geological conditions, both slurry shields and EPB shields have optimum (or original) application ranges. The suitability of a method is often judged based on the grain-size distribution of the *in situ* soil [2,5–7].

For slurry shields in strongly permeable ground, the pure bentonite suspension cannot guarantee the buildup of the necessary filter cake. Fillers or high molecular weight polymers must be added in order to be able to maintain the pressure at the tunnel face [8,9]. In clayey soils, the risk of clogging exists in different zones during the excavation process, such as the cutting wheel, slurry circuit, or separation plant. In this case, polymers can be added to reduce the clogging potential [10]. In particular, the use of dispersing polymers can change the rheological properties of the bentonite suspension [11], which can result in drawbacks if different soil layers are predominant within the same tunnel section. For EPB shields, a certain minimum amount of fines in the soil is required (a minimum of 10% lower than 0.06 mm). The fines content guarantees a certain amount of cohesion and resistance of the earth mud, so that it can fulfill its function as a face-supporting media. If the fines content is too low, high molecular weight polymers, bentonite, or fillers may be added. Foam additives are also used in most EPB drives in order to reduce wear, resistance, and pressure fluctuations in the machine. The surfactants are passed through a foam generator to increase their volume by 10–20 times, and are then injected at the cutterhead, as they are relatively resistant against mechanical destruction. Surfactants act to optimize the paste-like behavior of the soil. Experience from all over the world in the addition of different conditioning agents has permitted the continuous expansion of the possible application ranges of these excavation methods. The chemical additives that are available for underground works are numerous; Table 1 lists the main groups of polymers used, along with their properties and application. The working mechanisms of these polymers vary widely; in addition to electrostatic interactions between clays and polymers, adsorption, ion-exchange processes, and complexation reactions can play a role [12].

**Table 1**
Overview of polymer groups used in underground works.

| Group | Properties and application |
|---|---|
| Polysaccharides (e.g., xanthan and guaran) | • High-viscosity polymers, mainly used as an additive for bentonite suspension<br>• Xanthan: thixotropic behavior<br>• Guaran: reduction of filtrate loss |
| Cellulose ether (e.g., carboxymethyl cellulose (CMC) or polyanionic cellulose (PAC)) | • Regulator of viscosity and filtrate loss<br>• Effect is strongly dependent on the molecular weight, polymer charge, and charge distribution |
| Polyacrylamide (PAM) and partially hydrolyzed polyacrylamide (PHPA) | • Regulator of viscosity and filtrate loss<br>• Anionic, non-ionic, or cationic<br>• Effect is variable with polymer concentration, charge, and molecular weight |
| Polyacrylates | • Anionic, often sodium polyacrylates<br>• Low molecular weight polymers act as dispersants; high molecular weight polymers can enhance viscosity |

### 2.2. Soil-conditioning research

Due to the growing importance and potential of soil conditioners for tunneling practice, a high research effort has been generally put into practice in order to investigate their effects on soil behavior around the world. Since the state-of-the-art report by Milligan [13], many laboratory tests using standard laboratory devices and others using newly developed devices [14,15] have brought insight into the working mechanisms of the different products and into the resulting soil behavior of different soils [16,17]. These advances have resulted in the evaluation of clogging potential in clay-rich soils for TBM excavation and the mitigation of this issue [18], and have also resulted in the analysis of working mechanisms and the development of new chemicals for application [12,19]. Also of high interest are the surveying and modeling of the soil behavior in the pressure chamber [20–22]. The current article reviews the application of soil-conditioning chemicals in Switzerland; it does not cover all the advances and research that have occurred in soil conditioning in recent years.

### 2.3. Environmental aspects

The use of polymers and other chemical additives leads to chemically treated soil material. For every project, a risk analysis must be carried out with regard to the environmental impact of the substances used (especially on the groundwater). In general, the ecological relevance of the chemicals used is relatively low [23]. The impact of the products on the environment is judged on the basis of how their toxicity affects aquatic organisms in terms of $LC_{50}$[†] and $EC_{50}$[‡] values, and on their biodegradation properties. In general, due to their influence on water surface tension, foams are more dangerous for aquatic organisms and show lower $EC_{50}$ values (between $10\ mg{\cdot}L^{-1}$ and $100\ mg{\cdot}L^{-1}$, although these are often higher for current products). Surfactants are generally biodegradable and degrade within a relatively short time. In contrast, although polymers have lower biodegradation rates, they have high $EC_{50}$ values; therefore, polymers can be classified as harmless to humans and the environment.

## 3. Experiences in mechanized tunnel drilling in Switzerland

### 3.1. Overview

Constructed from 1989 to 1993 using a mix shield, the Grauholz tunnel was the first TBM-bored tunnel in loose ground with a large diameter (>10 m) in Switzerland [24,25]. It was followed by the construction of the Oenzberg tunnel in 1999 and the Zimmerberg base tunnel in 2000–2001; both of these tunnels used TBMs excavating in SM in the loose ground sections [26]. In 2007, the first and (thus far) only large-diameter EPB-TBM was installed in Switzerland for the Büttenberg tunnel and the Längholz tunnel near Biel [6,27]. For the Weinberg tunnel (2013) and the Eppenberg tunnel, slurry shield TBMs were recently installed again [28]. All tunnels in Switzerland have a combination of rock sections (often molasse) and sections of heterogeneous loose ground with varying properties (Fig. 1). The groundwater table also often varies over the tunnel length.

Table 2 [6,24,26,27] gives a summary of the respective diameters of these tunnels, along with simplified descriptions of the geology encountered for each. Fig. 2 shows the corresponding cutterheads. In addition to the tunnels with large diameters, sev-

† $LC_{50}$ refers to lethal concentration 50; that is, this concentration of the test substance in water is lethal for 50% of the tested organisms during the test period.

‡ $EC_{50}$ refers to effect concentration 50; that is, this concentration of the test substance in water causes effects in 50% of the tested organisms during the test period.

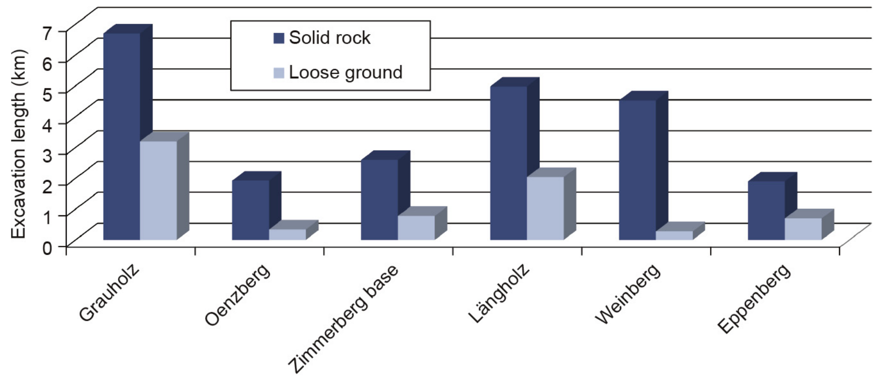


**Fig. 1.** Summary of TBM excavations in Switzerland with a large diameter (>10 m), loose ground sections, and necessary full-face support.

**Table 2**
Overview of the diameter and geology of large-diameter tunnels in loose ground in Switzerland (after Refs. [6,24,26,27]).

| Tunnel | TBM | Diameter | Geology |
|---|---|---|---|
| Grauholz | Mix shield | 11.60 m | Molasse, Quaternary gravels, sands |
| Oenzberg | Mix shield | 12.30 m | Molasse, moraine, glacial and fluvial gravels, sands |
| Zimmerberg base | Mix shield | 12.36 m | Molasse, fluvial gravels, lacustrine clays |
| Längholz | EPB shield | 12.60 m | Molasse, lacustrine clays, moraine, silty sands |
| Weinberg | Mix shield | 11.20 m | Molasse, gravel, moraine, lacustrine clays |
| Eppenberg | Mix shield | 12.75 m | Molasse |

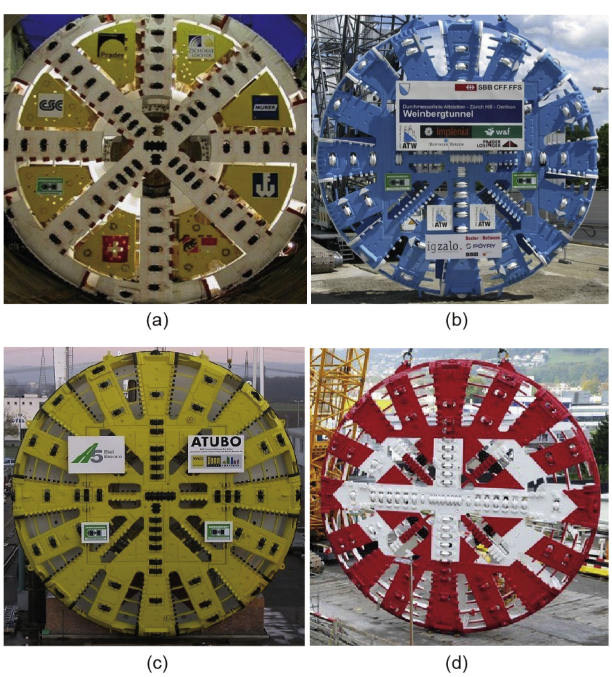


**Fig. 2.** Cutterheads for (a) the Zimmerberg base tunnel (1999) and the Oenzberg tunnel (2001), (b) the Weinberg tunnel (2008), (c) the Büttenberg tunnel and the Längholz tunnel (2008), and (d) the Eppenberg tunnel (2016).

eral TBM excavations took place with diameters from 5 m to 10 m; examples include the Thun flood-relief tunnel (diameter 6.3 m) and the pedestrian passenger tunnel at Zurich airport (diameter 6.3 m). For most of these smaller tunnels, the working face was successfully supported using the SM. In the Thun flood-relief tunnel, highly permeable gravels under the groundwater table were supported with the help of a heavy bentonite suspension (i.e., a mixing ratio up to 80 $kg{\cdot}m^{-3}$).

## 3.2. Slurry shields

### 3.2.1. Grauholz tunnel

The geological conditions along the Grauholz tunnel are strongly influenced by glacial deposits and are therefore very heterogeneous. The tunnel excavation crossed glacial tills in and above the groundwater, as well as a larger part of molasse in the middle of the tunnel [25]. Partially sandy gravels with high permeability and a low silt content (<6%) were predominant. The bandwidth of the grading curves is shown in Fig. 3.

During the excavation process with slurry support, no major problems occurred. However, tool changes in the strongly permeable ground were quite challenging. For these situations, the face stability was guaranteed by air pressure application. In two instances, instabilities at the tunnel face occurred. To prevent the loss of air for the drilling stoppages, the supporting slurry was additionally conditioned as follows [25]:

- The amount of silt content in the suspension was kept artificially high by only partially separating the slurry. The higher density of the slurry with the fines content guaranteed lower penetration depths of the slurry.
- The addition of sawdust and polymers to the bentonite suspension led to additional clogging and sealing of the pores. The artificially created membrane helped to guarantee the stability of the tunnel face.

### 3.2.2. Zimmerberg base tunnel

Along the Zimmerberg base tunnel, a mixture of moraine, gravel, and clay deposits was encountered (Fig. 4) [9]. In particular, the gravels had very high permeability, of up to $k > 1 \times 10^{-3}\ m{\cdot}s^{-1}$, interstratified by blocks and boulders. The tunnel section is partially below the level of the groundwater.

Due to the presence of zones with high permeability, there was uncertainty concerning the reliability of the slurry support. Therefore, the following measures were taken during the excavation with slurry support [26]:

- Slurry was partially conditioned, with bentonite (40 $kg{\cdot}m^{-3}$), sand (100 $kg{\cdot}m^{-3}$), polymer (Carbogel C190, 0.5 $kg{\cdot}m^{-3}$), and Vermex (expanded vermiculite, 20 $kg{\cdot}m^{-3}$) being used. When used with the polymer and sand, vermiculite affects the clogging of pores of the gravel and the buildup of the filter cake. Due to the additives that were used, the separation process of the slurry was significantly hindered; as a result, the performance of the chamber filter presses limited the efficiency of the excavation. Therefore, the conditioned suspension was used only in exceptional cases.

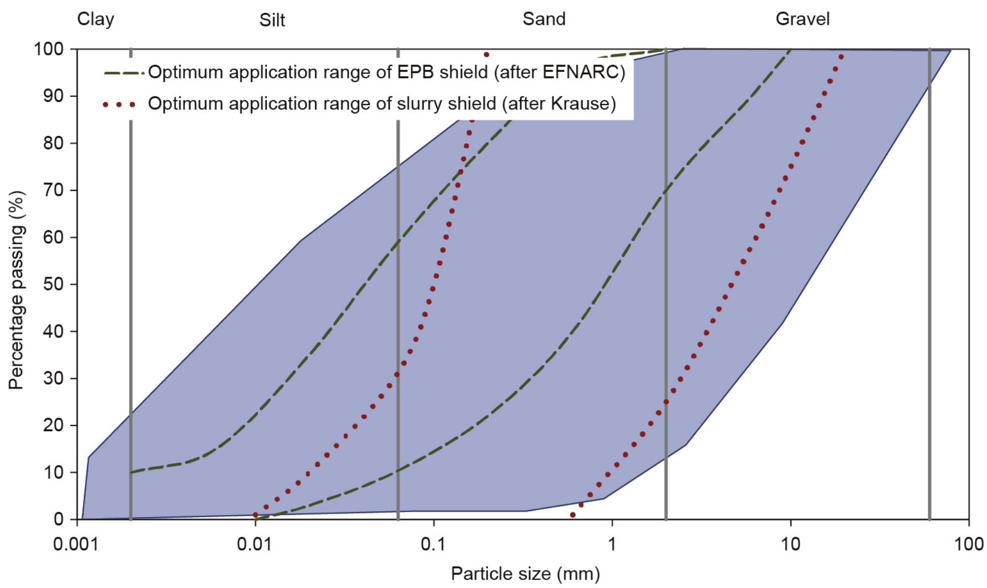


**Fig. 3.** Bandwidth of the grading curves of the Grauholz tunnel (after Ref. [25]).

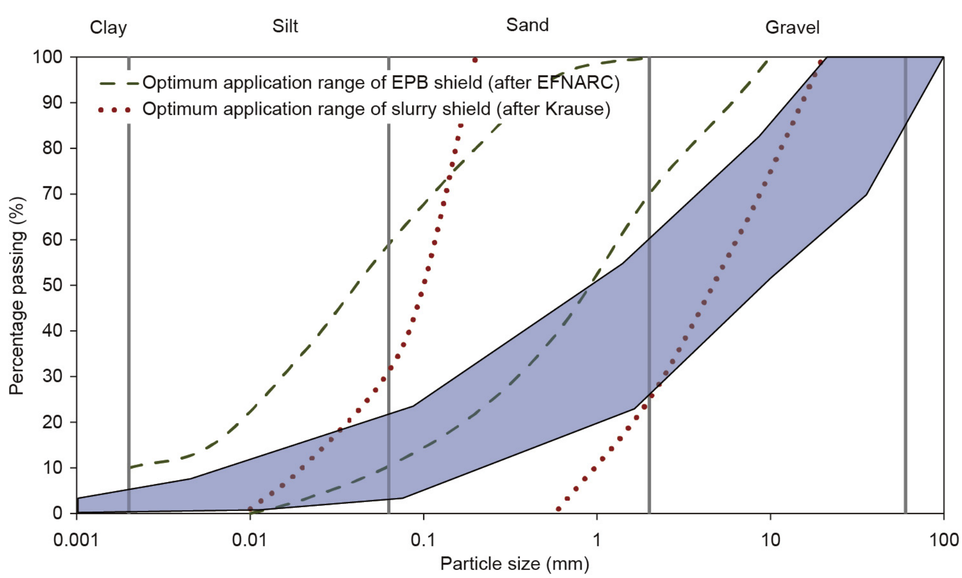


**Fig. 4.** Bandwidth of the grading curves of the Zimmerberg base tunnel (after Ref. [9]).

- Other additional supporting measures (e.g., injections) guaranteed a reduced risk of face collapse and high settlements during stoppages and tool changes at the drilling head.

### 3.2.3. Weinberg tunnel

The Weinberg tunnel crosses the upper molasse and, over a distance of 280 m, different loose soil deposits with differing properties. The ground moraine of the glacier, which includes boulders and partially fine sands, is overlain by clay deposits. The gravels of the Limmattal, which have high permeability ($k = 3 \times 10^{-3}$ $m{\cdot}s^{-1}$), were also observed. The composition of the supporting slurry for different geological conditions was determined in preliminary tests, and is summarized in Table 3 [28].

Excavation in the zones with high permeability occurred without significant issues, although the following minor problems were reported:

- Leakages in the pipe connections of the slurry circuit after the start of the excavation.

**Table 3**
Slurries used for excavation of the Weinberg tunnel (after Ref. [28]).

| Soil layer | Slurry used |
|---|---|
| Molasse | Water + bentonite (10 $kg{\cdot}m^{-3}$) |
| Moraine | Water + bentonite (30 $kg{\cdot}m^{-3}$) |
| Clay deposits/gravels | Water + bentonite (40 $kg{\cdot}m^{-3}$) |
| Soil layers/gravels with $k > 1 \times 10^{-4}$ $m{\cdot}s^{-1}$ | Possible addition of Ibeco Seal or the polymer Carbogel C190 |

- Low excavation rate (3 $m{\cdot}d^{-1}$) in the molasse, due to the limited performance of the chamber filter presses and the high amount of fines in this soil layer.
- Sustained interruption of the excavation due to soil clogging at the drill head and the resulting flushing for removal.
- Pressure loss in the clay deposits at air pressure entrances; and
- Wear and hindrance due to existing construction elements in the ground, such as retaining walls or slurry walls.

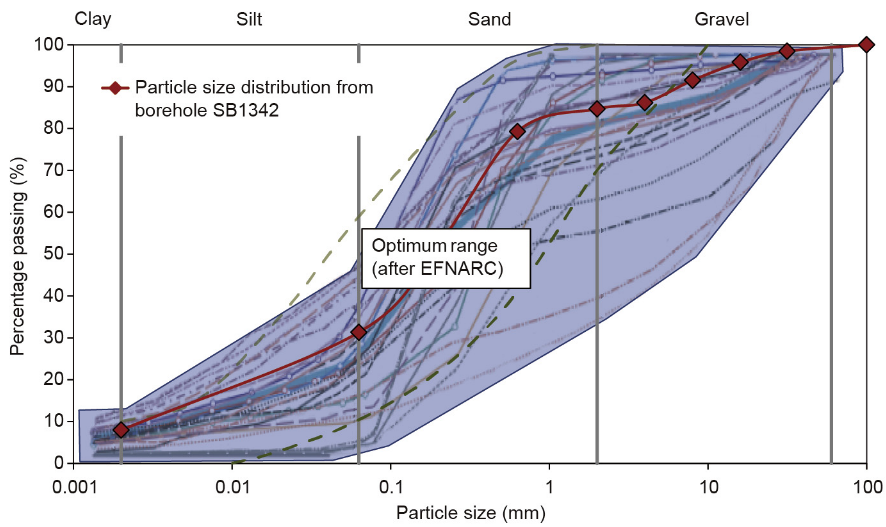



**Fig. 5.** (a) Bandwidth of the grading curves of the different soil layers along the loose ground section, and averaged grading curve of the tunnel section at location SB1342; (b) sample with *in situ* water content (fraction <4 mm).

### 3.3. Earth pressure balanced shield

#### 3.3.1. Geological conditions in the loose ground section of the Längholz tunnel

The geological conditions along the Längholz tunnel are very heterogeneous as well [6,27]. In total, 12 different soil layers, from gravels over silty sands to lacustrine clays, were identified. The soils were deposited during the last glacial period and are therefore pre-consolidated. Along the same tunnel section, different soil layers with varying properties were predominant. In addition, the hydrological conditions were difficult, with the groundwater table being located between 3 m and 10 m over the tunnel apex. Fig. 5 shows the bandwidth of the grading curves of the different soil layers, which were determined in the laboratory using material from different boreholes. In the zone of the lowest vertical cover of about 6 m, two different soil layers were predominant (a sandy gravel and a sandy silt). The grading curve for each separate soil is not ideal for an EPB drive; however, the grading curve over the total cross-section (combining both layers) was shown to be in the middle of the optimum range (Fig. 5). For an EPB drive, the properties of the mixed soil over the whole tunnel section are important and can offset the extreme properties of problematic soil layers (e.g., high permeability).

#### 3.3.2. Influence of conditioning on soil properties

In order to maintain the supporting pressure during the excavation process, the injection of conditioning agents was appropriate. The following main effects were thus induced by the application of conditioning agents:

- The incorporated foam bubbles guaranteed a certain compressibility of the excavated soil mass, and therefore reduced pressure fluctuations.
- The lubricating properties specifically supported the production of a more homogeneous earth mud and mud flow through the machine.

The optimum conditioning parameters are normally evaluated based on laboratory conditioning tests such as slump tests, shear tests, fall cone tests, or others. The tests are chosen according to the geological conditions and the desired effect of the chemicals. The following simple slump test presents data on the original soil material from borehole SB1342 of the construction site, along with one of the foam additives that was used. The soil preparation procedures followed the general preparation procedure given in Ref. [12]. The mixtures were prepared with a Hobart mortar mixer, which mixed different foam volumes—that is, foam injection ratios (FIRs)—with the basic soil with a defined water content. Based on these laboratory tests, the efficiency and ranges of soil-conditioning parameters could be estimated (Table 4).

The effect of the foam is demonstrated in Fig. 6. Foam application essentially increases the air-void ratio ($V_{\mathrm{air}}$) in the Biel soil. The injected foam is relatively resistant to mechanical action in the pressure chamber, which allows the foam bubbles to be incorporated into the soil matrix. This leads to an increase in air volume in the soil of 15%–25% at the suggested FIR of 20%–40% (both parameters are related to the volume of *in situ* soil). The high $V_{\mathrm{air}}$ allows a better control of the pressure in the chamber and acts analogously to the air cushion in a slurry shield.

The conditioned soil material must be squeezed through the TBM while producing as little torque and wear as possible. On the other hand, a certain soil resistance is essential in order to guarantee the supporting pressure on the tunnel face, which ensures the face stability as well as small settlements at the surface and in the surrounding soil. The positive effect of foam conditioning on the deformation properties of soil samples from borehole

**Table 4**
Soil-conditioning parameters according to laboratory tests.

| | Parameter |
|---|---|
| Conditioning chemical | Rheosoil 143 |
| FIR: Injected foam volume related to volume of *in situ* soil to be excavated (after Ref. [29]) | 20%–40% |
| Foam expansion ratio (FER): Volume of foam related to volume of foaming solution (after Ref. [29]) | 10% |
| Weight concentration of foaming chemical related to added water-foam mixture | 3% (corresponding to 0.6–1.2 $\mathrm{L{\cdot}m^{-3}}$) |

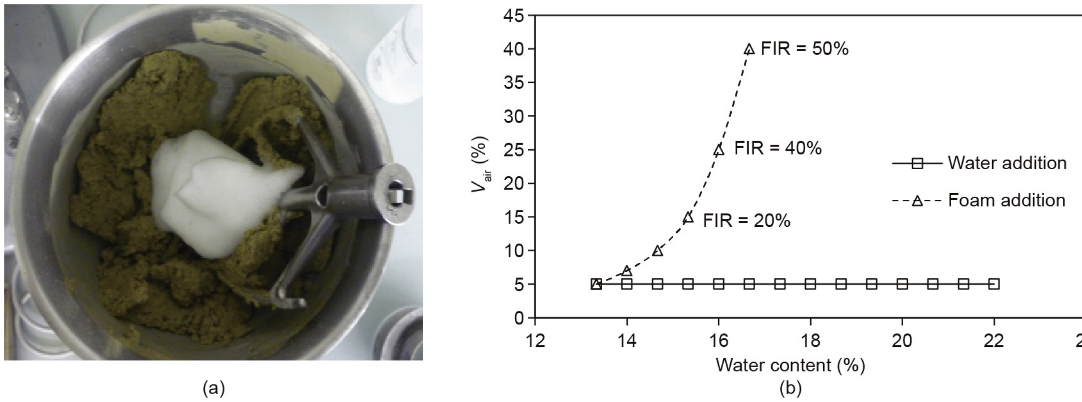


**Fig. 6.** (a) Mixing of soil sample with foam; (b) impact of foam addition for different FIRs on the $V_{air}$ in the Biel soil.

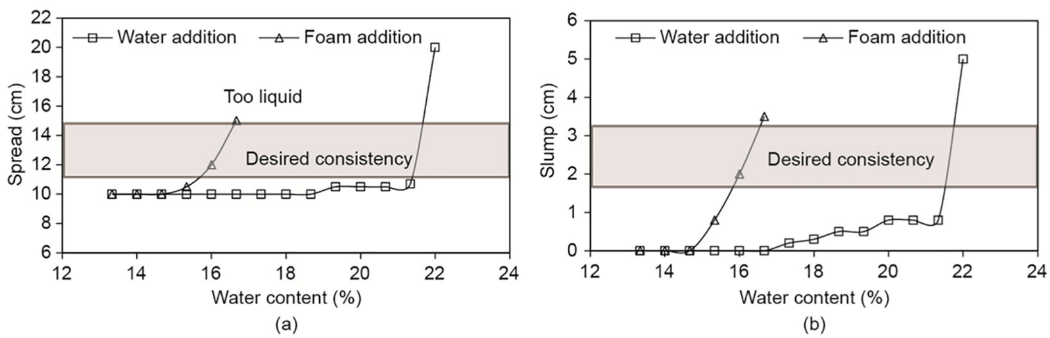


**Fig. 7.** Influence of water and foam addition on the slump behavior of the Biel soil (mini slump test with cone height $H$ = 60 mm, lower cone diameter $D_1$ = 100 mm, and upper cone diameter $D_2$ = 70 mm). (a) Spread behavior; (b) slump behavior.

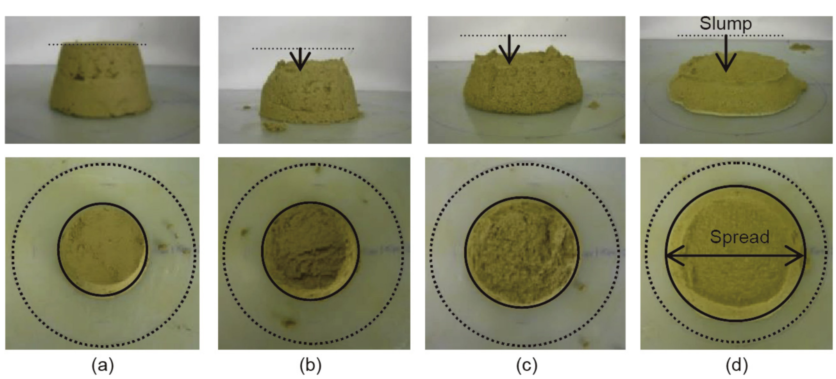


**Fig. 8.** Slump flow tests with the mini slump test (cone height $H$ = 60 mm, lower cone diameter $D_1$ = 100 mm, and upper cone diameter $D_2$ = 70 mm) and mixtures with different foam additions (all mixtures have the same overall water content). (a) FIR = 0; (b) FIR = 20%; (c) FIR = 40%; (d) FIR = 50%.

SB1342 is demonstrated in the slump flow test (Figs. 7 and 8). Without the addition of conditioning agent, the silty soil does not show a plastic behavior. A critical water content can be identified, at which the soil consistency changes from solid to liquid. This behavior is also manifested by the missing plasticity index of the *in situ* soil at this location. The addition of foam has two main effects: It reduces the amount of necessary liquid to be added in order to reduce the soil resistance, and it permits the development of a certain plastic range to be observed.

*3.3.3. Injection rates from the construction site*

The amounts of injected chemicals varied to a large extent, depending on the detailed geological conditions (between 0 L·m$^{-3}$ and 1.2 L·m$^{-3}$). To reduce the environmental impact, the injection rates were kept to a minimum.

In the zone of low overburden, the control of the supporting pressure was of high importance; in general, small settlements and no problems were encountered when drilling through this section.

For the maintenance works in the chamber, several entrances under air pressure were necessary. A bentonite suspension was pumped through the foam injection lances into the chamber in order to allow the buildup of a membrane, the application of air pressure, and tool changes and revisions to be carried out.

*3.3.4. Deposition and environmental aspects*

For the Längholz tunnel construction site, batch leaching tests were carried out according to the Swiss legal regulation (TVA (F-22)) prior to the excavation. These tests allow the determination of the leaching amounts of the different chemical compounds of the

**Table 5**
Maximum permissible values of DOC.

| | DOC in inert waste | DOC in groundwater |
|---|---|---|
| In Switzerland | 20 mg·L$^{-1}$[a] (B-material[b]) | 1–4 mg·L$^{-1}$[c] |
| In the European Union | 500 mg·kg$^{-1}$ dry waste[d] | 1–4 mg·L$^{-1}$ |

[a] Evaluated in the leaching test according to TVA (F-22) with distilled water and a liquid/solid ratio of 10:1.
[b] After the Swiss federal regulation *Verordnung über die Vermeidung und Entsorgung von Abfällen* (December 2015).
[c] After the Swiss federal regulation *Gewässerschutzgesetz* (November 2015).
[d] After the European Environment Agency's guideline *Guidance on Sampling and Testing of Wastes to Meet Landfill Waste Acceptance Procedures* (2005).

additives under laboratory conditions. The amount of dissolved organic carbon (DOC) is of primary interest; threshold values for this substance exist for the maximum concentration in different classes of material disposal. In order to be categorized as an inert material, the concentration of DOC in the material should not exceed a value of 20 mg·L$^{-1}$ (concentration in the liquid substance evaluated in the batch leaching test). A further threshold value exists for the maximum concentration of DOC entering the groundwater (1–4 mg·L$^{-1}$) (Table 5).

The preliminary tests were used to determine the critical amount of injection chemicals leading to a specific class of disposal. Trough-specific monitoring during the excavation surveyed the concentration of DOC, and it was confirmed that the specific values for the disposal classes were not exceeded. A further problem of material deposition was the soft and sometimes almost liquid material consistency, especially in geological zones with low fines content of the *in situ* soil. As shown before, the application of an optimized chemical addition can reduce the liquefaction tendency of the material by introducing some plasticity and minimizing the injection of water. A higher volume of injection chemicals is accompanied by a greater degree of environmental pollution and higher costs for disposal, leading to a certain conflict of interest. The excavated material could be partially distributed and compacted mechanically, as shown in Fig. 9; unfortunately, this mechanical treatment was not always possible.

## 4. Conclusions for further projects

The variability of the geological conditions in Switzerland requires an excavation method that is adaptable to different soil compositions such as rock, soft rock (molasse), and a variety of loose soils with different properties within the same tunnel excavation. Developments in TBM technology and in chemical additives have significantly expanded the application range of mechanical excavation methods. This process is still ongoing; for example, for excavations in highly permeable sand and gravel, new high-density slurry/polymer combinations have been recently developed.

For every mechanical excavation with a large diameter, the application of conditioning agents must be considered independently of the specific excavation mode (i.e., whether SM or EPBM). Their application must be planned thoroughly. The continuous development of these chemicals (both foams and polymers) has improved their application, and allows enhanced control of their properties for earthworks application. In this context, their resistance to pH changes and salts in general and their biodegradation properties are of importance. In addition, chemical additives are being optimized with respect to their environmental impact; their aquatic toxicity values and their total organic carbon (TOC) values are continually being reduced.

To evaluate an excavation method, the pro and cons of SM or EPBM must be investigated. With the existing technology, EPBM can bring the following benefits to an excavation:

- If different soil layers over the cross-section are predominant (i.e., under mixed face conditions), soil layers with extreme conditions (e.g., high permeability) are not particularly critical. The mixing process generates an artificial soil with medium properties.
- If the geological conditions are favorable for excavation, the TBM advance rate is not limited by the separation facilities and separation processes. This allows faster excavation rates and results in reduced space requirements and economic benefits.

Early consideration of the disposal aspects is of special importance to the success of every tunneling project with mechanical excavation. The application of EPB-TBMs produces a large amount of chemically treated material that must be deposited in an appropriate landfill with no risk of groundwater contamination. In addition, the application of bentonite and additives for slurry excavations produces further excavation material that must be disposed of. An early evaluation of possible disposal sites with the appropriate environmental risk analysis is absolutely essential and can prevent further problems from occurring later on during the project. The handling of the material consistency after the excavation should also be considered in the disposal concepts. Secondary treatment of the material after excavation with lime or other workability improvement methods can prove beneficial.

An environmental risk analysis and consideration of the conditioning and disposal aspects are key parameters for every project; these factors can influence the choice of the excavation mode and of the TBM, and should therefore be carried out prior to the decision on whether to use an EPB or slurry shield. In the early project phases, the variability of the detailed excavation mode should be maintained.


**Fig. 9.** Disposal of conditioned soil with favorable consistency.

## Compliance with ethics guidelines

Rolf Zumsteg and Lars Langmaack declare that they have no conflict of interest or financial conflicts to disclose.

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