

Safety System in Urban Tunnelling; The Zimmerberg Tunnel

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1 Introduction

In tunnelling the growing variety and complexity of technical problems as well as the high safety levels required during construction call increasingly for a methodical procedure in the analysis and handling of risks. Thus, in recent years, risk management, system safety, safety planning etc. have been applied more and more in underground construction.

In the present work we have a threefold aim: First, the clarification of the most important terms and concepts in relation to 'risk and safety', in order to elucidate their basic meaning and present their relationship to each other in a general form. Second, the concept of the 'safety plan' is discussed in detail for the special case of urban tunnelling. Third, the powerfulness of the theoretical concepts is illustrated by means of an example, i.e. for a section of the Zimmerberg Tunnel.

2 Concepts

One of the most important achievements in the field of 'risk and safety' is its own specific conceptual structure. The fact that important technical terms are often used in a different sense or that several words of similar meaning stand for more or less the same conceptual content derives from the broad spectrum of applications and the socio-political relevance of the topic. The expressions used in colloquial speech play a decisive role, so that it is always necessary to check the original meaning of the terms.

In the following we discuss each of the most important basic concepts and point out their interrelationship. Listing the concepts is not done alphabetically but according to contextual criteria. Most terms have a clear reference to their object, which is why a good overview of the concepts provides a direct introduction to the problem as a whole.

Damage: Negatively evaluated consequence of an event or a process [1]. As a rule, damage is equated to the loss or the impairment of something of value. The type, amount and awareness characterise the damage: The *type* of damage can be subdivided into damage to person or property, increased costs, extended deadlines, loss of reputation, etc. The possible *amount* of damage is obvious in some individual cases; usually however it has to be determined or estimated by means of demanding detailed investigation. The *awareness* of damage has a complicated background and is important for risk acceptance (see also Risk Evaluation).

Uncertainty: Opposite of definiteness. It finds its expression in three types [2]. Statistically given variability, non-statistically given variability and ignorance. Here we have a concept of great breadth. Thus in common everyday language there is a whole range of expressions frequently used in connection with risks which allow different nuances of meaning. Take for example expressions like certain and uncertain, safe and unsafe, definite and indefinite, doubted and undoubted, possible and impossible, probable and improbable, questionable and unquestionable.

Probability: Assumed correctness or practical certainty [3]. The affinity to *uncertainty* is obvious. The term comes from the Latin word 'versimiles', i.e. true + similar [3]. In the strict mathematical sense probability is the quantitative estimate of the possibility that an accidental event takes place [4].

An event is accidental if, under given conditions, it can take place or not take place. If under certain conditions one of n successive events must take place, whereby none of the events has preference over another, one says that these events have the same probability $w =$

$1/n^1$. The probability of an arbitrary event is between 0 and 1.

Risk: The possibility that, due to a state or a process, damage can result [1]. According to another definition one understands damage evaluated on the basis of probability of occurrence and amount of damage. In a more restricted sense risk R is defined as a product of amount of damage A and probability of occurrence w: $R = A \times w$. Thus the definition consists of two elements: damage + uncertainty. The word risk is derived from the verb 'risciare', which in colloquial Italian means 'run into danger' or 'dare to attempt something', and originally from the common Latin 'risicare' (negotiate obstacle). In the Greek the word 'rhiza' stands for root, rocks [3].

If one is concerned with events and processes, which are only due to technology, one speaks of 'technical risks'. These are unlike so-called business risks such as those investigated by firms. Here the saying "The bigger the risk, the bigger the chance of profits" is apt. In contrast, with technical risks involving the safety of persons it is inappropriate to speak of chance in the sense of stroke of luck or favourable opportunity [3].

Danger: Threat of damage [3]. State or process from which damage can arise [1]. It is clear that danger and risk are related words. Expressions like 'risk of danger', 'threat of risk' or 'risk potential' are pleonasm and have to be rejected (or at least avoided). The expression 'risk of loss' is also a linguistic inconsistency, since the term risk already implies the possibility of loss. The main difference between danger and risk is that only for the latter is there a mathematical definition.

Hazard: Danger related specifically to a particular situation or object [1].

Hazard Scenario: According to the relevant Swiss Code [5] this is a possible critical situation or an undesired event for a structure. In the following we mainly employ the term 'undesired event'.

¹ For instance, in the case of a game of dice the condition for statistical variability is fulfilled, so that the probability of occurrence equals one of the six numbers, $w = 1/6$. If, however, there is some uncertainty whether all 6 numbers are present only once and not more than once (falsification), then this condition is not fulfilled and a numerical treatment of the probability is impossible. In estimating the possible outcome of a throw other factors, which cannot be handled mathematically, have to be taken into consideration, like the moral character of the player.

Undesired Event: Occurrence that can lead to detrimental consequences or damage. This term involves the terms 'risk' and 'damage', but relates primarily to a process and inquires about its probability of occurrence or about the extent of possible damage. The expression 'undesired event' is emotionally less encumbered than the word 'risk'.

Risk Analysis: Systematic procedure to characterise an undesired event regarding frequency of occurrence and the amount of damage [1]. According to another definition – going under the name 'hazard analysis' - it signifies a systematic identification and characterisation of risks [6]. The methods of risk analysis differ according to the area of application.

Risk Management: Use of measures and methods with the goal of achieving the desired safety [1]. The term is often employed in the same sense as risk analysis, risk control, system safety etc.

Types of Risk: Characterisation of risks according to specific evaluation criteria. [2].

Accepted Risk: As fixed by codes [1] this signifies an admissible known and therefore acceptable risk according to clear evaluation criteria. In the descriptive sense, by it one understands a residual risk after the application of planned safety measures. It comprises accepted, possibly falsely estimated and possibly unforeseen risk [1]. According to this definition it is not meaningful to speak of the 'minimisation' of a risk, because such an action is completely non-binding. In the mathematical sense a risk does not usually possess a minimum, so that consequently a successful minimisation would always have to result in its disappearance.

Risk Control: Reducing risk to the accepted risk. Synonym for 'overcoming risks' [7].

The above technical terms all concentrate on the possibility of loss and damage. There are, however, a number of expressions which point to the opposite idea of being protected from loss and damage. The connection between the two categories is obvious. In many cases there is even an unmistakable duality between the conflicting concepts.

Safety: To be protected, protection [3]. Complete absence of a particular risk or non-existence of a risk

beyond the acceptable degree [1]. Thus danger is included in the concept of safety.

Safety Concept: Totality of activities and precautions with the aim of limiting the risks in a system to the accepted risk; closely connected with 'risk management'.

System: Collection of parts, each independent of one another, which are interlocking or interacting [3].

System Safety: State of a system having acceptable risk (see also Safety Concept). The expression 'system safety' is used interchangeably with 'risk management' in the English speaking world.

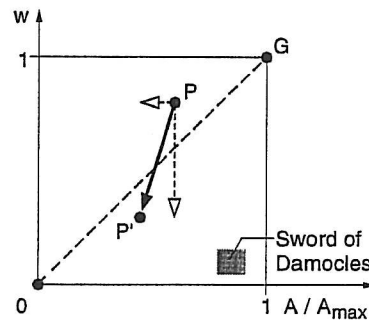
The terms in the first category, like loss, damage, danger, hazard, hazard scenario, etc., have their proper place in risk analysis and risk management. Those in the second category, with terms like protection, safety, safety concept, safety plan, certainty, reliability, etc., have more to do with communication tasks. The emotional association of the first category with fear, anxiety, doubts, etc., is also evident, just as the second category with a feeling of being protected, of having no reservations, etc. One thinks for example of the expressions 'dam catastrophe' and 'dam safety', which represent two sides of the same coin, but which create quite different emotions: worry – doubt on the one hand, calmness – confirmation on the other. Although the increase of safety is the same thing as reducing the risks, depending on the situation the one or the other formulation is preferred.

3 Risk Evaluation

Within the sphere of risk management 'risk' is regarded as an entity, which, depending on the nature of the problem at hand, is evaluated either quantitatively or qualitatively. An evaluation, regardless of how it is carried out, proceeds in three steps: evaluation of the possible amount of damage, of the probability of occurrence and of the combined effect of both. The combination is usually considered as a product of both factors, even if the lack of numerical values for the factors does not allow one to come up with an arithmetical operation. If, as a special case, the probability of occurrence can be quantified statistically as also the amount of damage, then one can use the formula given above, $R = A \times w$.

Fig. 1

Schematic representation of the quantities influencing risk



A/A_{max} : Relative damage

w: Probability of occurrence

In the case of most technical risks, especially those in tunnelling, the probability of occurrence can only be estimated and not specified according to the criteria of statistically given variability. Often the determination of the amount of damage presents great difficulties, so that risk evaluation usually has to be carried out qualitatively. The influence of the individual components A and w on R is illustrated in Fig.1. If one works with a relative amount of damage A/A_{max} , then both factors lie within the range 0 and 1. According to definition, the value of R, which one can visualise as a quantity plotted normal to the plane of the figure, vanishes along both co-ordinate axes. The straight line O - G represents an axis of symmetry and shows the direction of the biggest increase of the value of risk from the origin of the co-ordinate axes O to the point G.

If one wants to reduce the risk characterised by the point P ($P \rightarrow P'$) this is achieved by reducing the corresponding starting values A/A_{max} and w. Certain measures are specific, i.e. they either limit the damage or reduce the probability of occurrence.

A special case of risk is given by a very large amount of damage combined with an extremely small probability of occurrence (Fig.1). This type of risk is called the Sword of Damocles [2], which considering the low probability of occurrence is not an apt description². In practice this type of risk is not treated uniformly: Some always consider it as an accepted risk and from the very beginning it is really excluded and relegated to vague further considerations. Others make it the subject

² This is based on the story from antiquity with a sword hanging by horse's hair over the head of Damocles, the servant of the tyrant Syrakus. This denotes the risk with the greatest amount of damage (loss of life) combined with the highest probability of occurrence (tearing of the horse's hair)

of detailed investigations and study the possibility of applying extensive countermeasures to reduce or even eliminate it.

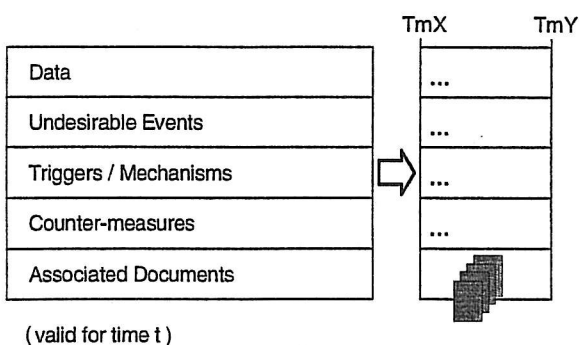
Finally, we want to draw attention to the fact that with many types of risk, besides the factors 'amount of damage' and 'probability of occurrence', other factors like reliability of estimation, reversibility of damage (e.g. damage to persons) consequences of delays (time between event and occurrence of damage) as well as mobilisation potential (conflicts with the public) have to be included in the risk evaluation [2].

In order to investigate the acceptance of a proven risk, besides the technical knowledge discussed above, an 'orientation knowledge' must also be included [2]. This orientation knowledge takes into account the demands of the public to be protected from damage (safety needs). If a risk was correctly determined (technical knowledge) and, on the basis of legitimate criteria, regarded as an accepted risk (orientation knowledge) then in the case of damage occurrence one cannot speak of a mistake on the part of those responsible.

4 Safety Plan in Urban Tunnelling

The term 'safety plan' was introduced into tunnelling practice some time ago, but there is still no generally accepted definition of what is meant by it. According to the most widely used sense of the term the safety plan is a tool of risk analysis and risk management. To a large extent it involves a visualisation of the objects it deals with, whereby for a clear cut system or subsystem the facts, assumptions, scientific knowledge, operational instructions, etc., are represented on a plan (Fig.2). The aspects of 'risk and safety', therefore, provide the client, consulting engineers, geologists, contractors, authorities, experts, etc., with a clear overview. Experience with the use of such a safety plan has been reported elsewhere [8, 9].

Fig. 2
Structure of a safety plan in urban tunnelling



The safety plan serves three purposes:

- a) The methodical recognition of possible undesired events, whereby experience plays a particularly important part³. In other words, it is a question of the determination of risk or the preparation of hazard scenarios. Behind these there are – as the word implies – graphical representations of events and mechanisms with undesired consequences. The great importance of this activity is evident alone from the fact that only recognised risks are taken into account in risk management since they alone can be eliminated or reduced.
- b) The assessment of the undesired event (see Risk Evaluation).
- c) The specification of measures to guarantee the required safety of the system (limiting the risks to an acceptable level). Since the unexpected presence of unfavourable geological or hydrogeological conditions is often the real origin of risks, it is very important to carry out an adequate geological investigation beforehand⁴ and the construction work has to be accompanied by a geologist. The so-called geological surprises are a fitting example of ignorance as a form of uncertainty.

In the execution of b) and c) the technical knowledge of those involved has priority, while in specifying the accepted risk, as mentioned above, the 'orientation knowledge' comes to the fore [2]. The ideal logical structure of the safety plan can be formulated as follows:

Idea → Analysis → Evaluation → Decision

As a rule such a procedure involves iterations working alternately with pictures and ideas.

Structure

The first step is to define, in the sense of a *system demarcation*, the tunnel section that should undergo a risk analysis by specifying the kilometric distances $T_m X$ and $T_m Y$ (Fig.2). The system can comprise a whole

³ Here one thinks instinctively on the half joking saying: "Experience is to experience what one doesn't want to experience."

⁴ The most striking example for the elimination of a high risk solely by geological investigation is the Piora Trough. Due to the initial risk of safety (technically), economic and respecting deadlines the project for the 57km long Gotthard Base Tunnel beginning in 1998 was postponed. It has been shown that the sugar like grains of dolomite under high water pressures do not extend to the level of the tunnel.

construction lot or just a part of it, as for example when passing under a building, bridge foundation or important traffic arteries. It is clear that all considerations apply only to a particular point in time, e.g. for a certain phase of planning, execution or geological investigation. Obviously, the safety plan has to be constantly updated according to the actual state of knowledge; therefore it is both time and space dependent.

Regarding the *facts* (Fig.2), in urban tunnelling a series of factors have to be taken into account: topography, whether a built-up area is involved or not, traffic routes, underground facilities, geology, groundwater conditions, foreign objects that lie with the projected tunnel profile or in the immediate vicinity of the excavation, trial boreholes, aspects of the construction method (especially the elements of the excavation supports), etc.

In the category *undesired events* the main interest in urban tunnelling is, on the one hand, collapse reaching up to the ground surface and, on the other, inadmissible settlements and their consequences.

In is now necessary to check all possible *triggering mechanisms*, which could lead to an undesired event. In the case of collapse up to the ground surface, for example, the commonest causes are the collapse of the working face (including the filling up and flooding of substantial stretches of tunnel) and failure of the roof supports. Other causes are often inadequate control of the groundwater, unexpected unfavourable geological conditions and defective execution of the work.

In the group *measures*, those precautions are listed which reduce the risks, given by the undesired event, to an acceptable level. In many cases, a particular risk can not only be reduced, but also even eliminated.

If one speaks of the *control* of a risk, one usually means the methodical execution of observations, especially field measurements (monitoring). These are also measures to reduce a risk, which is why they are included in the safety plan. Monitoring aims either to limit the amount of damage or the probability of occurrence, or both. One should, to be sure, note that such observations and measurements are only useful as a means of risk control, if the undesired event is progressive, i.e. with a sufficient time delay. Only if this is the case can the results of observation and measurement give clear indications or criteria (alarm values) for the use of the contingency measures. If, for

instance, there is failure of a structural element without advanced warning in the form of deformations (brittle failure) then deformation measurements are of no use for controlling the risk of failure.

A number of *documents* also belong to the safety plan (Fig. 2). These provide additional information, the reasons for doing something, instructions for actions to be taken, etc. Since the complexity of a safety problem often goes beyond the possibility of a visual representation, detailed reports are necessary. Reference to such documents is given at the corresponding place in the safety plan.

Execution

The safety plan always has reference to a particular project, prepared according to standard building and construction rules. It guarantees that the aspects of 'safety and risk' are recognised according to their importance. As a result modifications can be made to the original project together with appropriate contingency measures.

In order to achieve an adequate measure of objectivity it is recommendable to bring in experts who are not directly involved in the project or construction work. Since they are not bound by the deadlines and economic aspects of the project they are unfettered in their approach to the risk analysis. They may even be of the same firm or external experts. The setting-up of specialist advisory groups, which accompany the project dealing exclusively or at least in the main with questions of safety, has also been useful. In such groups the first priority is: avoid unexpressed (unarticulated) certainties, apply doubt methodically.

5 Zimmerberg Tunnel

In the following the above explanations are illustrated by means of the problems encountered when tunnelling through the soft ground section of the Zimmerberg Tunnel. The project has been described in detail elsewhere [10], so that here we only need to discuss those aspects that were relevant for the risk management study.

The 700 m long stretch in soft ground (Fig. 3), consisting of moraine, river gravel and lacustrine deposits, lies between the Portal Lochergut and the section in bedrock (Upper beddings of mudstone and sandstone). The river gravel includes blocks and erratic boulders (up to several cubic metres in size) and

exhibits a high permeability ($k \geq 10^{-3}$ m/s), whereas the lacustrine deposits are rather impermeable. In the moraine the water table lies at the elevation of the apex of the tunnel and falls gradually to about 4 m below the roof of the tunnel at the Portal Lochergut. Over the whole stretch the tunnel passes under a built-up area. In one case a tall building (the SSF building) lies directly over it, its underground garage lying within the cross section of the planned tunnel tube. This required the removal of the lowest parking floor as well as the underpinning of the whole building [10].

From the beginning it was clear that this construction lot exhibited a very high risk of failure involving a failure extending up to the ground surface. In this respect, among others, the following factors can be mentioned:

- large excavation profile ($\varnothing=12.3$ m)
- small depth of overburden (6 – 15 m) in comparison to the tunnel diameter
- small distance to the foundations of buildings (3 – 6 m)
- tunnel within the groundwater
- unfavourable character of the ground
- presence of foreign objects like prestressed anchors of neighbouring excavation support systems

If there is a case of failure reaching up to the ground surface in an undeveloped area (Fig. 4a), then the damage is limited to extra work and a possible delay in completion, which can be easily estimated. However, if such a failure occurs in a built-up area (Fig. 4b) the threat to the residents, the road-users, etc., due to the

Fig. 4
Ground failure up to the surface

a) in undeveloped area



b) in built-up area

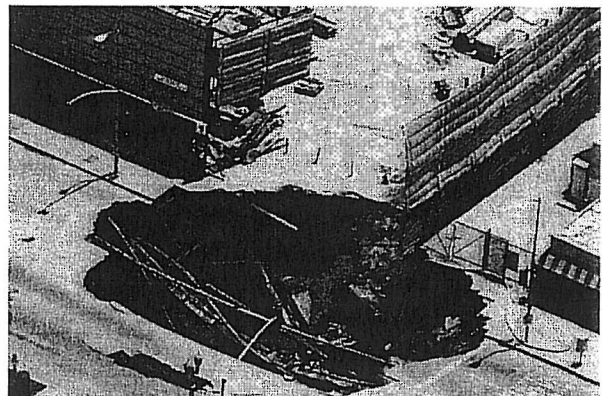
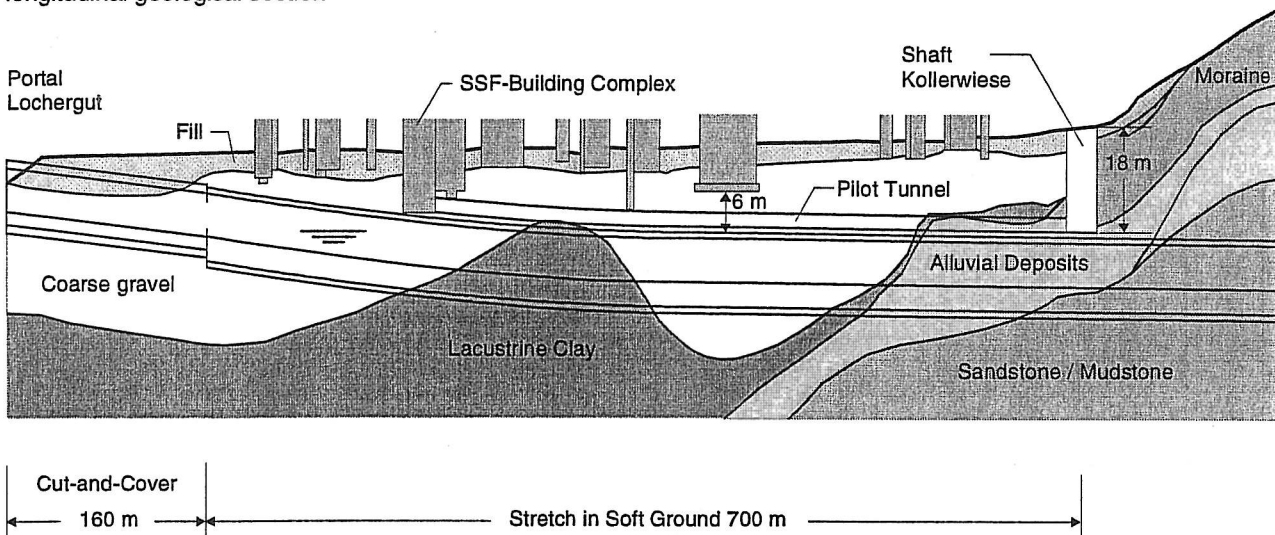


Fig. 3

The stretch in soft ground of the Zimmerberg Tunnel in longitudinal geological section



emotional aspects of such events, can lead to extremely difficult situations (mobilisation effect). For example, case studies from abroad show that people and politicians can lose confidence in technology following this type of failure. As a result even the work on projects had to be stopped which had nothing to do with the cause of failure. For good reason, therefore, the client in the case of the Zimmerberg Tunnel showed great interest in risk management already in an early phase of the project. The evaluation of different tunnel drive concepts led finally to the choice of a shield machine with slurry support (Hydroshield).

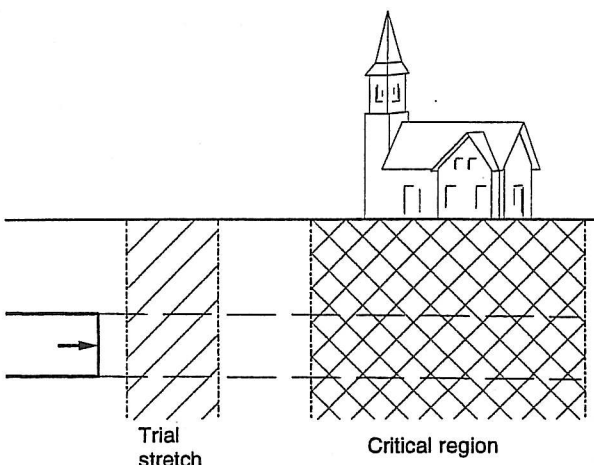
In many cases it is possible to clarify open questions purely empirically by having a trial stretch (Fig. 5). The amount of damage resulting from failure up to the ground surface is in this way limited and can be determined with sufficient accuracy in advance. The construction experience gained in this way can then be utilised in the decision making when driving under a critical zone. A similar case has been reported elsewhere [8].

In the Zimmerberg Tunnel, because of the heavily built-up area above it, there was no opportunity to carry out such a trial investigation. Therefore one had to choose a procedure, which despite an inadequate knowledge of numerous factors, still guaranteed the required safety against collapse of the ground above the tunnel over the complete stretch under consideration. It was shown, to be sure, that when driving the TBM from the rock into the soil particularly favourable conditions existed:

- minor importance of the roads that had to be driven under at the beginning
- relatively large depth of overburden (15 m)
- high in situ density of the moraine

Fig. 5

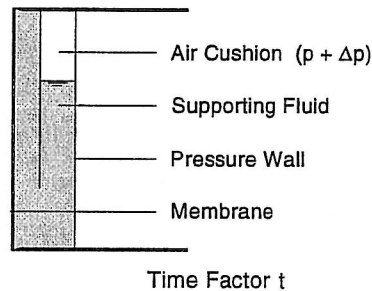
Location of a trial stretch, fitted with field instruments, near a critical driving zone [9]



Before we look in detail at the system safety in this construction lot, we want to remind readers of the support mechanism of the Hydroshield:

Fig. 6

Support mechanism in the Hydroshield method

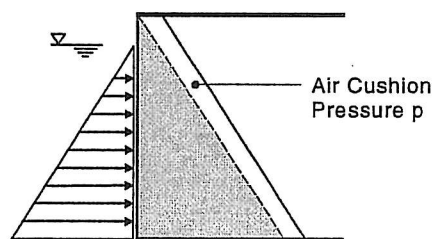


The working face is constantly supported by the slurry (suspension) during the removal of the soil (Fig. 6). Due to the continuously forming filter cake, usually the slurry cannot penetrate the ground, which is why one speaks of a membrane. The pressure of the slurry is regulated by the air cushion pressure. In the stability analysis the pressure fluctuations ($p \pm \Delta p$) associated with the operations and the time factor – especially the times of standstill – have to be taken into account.

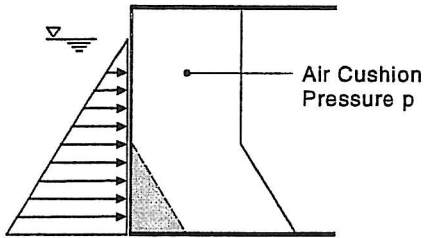
During driving the chamber with the slurry is completely full, so that the external water pressure shown in Fig. 7a is compensated by the slurry. In order to ensure stability of the working face even with little or zero soil cohesion, in addition an air cushion pressure is necessary. The conditions are quite different if the slurry is partially or completely lowered, as is the case when working in the chamber. Thus, in this case, the air pressure in the roof can be excessively large.

Fig. 7

Conditions during operation of Hydroshield



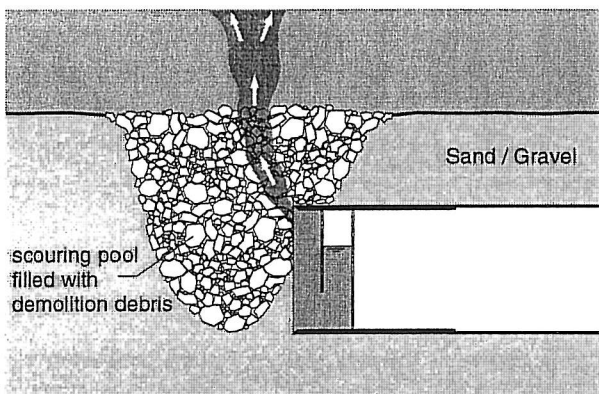
a) when driving



b) when inspecting the working chamber

After these preliminaries it should be clear that only a loss of the slurry support can cause a failure of the working face. During excavation or a pause for work in the chamber, the membrane action can be lost and the slurry can penetrate so far into the ground that the support action no longer suffices to maintain equilibrium. This could happen, for instance, if an unexpectedly high soil permeability is encountered, for which the slurry mix is not appropriate. Unexpected foreign bodies (pipes, sewers) can also exert an influence by allowing the slurry to escape in large quantities. A particularly striking example (Fig. 8) has been described by Braach [12].

Fig. 8
Example of the loss of slurry [12]

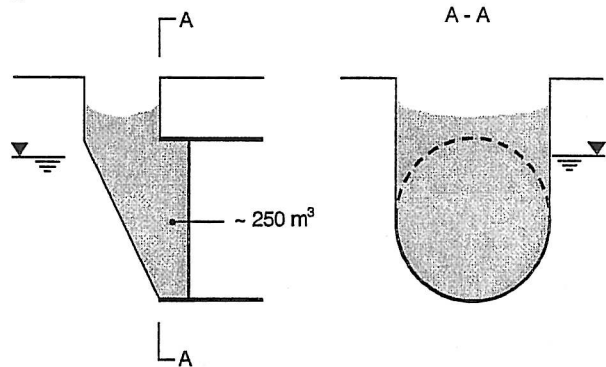


When carrying out maintenance work in the working chamber the air pressure can drop due to blowouts, which can also lead to failure of the working face. Factors which favour such a process are either a higher air pressure combined with a low permeability of the natural soil in the region of the roof or the loss of the membrane action of the filter cake due to drying out. One also has to pay attention to the lifting (break-up) of the soil at low overburden depths and the existence of foreign objects.

To try to estimate the consequences of a failure extending up to the ground surface when using the Hydroschild one has to remember that the amount of material (a mixture of soil and slurry) that breaks in or

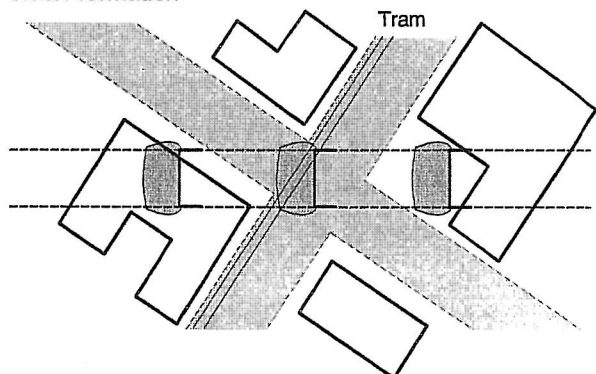
flows into the chamber is limited to the free volume of the working space if the lock gates are closed. In the case of the Zimmerberg Tunnel this volume amounts, none the less, to about 250 m³ (Fig. 9). Should failure of the working face occur, the slurry, due to its low unit weight, would be pressed upwards through the collapsed soil material (Fig. 4a)⁵.

Fig. 9
Filling up of the working chamber with soil debris due to instability of the working face and failure up to the ground surface



Depending on the free volume of the working space, in the case of failure up to the ground surface an external crater-like surface may form (Fig. 4). Its extent in length and cross section can be represented as in Fig. 9. In cohesive soil the crater walls above the crown of the tunnel are practically vertical. In the situation shown in Fig. 10 it is evident how the consequences of such a failure may differ according to the position of the crater along the tunnel axis.

Fig. 10
Varying amount of damage due to failure extending to the ground surface for different positions of the resulting crater formation

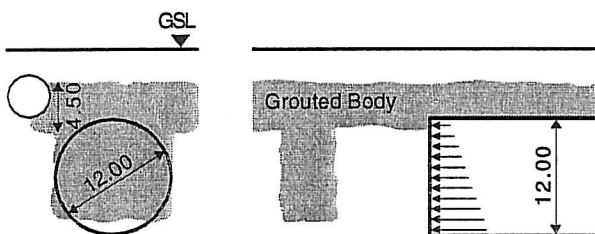


⁵ Therefore, with the conventional shield the advantage is pointed out that this mechanism cannot take place. But in a comparison of the two methods of driving there are many other influential factors.

Measures: In the river gravel, due to the presence of zones of extremely high permeability the reliability of the support action of the slurry is questionable. It was decided therefore to implement supplementary measures: From the Portal Lochergut up to the SSF building a 140 m long protective tube (umbrella) was constructed [10]. In addition, from the auxiliary shaft at Meinrad Lienert Platz a 470 m long auxiliary tunnel was driven parallel to the main tunnel. The latter served in the first place to create a continuous grouted body above the tunnel. In certain places the grouted body was enlarged to "stations" (Fig. 11), where pre-planned maintenance work on the cutting head had could be carried out. The auxiliary tunnel also offered the possibility, if necessary, of having access to the cutting head from any place as well as carrying out additional grouting work.

Fig. 11

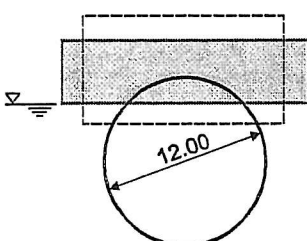
Measures to prevent failure to the ground surface: special slurry mix and through-going grouted body



Grouted body: Its main purpose was, in the case of collapse of the working face, to bridge over the resulting void thus avoiding a failure reaching up to the ground surface (Fig. 12). To achieve this goal the shape and size of the grouted body had to be determined together with the type of grout and the amount per cubic metre of soil, on which in turn the planning of the grid of drill holes and the grouting intervals along the individual drill holes depended. The criteria for the quality of the grouted body were a minimum required strength and a satisfactory homogeneity.

Fig. 12

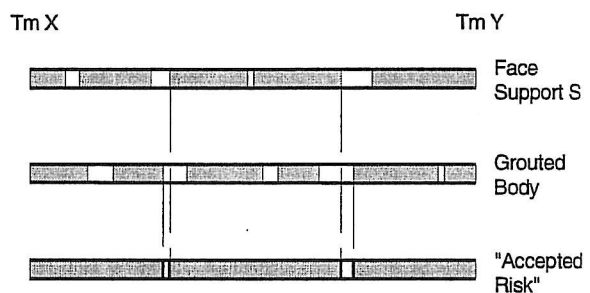
Selection of the shape and dimensions of the grouted body



Slurry support: In view of the erratic nature of the highly permeable river gravel it was decided to use a slurry mix which has already proved itself satisfactorily in the region of Zurich in the same river gravel with a different Hydroschild project [13]. The composition of this especially viscous slurry for 1 m³ of water was: 40 kg/m³ bentonite, 100 kg/m³, 0.5 kg/m³ of polymer material and 20 kg/m³ of Vermex. The latter is a brand name for exfoliated (expanded) vermiculite, consisting of aluminium-iron-magnesium-silicate, belonging to the family of micaceous minerals. Due to its high porosity the unit weight is only 8 – 9 kg/m³. Together with the polymer material and the sand, the vermiculite ensures that in the formation of the filter cake in river gravel deposits the large pores near the surface are filled. The shear strength (viscosity) of this mixture was determined according to the guidelines available in engineering practice. Decisive were the results of laboratory tests (so-called support pressure tests) to determine the maximum air pressure at which the filter cake was broken through for a particular slurry suspension in a standard test soil [13]. It ought to be mentioned, however, that such a composition of the slurry has disadvantages in operation (transport, separation), so that in the end it was only used in exceptional circumstances. For this reason the requirements placed upon the grouted body were increased.

Fig. 13

Accepted risk for a failure up to the ground surface from the coincidence of insufficient support of the working face and a defective place (insufficient strength) in the grouted body

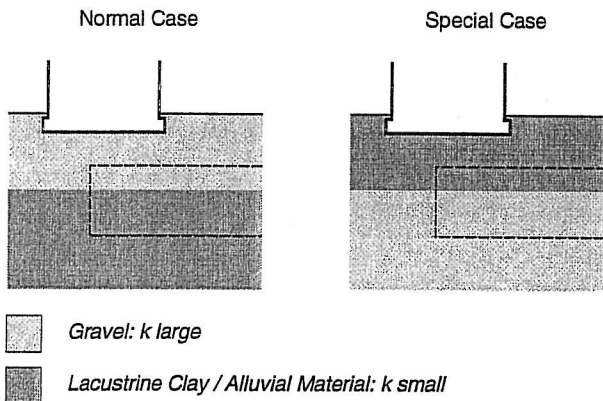


Although the basic decision was made, on the one hand to dimension the grouted cover for the case of a collapse of the working face, and, on the other hand, to design the slurry suspension for a higher soil permeability, there still remained some risk of a failure

up to the ground surface. The probability of occurrence of local defects in the grouted body or for the loss of slurry support action could always be classified as small thanks to the special efforts and controls carried out; the coincidence of both factors was judged to be much less probable⁶. The diagrammatic representation in Fig. 13 illustrates this train of thought.

Fig. 14

Cases of a 'mixed' working face



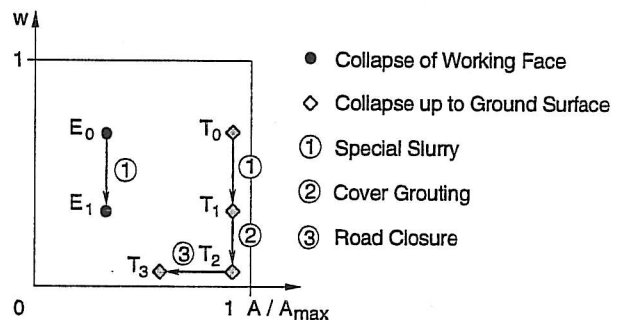
That the occurrence of defective places in the grouted body does not have to obey the law of chance (see under "Probability") we illustrate by way of a 'mixed' working face (Fig.14): Usually the river gravel lies above the lacustrine deposits. As a result the conditions for producing a grouted body and also for the support of the working face are favourable. With the reversed sequence of the layers the success of a grouted cover is doubtful, since due to the small depth of overburden both the grouting pressure and the quantity of grout are limited (causing cracking and heave of the ground surface). The membrane action in the underlying river gravel possessing high permeability also has to be questioned, so that in such cases the river gravel, because of the danger of collapse of the working face, also has to be grouted.

We return now to the question of risk management for the case of failure up to the ground surface. In Fig.15 the individual steps to reduce risk are presented in diagrammatic form. The starting point is given by the point E_0 , which represents the risk of collapse of the working face. Since such a collapse is the trigger for failure to the ground surface both events are deemed to have the same probability of occurrence. Since failure

to the ground surface results in the greater amount of damage, it is described in the diagram by the point T_0 . What does the choice of an improved slurry mix bring? It reduces the probability of occurrence of failure of the working face and moves the point E_0 vertically to E_1 . Thereby the point T_0 undergoes the same movement down to point T_1 . Requiring a throughgoing grouted body further reduces the probability of occurrence of failure to the ground surface, so that one arrives at the point T_2 ("The Sword of Damocles"). Now in order to achieve an acceptable risk it was necessary to close the roads and evacuate certain buildings for the period of driving the tunnel under them. The corresponding point is denoted by T_3 and represents at the same time the accepted risk.

Fig. 15

Reducing the risk of failure extending up to the ground surface to the accepted level



It should be pointed out that the explanations given here only give a broad outline of the problems encountered in the Zimmerberg Tunnel. For example, the requirement of a through-going grouted body also reduces to some extent the risk of failure of the working face. The same can be said of the extensive monitoring program (risk control), which also aimed to reduce the amount of damage in the case of failure extending up to the ground surface, but was not considered in Fig.15.

6 Final Remarks

'Risk and Safety' is a topic that encompasses engineering and has developed in recent decades to become a subject in its own right [14]. Its conceptual structure and its methods allow a rational treatment of risks. Tunnelling, especially urban tunnelling, can fall back on these fundamental principles. For example, the use of the safety plan in practice has proved to be very successful. The formalisation of the procedures as well as the visualisation of the facts and of the knowledge

⁶ The probability for the simultaneous occurrence of several events is the product of their individual probabilities of occurrence.

promotes clarity and enables the co-operation of experts from different professional backgrounds. The power and efficiency of the safety plan in urban tunnelling has again proved its value in the case of the soft ground section of the Zimmerberg Tunnel.

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