

# Water Leakages in Subsurface Facilities: Required Watertightness, Contractual Matters, and Methods of Redevelopment

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**Abstract**—Bitumen and plastic sealing materials, as well as watertight concrete, have been used in construction of underground structures for almost thirty years. The question of which type of sealing material hinges on the degree of tightness required of the structure. This report, prepared for the ITA Working Group on Research, examines various classification systems for determining the degree of required watertightness, and damage likely to result from failure to meet the prescribed standard of tightness. The paper also discusses contractual aspects pertaining to permissible leakage water rates, and to repair work that might be necessary to ensure the required degree of watertightness in a structure.

**Résumé**—Le bitume et les joints en plastique, ainsi que le béton étanche, sont utilisés dans la construction de structures souterraines depuis près de trente ans. La question de savoir quel type de matériau utiliser pour le joints dépend du degré d'étanchéité demandé à la structure. Ce rapport, préparé pour le groupe de travail de recherche AITES passe en revue un certain nombre de systèmes de classification qui déterminent le degré d'étanchéité nécessaire ainsi que les dommages qui risquent de se produire si les spécifications d'étanchéité prescrites ne sont pas satisfaites. Ce rapport traite également de certains aspects contractuels concernant les taux de fuite d'eau acceptables, et les réparations pouvant être nécessaires afin d'assurer le degré d'étanchéité requis dans une structure.

## 1. Introduction

For decades, buildings have been provided with a skin seal to protect them successfully against encroaching water. Both bitumen-based and plastic sealing materials (see Figs. 1 and 2) have been used for this procedure. The Berlin and Hamburg underground railway tunnels, dating back to the beginning of this century, represent examples of this type of protection, as do a large number of German Federal Railway tunnels that have been subsequently modernized by adding sealing material.

Since the mid-'60s, traffic tunnels with larger dimensions also have been constructed using watertight concrete. Initially this sealing method, which originated during the expansion of the Hamburg underground railway network, was confined to the cut-and-cover method and to one- or two-track route tunnels. However, for about the past 20 years, watertight concrete also has been used increasingly for tunnelling by means of mining and, in particular, for the Munich underground system (see Fig. 3). Since then, in fact, skin seals based on bitumen or plastic and watertight concrete have been in competition, for traffic tunnel construction as well as for civil engineering projects.

The question with regard to the sense and purpose of a surface-area seal made of bitumen or of plastic sealing materials is one which—considered in light of the background described above—is a matter of hot controversy if leakages occur in individual cases. This is particularly true of water-pressure-resistant seals.

It must be noted, however, that in cases of damage, the wrong sorts of arguments are often put forward. After all, skin seals cannot always be replaced unproblematically by water-

tight concrete. For example, the concrete requires areal surface protection if extremely aggressive water is present, in accordance with [German Standard] DIN 4030 (1989).

Free carbonic acid and sulphates have a particular role to play in such a case. However, the sealing effect of watertight concrete is frequently inadequate if the climate in the interior of the structure is subject to major fluctuations. The water vapor diffusion, even given high-quality concrete, is too great unless additional measures are



Figure 1. Workers using bitumen-based strips and welding them overhead.

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Figure 2. Tunnel sealing by means of plastic sealing strips.

taken, in particular for structures that are intended to serve:

- As storage facilities for goods affected by moisture (e.g., paper, foodstuffs);
- As electronic data processing plants; or
- For long-term accommodation of personnel.

For this reason, great care must be taken in each individual case to assess which of the two basic sealing principles should be applied. The decision must be made at an early stage in the planning because the choice of sealing material has various consequences, of both a constructional and an operational nature.

The question of the required degree of tightness, depending on the intended use of the subsurface facility (e.g., for accommodating persons, for storage, for traffic, for sewage) is of great significance for both sealing principles.

It is the degree of tightness required, above all, that influences the formulation of the contract, or, to be more precise, the bidding procedure and the regulations pertaining to the guarantee. Therefore, it is essential to arrive at an unmistakable definition for the required sealing effect. Quite independently of the chosen sealing principle, a suitable concept for repair should be stated from the very outset in case localized leakages occur. The various aspects of tightness and repair are discussed in greater detail below.

## 2. Required Tightness

It is no secret that in the Federal Republic of Germany, the **watertightness** of subsurface facilities is stressed very highly indeed. Compared to other

countries, the existing standard is outstanding. At the same time, this standard implies increased outlay of both time and costs.

Generally speaking, a high standard of execution requires a longer construction period as well as the use of high-quality and, therefore, for the most part more expensive materials. In addition, the work must be carried out by highly trained workers with the greatest possible care.

In comparison to normal concrete, for example, watertight concrete requires a more harmonized concrete recipe, more intensive compacting, additional reinforcing or smaller gaps between rods, extra construction requirements, longer stripping periods

(if stripping is required), and more **extensive** post-treatment measures. In many cases, these measures have to be **finished** off by not inconsiderable subsequent improvements in the form of injections, which have to be carried out as a secondary performance before the period of guarantee is accepted and takes effect.

It is quite obvious that cost components related to quality improvement increase more than proportionally with every further improvement in quality. This recognition is nothing new. As a consequence, the **definition** "bone dry," which at one time gave rise to considerable **discussion** and which was **even called for by certain German clients**,



Figure 3. Inner shell made of watertight concrete during underground railway construction in Munich.

is no longer stipulated in the construction contract—at least, not in the case of tunnels built by mining means. The concept was always defended by arguments relating to requirements in the signal and electro-technical fields. On the other hand, it was at no time contained in technical guidelines, e.g., from the Association of Public Transport Corporations and the German Federal Railway or in the ordinance governing the construction and operation of tramways.

Generally speaking, any possible dependence on the intended use of the facility must first of all be clarified when considering the required degree of tightness. In this connection, there is no suggestion among experts that less stringent demands should be placed, in general, on tunnels for utility purposes than on traffic tunnels. The main consideration appears to be that the tunnel must be dry enough to ensure that it can be used without disturbance for its planned service life. Consideration of a wider range of possible types of use results in the sort of picture presented in Table 1.

In terms of traffic tunnels, we must differentiate between sections that are located in the zone where frost takes effect (see Fig. 4) and those frost-free sections that are encountered further

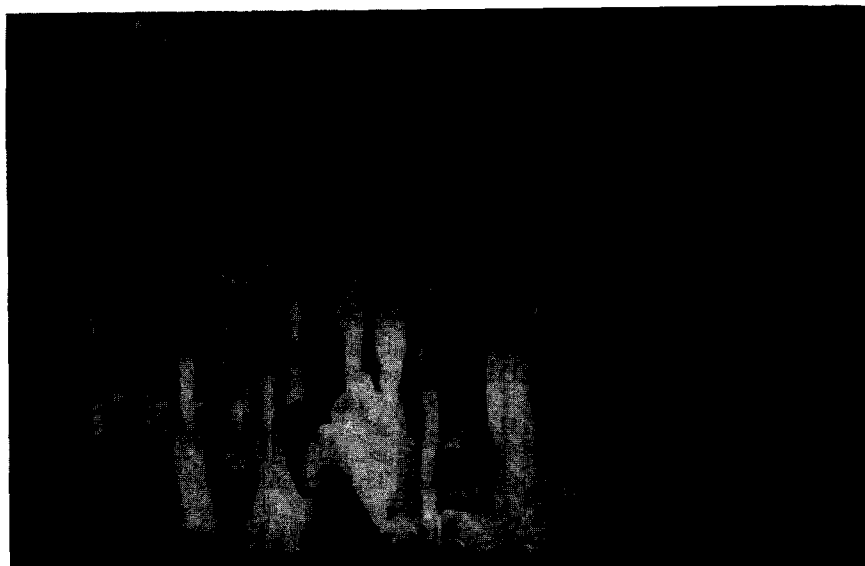


Figure 4. Formation of ice in an underground railway tunnel in the vicinity of a station. (Photo: Baubehörde Hamburg)

inside the tunnel. The length of frost-endangered tunnel sections—measured from the portal—depends above all (outside of urban areas) on the general position of a tunnel vis-à-vis the prevailing weather direction and on the surrounding topography, as well as on the level and line taken.

For example, in a tunnel in western or central Europe that is affected by a prevailing west-to-east weather pattern, a west-to-east line undoubtedly will be much more affected by the elements than is a line running from north to south.

In the same way, it can be assumed

Table 1. Required degree of tightness related to the use to which the tunnel or construction is planned.

Degree of Required Watertightness	Nature of Use of Tunnel/Structure	Likely Damage/Problems to be Expected
Higher	People present for lengthy periods	Chronic illnesses
	Storage of goods affected by moisture (paper, foodstuffs)	The quality of the goods is diminished or goods may be entirely spoiled
	Traffic tunnel sections affected by frost (portal zones, pedestrian tunnels)	Icicle formation in the clearance profile; reduced traffic safety
	Frost-free traffic tunnel sections	Damage to the building material, possibly resulting in reduced stability
	Utility tunnels	Damage to the building material, possibly resulting in reduced stability, corrosion of lines
Lower	Sewage tunnels	Damage to the building material, possibly resulting in reduced stability; eventual added load for the clarification plant; environmental pollution

that a tunnel built as the continuation of extended valley, which determines the wind direction, is endangered by frost over a greater length than is a tunnel located in a lateral direction to the valley.

Measurements carried out by the Swiss Federal Railways (SBB) have revealed that in the case of one-track railway tunnels, the frost penetration depth into the tunnel amounts to about 400 m at the weather intake side, compared to a frost penetration depth only between some 50 and 100 m at the weather exit side.

Again, it is known that certain German Federal Railway tunnels, which are located in particularly exposed positions, and that are longer than 1 km, can be completely frozen during severe winters. In general, because the possibility of at least partial reversal of the climatic conditions cannot be excluded, it is advisable to undertake sealing measures (skin seal or watertight concrete) for traffic tunnels over a minimum length from the portal, e.g., some 300 to 400 m.

Figure 5 shows recommended minimum lengths for sealing measures for traffic tunnels. For shorter tunnels, the recommendation involves installing sealing along the entire length of the tunnel.

In the case of longer tunnels, the decision concerning whether or not to install sealing in those parts that are located in the interior of the tunnel depends on the water conditions encountered during drive, or on the

results of the geotechnical pre-investigations. In this connection, the demands placed on the degree of tightness corresponding to Table 1 can be set lower in the interior than in the vicinity of the portal.

This principle is frequently applied for highway tunnel construction in Austria and Switzerland, as well as in the Federal Republic of Germany. The German Federal Railway installed a continuous plastic sealing membrane in most tunnels of the new high-speed lines between Hanover and Würzburg, as well as between Mannheim and Stuttgart, which will be taken into operation in 1991.

The information in Table 1 permits us to reach a consensus about qualitative differences relating to the required tightness, depending upon the use of tunnel. The next step is to quantify the different demands—a task that is a great deal more difficult to accomplish. The German League of Cities has provided starting points for a number of years. An attempt was made to define permissible leakage rates in underground railway constructions in a large number of German cities. Table 2 includes the relevant details.

A use-related differentiation of the tightness requirements has been carried out in the case of this model as well. It is based on considerations devised by the STUVA and the Stuttgart Otto-Graf-Institute at the end of the 1960s (Girnau and Haack 1969; Henke et al. 1975). Numerical limits relating to the permissible average

leakage water rates were provided, without regard to the chosen type of seal. These limits are so minimal for facilities used for accommodating people and for underground and rapid transit system tunnels that they can scarcely be checked in practice.

If, for example, an internal diameter of approximately 6 m and, consequently, an internal wall circumference of about 20 m are assumed for a one-track underground route tunnel, then the permissible leakage water rate amounts to 0.2 l per day and per meter of tunnel. However, such a leakage rate is already accounted for by the rate of evaporation, especially if the existence of strong air movements caused by the passage of trains is taken into consideration.

Taking the above-mentioned value, and assuming one leakage for a tunnel section of 100 m results in a permissible leakage water rate of up to 20 l per day—or, for 1,000 m, of up to 200 l per day.

These figures demonstrate that the deliberations concerning permissible leakage essentially must be rounded off by a reference length. In fact, the German League of Cities selected a block length including block joint, i.e., a tunnel section from block centre to block centre. Given this solution, which has been accepted by the responsible working group as a provisional working basis (German League of Cities 1978), the German League of Cities inclines towards a permissible leakage water rate for underground and rapid transit system tunnels in accordance with line 3 of Table 2. Similar approaches used in other countries will be examined in more detail at a later stage.

Consider the case of a motorway tunnel (two-lane carriageway) constructed by mining means. For this tunnel, which has a cross-sectional area of approximately 100 m<sup>2</sup> (i.e., with approximately a 35-m internal wall circumference), a leakage water rate of up to 3.5 l per day and per m of tunnel (which corresponds to 350 l per day for a length of 100 m) would be permissible, according to Table 2.

For the tunnels along the Federal Railway's new high-speed lines, which are roughly the same size, a permissible leakage water rate of up to 1,750 l per day has been obtained. However, this latter value appears to be rather on the high side. Furthermore, it does not agree with the following conception put forward by the German Federal Railway itself.

In accordance with Table 2, for a sewage gallery of approximately 2 m clear diameter, the maximum leakage water rate, given an internal wall circumference of approximately 6.5 m, should amount to 6.5 l per day and per m of gallery. This figure relates only to

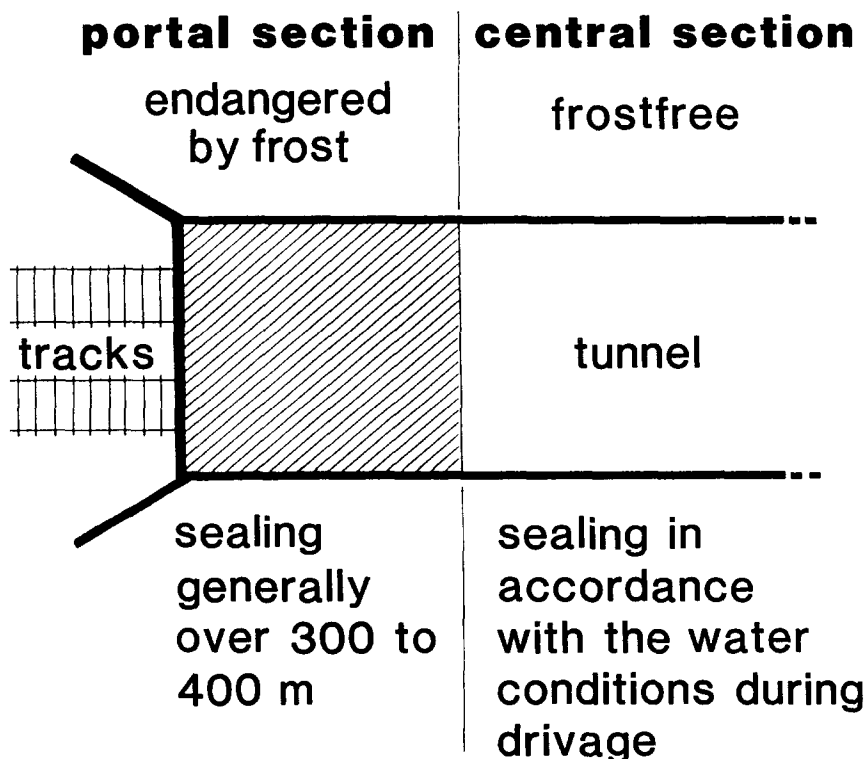


Figure 5. Recommended minimum lengths for sealing measures for traffic tunnels.

**Table 2. Permissible daily leakage water rates, depending upon the use of subsurface facilities, according to findings of the Otto-Graf-Institute. Note: The leakage water rate present at particularly noticeable leakage points must not exceed ten times the average leakage water rate value.**

Line	Moisture Characteristics	Purpose	Permissible Daily Leakage Water Rate (l/sq. m)
0	1	2	3
1	Completely dry	Storerooms, restrooms	0.001
2	Substantially dry	Underground/tramway tunnels	0.01
3	Capillary penetration of moisture	Road, pedestrian tunnels	0.1
4	Weak trickling water	Rail tunnels	0.5
5	Trickling water	Sewage tunnels	1.0

groundwater of precipitation entering the gallery. Given the capacity of the sort of clarification plants currently in use, this additional quantity of water that must be coped with certainly does not pose any problem. On the other hand, if the direction of flow is reversed—i.e., if the loss of sewage of the same

proportions flows into the earth—the situation cannot, by and large, be tolerated, for environmental reasons.

When the German Federal Railway drew up its tunnelling guidelines (1984), it did not define any permissible leakage water rates. However, it identified three classes of tightness

(see Table 3). The relevant moisture characteristics correspond to those contained in lines 1 to 3 of Table 2. This reveals, for example, that the limit value of the permissible leakage water rate for railway tunnels, given in line 4 of Table 2, is too high as far as the German Federal Railway is concerned.

**Table 3. Tightness classes of the German Federal Railway depend upon the use of the subsurface facilities.**

Tightness Class	Moisture Characteristics	Use of Tunnel	Definition
1	2	2	4
2	Completely dry	Storerooms and workrooms, restrooms	The wall of the lining must be so that that no moist patches are detectable on the inside.
3	Substantially dry	Frost-endangered tunnel sections	The wall of the lining must be so tight that only slight, isolated patches of moisture can be detected on the inside (e.g., as a result of discoloration.  After touching such slightly moist patches with the dry hand, no traces of water should be detectable on it. If a piece of blotting paper or newspaper is placed upon a patch, it must on no account become discolored as a result of absorbing moisture.
4	Capillary moisture penetration	Tunnel sections and rooms for which Tightness Class 1 or 2 is not required	The wall of the lining must be so tight that only isolated, locally restricted patches of moisture occur.  Restricted patches of moisture are such that they reveal that the wall has been penetrated by moisture, and a piece of blotting paper or newspaper discolors if placed upon it—but there is no trickling water evident.

The rules of the German Federal Railway, like those of the German League of Cities, basically apply to facilities made of watertight concrete, as well as to those provided with a skin seal.

In a further step, shown in Column 3 of Table 3, it was ultimately determined which tightness class should be applied for which parts of the tunnel. In this case, the differentiation that was applied corresponds to the principle that is applied in Table 1. Generally speaking, the German Federal Railway assumes that tightness Class 1 cannot be achieved using watertight concrete (see DS [German Railway Standard] 853, 1978, explanation pertaining to Paragraph 99 of the Tunneling Regulations).

The supplementary explanation relating to testing methods (given in Column 4 of Table 3) seems to be of special importance. In this case, emphasis was placed above all on assessment criteria that can be more or less applied by anyone on the site, without having to resort to complicated means of measurement.

In defining tightness Classes 2 and 3, there is talk of "isolated weak penetration of moisture" or "isolated and locally restricted patches moist to the touch." A question is raised—quite recently, in the concrete case of a leaking tunnel—pertaining to the permissible areal expansion of such isolated moist patches.

Clearly, the German Federal Railway's conception in this case is not confined to patches as large as the palm of the hand. This would be unrealistic for a tunnel that is several thousand meters long—and which, furthermore, might be located entirely, or at least partially, beneath the groundwater level.

On the other hand, the expansion of patches that are moist to the touch over extensive areas of a tunnel block perhaps 10 m long certainly is not intended either. If the entire roof zone or a complete wall area of a block has been penetrated by moisture, the situation may be described as intolerable.

According to the tunnelling regulations of the German Federal Railway, the penetration of moisture on partial areas extending over a few continuous square meters is still regarded as acceptable. It goes without saying that this situation applies merely to isolated tunnel blocks and must not on any account occur block after block.

Viewed from this perspective, the establishment of a block-related partition system in conjunction with a sealing skin is to be recommended, especially for tunnels located in groundwater. Figures 6 and 7 provide details of how such a system is set up in principle, as well as an example for loosely laid plastic seals. The full efficacy of such a partition system is assured only if all of the working joints that run horizontally and all of the ring joints of the inner shell are included *without exception*.

This system applies to route and station tunnels in the same way as to possible cross-cuts, connecting tunnels or initial structures. In the roof area, the jointing trip system has to be rounded off by the installation of injection hoses (or specially shaped rubber profiles, as shown in Fig. 8), so that any zones in the ring joints that could possibly have been insufficiently concreted can subsequently be properly closed.

The Federal Railway's Munich Central Office (Bundesbahn-Zentralamt) is going to include a diagram in accordance with Figure 6 in the next revised edition of its tunnelling guidelines

(publication of which is planned for 1991). In this way, the importance of the partition system, which until now has only been mentioned in the guidelines, will be underlined.

In the United States and in various other countries, the permissible leakage water rate is defined in conjunction with the cited reference length. Table 4 provides examples of various underground railway systems classified by such a system. It can be seen that this method of defining permissible leakage water rates allows a greater leakage rate for the shorter reference length than for the longer tunnel section.

This method appears advisable in view of the considerations relating to Table 2. It must be noted, however, that the permissible leakage rates for underground railway systems in the United States, compared to those of the Otto-Graf-Institute (see Table 2, line 2), are assessed higher, even for the greater reference length, by a factor of nearly 100.

In other words, for a tunnel section length of 100 m, again with an inner wall circumference of approximately 20 m, a leakage water rate of up to 1,800 l per day is given (using the example of Washington, D.C.). This rate appears to be extremely high, even if it is divided up to account for a number of damaged spots resulting solely from the state of the construction (e.g., corrosion of the reinforcement).

On the other hand, the maximum leakage rates applied to Buffalo (New York, U.S.A.), Melbourne and Antwerp, are of the same magnitude as the limit value, shown in Table 2, for the capillary penetration of moisture for road and pedestrian tunnels.

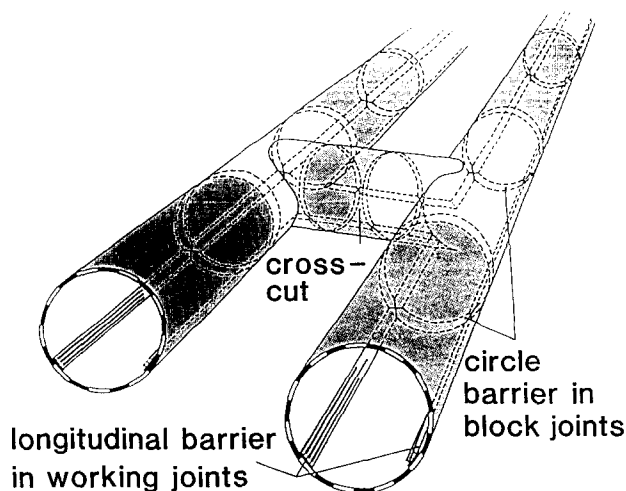


Figure 6. Principle of a "barrier" participation system, used in conjunction with a sealing skin. This type of system is especially recommended for tunnels in groundwater.

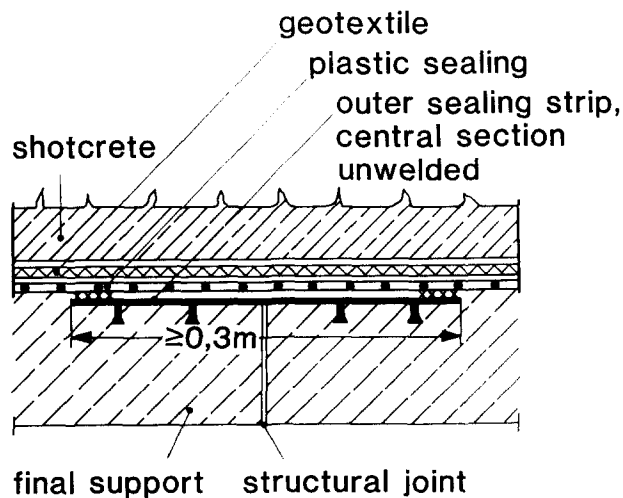


Figure 7. Example of partitioning of structural and working joints of the inner shell, given a water-pressure-resistant seal made of loosely laid plastic sealing strips (German Federal Railway).

Table 4. Examples of permissible daily leakage rates in various international cities.

Underground Railway Systems	Short Section		Long Section	
	Daily Leakage Rate (l/sq. m)	Reference Length (m)	Daily Leakage Rate (l/sq. m)	Reference Length (m)
1	2	3	4	5
Washington, D.C. (U.S.A.)	10.7	3.5	0.9	80
San Francisco (U.S.A.)			0.9	80
Atlanta (U.S.A.)			0.9	80
Boston (U.S.A.)			1.8	35
Baltimore (U.S.A.)	5.3	3.5	0.7	35
Buffalo (U.S.A.)	0.4	10	0.2	1,000
Melbourne (Australia)	0.25	10	0.1	1,100
Antwerp (Belgium)	0.25	10	0.1	100

On the basis of the various applications for a solution in Tables 1 to 4 and their assessment, Table 5 provides, in summarized form, proposals for use or length-related determination of permissible leakage water rates for operating different types of tunnels.

Again, the limit values should apply regardless of whether a tunnel is made of watertight concrete or is provided with a skin seal. In comparison to Table 2, the permissible leakage rates for short reference lengths have been raised for rooms accommodating persons and for underground railway tunnels; retained for road and pedestrian tunnels; and reduced for railway tunnels. The limit value for sewage tunnels remains unaltered. The recommended permissible leakage rates for large reference lengths are, in general, half as high as for rates for short reference lengths. The relationships shown in Table 5 and the proposed numerical values will be discussed intensively in expert circles in the months ahead.

### 3. Contractual Matters

The determination of permissible leakage water rates also involves contractual matters. As mentioned in the introduction, the bidding procedure and the regulations concerning the guarantee are affected first and foremost.

In order to eliminate misunderstandings and subsequent disputes as much as possible from the very outset, the client should clearly indicate in the technical preamble, what sort of tunnel state is expected and should be adhered to vis-à-vis the tightness. In this connection, the client can resort to the general division into tightness classes, or to the description of the

moisture characteristics in accordance with Table 3 (or Table 5).

Basically, however, clients must be aware that tightness class 1 can be arrived at only by means of an expertly planned and executed seal skin. Because of its physical properties, watertight concrete is not suitable for such high requirements. The tunnelling guidelines of the German Federal Railway (1984) expressly point this fact out, as noted above. For this reason, both from the technical and economic points of view, it is advisable to demand tightness class 2 for watertight concrete.

In the invitation for tenders, reference must be made to the fact that local improvements through injections have to be carried out until the point at which the tightness class demanded in the contract is reached. Then, and only then, is it time for acceptance, which in turn signifies the beginning of the period of guarantee.

The client should also indicate the required tightness class for skin seals. Should this requirement later prove not to have been adhered to as a result of construction faults or damage resulting from subsequent work, then appropriate redevelopment measures must be undertaken. In the case of the cut-and-cover method, this can entail excavation at certain places if damage in the wall or roof area has occurred, in order to arrive at the standards of performance laid down in the contract.

Such redevelopment possibilities are excluded from the very outset for the floor area, as well as for all mining methods. In such cases, injections must be carried out. If the degree of tightness specified in the contract is still not achieved, then long-term effective ancillary measures should be undertaken.

These include umbrella-like drain-off devices (see Fig. 9), which catch the leakage water that penetrates and transfers it to the tunnel drainage system, which is usually present for getting rid of waste water.

Under certain circumstances, this work signifies continuous operational costs (e.g., for pumping off the leakage water) and water discharge costs, as well as generally increased maintenance costs. It goes without saying that for such solutions, questions pertaining to the clear space, undisturbed operation of the tunnel, and the long-term state of the tunnel structure are of major significance.

The definition of different tightness classes with related permissible leakage water rates might give rise, in some places, to the fear of a general and contractually anchored reduction in quality. However, this problem should not arise, as we see on closer examination of the issue. After all, it is simply not possible technically to create a skin seal or a construction made of watertight concrete with the aim of arriving at a certain degree of leakage in order to adhere to an agreed-upon permissible water leakage rate. In other words: contractors are still obliged today, as they were in the past, to plan and provide proper, skilled work in order to attain a tunnel that is as watertight as possible.

The relevant technical documents, as well as the bidding procedure, must show clearly and verifiably that the intended tightness class can reliably be achieved, *given faultless execution of the construction work*. However, because building today still largely involves manual labor, human inadequacies during the planning and execution phases cannot safely be pre-

Table 5. STUVA's proposal for determining use- and length-related permissible daily leakage water rates in German tunnelling.

Tightness Class	Moisture Characteristics	Intended Use	Definition	Permissible Daily Leakage Water Quantity (l/sq. m), Given a Reference Length of:	
				10 m	100 m
1	2	3	4	5	6
1	Completely dry	Storerooms and workrooms, restrooms	The wall of the lining must be so tight that no moist patches are detectable on the inside.	0.02	0.01
2	Substantially dry	Frost-endangered sections of traffic tunnels; station tunnels	The wall of the lining must be so tight that only slight, isolated patches of moisture can be detected on the inside (e.g., as a result of discoloration).  After touching such slightly moist patches with a dry hand, no traces of water should be detectable on it. If a piece of blotting paper or newspaper is placed upon a patch, it must on no account become discolored as a result of absorbing moisture.	0.1	0.05
3	Capillary wetting	Route sections of traffic tunnels for which Tightness Class 2 is not required	The wall of the lining must be so tight that only isolated, locally restricted patches of moisture occur.  Restricted patches of moisture reveal that the wall is wet, leading to a discoloration of a piece of blotting paper or newspaper if placed upon it—but no trickling water is evident.	0.2	0.1
4	Weak trickling water	Utility tunnels	Trickling water permitted at isolated spots and locally.	0.5	0.2
5	Trickling water	Sewage tunnels		1.0	0.5

cluded. For such cases, it is essential to know to what extent improvements and redevelopment are necessary and, above all, economically viable.

The tightness classes and the permissible leakage water rates provide both the client and the planners and contractors with essential yardsticks. The intention behind reaching agreement on these aspects and anchoring them in the contract is to avoid unacceptable expenditure on the part of the building firm. A clear delimitation of risks leads from the very outset to a more economical cost structure because the necessary improvements that might possibly be required are defined clearly in the contract.

#### 4. Redevelopment Methods

By and large, injections are used in order to improve watertight concrete structures, on the one hand; and to redevelop faulty skin seals or inner shells made of watertight concrete, on the other. Generally speaking, two-component resins on an epoxide or polyurethane basis are applied. It must be shown that these two materials are permanently compatible with the existing groundwater; with other building materials, such as concrete, steel, joint strips (elastomer or thermo-plastic); and, possibly, also with the materials comprising the skin seal. Usually an Institute of Hygiene has to certify the physiologically safe rating vis-à-

vis groundwater. The material to be grouted itself must be resistant to corrosion and to stresses caused by movements of the construction.

At present, numerous grouting agents with varying properties—in terms of both working with them and their final state—are available. As a result, it is difficult for the user to actually determine the most suitable material for sealing water-bearing cracks. The viscosity of the injection material should be as low as possible so that it can penetrate tiny crack widths (as little as 0.2 mm). Even in the case of wet crack walls, the injection material must be capable of adhering properly to the concrete and must possess



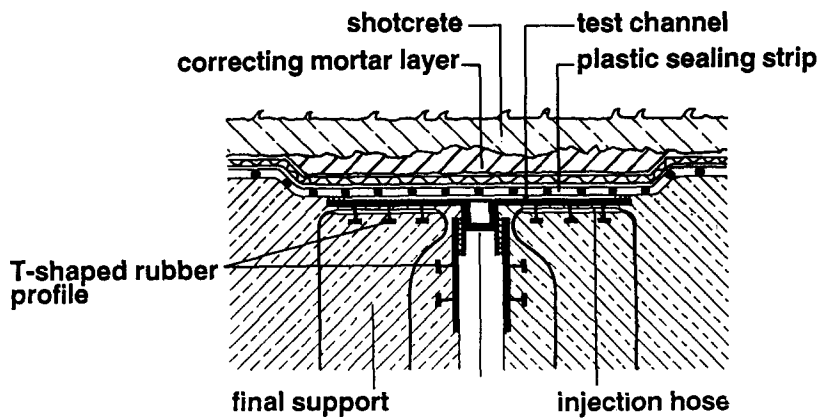


Figure 8. Example of a T-shaped rubber profile in the crown area of a tunnel given a water-pressure-resistant seal made of loosely laid plastic sealing strips.

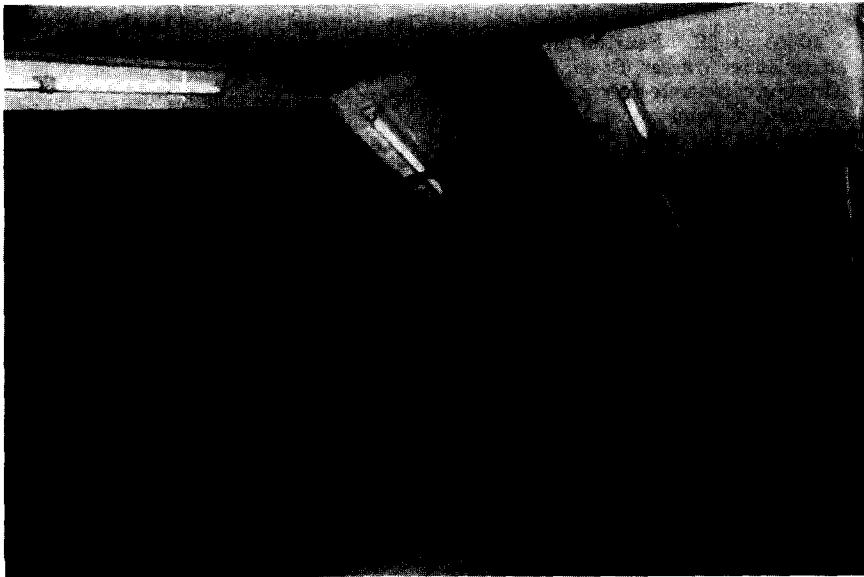


Figure 9. Example showing how leakage water can be caught and diverted by means of high-grade steel-plate bath (Tokyo Underground Railway).

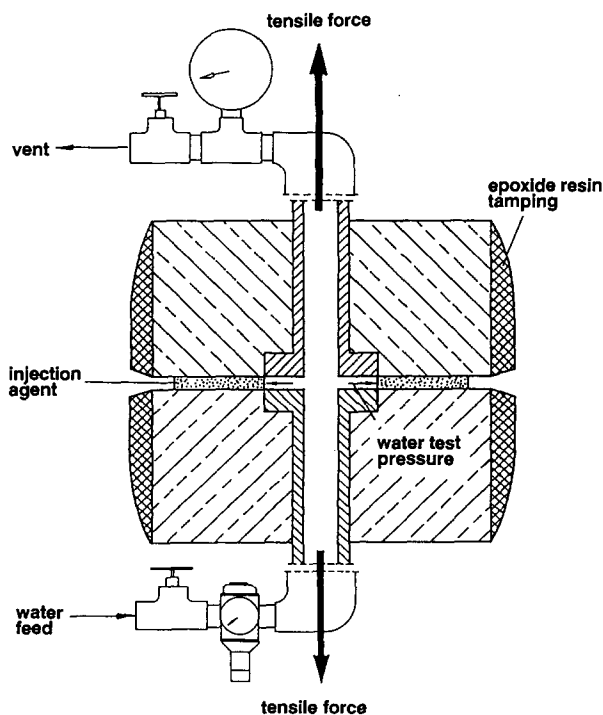


Figure 10. Sample mass for testing grouting agents (principle).

adequate expansion and contraction properties to cope with opening and closing of the crack resulting from changes in temperature or load.

For a number of years, STUVA has been carrying out model tests in order to investigate these properties. The injection material that is being tested is injected into a 5-mm-wide joint gap, subjected to approximately 1 to 2 bars water pressure. The concrete sample mass (see Fig. 10) is maintained at a minimum 1 bar water pressure for more than 24 hours before the injection, so that complete moisture penetration of the roughened joint flanks can be assumed.

During the injection process, the water contained in the gap is gradually displaced by the injection material via a vent. Following an appropriate period allowed for hardening, the samples are installed in a testing device (see Fig. 11). Subsequently, the water testing pressure in the interior of the sample is increased in stages of 0.5 bar until a maximum of 1.5 bar pressure is attained. The two halves of the sample are then slowly separated from one another by loosening the supporting screw rods and by exploiting the constantly retained internal water pressure. The injection material experiences a corresponding expansion in the process, provided that sufficient flank adhesion resulted in the first place.

The results of the tests carried out so far give rise to a certain amount of concern, in that only a very few grouting materials are sufficient to sustain expansion of 5% or more. Of a total of some 25 different makes examined, only two attained expansion values of

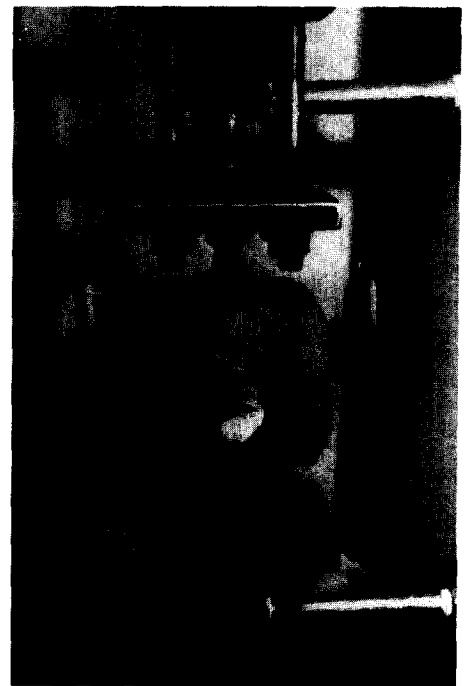


Figure 11. Experimental set-up used by STUVA to test properties of grouting agents.

over 20%. If a crack width of approximately 3 mm is assumed, and given 5% expansion, failure signifies a new leakage, given a crack widening of only 0.015 mm, or less than two-hundredths of a millimeter.

A number of the tested injection materials did not harden at all—or took several days to harden—at 10°C, i.e., at the temperature that usually prevails in a tunnel lining. Other materials shrank during the reaction phase. From the very outset, no flank adhesion was anticipated in their case. Other makes could not be used in practice because they are extremely vile smelling, aggressive to the skin, inflammable, or very difficult to measure out.

In sum, it can be said that, based on the existing results obtained from the model test series, a great deal of required development work remains to be carried out in the field of redevelopment injections. Perhaps the chemists, the specialised firms concerned and the construction industry can respond to this need.

## 5. Conclusion

The above-mentioned considerations and proposals aimed at better

assessment and elimination of incidences of water leakages in the case of subsurface facilities are intended to provoke an intensive discussion among experts at home and abroad. The relevant issues also were debated within the framework of the Working Group on Research within the International Tunnelling Association (ITA). In this way, proper starting points are assured for arriving at a consensus that is equally acceptable to clients and contractors—at both the national and international levels—with respect to the difficult assessment of the required degree of tightness and the acceptable amount of redevelopment. □

## 6. References

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