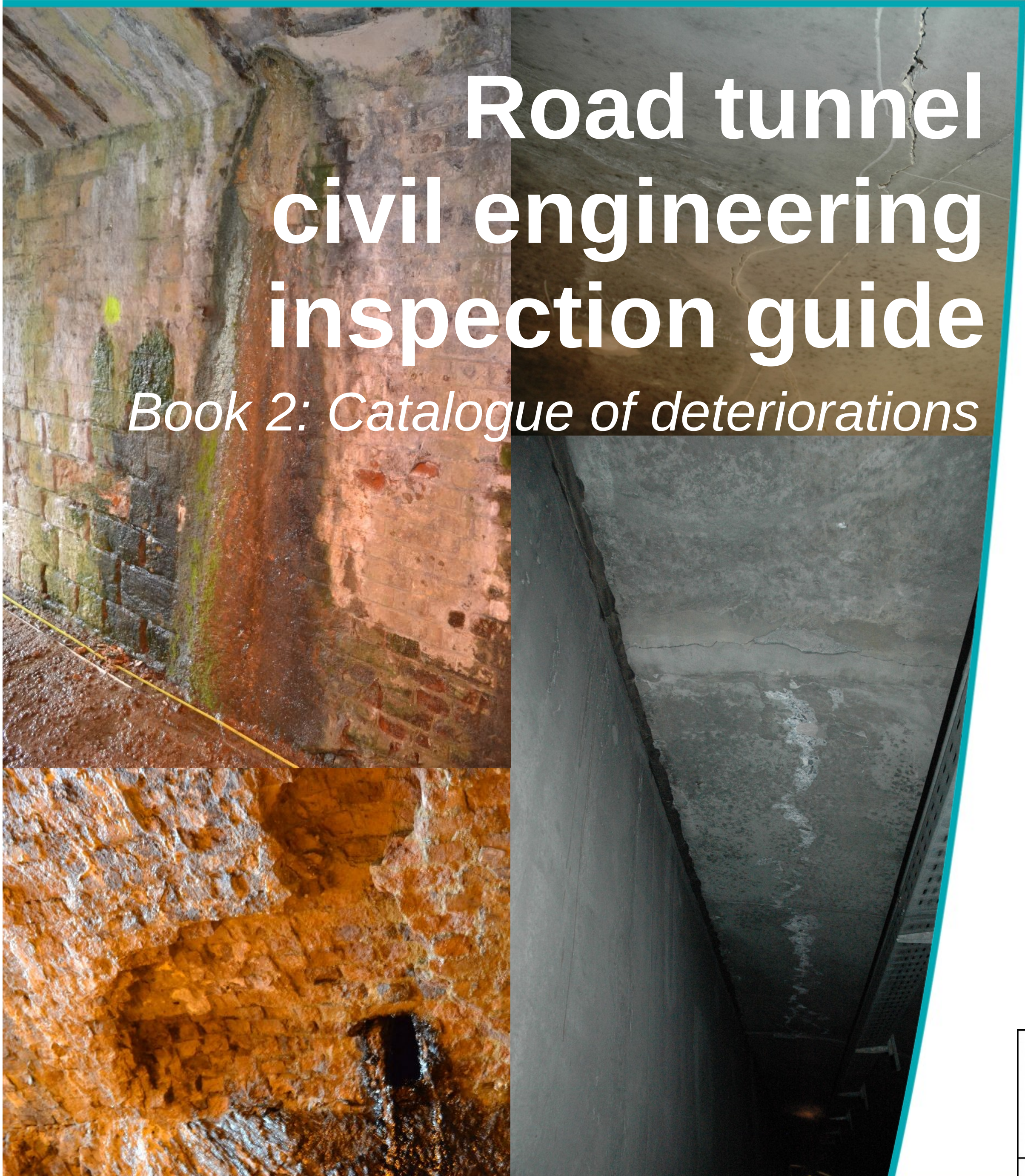
Guides

Road tunnel civil engineering inspection guide

Book 2: Catalogue of deteriorations



January 2015

Centre d'Études des Tunnels
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DISCLAIMER

This guide is the result of a process of synthesis, methodological assessment, research and feedback, either carried out or commissioned by CETU. It is designed to be used as a reference for the design, construction and operation of underground structures. As the guide takes stock of the state of the art at a particular time, the information it contains may become outdated, either due to developments in technology or regulations, or to developments of more efficient methods.

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Book 2: Catalogue of deteriorations

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1 FOREWORD

The "Road tunnel civil engineering inspection guide" is primarily intended for people in charge of conducting detailed civil engineering inspections of bored tunnels along the national road network which is managed by State authorities. It is also intended for tunnel managers who, in varying degrees, organize and capitalize on monitoring actions. This guide may also be used as a reference for any owner in charge of tunnels of this type.

The first book of the guide, entitled "From deterioration to analysis, from analysis to rating", provides recommendations on procedures and practical steps for observing, analysing and classifying deteriorations that appear in the various parts of a tunnel. It also proposes a rating method for tunnels: "Image Qualité des Ouvrages d'Art” (IQOA – Tunnels) (Quality Assessment of Engineering Structures") that provides two indicators, one concerning the condition of the civil engineering elements and the other concerning the presence of water. These indicators are included in the periodic assessment process defined by the Technical Directive on the Monitoring and Maintenance of Engineering Structures (Instruction Technique pour la Surveillance et l'Entretien des Ouvrages d'Art) (ITSEOA).

The present document constitutes the second book of the guide. Entitled "Catalogue of deteriorations", it provides additional information on the list the road tunnel deteriorations that figure in the first book. This "Catalogue of deteriorations" constitutes the main part of the guide.

Tunnel inspections are primarily based on observation and description. It was therefore decided to describe deteriorations and defects through their appearance rather than by focussing on the factors that trigger them.

Deteriorations, just like defects, can vary from the very discreet to the spectacular, both in terms of their visible manifestation and their extent. However, their severity does not necessarily depend on their "visibility". Water is a contributory factor in a considerable number of cases. The origin of these deteriorations or defects must be looked for, if possible during the inspection. Their severity and how they evolve almost always depend on a combination of internal causes, linked to intrinsic characteristics of the support, waterproofing and lining materials, (which can be considered as inherent weaknesses), and on external causes, which can be qualified as "attacks", linked to the surroundings, the behaviour of the rock mass or to the functions of the tunnel.

Obviously, as older tunnels encounter many more problems, there is more data concerning their deteriorations. The catalogue comprises sheets that describe the main deteriorations and defects observed in road tunnels and the ways to detect them, classify them and assess them. Each sheet includes:

- the designation of the deterioration (usual or customary name),
- its description (visual appearance of the deterioration): the manner in which the deterioration manifests itself to the observer,
- inspection or pre-diagnosis methods: the manner of detecting the deterioration, or revealing it if it is not visible,
- parameters to be measured: material or measurable elements that are linked to it,
- associated deteriorations or defects to be looked for: elements useful for the diagnosis,
- origins and possible causes: interpretations made, based on knowledge of the tunnel,
- aggravating factors: elements likely to worsen or accelerate the deterioration,
- consequences and possible evolution: description of how the deterioration will evolve in the absence of maintenance or repair work.
- dangers to users: imminent risk of incidents or accidents to users (the purple colour of the heading indicates the possible existence of a danger if the deterioration is present),
- risks to the tunnel and its structural elements: likelihood of changes to structural elements in the short or medium term (the colour of the heading corresponds to that of the maximum IQOA rating that can be assigned to the deterioration),
- monitoring: measures to be taken and observations to be made in the short or medium term,
- remedial measures: possible remedial treatments which can be applied to eliminate the deterioration or slow it down,

- observations: elements linked to other deteriorations or more detailed explanations of some of the previous points,
- additional information: descriptions, photographs and diagrams that explain and illustrate the deterioration.

Only the deteriorations or defects most frequently encountered in road tunnels are described in this "Catalogue of deteriorations". For descriptions of less common deteriorations affecting waterway tunnels or railway tunnels, the reader can refer to the "Catalogue of deteriorations in underground structures" published by the French Association for Tunnels and Underground Space (Association Française des Tunnels et de l'Espace Souterrain (AFTES) in 2005.

The many files archived by the CETU provide a great wealth of data in terms of the variety of road tunnels (the types of ground they pass through, the types of lining, the age and the state of conservation) and in terms of the diversity of the deteriorations that are described and photographed therein. They have enabled the present document to provide numerous real-life examples.

2 CATALOGUE OF DETERIORATIONS

2.1 Deteriorations due to water

List of deteriorations	Sheet number
Deteriorations due to water	
Water ingress	HY-1
Concretions	HY-2
Effects of freezing	HY-3
Efflorescence on mortar and concrete	HY-4

Water ingress	HY-1

Description (visual appearance of the deterioration)

Water ingress stems from the surrounding ground (fault, diaclasis, stratigraphic joint, entire surface area). In the case of lined tunnels, it occurs via a defect in the lining (crack, hole) or a construction element (joint, weep hole).

Inspection methods

Visual inspection

Parameters to be measured

Location of water ingress (to ascertain whether there is a correlation with the geology of the ground) – Pressurized or free-flowing water ingress – Flow rate – Measurement of the temperature and possible conductivity – Analysis of the water (to determine its origin: water table or another network)

Associated deteriorations or defects to be looked for

Unlined tunnels: Presence of geological discontinuities (faults, diaclases, sedimentary joints)
Lined tunnels: Obstruction of drainage systems – Leaks in the waterproofing system – Deterioration of the lining – Deterioration of the waterproofing system

Origins and possible causes

Lined or unlined tunnels: Fluctuation or change in the rate of flow of the water table of the surrounding ground – Water leaks from another network
Lined tunnels: Loss or absence of the lining's water-tightness – Failure of drains

Aggravating factors

Lined or unlined tunnels: Areas subject to freezing – Soluble or alterable nature of the surrounding ground – Significant flow rates and/or pressure
Lined tunnels: Open jointing – Cracking

Consequences, possible evolution

Unlined tunnels: Dissolution, leaching or erosion of the ground and possible collapse
Lined tunnels: Deterioration of the lining (leaching, erosion) and weakening of the structures – Falling of lining elements

Dangers to users

Falling of stalactites, deteriorated materials – Disruption and hazard for traffic (flooded carriageway, black ice, etc.)

Risks to the tunnel and its structural elements

Localized weakening of structural elements or the ground (and possibly even permanent damage to the tunnel)

Monitoring

Visual inspection

Remedial measures

Collection and channelling of water inflows (sealing strips, gutters, drainage with thermal insulation)
Total waterproofing
Repair or improvement of waterproofing systems
Repair by treatment of the ground and/or lining (injection)

Observations

See also sheet HY-3 (deteriorations associated with freezing)

Water ingress has various sources (water table, widespread or localized network leaks, etc.). It is particularly harmful in areas subject to freezing: it requires rapid and frequent interventions from operator personnel.

In road tunnels, water ingress has a particular impact on the installations in place (carriageway, lighting) and may result in disruption to traffic. Collection and drainage systems for water ingress may be considered before any repair work. An "umbrella" system may be put in place in order to channel the inflows of water towards the base of the side walls. In tunnels made of stone masonry, this "umbrella" effect may be achieved by covering the drainage network with a mortar coating.

Figure 1: water ingress on a sprayed concrete lining

Figure 2: deteriorated waterproofing coating caused by water ingress (due to poor workmanship and effects of freezing)

Concretions	HY-2

Description (visual appearance of the deterioration)

Limestone concretion: solid and sometimes thick crystallizations of calcite, in varying colours (impurities), which stick to the lining and come from cracks, porous areas or damp joints

Sulphate concretion: crystallizations of gypsum on joints or cracks, which are hard, brittle, often blackened (soot) and sometimes shiny

Inspection methods

Visual inspection

Parameters to be measured

Location (where concretions are beginning to appear) and extent (few or widespread concretions) – Surface area – Average thickness – Stability (for the thickest concretions)

Sampling for analysis if in doubt about the nature of the substance

Associated deteriorations or defects to be looked for

Water ingress
Other deteriorations of the support
Obstruction of drainage systems
Dissolution cavities
Weakening of the structure due to dissolution of the binder

Origins and possible causes

Limestone concretion: precipitation of calcium carbonate dissolved in water coming either from limestone in the surrounding ground or from the dissolution of the binder in the concrete or mortar

Sulphate concretion: sulphates transported by water from the ground or coming from combustion gases (particularly in old railway tunnels)

Aggravating factors

Dissolution of the binder

Consequences, possible evolution

Limestone concretion: spreading, increasing thickness of deposits that may result in falling fragments

Sulphate concretion: worsening of the sulphate attack

Dangers to users

Falling pieces of concretions (very rare)

Risks to the tunnel and its structural elements

Minimal if no proven sulphate attack

Monitoring

Visual inspection

Remedial measures

Preventive scaling if fragments of concretion tend to become detached
Treatment of water ingress

Observations

See also sheets HY-4 (efflorescence on mortar and concrete), RB-2 (concrete deterioration), ED-1 (intrados drainage), ED-2 (extrados drains and culverts) and ED-3 (roadway drains)

<u>Limestone concretions</u>:
These are the result of calcium carbonate (or calcite) precipitation on the facing due to water that has passed through the ground (and through a lining) under a pressure approaching atmospheric pressure. Surface carbonation of the concrete also favours a calcite deposit, but this comes from dissolution of the binder (see sheet RB-2).

The thickness and the extent of the concretions will be all the greater where water already has a high natural bicarbonate content (tunnels in limestone areas). Too much localized accumulation (from a joint or crack) may cause them to detach and fall. Speleology terms are used to describe the forms of these concretions more accurately:

- stalactites: on localized outlets;
- drip curtains or curtains: on linear outlets (cracks, joints); these show marked relief;
- coating or veil: the entire lining becomes invisible under a layer of concretions.

Concretion caused by water seeping in from the ground generally has a beige to yellowish colour which indicates impurities fixed by the calcite. Conversely, calcite coming directly from the dissolution of lime in the concrete is very white; it highlights fine cracks or forms stalactites or flowstones on the facing. These two types of calcite are also found in drainage systems.

<u>Sulphate concretions</u>:
Much more discreet than limestone concretions, or even absent in road tunnels, these hard, brittle, millimetre-sized crystallizations consisting of gypsum indicate the presence of sulphates either within the lining or coming from the ground. They are more common in old railway tunnels where coal-fired locomotives have generated a stock of sulphur that has impregnated the masonry. If in doubt, chemical analysis of these crusts is recommended in order to identify any attack.

<u>Figure 1:</u> limestone concretions encrusting the opening of an active karst in an abandoned tunnel

<u>Figure 2:</u> stalactites and white calcite flowstones on sprayed concrete (dissolution of the lime in the cement due to water percolating from the ground)

<u>Figure 3:</u> light calcite concretions (on the left); red gel deposit, rich in iron oxide (on the right)

<u>Figure 4:</u> crack with concretions of white calcite and reddish-brown deposits

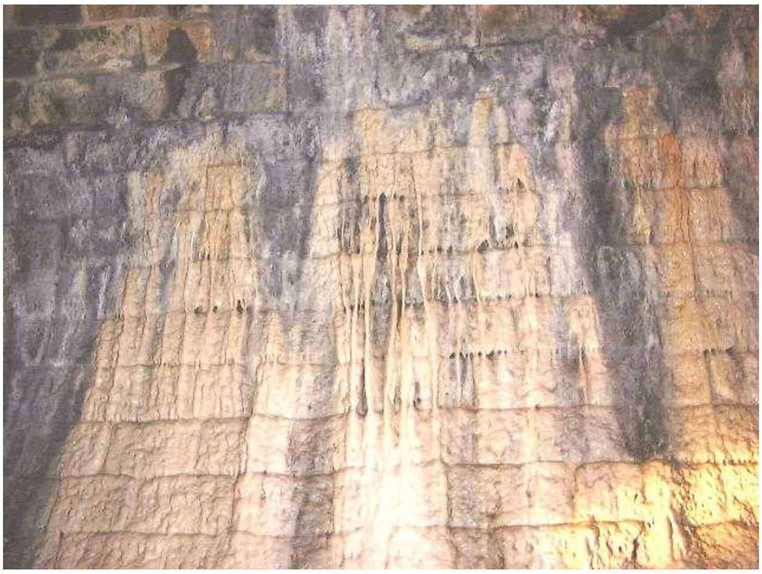


Figure 5: calcite concretions on stone masonry


Figure 6: stone masonry encrusted with calcite concretions

Effects of freezing	HY-3

Description (visual appearance of the deterioration)

The effects of freezing appear in various forms:

- formation of stalactites, packs or sheets of ice,
- surface crumbling of material or formation of cavities (concrete),
- bursting of non-insulated drains,
- expulsion of removable joints,
- heave of carriageway.

Inspection methods

Visual inspection

Parameters to be measured

Surface area where material is breaking away – Average depth – Consistency of the material affected (concrete)
Ruptures of drains

Associated deteriorations or defects to be looked for

Deterioration of masonry linked to the quality of the material (presence of frost-susceptible stone) – Risks of localized instability – Thinning of the lining – Blockage of drainage systems – Leaks in the waterproofing system

Origins and possible causes

Water circulating in a porous material – Prolonged sharp frost – Numerous freeze-thaw cycles
Use of unsuitable materials (frost-susceptible concrete, mortar or stone)

Aggravating factors

Orientation and altitude of the tunnel – Open jointing – Cracking

Consequences, possible evolution

Structural weakening
Drain failure
Falling of lining elements

Dangers to users

Falling stalactites or deteriorated materials, black ice on the carriageway and walkways, reduced accessibility to safety facilities

Risks to the tunnel and its structural elements

Localized weakening (deterioration of masonry due to spalling)

Monitoring

Visual inspection

Remedial measures

Daily scaling of packs of ice
Drainage with thermal insulation
Waterproofing
Repair of waterproofing systems
Repointing
Improvement of drainage in the arch

Observations

Freezing is a predominantly physical process that progresses into the material (stone, concrete, brick, breeze block). Its propagation is determined by the material's porosity and water content, and the frequency and intensity of freeze-thaw cycles. Freezing often manifests itself on the surface through crumbling, flaking or the loosening of small elements. It may reach the heart of the material causing significant splitting, delamination or cracking.

These visible mechanical effects are related to the hydraulic pressures that develop in the smallest pores that have not yet frozen and that will exceed the material's tensile strength, causing cracks and spalling.

In stonework, the porosity of the rock, which may be natural or due to thermal or structural stresses, facilitates water seepage and renders the material more vulnerable to the effects of freezing. Oolitic limestone, dolomite and sandstone are among the most sensitive rocks.

Figure 1: effects of freezing on large oolitic limestone stones

In cast concrete, the presence of 5 to 8% of small diameter (50 to 200 µm) air bubbles acting as an "expansion tank" limits the destructive effects of freezing. The role of air-entraining agents is to create a dense, stable network of bubbles in the concrete mix. In old concrete, though the level of porosity is higher, its distribution is not enough to offset its mechanical weakness. Eventually, in this type of concrete there may be significant deteriorations in more exposed areas (portals), but also in interior zones (areas saturated by permanent water ingress and areas exposed to de-icing salt).

In sprayed concrete, surface exfoliation is sometimes observed, particularly in roof sections, where water "stagnates" behind the sprayed concrete shell, keeping it continuously wet. In very harsh conditions, shotcrete may become progressively detached from the underlying surface due to the formation of ice at the interface. Large fragments may break away.

The accumulation of ice inside some tunnels creates significant operating constraints and may result in the destruction of fragile secondary structural elements (waterproof tanking, intrados drains, coatings).

Figure 2: stalactites and packs of ice on the ground

Figure 3: detached coating due to freezing

Figure 4: *frozen reinforced concrete side wall*

Figure 5: *spalling of concrete due to freezing, at the bottom of the side walls*

Figure 6: *pack of ice coming from a joint and spreading onto the walkway*

Efflorescence on mortar and concrete	HY-4

Description (visual appearance of the deterioration)

Efflorescence resembles white filaments that:

- form by extrusion through the pores of the material and have the appearance of "whiskers",
- are extremely fragile and have a salty taste,
- cover the entire joint or a variable sized surface area of a coating or concrete,
- appear or disappear very rapidly depending on the moisture level of the material or the ambient hygrometry.

Inspection methods

Visual inspection (with the naked eye and with a magnifying glass) and taste (salty taste)

Parameters to be measured

Location (where efflorescence is beginning to appear), – Surface area (localized or widespread) – Nature and extent of deterioration of the material

Associated deteriorations or defects to be looked for

Other deteriorations of the material – Swelling (masonry or coatings) – Loosening (coatings) – Exfoliation – Cracks – Gypsum concretions

Origins and possible causes

Mortar or concrete attacked by inflows of sulphated water, resulting in the formation of sodium sulphate
Presence of internal secondary ettringite (to be looked for using a scanning electron microscope), with widespread, destructive crystallization.

Aggravating factors

Poor quality of the material used– Water from the surrounding ground with a high sulphate content

Consequences, possible evolution

Significant internal swelling that may weaken the lining or loosen the coatings (masonry is highly sensitive to this)

Dangers to users

None

Risks to the tunnel and its structural elements

None if the attack is superficial.
If secondary ettringite is identified, rapid deterioration of masonry joints, swelling or possible of the concrete or coatings.

Monitoring

Visual inspection

Remedial measures

Preventive: mainly when selecting the cements
Corrective: not necessary if only efflorescence is present; if swelling has significantly affected the lining, it may need to be rebuilt.

Observations

Here, the term "efflorescence" has a deliberately restrictive meaning, in order to accurately characterise this particular type of surface deposit mostly found in old masonry. For other engineering structures, the term has a more general meaning, also covering the various concretions appearing on the facing.

See also sheets RM-5 (deterioration of mortar) and RB-2 (concrete deterioration)

Although belonging to the broad category of surface deposits, the efflorescence described here is a manifestation of the specific deterioration of the material caused by sulphates, which is reflected in its appearance and spread.

Masonry:
Efflorescence is restricted to the surface of joints. It has the appearance of white whiskers, which are sometimes very dense, and indicates sulphate attack on the mortar. Chemical analyses have identified it as being sodium sulphate, hydrated to a greater or lesser degree (not to be confused with saltpetre, which is a nitrate). This salt is released from the mortar by surface extrusion. It is the visible indicator of possible internal (and microscopic) formation of secondary ettringite or thaumasite, which are expansive pathogenic salts.

Efflorescence appears as the moisture level of the material fluctuates and it dissolves and disappears when it becomes wet.

Some cement mortar repointing or coatings can become detached by this crystallization coming from the old underlying mortar.

If in doubt, samples should be taken for chemical analysis and examined through an electronic microscope.

Concrete:
Much less spectacular than in masonry, efflorescence has been observed on the surface of some old concretes (gneiss aggregates), mortar coatings and sprayed concrete.
It may also appear on the surface of concrete located in poorly ventilated spaces in tunnels subject to heavy traffic (recesses, annular spaces between metal sheeting and excavated surfaces, utility corridors, etc.). In these cases it originates from the oxidation of the sulphur dioxide (SO_2) emitted by vehicles and in contact with a damp surface (acid attack).

Figure 1: efflorescence on old lime-based mortar

<u>Figure 2:</u> efflorescence on old lime-based mortar

<u>Figure 3:</u> efflorescence at ground level on concrete from 1976

2.2 Deteriorations due to the surrounding ground

List of deteriorations	Sheet number
Deteriorations due to the surrounding ground	
Karsts and cavities	ZI-1
Deteriorations at the portals	ZI-2
Slope instability	ZI-3

Karsts and cavities	ZI-1

Description (visual appearance of the deterioration)

Karst: this is a natural cavity or conduit formed by the dissolution of limestone or gypsum. Its dimensions may range from a few decimetres to several tens of metres
Cavity: this is an unlined excavation of human origin (underground quarry, military structure, gallery) or extensive natural void which forms in ground which has little cohesion and is due to a landslide and outwash of fines by the circulation of water (continuous or not)

Easy to identify when the tunnel cuts through them, these karsts or cavities may also exist in the surrounding area and affect the structure, without being detected.

Inspection methods

Visual inspection if the karst or cavity opens into the tunnel (its exploration does not fall within the scope of an inspection)
Radar investigations, mechanical sounding, topographic survey (levelling, convergence)

Parameters to be measured

Shape and extent visible at the surface of the excavation (unlined tunnel) – Nature and stability of any filling materials – Dimensions (when it is safely accessible without specific equipment) – Stability – Measurement of the flow rate in the event of circulation of water

Associated deteriorations or defects to be looked for

Knowledge of any earlier earthflows – Dolines (circular depressions with karstic relief) or lapies (formations created by rainwater run-off or by freeze/thaw cycles) at the surface – Settlement of the carriageway

Origins and possible causes

Dissolution of the material (limestone, gypsum) due to the circulation of water within the rock mass

Aggravating factors

Fractured surrounding rock – Active karst (circulation of water) – Conduit running tangent to the intrados

Consequences, possible evolution

Earthflows of existing filling materials or materials transported by water. These earthflows can sometimes be sudden and significant – Localized collapse of the carriageway

Dangers to users

Falling material and/or sudden violent water ingress (if the opening is located in the tunnel)
Increased risk if the karst is in a roof section or if a sinkhole reaches the carriageway

Risks to the tunnel and its structural elements

If a lining covers a void, it may be subject to loading, weakening or even rupture if the earthflow is massive (karst) or if the nearby cavity expands towards the tunnel (extensive landslides)

Monitoring

Visual inspection:
– monitor the frequency and amount of falling materials (karst or cavity opening out into the tunnel) and changes in water ingress and the solid material it carries,
– inspection of the networks.
Endoscopy in boreholes (karst or cavity hidden by a lining)

Remedial measures

Protective wire grid or wire netting that can be cleared (protection from falling blocks from within the karst / cavity)
Drainage with sufficient capacity for the flow rates of possible floods, resistant to obstruction but nevertheless inspectable

Observations

Karsts are the result of dissolution and entrainment phenomena found in limestone rock massifs: expansion of diaclases and joints, creation of cavities that may branch out and be numerous and significant in size. Their spatial distribution is never fully known. The quality of the ground surrounding the karst is not modified by the process.

Some other rocks, such as gypsum, may also contain karstic cavities. In contrast to limestone rock massifs, dissolution here is much faster and may therefore result in sinkholes above the tunnel but also below the invert.

Karsts could be more or less filled with external materials, but some retain the circulation of water at varying rates, often related to rainfall.

Karstic conduits do not always have protection or drainage. Their location in relation to the arch may lead to a local weakening of the excavation (formation of fragile rock bridges in cases where a conduit runs at a tangent to the intrados). Apart from natural karstic cavities, some tunnels cut across or run at a tangent to old man-made cavities such as quarries, slate quarries, channels, exploration galleries, etc.

As they are not always reinforced or backfilled and there is generally little knowledge of the way in which they are evolving, this may affect the stability of the nearby tunnel. In addition, some karsts or cavities could be hidden by the lining. They should be located (via archives, or from memory), inspected whenever possible and explored by drilling and video-endoscopy.

Figure 1: metal bars used as protection against falling, poorly consolidated materials from a karst

Figure 2: open conduit leading to the roof section of an unlined tunnel (traces of temporary flows mixed with red clay can be seen)

Deteriorations at the portals	ZI-2

Description (visual appearance of the deterioration)

Deteriorations may have various origins:

- natural portals:
    - unstable rock above the lanes.
- man-made portals:
    - common masonry and concrete deterioration mechanisms,
    - blockage and overload of rockfall canopies,
    - waterproofing defects,
    - weathering,
    - loosening, tilting or settling of the spandrel,
    - dislodging of stones by vegetation (roots),
    - instability of panelling/cladding.

Inspection methods

Visual inspection (often by touch)

Parameters to be measured

Area of the surface affected by the deteriorations – Filling of the canopy (if there is one) – Width of cracks – State of the drainage network– Quality of the lining or panelling materials – Instability index (particularly on stone capping elements and cladding / panelling)

Associated deteriorations or defects to be looked for

Stability of the immediate surrounding areas – Water ingress

Origins and possible causes

Ageing of the materials – Settlement of foundations – Slope movements (falling blocks) – Impacts from oversized heavy goods vehicles – Freeze-thaw cycles – Development of shrub vegetation – Poor workmanship during waterproofing installation or absence of waterproofing – Lack of regular maintenance

Aggravating factors

Area subject to frost – Poor evacuation of water – Blocked rockfall canopy

Consequences, possible evolution

Deterioration of the waterproof membrane
Localized or total rupture
Permanent damage

Dangers to users

Falling rocks or masonry elements
Formation of ice stalactites

Risks to the tunnel and its structural elements

Non-existent to high depending on the extent of disrepair of the tunnel and the intensity of the causes

Monitoring

Visual inspection
Installation of indicators and crack gauges (depending on the situation)
Increased monitoring or close observation (depending on the results of the measurements)

Remedial measures

Regular maintenance of rockfall canopies and mechanisms for draining surface water, clearing of vegetation
Protection of the portal and lanes by meshing and wire netting
Repairs tailored to the nature and extent of the deteriorations (refurbishment, reconstruction)

Observations

Additional information

Man-made portals have characteristic deteriorations:

- settlement, cracks
- tilting (separation from the body of the arch), particularly visible on old masonry spandrels,
- frequent presence of oblique cracks in the intrados (twisting of the structure due to settlement),
- chipping caused by falling stones, localized dislodged masonry due to vegetation,
- dents on the prefabricated panelling, fixed by bolts or secured onto a metal framework (the corrosion of metal fixtures must be monitored).

<u>Figure 1:</u> cracking and lateral tilting of a spandrel, untreated rockfall canopy

<u>Figure 2</u>: portal deformed by slope instability

Figure 3: fallen cladding due to impact from a heavy goods vehicle

Figure 4: loosened panelling on a spandrel

Slope instability	ZI-3

Description (visual appearance of the deterioration)

This is a generally slow down-slope movement of a mass of material, along a surface of rupture between two layers in an area of weaker ground

Inspection methods

Visual inspection of the natural ground and search for visible signs (landslide scar, surface of rupture, soil ripples at the foot of the slope, toppled vegetation, etc.)

Parameters to be measured

Estimation of the overall volume in question
Estimation of the speed (installation of inclinometers)
Hydraulic characteristics of the rock mass (piezometers, pore pressure sensors, etc.)

Associated deteriorations or defects to be looked for

Cracking of the tunnel structure – deformation of the tunnel structure – fracturing of the tunnel structure

Origins and possible causes

Nature of the ground – geomorphology of the site – vegetation – hydraulic regime of the rock mass

Aggravating factors

Creep – change in the hydraulic regime (saturation of materials, increase in pore pressures) – earthworks – natural erosion – accelerations produced by earthquakes

Consequences, possible evolution

Localized or total rupture
Permanent damage

Dangers to users

Falling of lining elements
Collapse of the tunnel structure

Risks to the tunnel and its structural elements

Monitoring

Visual inspection
Installation of monitoring instrumentation and crack gauges on the tunnel structure
Increased monitoring or close observation
Installation of inclinometers, piezometers, pore pressure cells and piezocones in the moving rock mass

Remedial measures

Earthworks
Drainage systems
Support structures
Planting

Observations

Additional information

A landslide is a generally slow down-slope movement of a mass of cohesive ground with variable volume and thickness. It occurs along a surface of rupture.
The surface of rupture may be curved (rotational slide) or along a pre-existing discontinuity (translational slide). The depth of this surface of rupture may vary from about one metre to several tens or even hundreds of metres in exceptional cases.
Landslide speeds remain variable. When there is a rupture, the land may slide vary rapidly, particularly when it is saturated with water.

Landslides of a controllable size may be dealt with by:

- earthworks (scaling and grading, construction of retaining walls at the foot of the slope, replacement of materials that have slid etc.);
- installation of drainage systems (collection of surface water, construction of drainage trenches, sub-horizontal or vertical drains, drainage curtains);
- construction of support structures: these structures may be flexible (gabions, reinforced ground) or rigid (walls);
- planting.

Figure 1: portal deformed by slope instability

2.3 Deteriorations in unlined sections

List of problems	Sheet number
Deteriorations in unlined sections	
Loose rock masses or blocks	NR-1
Sagging beds or plates	NR-2

See also the sheets relating to:

- deteriorations due to the surrounding ground: ZI-1, ZI-2, ZI-3
- cracking around blast holes: MO-1.

Loose rock masses or blocks	NR-1

Description (visual appearance of the deterioration)

Blocks detached from the rock mass due to discontinuities (which may or may not be open and filled with materials)
Locations from which blocks have already fallen are identified by a different colour rock

Inspection methods

Visual inspection from the carriageway, using powerful lighting (method often insufficient), and close-up inspection (by touch)
Auditory inspection by careful hammer tapping (sound response from the object, confirming actual or apparent instability)

Parameters to be measured

Measurement of the width of the main discontinuities or cracks and their pattern (direction, dip) – Estimation of the average spacing of the fracturing – Estimation of unit volumes and overall volumes – Estimation of the surface area affected

Associated deteriorations or defects to be looked for

Presence of materials inside the discontinuities (sand, clay, etc.) – Presence of moisture in the discontinuities – Presence of faults

Origins and possible causes

Original structure and fracturing of the rock mass – Natural decompression of the free surface – Fracturing produced by old blasts – Incomplete scaling after initial excavation or subsequent reaming

Aggravating factors

Discontinuities dipping towards the inside of the tunnel may facilitate the movement of rock masses (due to nature of the cross section) – Low shear strength of rock joints – Dense fracturing of the rock mass

Consequences, possible evolution

Progressive fall of loose adjacent blocks – Gradual creation of overbreaks
Damage to installations

Dangers to users

Falling blocks

Risks to the tunnel and its structural elements

Gradual weakening of certain parts of the arch (loss of passive block pressure)
Natural expansion of the cross section

Monitoring

Visual inspection
More frequent monitoring: report location (note the metric location marker), volume and frequency of falling blocks

Remedial measures

Actions tailored to each tunnel:

- periodic and preventive scaling,
- immediate protection using wire netting (for small blocks),
- bolting (for large blocks),
- lining (shotcrete).

Observations

See also sheet NR-2 (sagging beds or plates)

Unlined excavations change due to the loosening of the ground, which is more rapid if the rock is fractured or subject to weathering (shale, marl).

The diagnosis is based on close visual observation, from several angles, and on hammer tapping. This action often unintentionally eliminates the deterioration if it is small in volume, and consequently great care should be taken. Hammer tapping also enables a qualitative assessment of the degree of instability of the surface of an excavation, as its appearance may be very deceptive.

The most dangerous scenario is that of loosely structured ground, where "blocks" are not visible. This is the case, for example, with some dolomitic limestones, with barely visible discontinuities, in which instability can only be detected by hammer tapping. The sound response from the rock is the only indication of surface loosening, and attempts can then be made to define its extent and the risk of instability.

In a highly fractured rock mass, attempts must be made to identify the main characteristics of the unstable areas (volumes, thickness, localized or general instability), in view of scaling or reinforcement.

Figure 1: fractured mass separated from the surrounding rock by a clayey joint or "unstable rock bridge" (scaling is possible as an initial measure)

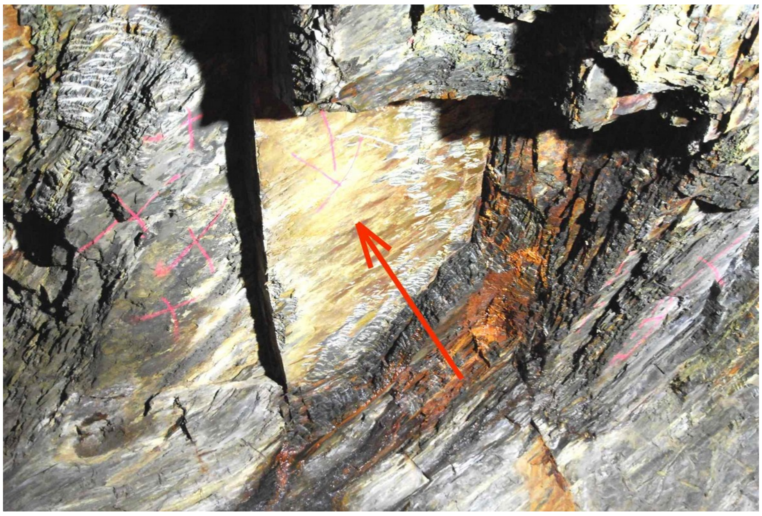
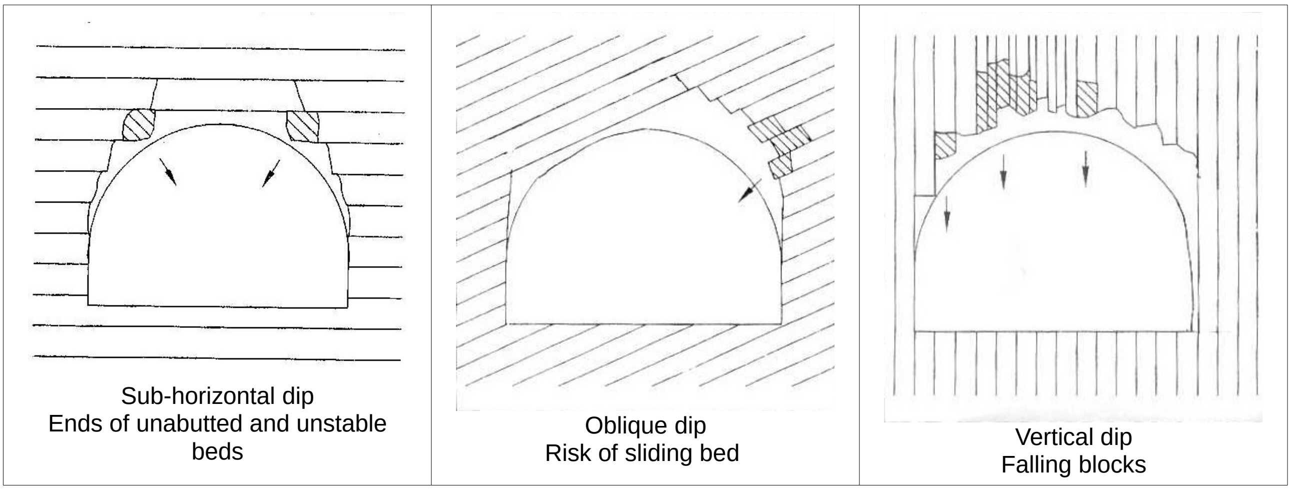


Figure 2: solid, hollow-sounding slab at the end of hard unstable beds with plates of crumbly shale

Figure 3: residual instabilities reinforced with sprayed concrete in the lateral reaming area



<u>Figure 4:</u> fallen masses or blocks (low to average unit volumes but multiple occurrences)

Sagging beds or plates	NR-2

Description (visual appearance of the deterioration)

Strata or plates, with a non-existent or very slight dip, break away from the rock mass, sag and present open joints between beds.

Inspection methods

Visual inspection, from the carriageway with powerful lighting (method often insufficient), and close inspection (by touch)
Auditory inspection by hammer tapping (sound response from the object, actual or apparent instability)

Parameters to be measured

Average thickness of the plates – Width of joints or cracks – Relative movements of elements – Estimation of unit volumes and overall volume – Estimation of the surface area

Associated deteriorations or defects to be looked for

Cracking of the slab (weakening)

Origins and possible causes

Structural origin, possibly aggravated by rock scaling or the shape of the excavation

Aggravating factors

Horizontal bed (in roof section) – Weathering of the rock – Presence of clay and moisture in the discontinuities

Consequences, possible evolution

Rupture of the visible plate, sometimes with significant rock falls
Progressive creation of overbreaks
Damage to installations

Dangers to users

Falling plates

Risks to the tunnel and its structural elements

Natural expansion of the section
Gradual weakening of certain parts of the arch (absence of passive pressure between blocks)

Monitoring

Visual inspection
More frequent monitoring (report the metric location marker number of small falling blocks indicating further deterioration, note the appearance of cracks)

Remedial measures

Actions to be tailored to each tunnel:

- periodic and preventive scaling,
- immediate protection using wire netting (for small blocks),
- bolting (for large blocks),
- construction of a lining (concrete spraying)

Observations

See also sheet NR-1 (fallen masses or blocks)

Additional information

This is a common deterioration that is primarily found in stratified rock masses, in areas where the stratification runs at a tangent to the intrados. This situation may also occur in metamorphic rocks with a high level of schistosity, in which the division into plates appears clearly at the intrados.

A horizontal rock bed in a roof section behaves like a beam on simple supports. Despite its apparent rigidity, it creeps with time and can break at pre-existing micro-discontinuities. After the block has ruptured and fallen, the base of the bed is weakened on either side and becomes potentially unstable: the situation is now that described in the sheet entitled "loose rock masses or blocks".

The level of risk obviously depends on the dip of the layers in relation to the direction of the tunnel, but also to the surface area of the visible slab, its degree of fracturing and the presence of clay or marl in the joints between beds. If the bed is very homogeneous (this is mostly frequently the case in limestone) and thick (greater than one metre), this type of problem is not likely to occur.

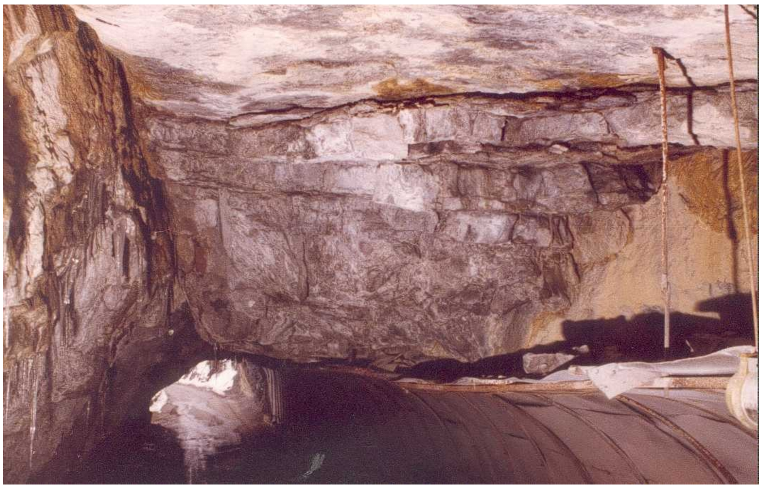
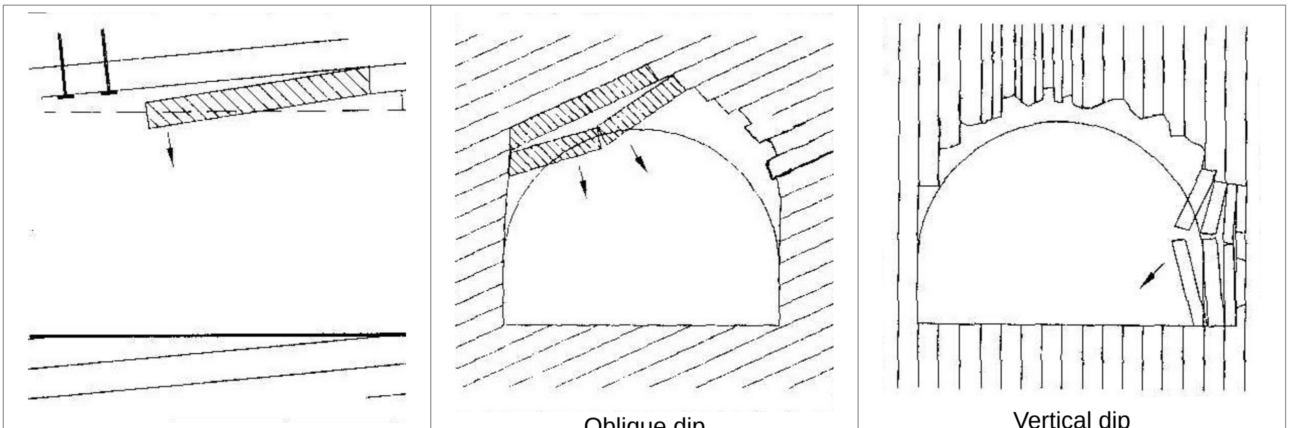


Figure 1: block that has fallen on metal sheeting, indicating weakening of the end of a limestone stratum (the presence of two damp vertical discontinuities at the sides constitutes a potentially hazardous long-term situation for the entire central part of the rock)

Figure 2: loosened plates at a 45° angle in the tunnel haunch



Sub-horizontal dip Sagging in the roof section (longitudinal section)	Oblique dip Sagging and rupture in the haunch	Vertical dip Sagging and rupture in the side wall

<u>Figure 3:</u> sagging beds or plates (unit volumes may be high in hard rock with a low degree of fracturing)

2.4 Deterioration of lining materials – Stone or brick masonry linings

List of deteriorations	Sheet number
Deterioration of lining materials Stone or brick masonry linings	
Honeycombing	RM-1
Flaking	RM-2
Exfoliation	RM-3
Spalling due to compressive load	RM-4
Deterioration of mortars – Voids in joints	RM-5

Honeycombing	RM-1

Description (visual appearance of the problem)

The stone (or brick) appears hollow between projecting mortar joints. The bottom of the pits or cavities is always clean and sound.

Inspection methods

Visual inspection
Manual inspection (hammer tapping)

Parameters to be measured

Average depth of the honeycombing – Intrados surface area affected – Compactness of the lining (hammer tapping of the stones)

Associated deteriorations or defects to be looked for

Poor general quality of the lining

Origins and possible causes

Superficial deterioration of sandstone or dolomitic stones: variations in hygrometry, low-level chemical actions, damaging the natural cement of the rock

Aggravating factors

Poor quality bricks – Porous or frost-susceptible stones

Consequences, possible evolution

Spreading, widthwise or depthwise

Dangers to users

None

Risks to the tunnel and its structural elements

None if the problem remains superficial and in a small area

Monitoring

Visual inspection
Depth measurements

Remedial measures

Repairs only need to be considered if the problem has a localized effect on the strength of the arch, which is very rare

Observations

Not to be confused with "scaling" (sheet RM-2) or arenization (underground weathering of granitic rock)

Additional information

Honeycombing occurs mainly at the surface of sandstone blocks, (whose resistance to deterioration depends on that of the original binder), or dolomite blocks. The sometimes high microporosity of the former makes them even more sensitive to variations in humidity and temperature. There is thus a loss of material (sand) from softer areas either during water or vapour transfers to the surface of the material or during capillary action. This physical process may be accompanied by minor chemical actions affecting the natural cement (dissolution of the calcite cement in sandstone or sandstone molasse, dedolomitization of the grains due to sulphate attack in dolomites).

The term "wind erosion", sometimes used, is incorrect, even though it may have a similar appearance. This type of erosion is caused by abrasive sand particles transported by the wind, which are conditions that do not exist in tunnels. On the other hand, air movements play a key role in the variations in temperature and moisture of the intrados.

This stone deterioration is rarely widespread or deep and usually has no consequences for the structure. It may pre-exist in natural outcrops.

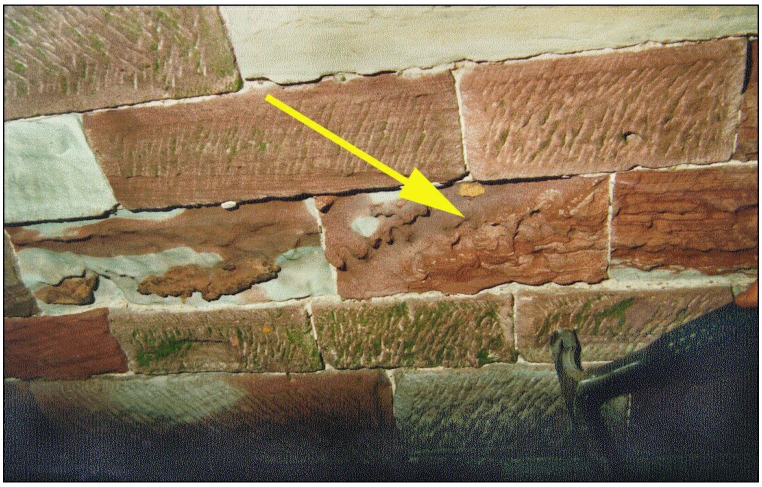


Figure 1: honeycombing in sandstone blocks

Flaking	RM-2

Description (visual appearance of the deterioration)

Flaking is a form of deterioration limited to the actual stone, which appears flaky on the surface. The individual layers are fragile and always thinner than one centimetre (forming a thin film).

Inspection methods

Visual inspection

Parameters to be measured

Nature of the stone – Extent of the phenomenon (very localized, dispersed or widespread) – Location in relation to the tunnel's portals

Associated deteriorations or defects to be looked for

Exfoliation – spalling under compressive load

Origins and possible causes

Deterioration of the stone due to migration of salts to the surface

Aggravating factors

Face bedding of stones – Periodic water ingress – Freeze/thaw cycles – Strong drafts

Consequences, possible evolution

The flaking process slowly grows deeper

Dangers to users

None

Risks to the tunnel and its structural elements

None

Monitoring

Visual inspection

Remedial measures

Periodic "cleaning"

Observations

Not to be confused with honeycombing (sheet RM-1)

Flaking is the deterioration of stone into thin uniform layers that are parallel with the facing. In general, it affects areas with stone of a similar nature (often sandstone). Depending on their thickness, layers are described as films (1 mm), crusts (several mm) or plates (1 cm). However, layers more than 1 cm thick fall within the field of exfoliation. This external rigid layer tends to detach from the mass of stone and a powdery or sandy material lies underneath it, which may be released by blistering or bursting of the superficial layer, giving the stone a cankered appearance. A layer of soot is often present on the surface, which is indissociable from the superficial layer.

Flaking is characterised by a change in the chemical nature of the superficial layer. It is linked to the action of atmospheric sulphur compounds (smoke, exhaust fumes, soot) that form acidic solutions when mixed with water. The chemical changes in the superficial layer are caused by the migration of these solutions, which either penetrate the stone or rise to the surface where they evaporate and deposit salts (calcium sulphate in particular).

The flaking process may be accelerated by the use of repointing mortars that are less permeable than the stones or the original mortar; water vapour is therefore transferred into the stone, whereas the more permeable original mortar tended to protect it.

The defect (rather than deterioration) is generally discreet and has no serious consequences in road tunnels. It is aggravated in the presence of selenitic water or atmospheres heavily polluted by exhaust fumes. This type of manifestation is typical of old railway tunnels (coal combustion producing sulphur compounds).

Figure 1: flaked stone (the sandstone masonry has been repointed some time ago using a compact and cement-rich mortar that has probably accelerated or even initiated the flaking process by enabling water to enter the stone)

Exfoliation	RM-3

Description (visual appearance of the deterioration)

Exfolitation is a form of deterioration limited to the stone itself. Beneath a sometimes intact appearance, layers a centimetre or more thick form parallel with the intrados. When some of these layers form naturally, this creates cavities on the surface of the arch.

Inspection methods

Visual inspection (if fragments have already fallen)
Manual inspection (layers that can be easily removed and are sometimes naturally unstable)
Auditory inspection (only hammer tapping detects the problem if the stone appears intact)

Parameters to be measured

Nature of the stone – Extent of the phenomenon (very localized, dispersed, widespread) – Surface area – Average thickness of the layers – Depth of the cavities formed by falling elements

Associated deteriorations or defects to be looked for

Efflorescence on mortars – Spalling due to compressive load

Origins and possible causes

Poor mechanical quality of the stone – Face bedding – Freezing – Variations in temperature and humidity – Existence of stresses within the lining

Aggravating factors

Freezing – Overloaded masonry – Face bedding – Porous and/or frost-susceptible stone – Poor quality bricks– Joints of irregular thickness

Consequences, possible evolution

Width-wise and/or depth-wise spreading due to coalescence of initially isolated areas (exfoliated areas joining together)

Dangers to users

Falling fragments

Risks to the tunnel and its structural elements

Thinning of the lining over a significant area

Monitoring

Visual inspection
Manual inspection
Auditory inspection

Remedial measures

Periodic scaling
Concrete lining if the reduction in thickness of the masonry becomes significant

Observations

Not to be confused with "spalling of stones due to compressive load " (sheet RM-4)
Synonym: onion skin weathering, delamination

Additional information

The stone's surface is sometimes intact. Inside, it is divided by cracking planes parallel with the surface, which results in a hollow sound on hammer tapping. The thickness of each layer is greater than one centimetre. Sometimes, layers fall and the intrados is dotted with cavities of varying depths and sizes. On visual inspection, there is no noteworthy petrographic change in the structure of the layer. The cause of exfoliation seems to be linked to a physico-chemical deterioration and to the effect of mechanical stresses, which occur either successively or concomitantly.

The main difference with flaking lies in the fact that these layers are very easy to scale, even by hand.

Overall assessment for the tunnel as a whole may be difficult. For example, exfoliation in the intrados may very well be caused by poor stone quality, and accentuated by the existence of even moderate stresses occurring in the body of the arch, whereas these same stress values would have no effect on masonry constructed with stronger stones.

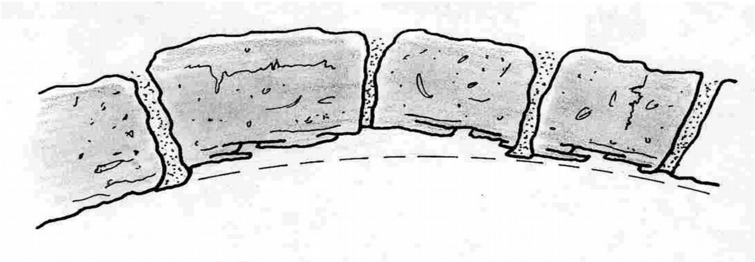


Figure 1: diagram of exfoliation

Figure 2: exfoliation of fragile, frost-susceptible oolitic limestone masonry

Figure 3: exfoliation and delamination of limestone masonry

Spalling due to compressive load	RM-4

Description (visual appearance of the problem)

This is rupture of the stone (or brick), forming a spall at least a centimetre thick, which is loosened and trapped between adjacent stones (or bricks). The spall can rarely be removed by hand. The fracture surface is clean and conchoidal (not flat but smooth). The phenomenon may involve several adjacent stones and their mortar joints. This is a structural deterioration that is unrelated to the quality of the stones (or bricks).

Inspection methods

Visual inspection (in low-angled light)
Auditory inspection ("ringing" sound indicating stress)

Parameters to be measured

Extent of the phenomenon – Location (start metric location marker number, end metric location marker number) – Location in the profile (crown or haunch) – Average thickness of the spalls – Average thickness of the mortar joints (the spalled stones are often in direct contact with each other from the outset)

Associated deteriorations or defects to be looked for

Deformation of the cross section – Cracks – Joint separation – Carriageway deterioration

Origins and possible causes

Excess local stresses in the lining, exceeding the mechanical strength of the stones or bricks

Note: The term "spalling under compressive load" should be reserved exclusively for deteriorations where it is clear that the origin is predominantly mechanical.

Aggravating factors

Face bedding – Poorly bedded stones – Insufficient mortar when laying courses (stones touching)

Consequences, possible evolution

Width-wise or depth-wise spreading
Even if there is no deformation of the arch (common), this phenomenon is critical

Dangers to users

Risk of falling spalls, which are "pushed out" over time

Risks to the tunnel and its structural elements

Local weakening of the lining
Start of a lining rupture mechanism (hypothesis to be considered in all cases)

Monitoring

Visual inspection (fallen spalls)
Auditory inspection (extent of the problem)
Measurements of the deformation in the cross-section
Measurements of stresses in the lining
Increased monitoring or close observation depending on the results of the measurements

Remedial measures

Frequent scaling
Installation of wire netting (safety of users)
Repairs involving reinforcement or even reconstruction of the structure, depending on the results of monitoring and measurements

Observations

Not to be confused with "exfoliation" (sheet RM-3)

Spalling due to compressive load is caused by stress exerted on the stone between pressure points that exceeds its mechanical characteristics. It breaks in the same way as in a point-load splitting test. Its presence within a lining indicates that the lining is subject to stress.

The surface part of the stone is loosened and detaches in spalls several centimetres thick across the entire width of the stone, but remains in place. The difference with exfoliation is the conchoidal shape (even but not flat) of the fracture surface and the impossibility of accurately repositioning the spall when it has been removed. The beginning of spalling, which is invisible, is detected with a hammer by its hollow or ringing sound. With persistant hammering, the spall can be detached, sometimes suddenly.

Some stones do not present this form of spalling, but cracks that are characteristic of crushing, generating unstable debris.

Spalling is usually aligned across one or more rows of consecutive stones.

Note: Spalling under compressive load could also be described as rupture of the stone.

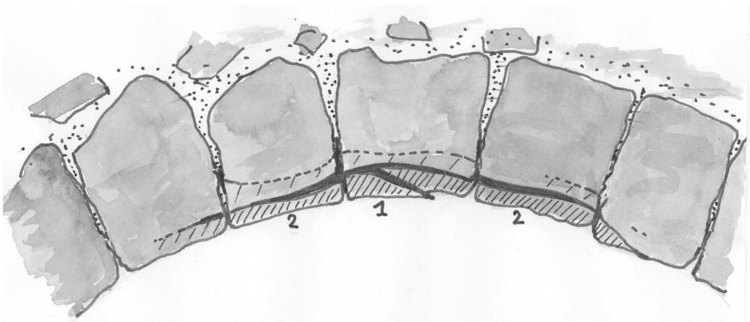


Figure 1: diagram of stone spalling at the crown (arch heave) (note the absence of mortar between stones which therefore touch each other; the falling of a type 1 spall destabilises the type 2 spalls that were previously held in place; if the base of the fallen spall still sounds hollow, this means that new spalls are forming, shown by dotted lines).

Figure 2: stone spalling at the crown (the parts that appear smooth are the scars left by fallen spalls up to 10 cm thick; note the almost total absence of mortar in the longitudinal direction, as well as a loosened spall still in place, held in place from the sides)

<u>Figure 3:</u> stone spalling on the side wall (the spall has broken away 15 mm from the wall and cannot be detached by hand; the upper and lower stones are in direct contact, as there is no mortar)

Deterioration of mortars – Voids in joints	RM-5

Description (visual appearance of the deterioration)

The mortar is loose and damp, and sometimes reduced to sand. The joints become hollow due to progressive loss of mortar.
When the masonry is coated, this deterioration may be detected by higher moisture and cracking of the coating.

Inspection methods

Visual inspection
Manual inspection (scraping of the joints and investigation using a hammer or any other fine tool in order to determine the hardness of the mortar)

Parameters to be measured

Consistency – Colour – Depth of the voids – Affected surface area on the lining – Location (start location marker number, end location marker number) – Location in the cross section – Nature of the constituents (stone or brick, binder)

Associated deteriorations or defects to be looked for

Efflorescence on the mortar – Water ingress – Poor quality of the stones– Profile deformations - Bulging – Loose stones – Hollow-sounding areas

Origins and possible causes

Superficial disintegration of the binder – Debonding due to attack by aggressive water - Ageing

Aggravating factors

Significant water ingress which is highly mineralised (sulphates in particular) – Arch deformations - Poorly bedded stones – mortar beds that are uneven or too thick

Consequences, possible evolution

Width-wise and depth-wise spreading in the presence of significant moisture
Weakening
Deformation
Falling stones or bricks
Permanent damage to the structure if lack of maintenance

Dangers to users

Falling elements

Risks to the tunnel and its structural elements

Progressive weakening

Monitoring

Visual inspection (extent)
Manual inspection (depth)
Analyses of water and mortar

Remedial measures

Drainage
Repointing
Grout injections if mortar deep inside the masonry has disappeared
Reinforcement or reconstruction

Observations

See also sheets HY-4 (efflorescence) and RB-2 (concrete deterioration)

The oldest mortars that are still visible in tunnels are generally light in colour, which means that they were produced with hydraulic lime. These were used almost exclusively in the construction of tunnel arches during the second half of the 19th century. Lime-cement mortars could also have been used (2/3 Portland cement and 1/3 fat lime). Cement-based mortars, used more recently, are generally darker.

The proportion of mortar in a volume of masonry varies between 8 and 30%, depending on the quality of the stone bonding; in brick masonry it is more or less 30% .

Old mortars are highly sensitive to chemical attacks and constitute the weak point of masonry. They have significant but very fine porosity, introducing strong capillary suction compared with that of the adjacent stones, which have larger pores. They act as a protective "sponge" for the stones, but as their carbonation is old and deep, they are highly sensitive to any acid attack. Unlike concrete, they no longer have alkaline reserves able to protect them, which explains their sometimes complete disintegration.

The gradual loss of mortar from joints is a common phenomenon in tunnel masonry, proven by the many successive repointing operations visible in certain tunnels. Voids in joints will lead to permanent damage of structural elements if not treated in time.

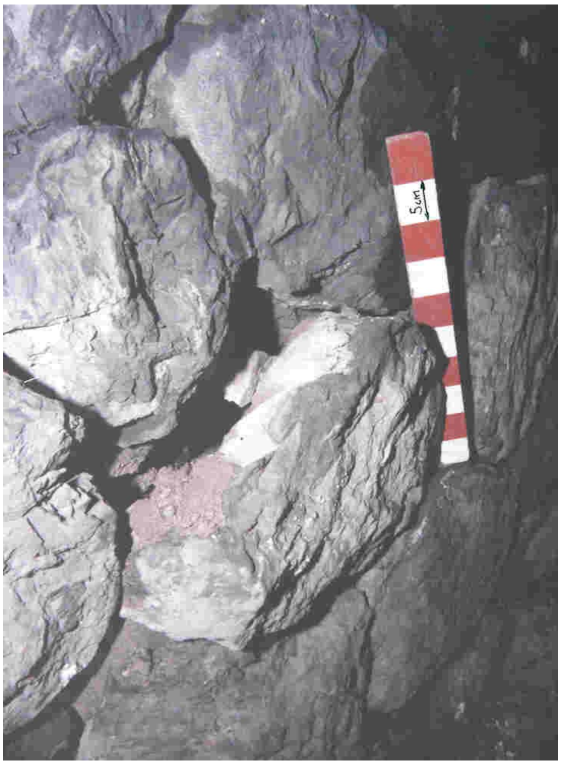
The deterioration of mortar usually affects the entire thickness of the masonry and is caused by leaching, due to seepage water rich in CO_2 or sulphates. The final stage is either dry and powdery or moist and pasty sand and the bonding is then close to permanent damage.

This deterioration may develop from the intrados by progressive disintegration of the binder, causing the mortar to recede into the joint. The slow loss of mortar is similar to the honeycombing mentioned for sandstone. The visible mortar remains compact and hard. The manner in which this deterioration evolves needs to be monitored.

The loss of mortar may also concern the extrados or the heart of the masonry without revealing very visible deteriorations on the intrados. In this case, only mechanical investigation by boring can highlight the loss of binder in the extrados. Seepage through the masonry into the intrados is the only visible clue to this defect. This can be easily located in the case of uncoated masonry. However, in the case of coated linings, seepage is widespread and difficult to locate. In this case, remedial measures consist of injecting cement grout to regenerate the structure and in particular to secure it to the ground.

In addition, repointing can sometimes hide completely deteriorated or even absent mortar. This point should be checked by a few taps with the hammer.

This deterioration is much quicker if the stone is poorly bedded and the mortar beds are uneven or too thick. However, the processes are fairly slow and allow time to carry out investigations, then repairs, so long as regular monitoring is maintained.



<u>Figure 1:</u> total decomposition of mortar, which will lead to permanent damage to the side wall (the aggravating factor here is the absence of a masonry course)

<u>Figure 2:</u> joint disintegration, typical of a lack of maintenance (wood dowels were probably used to secure stones or stop local water ingress; the stones, although of good quality, have almost come loose)

2.5 Deterioration of lining materials – Concrete linings (cast in situ or precast)

List of problems	Sheet number
Deterioration of lining materials Concrete linings (cast in situ or precast)	
Chipping	RB-1
Concrete deterioration – Swelling	RB-2
Spalling due to compressive load	RB-3
Spalling due to corrosion of reinforcements	RB-4
Sprayed concrete deteriorations	RB-5

Chipping	RB-1

Description (visual appearance of the deterioration)

The scar left by the loss of a fragment of lining on a protruding part or sharp edge (in particular in casting joints) is referred to as chipping.

Inspection methods

Visual inspection
Manual inspection

Parameters to be measured

Location – Extent of the chipping in relation to the structure affected

Associated deteriorations or defects to be looked for

Cracks – Signs of deterioration – Unstable elements still in place around the part that has been lost (spalls) – Traces of friction or impact

Origins and possible causes

Accidental impact during operation or damage during construction (during form removal, or handling in the case of prefabricated elements)

Aggravating factors

Deterioration of materials (freezing) – Water ingress – Exposure of reinforcements

Consequences, possible evolution

Spread of the deterioration and weakening of the structure (if the cause is deterioration of the materials)
Instability of the affected structure (if the cause is accidental and the structure light)
Corrosion of steel reinforcements (reinforced concrete)

Dangers to users

Non-existent, unless the structure has been weakened

Risks to the tunnel and its structural elements

Non-existent to significant (due to weakening of thin concrete elements)

Monitoring

Visual inspection
More frequent monitoring (note the repetition of impacts in the same places)

Remedial measures

No specific action if the structure is not dangerously affected
Residual elements must be scaled.

Observations

Not to be confused with "spalling due to corrosion of reinforcement" (sheet RB-4), even though the appearance may be similar. The cause and evolution are different.

Chipping affects the continuity of the material from which a fragment has come away.
Therefore, here the term chipping will be reserved for defects affecting the sharp edges of structural elements (stones, cast concrete) and caused by:

- accidental impacts,
- or a problem with form removal,
- or deterioration of the material (when frozen, sharp edges of stone or concrete will take on a rounded appearance that may be considered as chipping).

Treatment should only be undertaken if the degree of deterioration compromises the stability of the structure, or if reinforcements have been exposed (steel passivation and patching).

Figure 1: chipped thin prefabricated element following an impact (traces of friction)

Figure 2: chipping at the bottom of a ventilation slab support that probably occurred during form removal; on the left, a spall remains that has not yet fallen

Deterioration in concrete – Swelling	RB-2

Description (visual appearance of the deterioration)

The early stage consists of lime surface deposits resulting from internal dissolution.
In the final stage, somewhat loose pockets may be located at construction joints or appear at random locations on the segmental ring. They are sometimes present under a film of laitance which is still intact.

Swelling results in macro-cracking.

Inspection methods

Visual inspection
Hammer tapping (cohesion of the material)

Parameters to be measured

Location in the tunnel profile (systematic or random) – Surface area and depth of the pockets – Consistency and colour – Stability

Associated deteriorations or defects to be looked for

Continuous water ingress – Significant cracking – Signs of sulphate attack (efflorescence)

Origins and possible causes

Dissolution of the binder (action of CO_2, sulphates, chlorides) then leaching – Formation of expansive compounds (ettringite) – Alkali reaction – Freezing

Aggravating factors

Concreting during freezing weather – Cement under-dosing – Freezing – Circulation of water – Excessive compression of the lining

Consequences, possible evolution

Gradual increase in porosity – Increased penetration of aggressive agents – Loss of cohesion – Thinning of the lining due to gradual erosion

Dangers to users

Falling elements (aggregates, fragments)

Risks to the tunnel and its structural elements

Weakening of the structure
Local or generalized permanent damage

Monitoring

Visual inspection
Hammer tapping (consistency, depth)
Water and concrete analyses

Remedial measures

Drainage
Grout injection
Patching after scaling
Reconstruction (sprayed concrete and welded mesh)

Observations

See also sheets HY-4 (efflorescence) and RM-5 (deterioration of mortar)

Concrete deterioration

Aggressive agents are diffused much better within material that is porous (and permeable) with a repeatedly renewed level of moisture that remains at around 60% (neither dry nor saturated). Their harmful effect depends on their continuous supply, but as these agents are inexhaustible in relation to the material's reactive constituents, the evolution of the material is ultimately governed by time. Temporary stabilization may occur, but quite often, in old poor quality concrete, there may be complete deterioration.

Concrete is said to be deteriorated when the aggregates gradually become dislodged from the binder, which appears loose, sandy, or almost absent. This fairly general term covers the concrete's local or generalized state of destruction, which may have different origins. The many complex reactions that take place within the concrete or mortar will only be very briefly summarized below.

Dissolution

As the pore solution of concrete has a pH close to 13, it is chemically unstable when faced with any external attack, which will obviously be more acidic. The acidic chemical action always starts by the dissolution and then crystallisation of neoformed compounds that may be binding, non-binding, or even expansive. In tunnels, the main chemical attacks come from atmospheric carbon dioxide (CO_2), fresh water or water that contains few minerals, sulphated (selenitic) water, sulphur dioxide (SO_2) emitted by exhaust fumes, and also chlorides.
Water loaded with carbon dioxide primarily dissolves the portlandite of the binder to form a highly soluble bicarbonate which will be entrained. This loss of mass increases the permeability of the concrete. At the same time, this bicarbonate will react with the portlandite to produce calcite, (a highly stable binding carbonate), and water. This construction phase will reduce the permeability. But the dissolution cycle continues to act on the portlandite and the neoformed calcite due to a constant supply of CO_2.
Depending on the initial porosity and permeability of the concrete, one or other of these two aggressive actions will dominate. Generally, the formation of stable carbonates in the network of pores gradually reduces the permeability, thereby slowing down the diffusion of acids. The alkaline reserve at the heart of the concrete may also act as a barrier.

Leaching of the binder after dissolution

Close to the free surface, a proportion of the highly soluble calcium bicarbonate will migrate to the surface (osmotic pressure) through local defects in the concrete (segregations, cracks). On contact with the CO_2 in the air, and due to evaporation, there will be a varying degree of calcite deposit on the lining.
Clearly, concrete that is not very permeable and contains little lime will withstand the acid attack better and retain its mechanical characteristics longer.

Cement under-dosing

Cement under-dosing explains the absence of binder observed in some concretes, particularly when they date back to times when specifications and checks were not as strict as they are today. In addition, leaching may more specifically occur in these more permeable areas.

Concrete cast during freezing weather

When concrete is subject to freezing when setting, its mechanical strength is reduced. Its structure is more porous and it will be much more vulnerable to external aggressive agents.

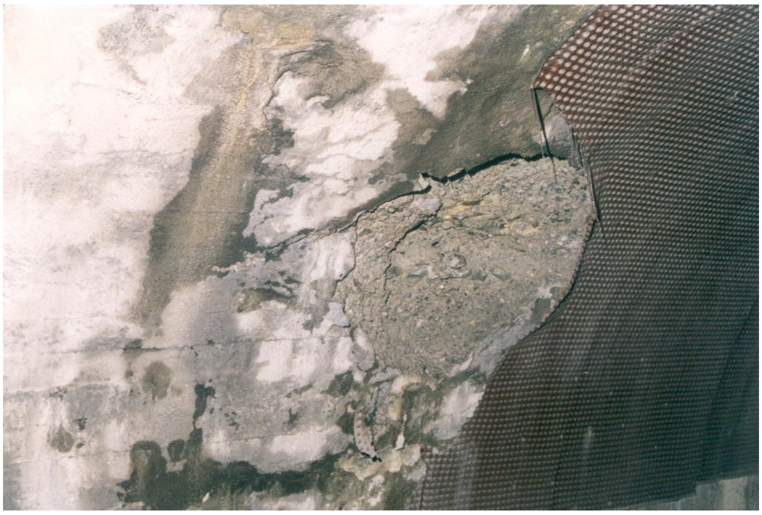
Swelling

Within the intrados, swelling results in a macro-cracking pattern with decimetric spacing, often highlighted by traces of moisture and surface gel deposits. As it evolves, it may cause the lining to disintegrate and fall. The phenomenon corresponds to an increase in volume which occurs throughout the entire mass of the concrete. Three main causes can be distinguished.

Formation of expansive compounds
Ettringite – also known as Candlot's salt – forms either when there is an excess of gypsum, free lime or free magnesium in the cement or when sulphated water attacks a cement rich in tricalcium aluminate. The lime of the binder is dissolved, giving rise to the formation of calcium sulphate, which itself immediately dissolves (entraining material), and to expansive (secondary) gypsum. This then reacts with the cement's tricalcium aluminate to form ettringite or thaumasite. These highly expansive, non-binding compounds are primarily responsible for the disintegration of some old concretes, due to the gradual destruction of inter-granular bonds. Although invisible to the naked eye, these particular salts often have a characteristic marker that appears on the free surface in the form of white, unstable fibrous efflorescence.
To prevent the concrete from reacting with sulphated water, special cements are used that are low in tricalcium aluminate or rich in slag (or a mixture of slag and fly ash).

Alkali reaction
Alkali reaction can be compared to a heterogeneous solid-liquid chemical reaction between the aggregates and the binder's alkaline pore solution. The most common form is alkali-silica reaction, which occurs with rocks containing amorphous silica (opal, chalcedony) or microcrystalline silica. An alkali-silica gel forms that causes the expansion and cracking, or even mechanical weakening, of the concrete.

Freezing
The effect of freezing may be a factor that aggravates prior deterioration that has favoured the entry of water into the heart of the concrete mass. This is a particularly likely cause close to tunnel portals.


Crack 1: *concrete deteriorated by dissolution and leaching, then freezing*

Spalling due to compressive load	RB-3

Description (visual appearance of the deterioration)

A rupture seen in the form of one or more shear cracks delimiting spalls of all sizes. It is a structural deterioration.

Inspection methods

Visual inspection in low-angled light
Auditory inspection (hammer tapping)

Parameters to be measured

Dimensions of the spalls (surface area and presumed thickness) – Position in the cross section (crown or haunch) – Width and misalignment of the cracks

Associated deteriorations or defects to be looked for

Abnormal cracking of arch (networks of cracks in a particular direction, offset sides, etc.) – Deformed profile – Nearby areas in an apparently good condition but sounding hollow

Origins and possible causes

Excessive compression in the lining, exceeding the mechanical strength of the concrete (tensile stresses perpendicular to the lining increase and create spalls)

Aggravating factors

Low height to span ratio of arch – Heterogeneous or poor quality concrete – Poor design of the structure

Consequences, possible evolution

Further deterioration both in terms of the area affected and the severity – Critical phenomenon (even if there is no deformation of the arch in most cases)

Dangers to users

Falling fragments of weakened concrete

Risks to the tunnel and its structural elements

More or less complete rupture of the lining

Monitoring

Visual inspection(fallen spalls, extent of the deterioration, width of cracks)
Auditory inspection (extent of the deterioration)
Measurements of profile deformations (convergence)
Measurements of stresses in the lining
Increased monitoring or close observation (depending on the results of the measurements)

Remedial measures

For the safety of the users: frequent scaling – installation of retaining meshing
Repair, by reinforcing the structure, or even reconstruction (depending on the results of the monitoring and measurements)

Observations

Not to be confused with "spalling due to corrosion of reinforcement" (sheet RB-4)

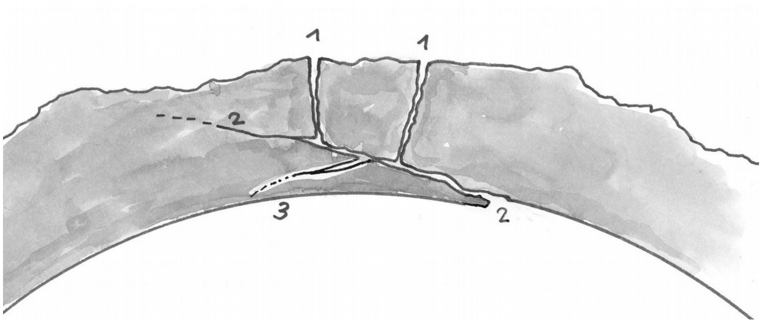
In concrete arches (cast or sprayed), spalling due to compressive load may occur in any point of the profile and take the form of shear cracks with loosening of spalls. The lining splits rapidly under the effect of excessive stresses to the intrados. These deteriorations are located along one or more tunnel generatrices and often in the arch crown.

When intrados shearing occurs, the phenomenon is clearly visible in low-angled lighting and when close enough to the arch.

If spalling is not yet visible, hammer tapping, however, and its characteristic vibratory response, may indicate the phenomenon. Thus, an intrados that only shows discreet cracking but that sounds hollow at a well-determined height of the cross section may indicate stress. Chipping at specific areas with the hammer sometimes highlights the shear crack.

<u>Note:</u> *Excessive compression within a lining may also generate horizontal cracks parallel to the intrados that are more difficult to detect and can only be identified by hammering.*

A spalling diagnosis should also include convergence measurements in the area affected, in order to determine how the deformation is likely to evolve. Measurements using a flat jack at several points of the cross section are used to find out the compressive stress values in the lining.



<u>Figure 1:</u> diagram of the concrete spalling mechanism in the arch crown; the intrados is compressed and the following situation occurs: tensile cracks in the extrados (1), shear cracks in the intrados (2), the crack is wide because the ground material expands and tends to push forward the spall that is forming; the root of the spall (3) breaks rapidly and becomes unstable; the entire underside sounds hollow.

<u>Figure 2:</u> start of concrete shearing in the crown (the shear crack is shown clearly here; the edge is fragile)

Spalling due to corrosion of reinforcement	RB-4

Description (visual appearance of the deterioration)

This concerns spalls that have fallen or that have loosened but are still in place, showing the oxidised reinforcements (falling concrete cover or laitance).

Inspection methods

Visual inspection
Auditory inspection (hammer tapping, particularly if the outline of the reinforcements is very clear)

Parameters to be measured

Dimensions and thickness of spalls – Extent of the areas where the reinforcement is visible – Degree of reinforcement corrosion

Associated deteriorations or defects to be looked for

Moisture – Alteration of concrete properties– Presence of many fine parallel cracks – Presence of hollow sounding areas

Origins and possible causes

Lining too weak (incorrect positioning of reinforcement bars or movement during casting) – Presence of water – No waterproofing of the extrados – Depassivation of reinforcements due to carbonation of the concrete and corrosion

Aggravating factors

Presence of water – No waterproofing of the extrados – De-icing salts (particularly at the portals) – Atmosphere loaded with exhaust fumes

Consequences, possible evolution

Extension of the spalling (oxidisation progressing along the reinforcement)

Dangers to users

Falling fragments or spalls (if the problem is located above traffic lanes)

Risks to the tunnel and its structural elements

Reduced concrete strength (depth of the deterioration limited to the thickness of the reinforcement cover)

Monitoring

Visual inspection
Auditive inspection

Remedial measures

Scaling, hacking
Complete removal and passivation of reinforcements
Patching

Observations

Additional information

This deterioration is rarely found in recent tunnels because they are only lined with reinforced concrete close to the portals or in areas where the profile is reinforced. It usually occurs over reinforcements that are too close to the intrados (less than 1 cm). It is triggered by a concrete carbonation process, which spreads from the intrados. The passivity of the metal reinforcements closest to the intrados is lost; the steel will therefore corrode and trigger spalling of the concrete due to the expansion of the oxidised metal.

A few tunnels (built between the 1950s and 1970s) were lined entirely with reinforced concrete. Without total waterproofing of the extrados, the problem appears mainly in damp, porous areas where carbonation has penetrated deeply. The percolation of water from the surrounding ground accelerates the corrosion. Expansion of the oxidised metal may then loosen concrete spalls 1 to 3 cm thick, creating a risk to users rather than to the structure (this deterioration rarely affects the entire tunnel). Pre-existing cracking never seems to be the cause of the deterioration.

The loss of the concrete cover exposes the reinforcements, and they appear rusty. Hammer tapping detects the problem before it is visible (the concrete sounds hollow around the spall along the line of the reinforcement). As the phenomenon evolves, action needs to be taken rapidly before pieces fall.

Spalling sometimes occurs on sprayed concrete in damp areas over bolt plates.

This deterioration also affects thin prefabricated elements, where it may be more rapid and extensive than in thick concrete. A thin covering over the reinforcement bars, together with transverse shrinkage cracking, can rapidly reduce their strength.

Figure 3 shows the outline of the reinforcements in the intrados of a side wall segment. Inspection drilling has confirmed that the outline is more marked when the reinforcements are closer to the intrados and that it disappears when the reinforcements are more than 5 cm deep. Fine shrinkage cracks may occur along the outline. Tangent reinforcements cause highly localized concrete spalling in the short term.

There are many reasons why the covering of the reinforcement might be thin: incorrect reinforcement installation, resonance of the reinforcement layer during internal or external vibration, minor segregation between reinforcements and formwork due to wall effects (proximity of the formwork and reinforcements), film of grease on the reinforcements.

This defect is very often found in recent tunnels but does not necessarily result in surface spalling.

Figure 1: *2 to 3 cm thick spall following corrosion of a reinforcement (concrete from 1963)*

Figure 2: *spalling in recent concrete*

Figure 3: *outline of the reinforcements in the side wall ring*

Figure 4: *concrete spalling due to corrosion and thin covering of reinforcements*

Sprayed concrete deteriorations	RB-5

Description (visual appearance of the deterioration)

Sprayed concrete may deteriorate in several ways:

- a particular cracking in the form of crazing,
- defects in the covering of the welded wire mesh, which may be visible in certain areas,
- insufficient thickness, particularly over rock (presence of protruding “edges”),
- superficial spalling of the concrete over welded mesh or rusted bolt heads,
- defective adhesion to the surface or weathered rock surface (hollow sounding areas),
- concrete spalls may break off and fall away.

Inspection methods

Visual inspection
Auditory inspection (hollow-sounding areas)
Hammer tapping (adhesion)

Parameters to be measured

Hollow-sounding areas (extent and location) – Adhesion of the concrete to the underlying surface (in particular at the edges of sprayed concrete panels) – Presence of localized instabilities – Thickness of the sprayed concrete (measurement or estimation) – Covering of the reinforcements (measurement or estimation)

Associated deteriorations or defects to be looked for

Water ingress – Long cracks – Wide cracks

Origins and possible causes

Poor workmanship (spraying on poorly cleaned or scaled surfaces, incorrect dosing of concrete constituents, significant variations in thickness) – Poor quality of the underlying surface – Water ingress – Faulty drainage – Ground swelling (in particular for non-reinforced sprayed concrete)

Aggravating factors

Ground swelling due to the presence of water – Sprayed concrete panels without welded mesh or fibres (old repairs)

Consequences, possible evolution

Localized instabilities (plates of sprayed concrete) – Deterioration – Disintegration of the concrete

Dangers to users

Falling elements

Risks to the tunnel and its structural elements

Minor to major depending on the intensity of the problems and the size of the areas concerned

Monitoring

Visual inspection (any new cracks)
Auditory inspection
Hammer tapping (adhesion)

Remedial measures

Scaling of unstable parts to ensure safety
Repair of the lining

Observations

See also sheet ED-8 (locally applied waterproofing materials)

Sprayed concrete is often used as support in excavation, before installation of the waterproof membrane and lining. This sheet only concerns the visible sprayed concrete that constitutes the tunnel's final lining (new or repaired) and applies to all mortars and concretes applied by spraying.

In chronological order, these include gunites, sprayed concretes (non-reinforced or reinforced with welded mesh), fibre-reinforced sprayed concretes and self-stabilising shells.

Gunites
These mortars, which are rarely reinforced, are sprayed in thin layers (1 to 3 cm on average), with the aim of stabilising the unstable surface of an excavation. Very rapidly deteriorated or loosened, gunites then no longer provide protection against falling stones.

Sprayed concretes
Used in old tunnels as reinforcements, these are thicker (5 to 15 cm) and are usually reinforced with welded mesh pinned to the rock. Their strength over time is generally very good.

Hammer tapping on concrete sprayed directly on to rock always reveals many hollow-sounding areas. It is not always just the concrete alone that sounds hollow, but sometimes the concrete together with locally loosened rock. As this type of thin lining is often installed on the surface of ground with variable cohesion, defects in terms of overall compactness are inevitable, even if adhesion to the rock is good.

It is therefore advisable to investigate whether abnormal cracking marks out areas that may then become unstable. The most critical situation is swelling ground that the lining cannot contain and that will lead to rupture of the structure.

Fibre-reinforced sprayed concretes
These concretes contain metallic or macro-synthetic fibres. They are sometimes used in combination with welded mesh. There is less cracking and rupture is more gradual.

Self-stabilising shells
These are constructed from reinforced sprayed concrete with complete waterproofing. For the moment, no specific deteriorations have arisen relating to the manufacturing technique.

As a waterproofing system was installed before spraying, a thin concrete shell will sound hollow across its whole surface without this constituting a deterioration.

Figure 1: insufficient covering of the welded mesh (poor workmanship)

Figure 2: sprayed concrete crazing over damp rock (shrinkage of non-reinforced concrete)

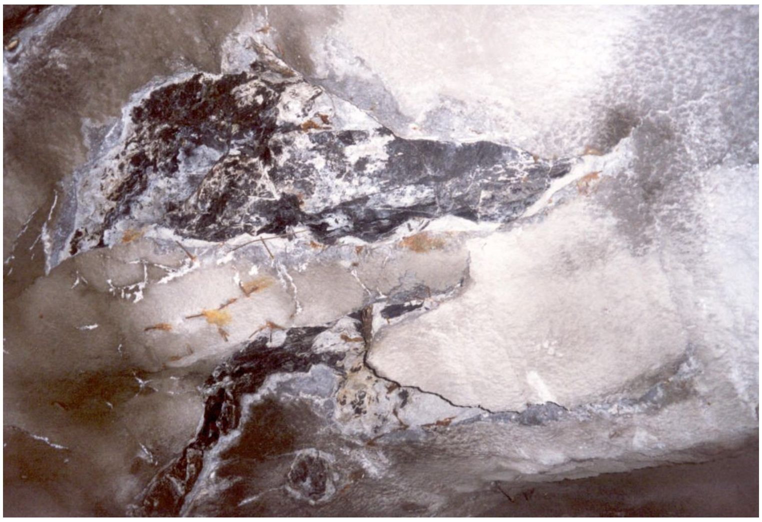


Figure 3: sprayed concrete that has fallen from a roof section (combination of incorrect spraying on damp and unstable shale ground subjected to prolonged freezing)

2.6 Deteriorations in waterproofing, drainage and surface water collection systems

List of deteriorations	Sheet number
Deteriorations in waterproofing, drainage and surface water collection systems	
Deteriorations in intrados drainage	ED-1
Deteriorations in extrados drains and culverts	ED-2
Deteriorations in roadway drains	ED-3
Deteriorations in extrados waterproof membranes	ED-4
Deteriorations in sheeting	ED-5
Deteriorations in waterproof tanking	ED-6
Deteriorations in thin mortar coatings	ED-7
Deteriorations in waterproof insulating panels	ED-8
Deteriorations in swellable waterstops	ED-9

Deteriorations in intrados drainage | ED-1

Description (visual appearance of the deterioration)

Various types of deteriorations can affect drainage systems installed on linings of tunnels originally designed without complete waterproofing on the extrados or where the external waterproof membrane is defective. There may be damage, loosening, tearing, clogging or leaks.

Inspection methods

Visual inspection
Video-endoscopy

Parameters to be measured

Location of leak outlets – Length of damp joint lines – Possible blockage by calcite or fines (visible loosening) – Height at which drains have been torn away (often following impact by a heavy goods vehicle)
Flow rate if a repair project is planned

Associated deteriorations or defects to be looked for

Deterioration of the lining – Abnormal dampness

Origins and possible causes

Poor construction – Penetration of fines due to deterioration in the lining or ground alteration – Water ingress – Impact by a vehicle
Accidental causes

Aggravating factors

Accidents – Undersized drain – Pronounced periods of freezing

Consequences, possible evolution

Loss of drainage efficiency – Increase in hydraulic thrust on the structure – Changes in location of water ingress or new water ingress

Dangers to users

Water or black ice on the carriageway – Icicles above traffic lanes

Risks to the tunnel and its structural elements

Deterioration of materials due to the presence of water (spalling of materials under the effects of freezing/thawing, corrosion of metal elements and installations)

Monitoring

Visual inspection

Remedial measures

Complete repair of drains

Observations

Water analysis if a repair project is planned

Additional information

These systems, installed on the intrados, only concern tunnels designed without complete waterproofing of the extrados in order to mitigate problems related to water ingress that are detrimental to the tunnel's operation. They are generally installed post-construction, on the joints between segmental rings or on certain cracks. They include:

- weep holes or drilled drainage channels (tubed or not) in side walls,
- sealing strips fixed to concrete construction joints or over cracks,
- drainage channels in the lining that house a fixed or removable drainage pipe.

The water channelled by these devices must be collected.

Drains deteriorate rapidly under harsh conditions, due to spalling caused by freezing or to rapid clogging with fines transported by the water.

Sealing strips stuck over joints and cracks often have tears or bonding defects resulting in leaks. Removable drainage pipes (PRT type) are only truly effective if the drainage channels are in straight lines and have very even sides. However, even when they are installed correctly, sometimes the porosity of poorly vibrated concrete allows moisture to pass through the areas surrounding the seal.

Although they collect most of the water, sealing strips and drainage channels do not constitute waterproofing but simply a linear collection system that is still likely to leak.

Removable systems installed in road tunnels are rarely removed for cleaning, because many of them are secured using metal hoops screwed into the concrete. In addition, reinstalling the pipe into its drainage channel can be difficult and cause further lateral leaks. Moreover, in tunnels equipped in this way, the friction of heavy-goods vehicles along the haunches may cause sealing strips or removable seals to break away or shear, including those protected by metal coverings.

In harsh climates, leaks from these systems cause the formation of icicles that must be removed daily. During this operation, the system may be damaged or loosened.

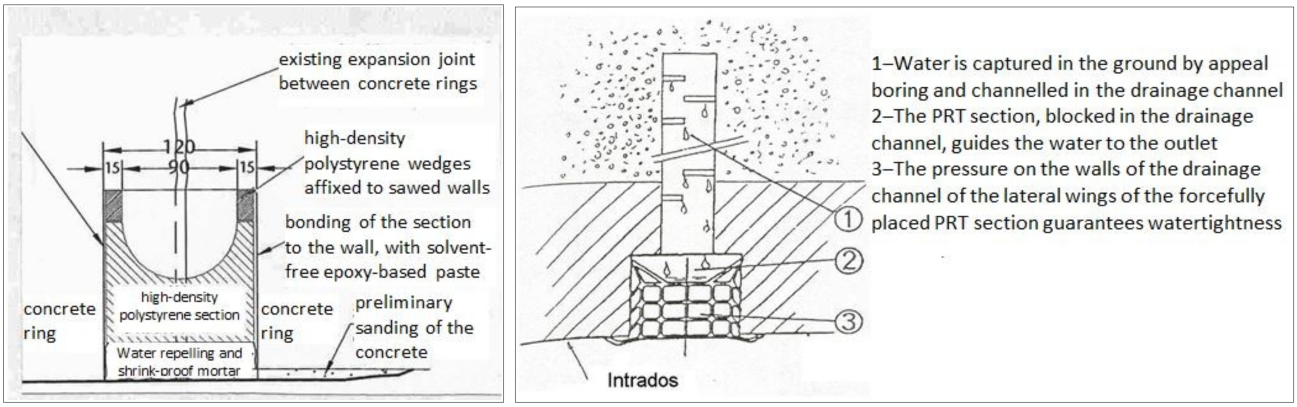


Figure 1: two types of linear intrados water collection systems

Figure 2: loosened sealing strip (the bottom of the collection system has been destroyed by freezing and is blocked)

<u>Figure 3:</u> sealing strip and removable seal (here PRT seal and Hypalon sealing strip) destroyed by friction from heavy goods vehicles

<u>Figure 4:</u> corroded and leaking zinc-plated steel intrados drain

Deteriorations in extrados drains and culverts — ED-2

Description (visual appearance of the deterioration)

These deteriorations may be of several types:

- blockage of drains and drainage channels due to calcite concretions or fines (visible via inspection chambers),
- blockage of pipes due to foreign bodies,
- crushing of circular drains (only visible by video-endoscopy).

Inspection methods

Visual inspection (extent of blockage of outlets, condition of inspection chambers).
Video-endoscopy

Parameters to be measured

Nature of visible filling materials (hard calcite concretions, deposits, miscellaneous debris) – Quantity – Reduction of the drain's width – Location of blockages in the drainage system

Associated deteriorations or defects to be looked for

Abnormal local dampness – Water ingress

Origins and possible causes

Water with a naturally high carbonate content (limestone rock) – Water enriched with carbonates due to leaching of support concrete (recent tunnels) – Poor workmanship or construction defects

Aggravating factors

Freezing – Lack of maintenance

Consequences, possible evolution

Loss of drainage efficiency – Local hydraulic loading – Damp visible in the traffic zone

Dangers to users

Damp carriageway – Black ice

Risks to the tunnel and its structural elements

None

Monitoring

Periodic visual inspection (at outlets)

Remedial measures

Cleaning with pressurized water
More intensive cleaning using a milling cutter
Use of "anti-calcite" tablets to dissolve the calcite (to be placed in inspection chambers)
Construction of a new drain which bypasses the blocked area

Observations

See also sheet HY-2 (concretions)

This type of drain is found in tunnels equipped with an extrados waterproof membrane. It is designed to capture water diverted by the waterproof membrane and direct it into a collector pipe. It is incorporated into the benches of the arch, beneath the finished carriageway (approximately 1 m). It is only accessible for cleaning from the inspection chambers that are often located in purpose-built recesses in the side walls. There is an outlet towards the main collector pipe in each of them.

Depending on the age of the tunnel, it may comprise elements made of reinforced PVC or polyethylene or a drainage channel covered with small concrete slabs or metal drainage tiles. These drains fall outside of the scope of conventional detailed inspections, because they can only be inspected by video-endoscopy.

The following common defects and deteriorations are often highlighted by video-endoscopy:

- concretions and deposits;
- poor workmanship or negligence:

- for PVC drains: crushing of the bench during concreting, use of "agricultural" drains that are too fragile;

- for encased drainage channels: vertical and horizontal offsets during casing which create barriers, foreign bodies of any type, significant variations in width, collapse of metal tiles or box drain covers, forgotten formwork totally blocking the drain.

In all, poor workmanship represents 50% of malfunctions.

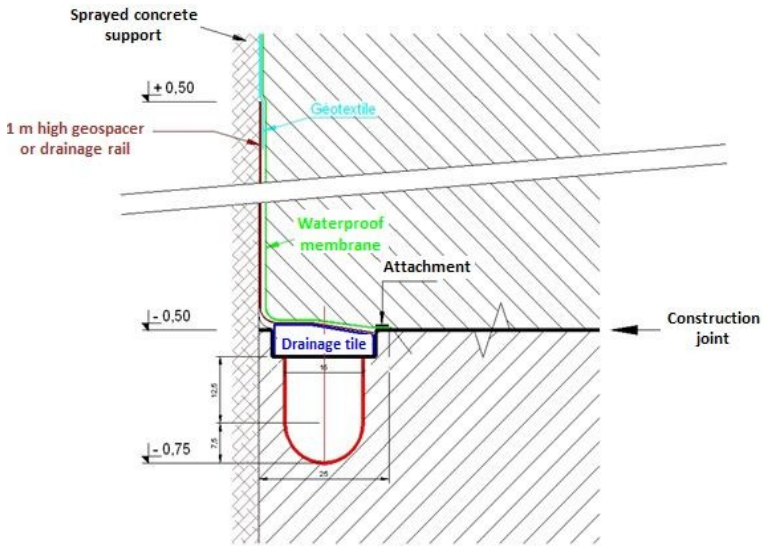


Figure 1: cross-section of a drainage channel at the bottom of a waterproof membrane

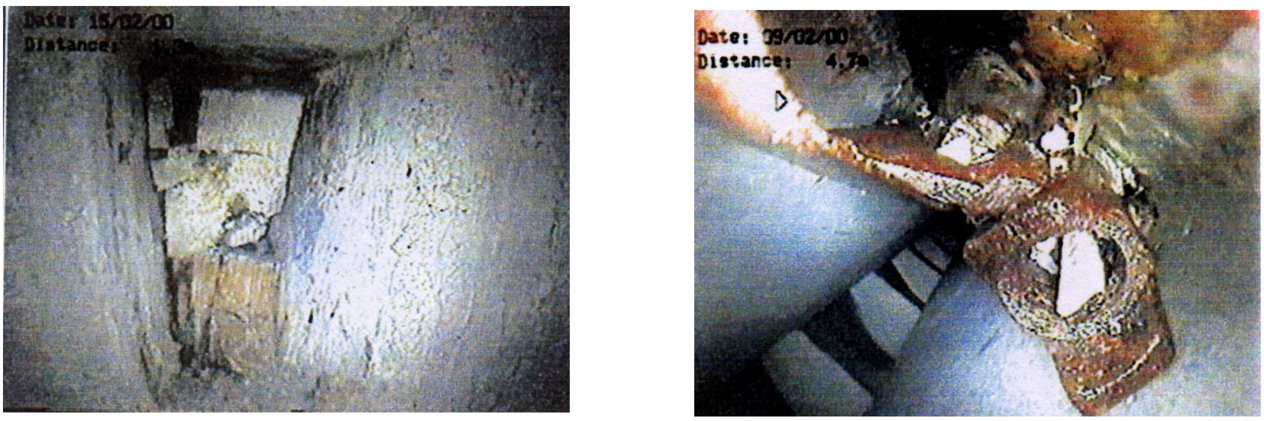


Figure 2: examples of drainage channels blocked with site debris (video-endoscopy)

Deteriorations in roadway drains	ED-3

Description (visual appearance of the deterioration)

Roadway drains can be blocked, crushed or broken. These deteriorations are only visible by endoscopy (where this is possible) and result in dampness on the carriageway unrelated to water ingress from the arch and in water seepage or stagnation in other structures (sumps, collector pipes, drainage channels with longitudinal slots).
Not all roadway drains are designed to be accessible and cleanable.

Inspection methods

Visual inspection (at outlets, if accessible, and inspection chambers)
Video-endoscopy

Parameters to be measured

Nature of the filling materials (hard calcite concretions, miscellaneous deposits) – Quantity (reduction in the drain's width) – Cracking of the carriageway (rigid carriageways) – Location and surface area of the carriageway affected by dampness – Location and nature of the outlets (localized or widespread, pressurized flow)

Associated deteriorations or defects to be looked for

Deteriorations affecting the carriageway (cracks, bulges, settlement, etc.)

Origins and possible causes

Mineral content of water, which may be either natural or acquired when passing through the porous concrete lining the drains – Poor workmanship – Poor design – Deformation of the structure or surrounding ground

Aggravating factors

Alterations in the surrounding ground – Lack of maintenance

Consequences, possible evolution

Loss of drainage efficiency – Local hydraulic loading – Visible dampness – Deterioration of the carriageway layers by rising water

Dangers to users

Locally damp or wet carriageway (with risk of black ice)

Risks to the tunnel and its structural elements

None

Monitoring

Periodic visual inspection (at outlets)
Monitoring and mapping of water discharges and any change in location

Remedial measures

High-pressure water cleaning (when the drains are accessible)
Use of tablets to dissolve the calcite (to be placed in inspection chambers, if any)
Construction of a new drain bypassing the blocked area

Observations

See also sheet HY-2 (concretions)

Longitudinal or angled roadway drains are installed in the foundation of the carriageway (between 0.5 and 1 m under the finished carriageway) and covered with porous concrete. They are designed to collect water in the carriageway and send it to a collector pipe. They are only visible at their outlets or in inspection chambers. Their design does not always enable regular cleaning.

This type of drain collects some of the water that percolates through the cement-bound aggregates (porous or not) present in the foundations of the carriageway. It is enriched with dissolved bicarbonate (from the lime in the concrete), which is immediately deposited in carbonate form (calcite) when it reaches the drain. The deposit will be greater if the water also comes from rock in which limestone predominates. Often small in diameter (100 to 150 mm), these drains can clog up very rapidly.

Before any inspection, the various drains and collector pipes must be accurately located using construction plans.

When inspecting the structure and with the agreement and help of the operator, efforts must be made to remove all inspection chamber covers and grates in order to observe the outlets and their state of blockage. This can reveal deteriorations and their location in the tunnel. Any dampness on the carriageway (not coming from the arch) suggests a blockage in a deep drain.

Limestone concretions in roadway drains represent 75% of blockages; the rest are due to miscellaneous deposits.

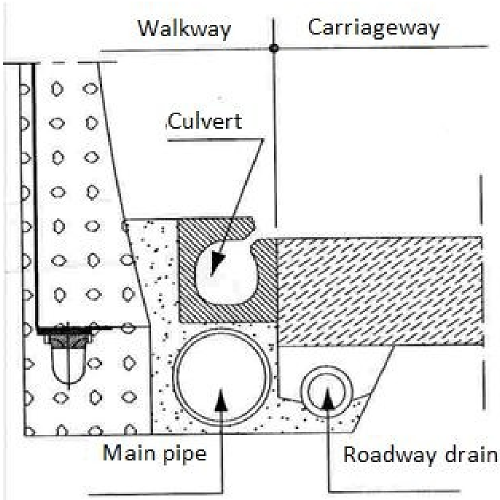


Figure 1: *extrados drainage channel, roadway drain, collector pipe and slotted drainage channel*

Figure 2: *video-endoscopy of a PVC drain blocked with calcite*

Deteriorations in extrados waterproof membranes	ED-4

Description (visual appearance of the deterioration)

Damage (movements, tears or folds) in the waterproof membrane, leading to a discontinuity (comparable to a void) within the concrete of the segmental ring. When the deterioration is visible, the membrane can be seen over a variable surface area during formwork removal on the intrados of the ring; otherwise, an area of hollow-sounding concrete may indicate movement, a tear or a fold in the membrane.

Inspection methods

Visual inspection
Auditory inspection (systematic hammer tapping of the entire intrados, even if no defects are visible)
Radar sounding

Parameters to be measured

Location – Surface area affected

Associated deteriorations or defects to be looked for

Water ingress – Wet cracks – Abnormally wide cracks and cracks with abnormal patterns – Highly visible and localized crazing

Origins and possible causes

Poor workmanship (membrane too taut or not taut enough between its fixings, tearing initiated by support elements or reinforcements)

Aggravating factors

Water ingress – Alteration of the surrounding ground

Consequences, possible evolution

Abnormal behaviour of the lining over the long term (presence of a discontinuity)

Dangers to users

None

Risks to the tunnel and its structural elements

Accelerated ageing – Additional deteriorations if water is present very close to the intrados (prolonged freezing)

Monitoring

Visual inspection (appearance of water ingress inside the concrete ring)
Auditory inspection

Remedial measures

Repairs carried out during construction (hacking, reconstruction of the waterproofing, patching) if the membrane is visible when formwork is removed
No repair if the deterioration is not visible and if the structure shows no related deteriorations or defects

Observations

See also sheet MO-2 (voids in the lining close to the intrados)

Additional information

In modern tunnels, PVC waterproof membranes are thermo-sealed and stud-driven into the rock to prevent water from the rock mass from coming into contact with the main lining. However, deteriorations such as water ingress and hollow-sounding areas may appear within the waterproof cast concrete rings. They may be caused by:

- a membrane installed too "loosely" (insufficient number of fixture points): concrete rising up into the formwork causes the formation of folds that may be close to the formwork and generate a very local hollow-sounding area;
- a membrane installed too "tautly": concrete rising up into the formwork at the location of overbreaks tightens the membrane beyond its yield strength; the concrete then passes behind the torn membrane, sometimes folding it back against the formwork or within its immediate vicinity; in this case there will be a more extensive hollow-sounding area;
- a metal support element, not cut back, that starts to tear the membrane.

Depending on the fixing method and the way in which the works are conducted, the damaged or displaced membrane will create abnormal discontinuities within the concrete, or even locally weaken a ring. Over the medium or long term, these local deteriorations may accelerate the ageing of the structure, regardless of whether the membrane is pierced or not.

Once concreting has been completed, the membrane cannot be regularly inspected unless it is brought back into the intrados and visible during formwork removal or if the concrete over the membrane is less than around ten centimetres thick (and sounds hollow on hammer tapping).

Figure 1: fold in membrane (localized hollow-sounding area)

Deteriorations in sheeting	ED-5

Description (visual appearance of the deterioration)

There may be either:

- deformations or tears due to impacts,
- or perforations due to oxidation,
- or the rupture of fixings on rails or of fixings anchoring the rails to the arch, due to corrosion.

Inspection methods

Visual inspection (observation of the space between the sheeting and the lining or the rock)
Monitoring (checking by hand whether any sheet elements are loose)

Parameters to be measured

Location – Surface area – Degree of oxidation of fixings and rails – Degree of oxidation of metal sheets (loss of galvanisation) or deterioration (other materials) – Incorrect alignment or overlapping of corrugations (corrugated sheets)

Associated deteriorations or defects to be looked for

Presence of fallen materials overloading the extrados of the sheets (volume should be estimated) – Deterioration of the tunnel lining – Water ingress

Origins and possible causes

Miscellaneous deterioration and corrosion – Impacts – Rocks or lining elements falling on to the sheets – Water ingress

Aggravating factors

Narrow cross-section of the tunnel (favouring impacts from heavy vehicles) – Age of fixings

Consequences, possible evolution

Failure of sheet fixings, leading to loose or falling elements
Water ingress on the carriageway

Dangers to users

Damage to large vehicles
Risk of falling elements

Risks to the tunnel and its structural elements

Progressive permanent damage to the structural elements

Monitoring

Visual inspection

Remedial measures

Replacement of elements, rails and fixings

Observations

Additional information

The generic term “sheeting” covers cladding sheets made of galvanised metal, fibre-cement or plastic. They comprise thin elements, often corrugated and bent to the radius of the intrados, fixed to the arch using rails anchored into the lining. The sheets themselves are rarely directly fixed to the arch. The annular space is at least 5 cm.

This process, which is already old, is still used in many tunnels in the dampest roof section areas to prevent water falling on the carriageway by sending the water to the sides.

Apart from their vulnerability, the sheets have the disadvantage of hiding certain damp-related deteriorations. If there are doubts about the stability of the lining (or excavation), one or more sheets should be removed during inspection.

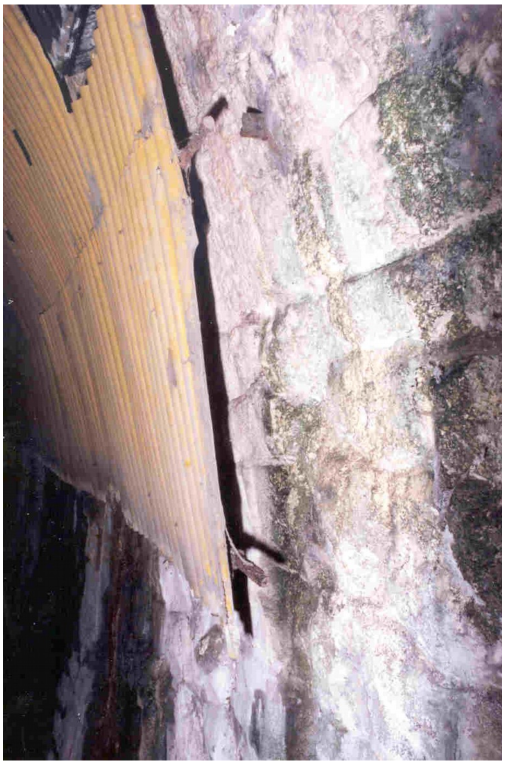


Figure 1: loss of a metal element and rupture of anchorage

Figure 2: fibre-cement panels (significant oxidation of the support rails and an element which has become unfixed)

Deteriorations in waterproof tanking	ED-6

Description (visual appearance of the deterioration)

Under the pressure of water on the waterproof membrane, detachment blisters may appear; these may burst under the effect of pressure or freezing.

In addition, after a few years, the products used to construct the tanking lose their elasticity and become fragile. The waterproof membrane cracks and concretions may form along the damaged areas.

Inspection methods

Visual inspection

Parameters to be measured

Location – Surface area – Presence of pressurized water in blisters – Adhesion of the membrane to the underlying surface

Associated deteriorations or defects to be looked for

Deterioration of the substrate where the membrane is damaged (swelling of reinforcements, cracks) – Water ingress

Origins and possible causes

Ageing of the tanking – Loosening, pressurization, bursting under the effect of considerable volumes of water – Effects of freezing

Aggravating factors

Substrate damp when the tanking was installed – Long cracks – Wide cracks – Poor quality of the substrate

Consequences, possible evolution

Re-occurrence of water ingress and concretions

Dangers to users

Water ingress on traffic lanes – Wet carriageways

Risks to the tunnel and its structural elements

Faster deterioration of the substrate due to permanent saturation with water behind the membrane

Monitoring

Visual inspection

Remedial measures

Jet cleaning

Removal of very damaged areas of tanking

Finding another local or global waterproofing solution depending on the extent of the deterioration and the flow rates of the inflows of water

Observations

Additional information

High levels of damp in some old tunnels, threatening their operation, led to the implementation of intrados waterproofing in the form of thin (1 to 2 mm max.) polyurethane resin membranes to fulfil the function of tanking. Deteriorations appeared rapidly due to the pressure of the water between the lining and the membrane. Depending on the quality of its adhesion and its elasticity, which reduces over time, the membrane loosens (pressurized blisters), then tears.

The result is an intrados that is once again wet and difficult to clean. Inflows of water reoccur at their initial sources. Where these membranes remain, they keep the substrate permanently saturated, which is detrimental in the event of freezing. Although this technique is suitable for reservoirs, it is not suitable for tunnels and is moreover no longer used.

Figure 1: deterioration of a resin membrane installed on masonry

Figure 2: blisters in the resin membrane filled with pressurised water

Figure 3: break up of tanking under the effects of freezing

# Deteriorations in thin mortar coatings	# ED-7

Description (visual appearance of the deterioration)

Deteriorations in thin mortar coatings are indicated by:

- faulty adhesion to the substrate (hollow-sounding areas),
- crazing,
- blisters and/or falling fragments of coating.

Inspection methods

Visual inspection
Auditory inspection by knocking or light hammer tapping

Parameters to be measured

Location and surface areas (hollow-sounding areas, blistered areas, areas without coating) – Average thickness of the coating – Presence of reinforcements – Adhesion of the coating – Presence of localized instabilities on the crazing

Associated deteriorations or defects to be looked for

Localized water ingress – Long cracks – Wide cracks – White efflorescence on/under the coating

Origins and possible causes

Ageing of the coating – Difference in thermal inertia between the substrate and the coating (generally with higher cement content than the substrate)

Aggravating factors

Presence of water – Freezing – Poor quality of the substrate and/or coating

Consequences, possible evolution

Spread of detached areas – Cracking of the coating under its own weight – Falling of coating fragments

Dangers to users

Falling of large sheets which, due to adhesion, may bring part of the substrate with them

Risks for to the tunnel and its structural elements

Minimal risk to the substrate

Monitoring

Visual inspection
Auditory inspection

Remedial measures

Preventive scaling (in the event of danger)
Repair of the damaged area or implementation of another process

Observations

Thin mortar coatings (1 to 3 cm) are sometimes installed after the construction of the arch to provide a certain level of water-tightness or, much later as a corrective measure, installed on a lining that is too wet or has deteriorated at an abnormally rapid rate. Their high-cement formulation gives them compactness (high modulus) and a certain level of impermeability (water-repellent admixtures).

They may deteriorate in several ways:

- gradual loss of adhesion to the substrate due to its poor quality, the action of water trapped by the coating, thermal "breathing" of the arch (cyclical seasonal deformations) or the action of freezing;
- cracking of the coating, which has a different rigidity or thermal behaviour to the substrate;
- internal chemical attack from the substrate, generating swelling that loosens the coating;
- falling of large pieces of coating, as the coatings are not usually reinforced (if they are, it is often with fine mesh that oxidises completely).

As it loosens, the coating may bring part of the deteriorated substrate with it. Inspection therefore requires some precautions.

Figure 1: cracked and loosened coating on old concrete

Figure 2: fallen coating (brick arch in a canal tunnel)

Deteriorations in waterproof insulating panels	ED-8

Description (visual appearance of the deterioration)

Waterproof insulating panels are protected by a lining or a separate cladding (sheeting, sprayed concrete). The product is thus not visible.
The main deterioration is moisture appearing in the lining or at the edge of the watertight area (often at the bottom of the panel).

Inspection methods

Visual inspection

Parameters to be measured

Location – Area affected by the problem – Flow rate of water ingress

Associated deteriorations or defects to be looked for

Cracking (in the case of sprayed concrete)

Origins and possible causes

Poor workmanship during installation – Accidental perforation during installation – Loosening under the effect concrete spraying

Aggravating factors

Pressurized water ingress – Impacts of vehicles on the panel’s protective lining applied to the intrados

Consequences, possible evolution

Loss of waterproofing capacity – Loss of insulating effect (system generally installed in tunnels exposed to significant and prolonged freezing)

Dangers to users

In the event of freezing, the formation of black ice and ice stalactites along leaks

Risks to the tunnel and its structural elements

None (if no other deteriorations)

Monitoring

Visual inspection

Remedial measures

Localized waterproofing by injection if possible or implementation of another technique for dealing with water ingress

Observations

Impossible to inject a separate thin shell
Guard against the risks of clogging of the drainage systems in place

Additional information

Waterproof insulating panels have been used to repair tunnels located in cold sites. Consisting of foam sheets/panels (3 to 5 cm thick), bonded or glued together and fastened to the rock mass with bolts, these water-tight systems are designed to protect against water ingress and provide thermal insulation to prevent the formation of ice behind them. They are protected on the intrados by sheeting (protection against vandalism and vehicle impacts) or by a sprayed concrete lining and welded mesh. In the latter case, dampness may reoccur, due either to poor workmanship in the assembly of the semi-rigid panels, to localized bonding defects or to loosening under the effect of concrete spraying.

Inspections show that water-tightness is never fully guaranteed, meaning that occasional (and difficult) re-waterproofing work is required over time.

This repair technique has now been replaced by self-stabilizing shells or other techniques that guarantee complete water-tightness.

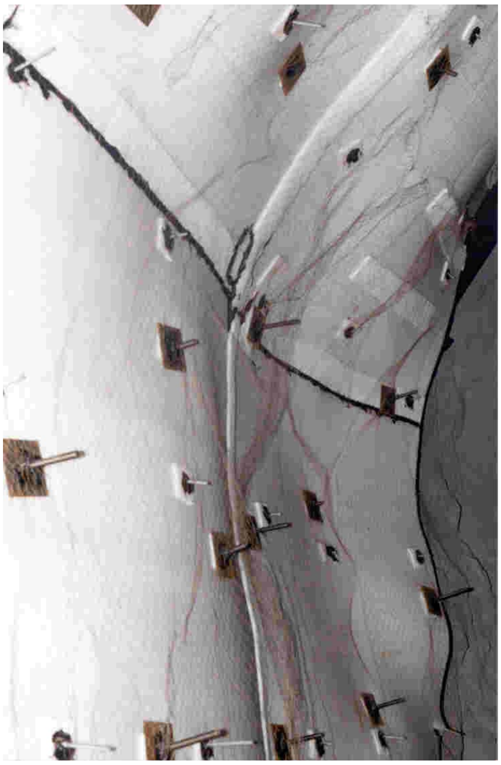


Figure 1: waterproof (Ethafoam) installed prior to welded mesh and shotcrete

Figure 2: same tunnel after a few years in operation

Deteriorations in swellable waterstops (seals)	ED-9

Description (visual appearance of the deterioration)

These seals are embedded in the concrete along construction joints to prevent the circulation of water or the presence of dampness. They swell on contact with water, guaranteeing water-tightness along the construction joints of concrete cast in situ. Deteriorations may be caused by failure to comply with the conditions for waterstop installation (lining, reinforcements, etc.): the stresses produced in the concrete by swelling of the joint may cause concrete spalls thicker than 10 cm.

Inspection methods

Visual inspection
Auditory inspection
Hammer tapping

Parameters to be measured

Location – Dimensions and depth of spalling – Water ingress – Extent of visible areas of reinforcements – Degree of corrosion of reinforcements – Hollow-sounding areas

Associated deteriorations or defects to be looked for

Cracking – Joint alignment deviation

Origins and possible causes

Failure to comply with installation conditions

Aggravating factors

Poor quality of concrete – Lack of reinforcement – Presence of gravel pockets along the construction joint

Consequences, possible evolution

Exposure and corrosion of reinforcements – Spalling of the concrete – Water seepage

Dangers to users

Debris which may fall on the carriageway

Risks to the tunnel and its structural elements

Local weakening of the structure (loss of thickness, corrosion of reinforcements, etc.)

Monitoring

Visual inspection
Auditory inspection

Remedial measures

Concrete hacking around the seal
Re-installation of the seal or installation of a new seal, depending on the installation conditions
Possible passivation of reinforcements and patching

Observations

Swellable waterstops must be used with a great deal of care, complying scrupulously with required installation conditions.

Additional information

Swellable waterstops take the form of polymerized polyurethane elastomer strips (such as Supercast SW20), which swell on contact with water. They are designed to limit water seepage via construction joints in concrete cast in situ.

Their use is generally limited to repair work or when connecting a new gallery to an existing tunnel.

The walls or inverts in which these waterstops can be incorporated must be no less than 20 cm thick. The waterstops must always be laid between two beds of reinforcements and installed, if possible, in the axis of the construction joint. In all cases, there must be a coating at least 50 mm thick between the cast faces and the first bed and at least 70 mm thick between the concrete face that will be in contact with the water and the first bed. The waterstops must not be in contact with the concreting hose or with the needle vibrator, and the concrete must not be poured directly on the seals.

The deteriorations that have occurred are due to non-compliance with installation conditions.

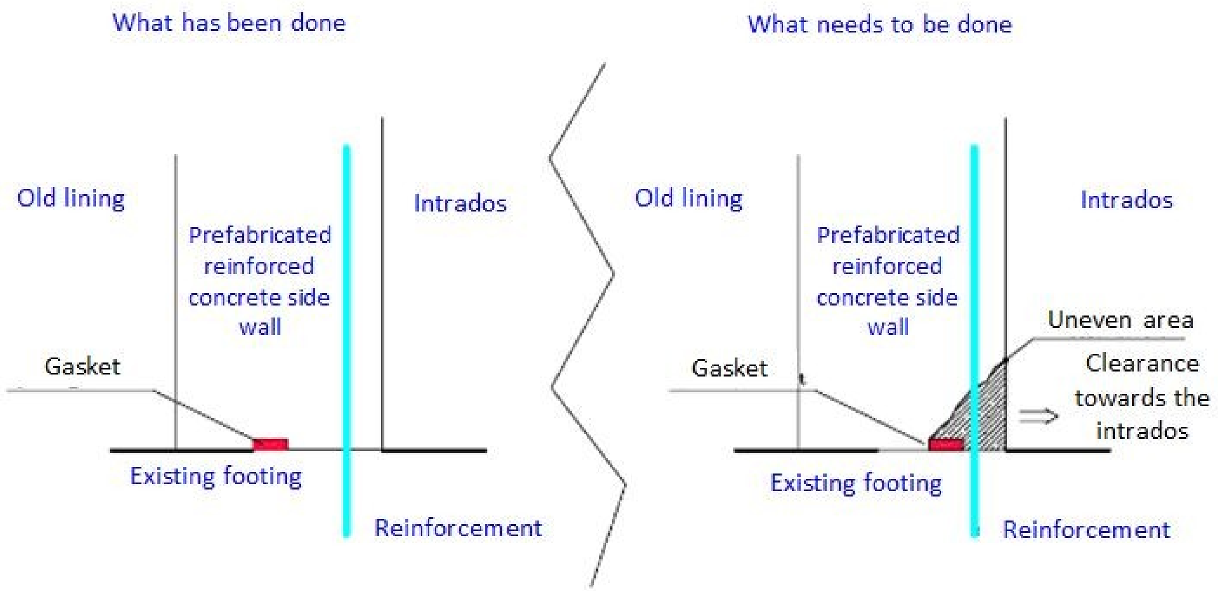


Figure 1: diagram explaining the deteriorations

Figure 2: concrete spalling along the joint between the walkway and the side wall

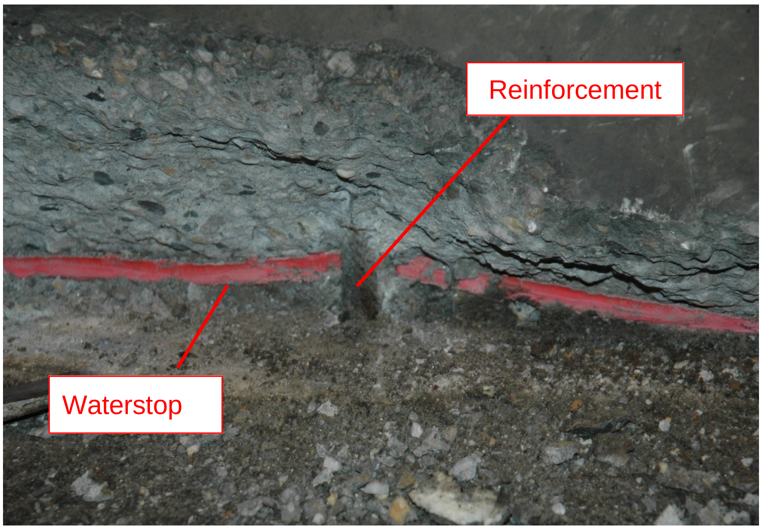


Figure 3: exposure of the reinforcements in front of the joint

2.7 Deteriorations affecting the structural elements and geometry of the tunnel – Cracks

List of deteriorations	Sheet number
Deteriorations affecting the structure and geometry of the tunnel Cracks	
Horizontal structural cracks	FI-1
Diagonal structural cracks	FI-2
Vertical structural cracks	FI-3
Shrinkage cracks	FI-4
Crescent-shaped cracks	FI-5

Horizontal structural cracks	FI-1

Description (visual appearance of the deterioration)

These cracks have an average plane parallel with the axis of the tunnel.
Masonry: they generally follow the mortar joints (joints between courses open up)
Cast concrete: crack width is generally wider than in the case of normal shrinkage

Inspection methods

Visual and manual inspection

Parameters to be measured

Number of cracks – Extent (start metric location marker, end metric location marker) – Width – Misaligned edges – Crack throw - Deteriorations at the edges of cracks – Determine whether cracks affect the stones or bypass them, remaining in the joints (masonry) – Determine whether cracks affect a single or several consecutive panels (cast concrete)

Associated deteriorations or defects to be looked for

Deformation of the lining – Hollow-sounding areas – Spalled stones or concrete – Abnormal cracking or deformations in the roadbed

Origins and possible causes

Crack of pathological origin related to deterioration of the lining, which may or may not result from the surrounding ground

Aggravating factors

Deteriorated lining (quality of the stones and mortar or the concrete) – Abutment defects – Voids in the extrados

Consequences, possible evolution

Weakening of the immediate area surrounding the crack, then the arch
Increased crack width
Appearance of new cracks
Falling blocks

Dangers to users

Low (inexistent in the event of isolated narrow cracks)

Risks to the tunnel and its structural elements

Weakening

Monitoring

Visual inspection (frequency to be adapted to the scale of the phenomenon)
Regular measurements of crack width and unevenness (three-dimensional crack gauges)
Profile deformation measurements (relative convergence)

Remedial measures

No action to be taken as long as the entire structure shows no sign of rapid deformation or instability

Observations

See also sheets FI-4 (shrinkage cracks) and DF-1 (flattened crown – symmetrical squeezing, asymmetrical squeezing)

Horizontal cracks tend to develop along a generatrix of the tunnel and may be located at almost any level of the cross section. The areas with cracks mark the position of pivotal points in the deformation of the cross section.

Masonry cracks:
This type of crack occurs almost exclusively in the joints, which open under the effect of deformation. Mortar is often present. Located in the crown or other parts of the roof section, cracks indicate profile flattening, whereas symmetrical squeezing (or asymmetrical squeezing) will cause cracks in the haunches (also known as springers).

Concrete cracks:
Cracks of pathological origin will often be wide (wider than in the case of typical shrinkage), misaligned and have uneven sides. They may form on pre-existing shrinkage cracks (reactivated by the deformation process) or on construction joints.

Figure 1: horizontal crack following deformation of the masonry (asymmetrical squeezing) confirmed by traces of friction from vehicles (mortar is still present on one side of the crack)

Figure 2: horizontal crack in cast concrete related to deformation of the lining under the thrust of the surrounding ground (the crack forms along the construction joint)

Diagonal structural cracks	FI-2

Description (visual appearance of the deterioration)

Also known as oblique cracks, their average plane is oblique in relation to the axis of the tunnel. There is rarely a single crack, but often several in succession.
Masonry: cracks generally follow mortar joints and have a step-like appearance
Cast concrete: crack width is generally wider than in the case of normal shrinkage

Inspection methods

Visual and manual inspection

Parameters to be measured

Number of cracks – Extent (start metric location marker, end metric location marker) – Width – Misaligned edges – Crack throw - Deteriorations at the edges – Determine whether the cracks affect the stones or bypass them, remaining in the joints (masonry) – Determine whether or not the cracks follow the edges of patching (concretes)

Associated deteriorations or defects to be looked for

Masonry: Deformation of the lining – Hollow-sounding areas – Deteriorated stones
Masonry and cast concrete: Formation of unstable panels (if cracks intersect) – Cracking of verges and walkways – Cracks or deformations on carriageways

Origins and possible causes

Crack of pathological origin often related to ground movement – Differential settlement – Twisting or oblique shearing of the arch in relation to the axis

Aggravating factors

Deteriorated lining – Voids in the extrados

Consequences, possible evolution

Weakening of the immediate area surrounding the crack
Formation of small unstable panels located between several successive cracks
Rupture of the structure

Dangers to users

Low (nonexistent in the event of isolated narrow cracks)

Risks to the tunnel and its structural elements

Weakening, or localized rupture

Monitoring

Visual inspection (frequency to be adapted to the scale of the phenomenon)
Regular measurements of the crack width and unevenness (three-dimensional crack gauges)
Profile deformation measurements (relative convergence)
Levelling

Remedial measures

No action to be taken as long as the entire structure shows no sign of rapid deformation or instability

Observations

Diagonal cracking, also known as oblique cracking, in the form of a single crack or several cracks in succession, often results from a twisting movement of the arch. Diagonal cracks have either a regular path or a path resulting from a combination of vertical and longitudinal cracks (such as where the crack follows joints in the masonry without passing through stones).

This deterioration must be taken seriously because it may indicate a serious problem for the structure (tilting of a portal, foundation settlement, slope instability, swelling, creep, active fault).

In non-reinforced cast concrete, cracking may occur on a pre-existing shrinkage crack, reactivated by the deformation process. Cracks will subsequently widen (becoming wider than typical shrinkage cracks) and have misaligned and uneven sides.

Figure 1: network of diagonal cracks in a concrete arch deformed by thrust from the ground above (a piece of concrete has already fallen due to rupture in the haunch, and a crack gauge is measuring a crack – the tunnel had to be closed a few years later)

# Vertical structural cracks	# FI-3

Description (visual appearance of the deterioration)

Cracks may affect all or part of the tunnel profile. Their average plane is perpendicular to the axis of the tunnel.
Masonry: cracks generally follow mortar joints or vertical construction joints between two rings of stones (toothed bonding).
Cast concrete: cracks are generally wider than those caused by normal shrinkage.

Inspection methods

Visual and manual inspection

Parameters to be measured

Number of cracks – Extent – Width – Location – Misaligned edges – Crack throw – Deterioration at the edges – Determine whether cracks affect the stones or bypass them, remaining in the joints (masonry)

Associated deteriorations or defects to be looked for

Deformation of the lining – Hollow-sounding areas – Deteriorated stones – Cracking of verges and walkways – Cracks or deformations on carriageways

Origins and possible causes

Fairly common defect with toothed bonding (masonry) – Deformation or change in thickness of the lining – Shearing of the lining (cast concrete) – Differential settlement

Aggravating factors

Deteriorated lining – Changes in the surrounding ground – Abutment defects between arch and ground – Bedding defects

Consequences, possible evolution

Weakening of the immediate area surrounding the crack
Widening of the cracks
Increase in unevenness / misalignment

Dangers to users

Low (inexistent in the event of isolated narrow cracks)

Risks to the tunnel and its structural elements

Weakening

Monitoring

Visual inspection (frequency to be adapted to the scale of the phenomenon)
Regular measurements of the width and unevenness (three-dimensional crack gauges)
Profile deformation measurements (relative convergence)

Remedial measures

No action to be taken as long as the entire structure shows no sign of rapid deformation or instability

Observations

See also sheet FI-4 (shrinkage cracks)

Additional information

Mostly appearing in a plane perpendicular to the axis of the arch, vertical cracks may be isolated and continuous, or appear as a series of successive cracks. This type of crack may occur in the immediate vicinity of a portal (change in thickness of the lining, settlement), but also in interior zones (influence of the rock mass, fault).

It should be determined whether they appear on an underlying discontinuity (masonry joint, toothed bonding) or if they are caused by something else.

In non-reinforced cast concrete, this cracking may occur on a pre-existing shrinkage crack, reactivated by the deformation process. Cracks will subsequently widen (becoming wider than typical shrinkage cracks), and have uneven and misaligned sides.

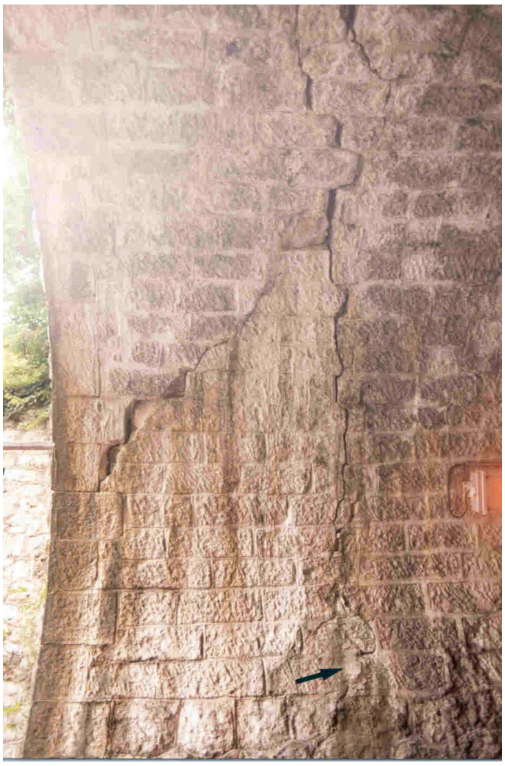


Figure 1: vertical crack combined with a diagonal crack

Shrinkage cracks	FI-4

Description (visual appearance of the deterioration)

Thin cracks, the length of which increases over time (visible from 0.1 mm). The sides show no unevenness. On non-reinforced cast concrete linings, widths are rarely greater than 3 mm.

In the event of deformation of the tunnel profile, some cracks may become wide open for structural reasons. In this case, they are considered to be pathological cracks and not shrinkage cracks.

Inspection methods

Close visual inspection under powerful lighting
Scanner readings in visible light

Parameters to be measured

Location– Quantity– Narrow or wide spacing between cracks – Width

Associated deteriorations or defects to be looked for

Inflows of water through cracks (tunnels without waterproof membrane on the extrados) – Hollow-sounding areas – Moisture

Origins and possible causes

Shrinkage occurs with normal ageing of the concrete. Cracks caused by shrinkage in non-reinforced concrete do not constitute a deterioration or a defect.
The level of shrinkage is related to many manufacturing, casting and curing parameters

Aggravating factors

Poor quality of concrete or, on the contrary, high cement dosage – Concrete reinforcements when there is no waterproof membrane on the extrados – Water seepage – Freeze-thaw cycles– Stresses in the lining

Consequences, possible evolution

Deterioration of the concrete caused by water ingress (tunnels without waterproof membrane on the extrados) – Corrosion of reinforcements – Narrowing or widening of cracks in the event of profile deformation

Dangers to users

No danger

Risks to the tunnel and its structural elements

No risk

Monitoring

Visual inspection
Mapping of cracks
Measurement of crack lengths
Monitoring (crack gauge) if a crack initially attributed to shrinkage widens abnormally or is uneven

Remedial measures

No repair (except for resin injection for waterproofing purposes)

Observations

See also sheets FI-1 (horizontal structural cracks) and FI-3 (vertical structural cracks)

Additional information

Shrinkage cracking is not actually a deterioration as such. It indicates the reduction in volume accompanying the setting and drying of the concrete and obstruction of the shrinkage.
However, this cracking shows up differently depending on the age or type of concrete, and arch inspections highlight the deteriorations that have been caused by its severity. Its description, even if basic, must enable it to be distinguished from cracks of pathological origin.

"Modern" non-reinforced cast concrete
Its composition is often well controlled; it is cast in good quality formwork; vibration enables good homogenisation of successive batches. It has good compactness and an even surface appearance. Shrinkage cracks are therefore easily identified, despite their fineness (0.1 to 0.3 mm initially, then 1 to 3 mm after several years).

Figure 1 illustrates a few of the typical forms that it takes:

- vertical cracks (1) develop from the bottom of the side wall; after a few years, they may join up with horizontal cracks;
- horizontal cracks (2) fairly rapidly indicate shrinkage of the mass of concrete in the plane perpendicular to the tunnel axis. They are almost always in the crown.

In all of the tunnels inspected to date, the widest shrinkage cracks (generally large horizontal cracks) stabilize at a width of around 2 to 3 mm, depending on the size of the intrados surface. Any greater width is suspect and possibly requires the use of monitoring instrumentation.

It is noted that in recent linings protected by a waterproof membrane on the extrados, there tend to be fewer cracks than in the past. This can be explained by excavation overbreaks attenuated by sprayed concrete used as a support, the presence of waterproofing materials limiting obstructed shrinkage, the better quality of cast concretes and their casting.

Shrinkage cracking does not necessary develop in the form of continuous cracks but may appear as widely-spaced and discontinuous crazing, particularly visible on cladding that has a high laitance content.

"Old" non-reinforced cast concrete
Shrinkage manifests itself as fairly narrowly spaced crazing, or sometimes as a seemingly random spacing of long vertical cracks. The composition (high water content) and casting of the concrete, but also irregular thicknesses and adhesion to the ground (no waterproof membrane), are mainly responsible for this. In this case, shrinkage may lead to deteriorations, if it enables considerable water ingress.
The significant porosity and heterogeneity of the oldest concretes mean that shrinkage is spread throughout the aggregates and cracks are less visible.

Reinforced cast concrete
The reinforcement layers that it contains prevent the development of shrinkage. Parallel, hairline cracks are often seen, oriented in line with the reinforcements.

Sprayed concrete
Shrinkage also affects this thin concrete but varies significantly. It may take the form of crazing with a narrowly-spaced pattern (tens of centimetres), generally visible only due to white calcite concretions. This is the case when it is sprayed directly on to the rock in situ, which prevents its free development. The presence of welded wire mesh does not completely eliminate shrinkage cracking.
Fibre-reinforced sprayed concrete has few or no cracks.
When the concrete is sprayed on a completely waterproof membrane, with a more even surface, shrinkage cracking does not disappear. Its development depends on the composition of the concrete and its casting conditions.
When dry-mix sprayed concrete is correctly applied, shrinkage is more limited due to a very low water content.

~10 m

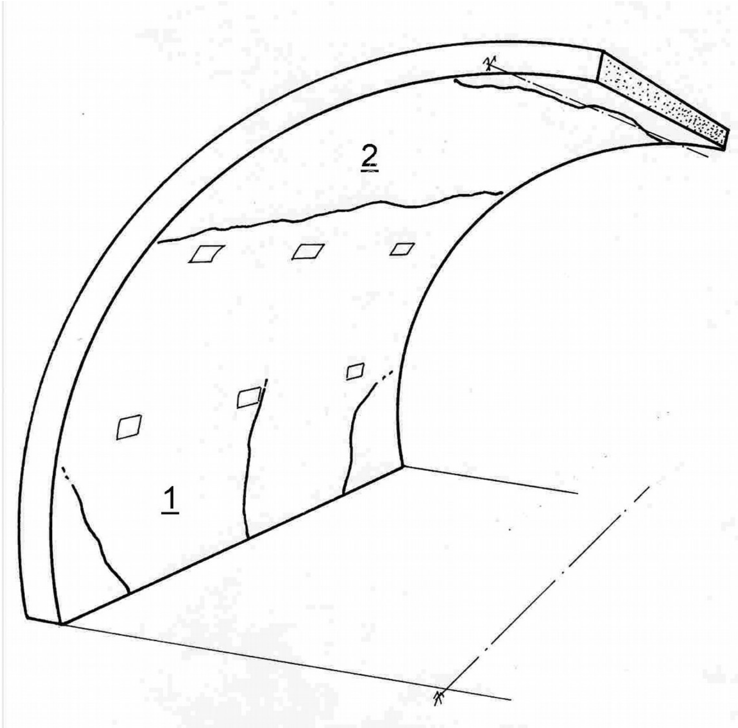


Figure 1: usual development of shrinkage within a segmental ring ("modern" concrete with a waterproof membrane applied to the extrados)

Figure 2: development of shrinkage in concrete from 1970 without a waterproof membrane applied to the extrados

Crescent-shaped cracks	FI-5

Description (visual appearance of the deterioration)

An even, curved crack, generally located in the roof section or haunch at the end of a segmental ring, that starts and ends on the same vertical construction joint.

Inspection methods

Visual inspection
Auditory inspection (hammering)

Parameters to be measured

Width – Uneven edges – Panel dimensions

Associated deteriorations or defects to be looked for

Hollow-sounding area (relatively thin panel that is detached from the rest of the ring)

Origins and possible causes

Fracture crack caused by the formwork of the adjacent ring bearing on a ring that has not yet reached its maximum strength: the formwork, which deforms during concreting, creates excessive isolated stress on the ring.

Aggravating factors

Incomplete grouting (void between the concrete and the support or the ground).

Consequences, possible evolution

Destabilisation of the panel in the case of a thin arch

Dangers to users

None (for the cases known to date), but careful checks should be carried out for thin structures

Risks to the tunnel and its structural elements

None (for the cases known to date).

Monitoring

Visual inspection.

Remedial measures

Injection into the cracks.

Observations

This type of deterioration is generally repaired directly on site by epoxy resin injections.
As it is due to poor workmanship, it is preferable to demand repairs to avoid the need for intensified monitoring.

Additional information

This deterioration is fairly common in modern tunnels, where concreting cycles occur in quick succession. This type of fracture usually appears in a haunch, and more rarely on the crown axis. It appears at the edge of the previously cast ring, which is subject to pressure from the formwork. This area of pressure is precisely the area where the pumped concrete may not be properly secured to the support. Any movement due to a gap, even small, can cause it to break due to rotation. The presence of a waterproofing membrane is sometimes enough to explain this "gap". The location of the curved cracks in the rings reflects the direction in which the lining was concreted.

In one known case, the fracture occurred when adjusting the formwork, which deformed as the concrete was poured (laitance leaks). The use of jacks at the base was enough to cause the fracture.

Several nested curved cracks have sometimes been observed, with no associated instability.

These areas, usually repaired by resin injection (rarely with needling), should however be carefully sounded during each in-depth inspection, and on an annual basis for many years for thin non-injected structures.

Figure 1: nested curved cracks in the haunch (the bottom of the photo corresponds to the walkway; concreting was carried out from right to left)

2.8 Deteriorations affecting the structural elements and geometry of the tunnel – Deformations

List of deteriorations	Sheet number
Deteriorations affecting the structure and geometry of the tunnel Deformations	
Flattened crown – Symmetrical squeezing – Asymmetrical squeezing	DF-1
Bulging	DF-2
Offset stone or brick courses	DF-3
Invert deterioration	DF-4
Arch rupture	DF-5

Flattened crown – Symmetrical squeezing – Asymmetrical squeezing	DF-1

Description (visual appearance of the deteriorations)

Flattened crown: an increase in the radius of curvature of the upper part of the arch.
Symmetrical squeezing: the upper part of the arch deforms, with the haunches coming closer together and the crown rising (ogival transverse profile).
Asymmetrical squeezing: this deformation only affects one side of the arch, between the base and the haunch, increasing the radius of curvature.

Inspection methods

Visual inspection (from a low angle for asymmetrical squeezing)

Parameters to be measured

Location (start metric location marker, end metric location marker) – Surface area – Degree of deformation (difficult to measure without profilometry) – Determine whether the deterioration stems from construction or arose later (strong likelihood of associated deteriorations in the latter case)

Associated deteriorations or defects to be looked for

Flattened crown: Wide cracking in the crown – Spring line spalling
Symmetrical squeezing: Wide cracking at the spring line – Spalling in the crown – Open joints – Loosened stones
Asymmetrical squeezing: Wide horizontal cracks on the squeezed side – Shear cracking – Spalling in the crown – Hollow-sounding area – Water ingress

Origins and possible causes

Flattened crown: Deformations dating back to construction (fairly frequent in old masonry) – Ground swelling – Reduced lateral abutment – Loss of ground cohesion and pressure on the crown of the arch
Symmetrical squeezing: Deformations stemming from construction (fairly frequent in old masonry) – Significant horizontal stress – Poor grouting in the crown – Ground swelling
Asymmetrical squeezing: Deformations stemming from construction (particularly in long, thin profiles) – Significant horizontal stress – Asymmetric ground pressure on the lining – Ground swelling

Aggravating factors

Faulty drainage – Lack of joint maintenance – Heterogeneous ground (for asymmetrical squeezing)

Consequences, possible evolution

Accentuation of deformations
Falling or spalling of stones
Arch rupture

Dangers to users

None in cases of construction deformation
Low to high risk (rapid evolution) if the problem is not a construction defect (narrowing of the cross-section, impacts or repeated friction of heavy vehicles, risk of falling spalls or stones)

Risks to the tunnel and its structural elements

Weakening

Monitoring

More frequent visual inspection
Deformation measurements (relative convergence, profilometry)
Stress measurements

Remedial measures

Reinforcement (installation of ribs and extrados injection, bolting, lining with sprayed concrete, etc.)
Reconstruction

Observations

To be distinguished from "Bulging" (sheet DF-2)

Flattened crown

This term is reserved for a deterioration that affects the roof section symmetrically. It can only be clearly seen through visual inspection of the facing from a shallow angle (from a bucket platform placed just under the crown, for example).

An in-depth inspection should always be conducted to look for associated problems in order to confirm either a construction-related deformation or a pathological deterioration. The latter may be indicated by spalling of the stones in the haunches due to compressive load.

Symmetrical squeezing

The term “symmetrical squeezing” refers to a situation where the side walls move inwards in a symmetrical manner. More common in very long, thin profiles, it can be easily seen with the naked eye from the ground. Traces of friction from heavy vehicles help to quickly identify it.

The presence of open joints in the haunches and spalling in the crown should thus be looked for.

Asymmetrical squeezing

Although this problem can be likened to "a squeezing" of the arch, the term asymmetrical squeezing was introduced to characterise a deformation that only affects one side of the profile and over a significant height. This deterioration is seen in tunnels with very long, thin ogival profiles.

It may be caused by evolution in heterogeneous ground causing pressure on one side of the arch. Deformation of the original formwork is another possible cause, if inspection and monitoring do not reveal any other developing deterioration.

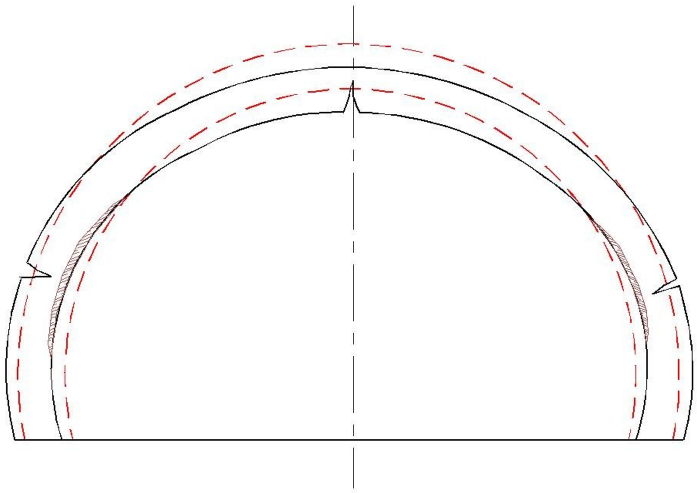


Figure 1: simplified diagram of deformation in a lining, resulting from flattening (the shaded areas indicate areas under compression, while the cracks show areas under strain) [dotted lines: theoretical profile, solid line: deformed profile]

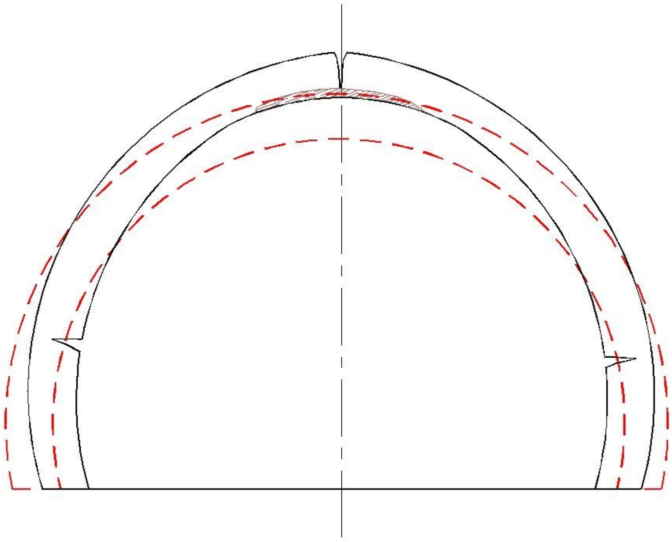


Figure 2: simplified diagram of deformation in the lining, resulting from symmetrical squeezing (the shaded areas indicate areas under compression, while the cracks show areas under strain) [dotted lines: theoretical profile, solid line: deformed profile]

Figure 3: symmetrical squeezing in the crown (already partially repaired with non-reinforced cast concrete, the deformation is continuing, crushing the remaining crown stones and concrete)

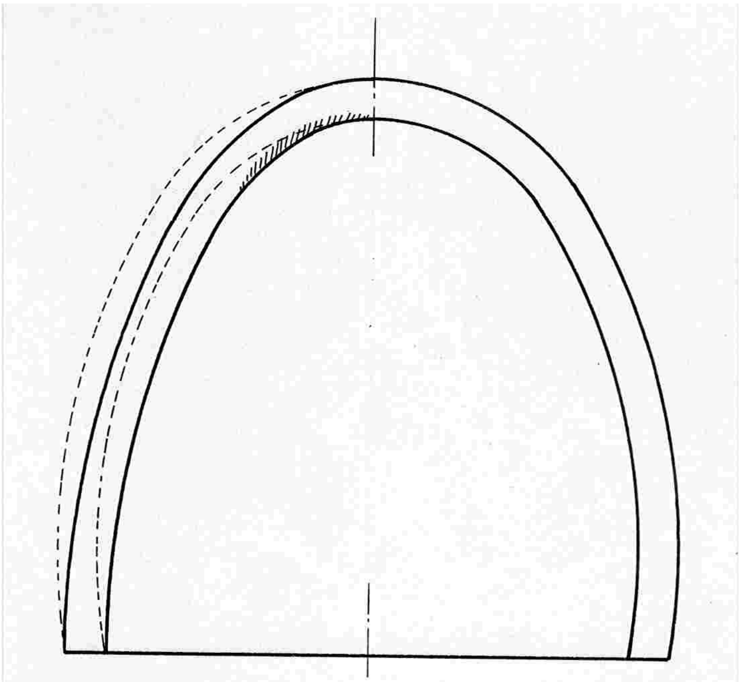


Figure 4: simplified diagram of deformation in the lining, resulting from asymmetrical squeezing (the shaded areas indicate areas under compression) [dotted lines: theoretical profile, solid line: deformed profile]

Figure 5: asymmetrical squeezing (the light part has lost its original curve)

Bulging	DF-2

Description (visual appearance of the deterioration)

A localized bulging of the facing. Mainly characteristic of side walls, it may sometimes occur higher in the tunnel profile.

Inspection methods

Visual inspection from a low angle
Auditory inspection (hammer tapping)

Parameters to be measured

Location (start metric location marker, end metric location marker) – Location in the profile – Surface area – Maximum outward distortion – Sound obtained from hammer tapping

Associated deteriorations or defects to be looked for

Deterioration of mortar and stones – Fallen or loosened stones – Damp – Cracking

Origins and possible causes

Bulging occurring during construction: Deformation of the rib – Construction joint
Subsequent occurrence: Settlement of the masonry due to deterioration of mortar – Pressure from the ground or backfill

Aggravating factors

Longitudinal cracks – Sliding of masonry courses – Faulty drainage – Lack of joint maintenance

Consequences, possible evolution

Localized permanent damage or falling of progressively loosened stones

Dangers to users

Apart from localized shrinkage, the danger to users depends on the strength of the structure itself.

Risks to the tunnel and its structural elements

Weakening then rapid localized permanent damage

Monitoring

Visual inspection
Auditory inspection
Measurements of outward distortion (simple in the case of a bulging side wall, through the use of a plumb line or ruler)

Remedial measures

Repointing
Anchors and tie rib
Reconstruction if caused by the ground

Observations

To be distinguished from "Asymmetrical squeezing" (sheet DF-1)

The term "bulging" is often used to describe inward deformations of masonry side walls. Bulging is very localized, unlike the other deformations mentioned (symmetrical squeezing, flattened crown, asymmetrical squeezing) which affect a large part of the tunnel profile. Bulges often sound hollow during hammer tapping.

Some masonry arches bulge systematically along the spring lines or side walls. It is therefore important to distinguish between a construction problem (construction joint at the top of the side wall), which is fairly common, and a problem that has appeared subsequently. If there are no other deteriorations associated with the bulging, it is probably a construction problem.

Some bulges are unrelated to any action from the ground but are simply caused by the sagging of poor quality lining under its own weight, sometimes aggravated by pressure from loose backfill. This deterioration is always accompanied by a deterioration of mortar, the weak point of masonry.

It is important to check the nature of the surrounding ground because its degree of alteration or its behaviour may be the main cause of this type of deformation. Consulting "as-built" records is essential if no recent investigation records are available.

If deterioration of the masonry is not advanced and if the degree of deformation remains acceptable for the tunnel's operation, repointing may be enough to slow down its development and stabilize loosened stones. Permanent repair often involves demolition and reconstruction according to the initial profile.

Figure 1: a bulging side wall, strengthened by anchors and tie rib

Figure 2: bulging nearing the stage of permanent damage (significantly deteriorated masonry)

Offset stone or brick courses	DF-3

Description (visual appearance of the deterioration)

One or more consecutive courses of masonry are offset in relation to the normal intrados profile, either set back or protruding.

Inspection methods

Visual inspection

Parameters to be measured

Location in the profile, length and height of the surface area affected, offset value, auditory inspection (hammer tapping)

Associated deteriorations or defects to be looked for

Opening up of longitudinal joints, cracking, voids in joints, general deformation of the profile, localized bulging

Origins and possible causes, aggravating factors

In side walls and spring lines, poor workmanship at construction joints (the most frequent cause)
In the roof section, poor laying of stone courses or localized misalignments due to blast from an explosion (mine blasting beneath the invert, military-related damage)

Aggravating factors

Voids in joints – Water ingress – Quality of the stones

Consequences, possible evolution

Offset occurring during construction: no consequences
Subsequent offset: weakening, or even local loosening of stones, and risk of rapid deterioration

Dangers to users

Not significant
Risk of elements falling from the roof section if the cause is accidental (subsequent to construction)

Risks to the tunnel and its structural elements

Inexistent if the offset has been present since construction.
Weakening of the lining if the cause is accidental (subsequent to construction)

Monitoring

Visual inspection

Remedial measures

Reinforcement by bolting or with sprayed concrete (reinforced or non-reinforced)

Observations

The stones are misaligned and may be set back or protruding in relation to the average surface of the intrados.

Stones may be set back due to poor course laying. However, when several courses of stones in the roof section are set back over a large surface area, this indicates a "blast" to the arch due to an explosion (wartime incident, blasting beneath the invert that is too violent). The consequence is a weakening of the entire lining, which will deteriorate much more rapidly. This deterioration is rare.

Protruding stones, without any other associated deterioration, may be attributed to poor course laying. This situation is common in arch spring lines, a construction joint area. If it is not a construction defect, the offset area may indicate permanent damage or significant deterioration of the structure.

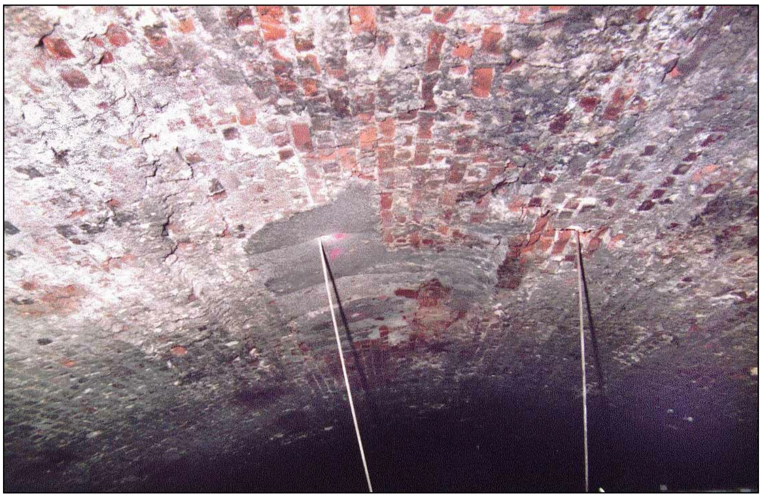


Figure 1: blast damage (the central part of the roof section has been lifted by the blast, then has fallen back into place with offsets in the brick courses; the rods mark the position of investigative drilling)

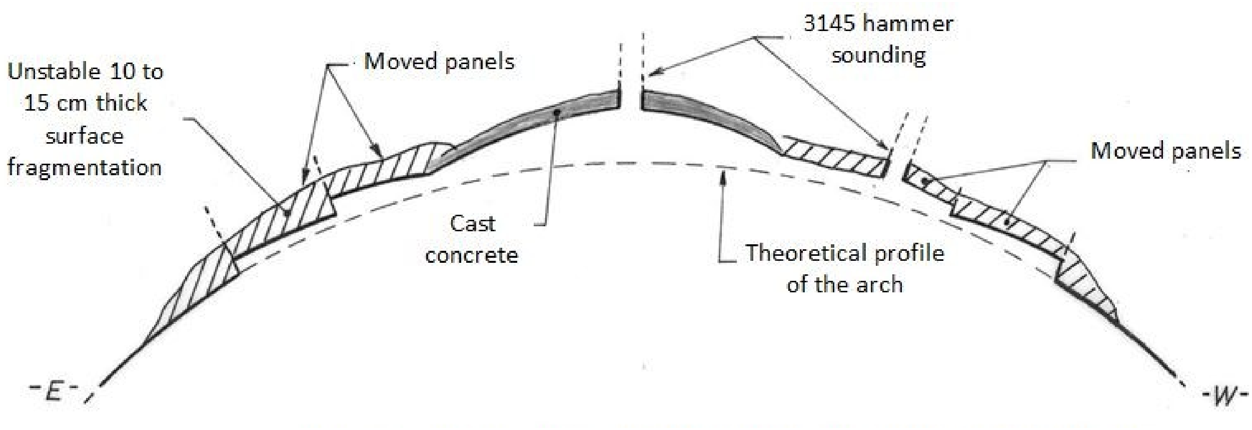


Figure 2: Drawing of supposed deteriorations in the blast-damaged area

Invert deterioration	DF-4

Description (visual appearance of the deterioration)

The deterioration often occurs in the form of localized invert heave or settlement, resulting in the presence of horizontal and sometimes vertical cracks, with uneven edges. When the invert is not visible, only deteriorations that are apparent on the carriageway or side walls are detected.
In some cases, the lack of invert or an undersized invert means that swelling of the ground (clay or heaving shale) cannot be treated.

Inspection methods

Visual inspection
Topographical surveys
Auditory inspection

Parameters to be measured

Location – Extent – Height of heave– Nature of the ground and invert (consult the construction records)

Associated deteriorations or defects to be looked for

Water ingress – abnormal deterioration in the arch (spalling in the crown, different extents and shapes of cracking) and in the side walls

Origins and possible causes

Heave: Swelling of the surrounding ground – High lateral pressure – Creep – Significant presence of water
Settlement: Insufficient bearing capacity of the ground due to its nature and the presence of water – Settlement or creation of voids

Aggravating factors

Heave: Pressurised water ingress – Insufficient invert strength (thickness or mechanical characteristics) – Poor connection between the invert and the side walls
Settlement: Leaks from drainage systems – Changing nature of the underlying ground (gypsum or clay) – Water table fluctuation – Entrainment of fines

Consequences, possible evolution

Deformation of rings – Dislocation of the invert – Collapse of the structure due to loss of bracing between side walls

Dangers to users

Risk of collapse or deformed carriageway

Risks to the tunnel and its structural elements

Weakening of the structure – Localized collapse

Monitoring

Visual inspection
Topographical surveys
Auditory examination
Regular measurements of crack width and unevenness (three-dimensional crack gauges)
Profile deformation measurements (relative convergence)
Increased monitoring or close observation (depending on the results of the measurements)

Remedial measures

Dependent on specific studies (reconstruction of the invert or reinforcement of the ring, drainage of the ground)

Observations

Additional information

The inverts in certain old tunnels are either counter-arched or flat and correspond to difficult geological areas that require reinforced arches.

If deformation of the structure due to changes in the surrounding ground (squeezing of side walls due to ground swelling, plane of slope instability crossing the tunnel) causes it to rupture, this can be seen in the form of invert heave or settling, as well as cracking and dislocation.

Settlement may also occur (to a lesser extent) following failure of the drainage systems: water circulating around the periphery of the pipes may adversely affect the invert's bedding layers if the surrounding ground evolves. The mechanical characteristics of these soils are changed (lower bearing capacity) and deteriorations appear under the influence of traffic-related loads.

The aggravating factors are water circulating in the ground, an invert that is not thick or strong enough and insufficient curvature or poor jointing between the invert and the side walls.

Repairs require demolition beforehand, which must be carried out carefully in small areas, to prevent side wall convergence during the time when they are no longer braced.

If the invert is not visible, deteriorations mainly take the form of cracking and heave of the carriageway.

On the State-managed national road network, there are currently no known cases of structural deteriorations arising from abnormal behaviour of tunnel inverts.

Arch rupture	DF-5

Description (visual appearance of the deterioration)

The rupture of an arch is preceded by warning signs.
Masonry: very wide cracks, pronounced spalling, falling stones, loss of mortar, profile deformations
Concrete: very wide cracks, offset edges, significant spalling of the concrete, tilted sections

Inspection methods

Visual and auditory inspection (hammer tapping)

Parameters to be measured

Crack characteristics (location, width, length, unevenness)

Associated deteriorations or defects to be looked for

Presence of unstable sections – Deterioration of materials – Water ingress – Nature of the surrounding ground or any backfill (portals) – Bulging – Flattened crown – Asymmetrical squeezing – Symmetrical squeezing

Origins and possible causes

Action of the surrounding ground – Arch overload – Complete deterioration of the lining

Aggravating factors

Evolution and swelling of the surrounding ground – Quality of the concrete and grouting mortar

Consequences, possible evolution

Acceleration and spread of the phenomenon
Permanent damage to the structure

Dangers to users

Risk of large volumes of material falling onto the carriageway

Risks to the tunnel and its structural elements

Collapse

Monitoring

Visual and auditory inspection
Close observation

Remedial measures

Reinforcements or reconstruction

Observations

The rupture of a lining (or the start of rupture) is a serious warning. Accumulating deteriorations that have not been seen and dealt with in time ultimately result in permanent damage.

Masonry

Permanent damage is often preceded by the appearance of bulging with cracks that intensify over time. The masonry collapses under its own weight (in side walls) or under the weight of backfill (arch) independently of any ground action. The most common cause of this type of event is the complete deterioration of the mortar. When spalling is associated with bulging (or asymmetrical squeezing or flattened crown), even though the mortar is still solid, the problem is more serious because it is caused by the ground. The areas spalled by the deformation take on a crumbled appearance before permanent damage.

Non-reinforced cast concrete

Rapid permanent damage is much rarer. Clear fractures appear, in the form of cracks with uneven edges delineating rigid panels that remain in place due to mutual friction, and allow enough time to intervene. The cause is always external to the structure.

Non-reinforced sprayed concrete

A fracture may occur due to local pressure (swelling) of the ground, starting with one or more cracks. The rate of development is much greater than in cast concrete and fragments may fall rapidly.

Figure 1: half the arch has fallen due to crushing of the side wall, consisting of very deeply delaminated, weak stones (this permanent damage was preceded by bulging of the side wall, which was not strengthened in time; the ground was not the cause of the deterioration)

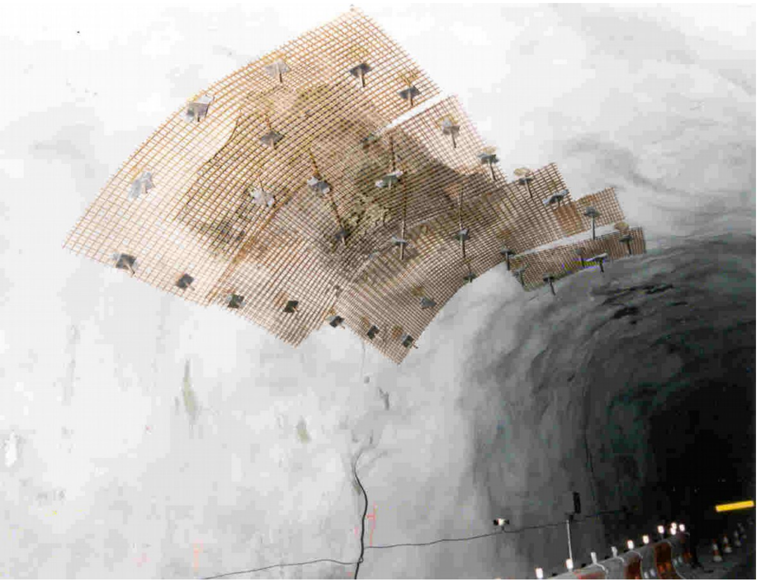


Figure 2: swelling of marls that have ruptured a sprayed concrete lining without welded mesh (repair under way)

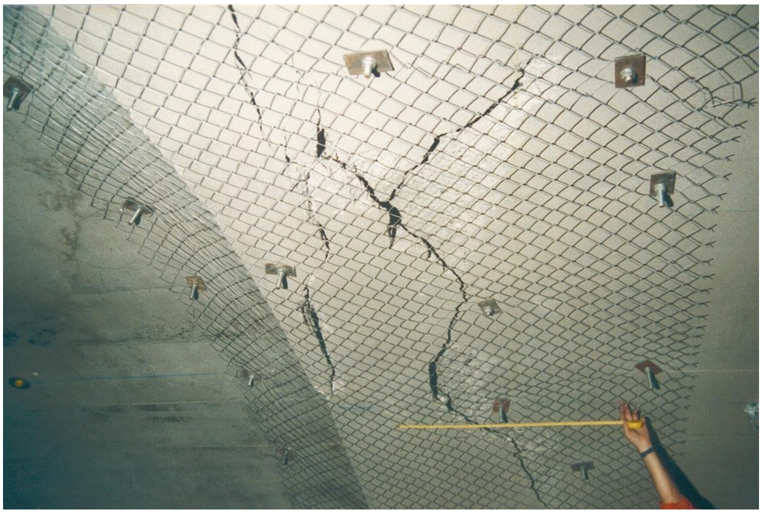
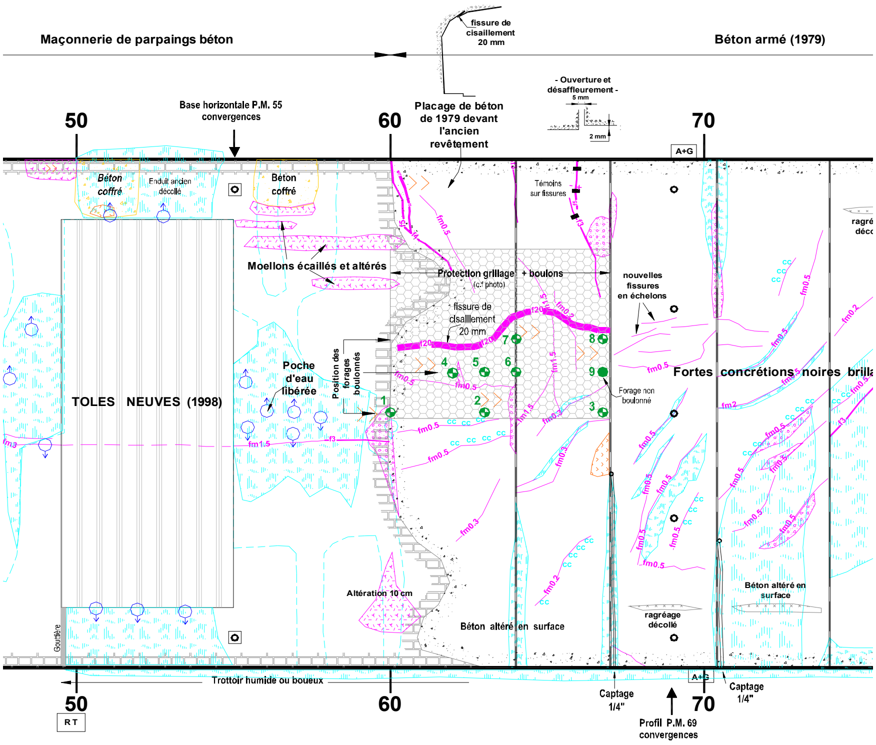


Figure 3: rupture of a reinforced cast concrete arch under the action of stresses that are too high



Figures 4a and 4b: rupture of reinforced concrete on part of the arch, with shear cracking

2.9 Deteriorations affecting the structural elements and geometry of the tunnel – Defects linked to workmanship

List of deteriorations	Sheet number
Deteriorations affecting the structure and geometry of the tunnel – Defects linked to workmanship	
Unstable blast hole bottoms	MO-1
Voids in the lining near the intrados	MO-2
Honeycombing	MO-3
Deteriorations in concrete construction joints	MO-4
Cosmetic defects with cast concrete	MO-5

Unstable blast hole bottoms	MO-1

Description (visual appearance of the deterioration)

Unstable blast hole bottoms can be identified by cracking radiating from drilled blast holes.

Inspection methods

Visual inspection around (or at the end of) blast holes visible on the facing
Auditory inspection (hammer tapping)

Parameters to be measured

Extent – Unit volumes and overall volume of unstable blocks

Associated deteriorations or defects to be looked for

Loosened blocks

Origins and possible causes

Old rock excavations – Significant angular deviation of the blast holes in relation to the axis – Too much explosive charge – Incomplete scaling after blasting

Aggravating factors

Significant fracturing of the rock prior to blasting – Unfavourable longitudinal profile or cross section

Consequences, possible evolution

Frequent block instabilities (gradual, significant loosening of rocks)

Dangers to users

Falling blocks

Risks to the tunnel and its structural elements

Low to non-existent
Damage to equipment in the event of falling elements

Monitoring

Visual inspection (note the frequency of falls of debris or blocks)

Remedial measures

Periodic scaling

Observations

See also sheet NR-1 (loose masses or blocks)

The term "blast hole bottom" refers to the end of a borehole where explosive charges are detonated.

In many old unlined tunnels, unstable “rings” can be seen at blast hole bottoms, made up of a large number of radiating cracks .

This type of instability is due either to too much explosive charge or to incomplete scaling of the excavation after the blasts. The deterioration rarely affects the entire intrados and is independent of the nature of the rock, even affecting rock of very good quality.

Figure 1: *limestone excavated at the beginning of the 19th century [fractures can be seen radiating from a blast hole; the entire rock is loosened and unstable]*

Voids in the lining near the intrados	MO-2

Description (visual appearance of the deterioration)

A void close to the intrados is a defect or a deterioration within a material or structure that must be investigated. It is detected during inspection thanks to a hollow sound.

Inspection methods

Auditory inspection (by hammering the lining, taking care to interpret the response from the underlying surface – clear ringing sound, hollow sound)

Parameters to be measured

Position in the arch – Surface area affected – Type of sound

Associated deteriorations or defects to be looked for

Deformation of the lining (masonry) – Denser or abnormal cracking (concrete) – Defects indicating a weakness in the arch (deterioration, cracks, water ingress, etc.) – Corroded reinforcements (reinforced concrete)

Origins and possible causes

Masonry: poor cohesion (dating back to construction or from subsequent deterioration), thin lining with poor or no adhesion to the ground, deep delamination, spalling
Cast concrete: incorrect filling (roof section), waterproof membrane that has moved or torn, inadequate thickness, spalling, bursting over reinforcement bars
Sprayed concrete: poor adhesion to the substrate, deteriorated substrate

Aggravating factors

Factors related to associated deteriorations

Consequences, possible evolution

Masonry, cast concrete, sprayed concrete: evolution related to associated deteriorations

Dangers to users

Dangers related to associated deteriorations

Risks to the tunnel and its structural elements

Masonry: aggravation of associated defects
Cast concrete: faster ageing in the weakened area
Sprayed concrete: aggravation of associated defects

Monitoring

Visual and auditory inspection (frequency to be adapted to the scale of the phenomenon)
Regular measurements of hollow-sounding surfaces

Remedial measures

Old linings: not all hollow-sounding areas need to be repaired; they must be identified based on additional investigations.
Recent concrete: injections in voids due to concreting defects (poor workmanship).

Observations

See also sheet ED-4 (deteriorations in extrados waterproof membrane)

Voids in the lining, close to the intrados, are often detected due to the material's sound response to the impact of a hammer. The process must follow these steps: delineate the area by hammering and map it on the arch investigation report, try to detect the most critical part of the area and look for associated defects or deteriorations.

Masonry

The side walls must be systematically sounded, which will give an initial idea of the compactness of the structural elements. As far as possible, the entire roof section must be sounded, and in particular the crown area, which tends to be inadequately bonded to the ground.

Non-reinforced cast concrete

Hammer tapping must be carried out even if the concrete shows no visible defects, because it may reveal an inadequate thickness of concrete (particularly in the roof section, where the grouting is often not carried out correctly). By way of example, a very hollow sound in recent concrete indicates a thickness of less than 10 cm.

Voids can be found in all areas of the cross section; they may indicate a tear or movement of the waterproof membrane towards the intrados, low thickness in line with an underbreak, or simply incorrect grouting. Efforts should thus be made to accurately delineate all of these areas, which may be very extensive (several tens of m²).

Figure 2: void dating back to construction, on the extrados of highly deteriorated concrete [the hollow-sounding lining is unstable around the opening]

Reinforced cast concrete

Located in roof sections or in haunches, a hollow-sounding area may indicate poor spreading of the concrete within the reinforcement layers or even a concreting defect (poor workmanship).

Figure 1: investigation window opened in a very hollow-sounding area [extrados void of 27 cm due to a concreting defect]

Sprayed concrete:

Void areas are a frequent occurrence and are caused either by adhesion defects, in particular due to insufficient coating of the wire mesh, or poor quality of the underlying rock. The added presence of wide cracks is a significant aggravating factor indicating a deterioration, the cause of which must be determined.

Honeycombing	MO-3

Description (visual appearance of the deterioration)

Areas of aggregates without fines, visible or hidden by a thin film of laitance. This is a defect which does not only affect the surface, but also deeper layers of the concrete.

Inspection methods

Visual inspection
Auditory inspection (hammer tapping)

Parameters to be measured

Surface area – Location (defect that is localized or spread across the entire segmental ring, located near the edges of a joint – Cause (related to a construction joint)

Associated deteriorations or defects to be looked for

Loose concrete – Hollow-sounding areas around the defect – Moisture

Origins and possible causes

Localized defect related to concrete laying (vibration effect) – Localized segregation of the material – Quality of the concrete (incorrect particle size of the constituents)
Note: some old concretes have a generalized "gravel pocket" appearance, even though the aggregates are well bonded.

Aggravating factors

Circulation of water (chemical deterioration, erosion) – Freeze-thaw

Consequences, possible evolution

Deepening of the cavities due to deterioration of the concrete and gradual falling of aggregates
Exposure of the reinforcements (reinforced concrete segment)

Dangers to users

Falling aggregates or small blocks of concrete

Risks to the tunnel and its structural elements

Localized weakening of the lining

Monitoring

Visual inspection (measurement of the possible increase in the depth and spread of the deterioration)
Auditory inspection

Remedial measures

Periodic preventive scaling
Repair of the area (patching, sprayed concrete and pinned reinforcement)

Observations

Additional information

This common defect in old concretes is caused by the concrete's formulation, its composition (often variable during the same works) and its casting (small batches, tamping instead of vibration).

There may be several causes:

- incorrect mixing,
- segregation during concreting,
- vibration not carried out properly (either by needle pokers or external vibrators).

This defect is also found in modern concretes, but only covers small areas and is located in areas where vibration is difficult (edges of segmental rings).
In non-waterproof linings, these areas with greater permeability may result in seepage, concretions, and faster deterioration of the concrete due to disintegration of the binder.

Gravel pockets are common in old concretes applied in many small batches with poor vibration. As preferred passages for water ingress, these areas may deteriorate rapidly, sometimes becoming loose and unstable, leading to localized weakening of the lining. In the absence of aggressive agents, their strength over time can be excellent.

Figure 1: gravel pockets on a concrete lining from 1936 [each layer of concrete is highlighted by an alignment of permeable and perfectly horizontal gravel pockets due to poor concreting]

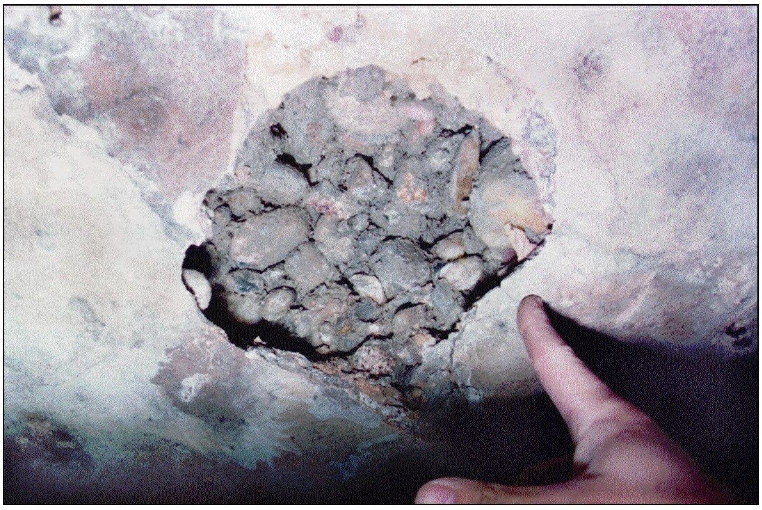


Figure 2: gravel pocket initially hidden by a film of laitance [its spread can only be mapped using hammer tapping]

Figure 3: gravel pockets

Deteriorations in concrete construction joints	MO-4

Description (visual appearance of the deterioration)

This deterioration affects the linearity, shape or filling of a joint that separates two adjacent cast concrete segmental rings. The edges of the joint may show spalling, flaking and cracks, causing subsequent deterioration of the concrete.

Inspection methods

Visual inspection (always check that the bottom of the joint is filled)
Auditory inspection (hammer tapping)

Parameters to be measured

Location – Extent – Hollow-sounding area (patching on the joint always loosens over time) – Any relevant measurements adapted to the extent of the deterioration

Associated deteriorations or defects to be looked for

Damp

Origins and possible causes

Poor workmanship – Relative movement between segmental rings

Aggravating factors

Poor quality of the concrete (compactness, gravel pockets)

Consequences, possible evolution

Spreading
Falling debris

Dangers to users

Risk of falling fragments from re-patched areas or larger concrete elements

Risks to the tunnel and its structural elements

None, if no other deterioration affects the two adjacent rings.

Monitoring

Visual inspection
Auditory inspection

Remedial measures

Scaling for safety purposes (possible installation of temporary meshing)
Reconstruction of the edges to their full depth (the joint must retain its freedom of movement; any superficial patching is inadvisable)

Observations

The presence of concrete residues on construction joints is very common in recent tunnels.

Joints between cast concrete rings are of different types:

- dry joints: they may be given no particular treatment; they sometimes appear as a groove (a pipe fixed to the formwork can be used to create a drainage channel between two rings) or be patched up with cement mortar;
- joints with elastomer strips: installed during concreting, these strips have bulged edges and often a tube in their central part; the bulges are designed to wedge into the concrete and the tube guarantees watertightness in the event of movement.

The main deteriorations noted in these joints are:

- spread of the joint crack into one of the rings; fragments then detach from one of the edges;
- fairly common presence of localized aggregate segregation along the edges; this results in water ingress in old concrete or localized instabilities;
- loosened and falling concrete related to badly installed formwork at the bottom of the joint;
- loosening and falling of the patching applied to joints for aeraulic or aesthetic purposes (in ventilation ducts).

Where formwork has been shaped using inflatable beads (Satujo type), the movement or perforation of these beads can cause specific problems illustrated in Figure 2.

Figure 1: deterioration in an elastomer joint

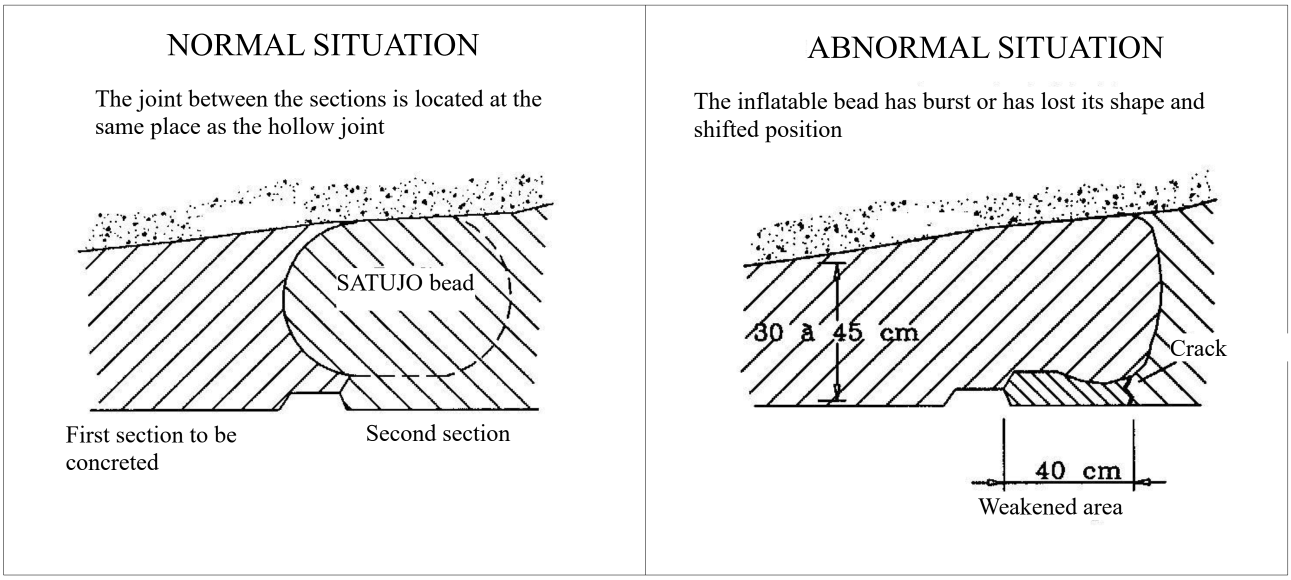


Figure 2: deterioration related to poor resistance of inflatable formwork during concreting

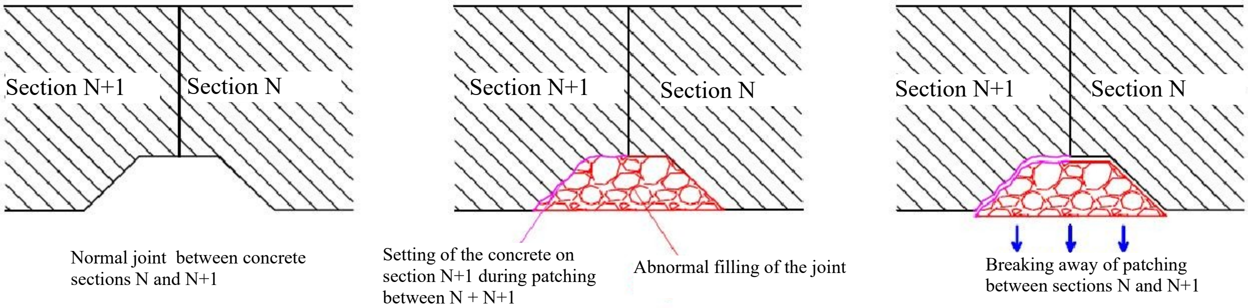


Figure 3: kinematic diagram showing the loosening of cement mortar filling in a dry joint

Figure 4: deterioration of a dry joint [movement between rings or concrete breakage during form removal]

Cosmetic defects in cast concrete	MO-5

Description (visual appearance of the deterioration)

Defects that alter the appearance, colour or uniformity of the intrados surface.

Inspection methods

Visual inspection
Auditory examination (hammer tapping)

Parameters to be measured

Extent – Surface area – Location – Density

Associated deteriorations or defects to be looked for

Local deterioration of the concrete (segregation, gravel pockets) – Damp – Hollow-sounding-areas – Cracks

Origins and possible causes

Composition of the concrete – Quality of the formwork skin – Effect of the form release agent – Casting and vibration of the concrete – Curing quality

Aggravating factors

None (if there are no associated deteriorations or defects)

Consequences, possible evolution

None (unless the associated deteriorations evolve)

Dangers to users

No danger

Risks to the tunnel and its structural elements

None (unless the associated deteriorations evolve)

Monitoring

Visual inspection
Auditory inspection

Remedial measures

None (unless the associated deteriorations evolve)

Observations

Additional information

Most of the cosmetic defects of cast concrete are the result of poor workmanship and non-compliance with recommendations during formwork, reinforcement, concreting or form removal. They are not considered as deteriorations in tunnels. For reference purposes, the following can be noted:

- bubbling (or blistering),
- crazing,
- gravel pockets,
- bleeding,
- mottling, colour variations,
- visible outline of the reinforcement, traces of rust,
- localized formwork deformations.

The document "*Défauts d'aspects des parements en béton - Guide technique*" (Cosmetic Defects in Concrete Facing – Technical Guide) published by the Clermont-Ferrand Regional Road and Bridge Laboratory, provides descriptions of these defects.

The following photos illustrate a few of these tunnel facing defects.

Figure 1: localized formwork deformation

Figure 2: dense crazing

Figure 3: bleeding

Figure 4: network of skin cracks

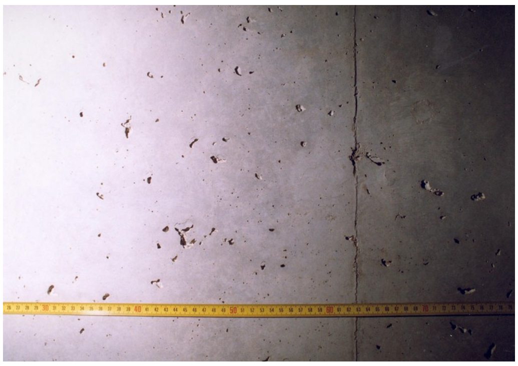


Figure 5: bubbling (or blistering)

2.10 Deteriorations in civil engineering elements

List of deteriorations	Sheet number
Deteriorations in civil engineering elements	
Deteriorations in carriageways	EQ-1
Deteriorations in slabs and partitions	EQ-2

Deteriorations in carriageways	EQ-1

Description (visual appearance of the deterioration)

Deteriorations may be of several types:

- crazing and potholes with rising water and fines,
- longitudinal and transverse cracks,
- localized bulging or sagging.

Inspection methods

Visual inspection

Parameters to be measured

Location (Metric location marker, lane) – Surface area affected – Visible rising water – Deformations of the surface course

Associated deteriorations or defects to be looked for

Block of drains or collector pipes – Abnormal cracking – Rupture of water collection systems – Settlement of foundations

Origins and possible causes

Calcite concretions in roadway drains and drainage network overload (most frequently) – Faulty or poorly designed drainage system – Lack of maintenance of the drainage network

Aggravating factors

Ground sensitive to dissolution or swelling – Significant water in the surrounding rock

Consequences, possible evolution

Rapid deterioration of the carriageway layers (particularly the surface course)

Dangers to users

From inconvenience up to loss of vehicle control (motorbikes, bicycles)

Risks to the tunnel and its structural elements

Risk of contact with roof elements, friction or impacts along the haunches of the arch by heavy goods vehicles (due to roll generated by carriageway deformations)

Monitoring

Visual inspection (continuous monitoring)

Remedial measures

Localized repair
Complete repair of the carriageway and drainage system

Observations

The carriageways of current tunnels can be considered as “over-designed” in comparison with open-air carriageways, as they are constructed on a concrete invert, which increases their rigidity.

In a number of old tunnels still in operation, thinner carriageways and poorly designed drainage result in rapid deterioration, but this is not specific to tunnels. Some old carriageways are made of concrete slabs; traffic stresses have rapidly resulted in the rupture of these slabs under the action of vibrations, and "pumping" phenomena have rapidly damaged the lower layers.

Blockages of deep drains which are designed to drain roadbed excavations, result in water rising through the surface course. Temporary lifting of the surface course has been seen.

Over time, water ingress, in the form of continual drops falling on the carriageway surface, starts to clog the asphalt, forming a thin, totally smooth sheet of calcite, of varying size. Shot-blasting these areas only has a temporary effect.

In circular-shaped tunnels, the carriageways may be made of cast in situ or precast reinforced concrete slabs. This design enables a space beneath the carriageway for ventilation, but leads to specific deteriorations related to the degradation of certain supports (oxidation, ejection of joints due to slab oscillation).

Figure 1: *crazing and potholes [foundation saturated with water, with areas dissolved under the effect of pumping resulting from the passage of vehicles]*

Figure 2: *water rising through asphalt*

# Deteriorations in slabs and partitions	# EQ-2

Description (visual appearance of the deterioration)

Slabs (intrados and extrados): fracture cracks in the corners of slabs, cracks in areas of concrete under tensile stress..
Supports: spalling of concrete around supports or where they meet joint elements (prefabricated elements).
Partitions: diagonal fracture cracks may occur where they meet the arch or slab; the partition may also crack around hangers.
Hangers: mostly corrosion (visible by rust traces).

Inspection methods

Visual inspection
Auditory inspection (spalls)

Parameters to be measured

Slabs: Location and form of the cracks (related to the reinforcements but also to the shape of the openings made in the slab) – Condition and deterioration of expansion joints and dry joints – Condition and strength of patching
Supports: Location, surface area and depth of spalling (note whether the end of the slab or the joist is affected)
Partitions: Position, width and shape of the cracks
Hangers: Signs of hanger corrosion (rust traces)

Associated deteriorations or defects to be looked for

Presence of deteriorations in the lining

Origins and possible causes

Slabs: Thickness of the concrete – Position and density of the reinforcements
Supports: Hard spots between the slab and support – Installation errors (prefabricated elements) – Thermal deformations of elements
Partitions: Hard spots between partition and slab/structure and support (inadequate expansion joints)
Hangers: Water ingress

Aggravating factors

Water ingress – Corrosion of hangers or reinforcements – Undersized support systems

Consequences, possible evolution

Concrete spalling due to corrosion of reinforcements
Reduction in aeraulic efficiency

Dangers to users

Slabs and supports: Spalls falling on the lanes
Partitions and hangers: None

Risks to the tunnel and its structural elements

Long-term weakening
Rupture of partitions due to excessive air pressure (rare)

Monitoring

Visual inspection
Auditory inspection

Remedial measures

Passivation of exposed reinforcements (fallen pop outs or spalls)
Repairs dependent on the nature of the materials and the severity of the deterioration

Observations

Slab

The terms ceiling, suspended ceiling and slab are used interchangeably. These are finishings installed in the tunnel, creating space adjacent to the roof section (or invert) of the main lining dedicated to the ventilation or even the evacuation of users in the event of a fire.

These structures always include transverse and longitudinal joints, often incorporating systems for airtightness and fire protection.

Ceiling elements may rest on supports (corbels or trenches), with a bearing (neoprene or polystyrene) used in-between to allow minor movements. This joint may move during its installation, creating contact between the two concrete elements. This leads to a risk of spalling of the support and spalls falling on the walkways or lanes (Figures 1 and 2). Cosmetic patching, mistakenly carried out in these areas, is rapidly "ejected" by the ceiling movements.

In the case of Freyssinet-type supports, the concrete of the slab is in contact with that of the support, but this assembly acts as a pivot that permits minor deformations of the slab.

Chipping observed at the end of the slab is not necessarily caused by movement of the elements or incorrect installation of the formwork, but may occur during the slab's form removal.

Partition

Spaces reserved for ventilation (fresh air, exhaust air and smoke extraction ducts) are sometimes partitioned. These thin partitions may be cast in situ (reinforced panels) or made from prefabricated panels or light stones.
For ceiling ducts, partitions sometimes incorporate the hangers (or anchors) supporting the central part of the ceiling. This may generate localized cracking specific to the partition, or even water ingress along the hanger. In the case of ducts located under the carriageway, the partitions partially support the carriageway slab and may undergo deterioration due to its movements.

Common deteriorations in partitions include cracks of varying sizes at vertical joints (that can be sealed with flexible products) and localized breaks at the top of the partition due to adhesion to the arch lining or to the carriageway slab.

Figure 1: spall fallen from beneath a trench

Figures 2a and 2b: chipping at the edges of slabs

2.11 Deteriorations associated with fire

List of deteriorations	Sheet number
Deteriorations associated with fire	
Deteriorations due to fire	IN-1

Deteriorations due to fire | IN-1

Description (visual appearance of the deterioration)

These deteriorations have a wide range of appearances, depending on the type of lining, the temperature and the exposure time: variation in the colour of the lining, crazing, deep spalling (craters), surface spalling, surface melting. The most severe deteriorations are often located in the roof section, where the temperature is the highest.

Inspection methods

Visual inspection
Auditory inspection (hammer tapping)
Measurements with a sclerometer (to measure the hardness of the concrete's surface)

Parameters to be measured

Location and extent of the deterioration – Colour of the lining – Dimensions and depth of spalled areas or craters – Dimensions of craters or spalls

Associated deteriorations or defects to be looked for

Weakening of mechanical characteristics (in sections adjacent to the fire zone and apparently unscathed) – Loss of the lining's watertightness – Damage to drains

Origins and possible causes

Vehicles on fire – Increase in temperature

Aggravating factors

Exposure to fire over a long time – Very intense fire (high temperatures) – High-strength concrete (faster and more significant spalling)

Consequences, possible evolution

Weakening of the structure – Risks of transfer of stresses related to the juxtaposition of structures with different rigidities – Consequences that may be serious if the fire is not controlled rapidly

Dangers to users

Following a fire, risk of falling debris as the arch cools (particularly under craters and in spalled areas)

Risks to the tunnel and its structural elements

Weakening of material characteristics and reduced thickness of linings, which may lead to collapse (these risks for the structure only appear if the fire was of sufficient intensity and duration)

Monitoring

Visual inspection
Auditory inspection
Condition of the remaining lining (measurement of residual thicknesses, sclerometer measurements, core drilling, etc.)

Remedial measures

Possible precautionary measures (installation of ribs, bolting, drilling to release hydrostatic pressure)
Repair (depending on the residual thickness): either restoration of the lining with sprayed concrete and welded mesh, after repair and sandblasting (or hydrodemolition), or demolition and casting of a new lining

Observations

Additional information

Deterioration caused to structural elements by fires in tunnels have a wide range of appearances that depend on the one hand on the types of linings affected, and on the other hand on the intensity and duration of the fire.

Although there is no doubt about the cause of the deterioration in severely damaged sections that are inspected prior to repair, there may be doubts in the case of tunnels for which no records are available. However, certain limited damage affecting the lining (change in colour, deterioration of material) can only be explained by fire, enabling any doubts to be dispelled.

Without going into the details of the deterioration mechanisms, a few characteristic appearances of linings affected by a fire are given below: colouring, deep spalling, surface spalling, weakening of mechanical characteristics and melting.

Colouring

The colouring of materials affected by fire may be characteristic of the temperatures reached and may depend on the nature of the concrete's constituents.

Deep spalling and surface spalling

When concrete heats up, two similar phenomena may result in loss of material: Deep spalling and surface spalling. Deep spalling designates the mechanism through which the concrete wall develops craters in its surface. Pieces of concrete are detached during the fire, often in the hottest and least confined areas, such as, for example, the down-facing corners of a ceiling beam (it is then referred to as corner spalling). We then see that significant triangular-shaped pieces break away, exposing the lateral reinforcement of the first steel layer. These pieces are fairly large and few in number. They are caused by detachment of the area of coating which is non-reinforced and located in these down-facing corners of beams. The detached pieces never come from within the reinforcement cage. The thicker the coating on the steel bars, the larger the pieces.

Surface spalling is the gradual and continuous detachment of small pieces of concrete which are forcefully ejected from the lining exposed to fire. These pieces are thin (a few millimetres),very flat and a few centimetres in size. Large numbers of what look like thin chippings gradually flake off over very large areas in relation to their size. This phenomenon may start in the first minutes of the fire. It depends on characteristics such as the concrete's composition and its associated properties, its water content and its state of stress. In some cases, it continues steadily at an almost constant speed until the fire is controlled. The thickness of the spalls reduces gradually over time. The presence of a reinforcement cage affects the phenomenon if the steel bars have a diameter constituting a physical obstacle to the expulsion of the concrete behind them. The phenomenon is therefore limited to areas not covered by bars. However, steel bars with small diameters more than fifteen centimetres apart do not significantly reduce the speed with which material gradually flakes off.

Weakening of mechanical characteristics

The increase in temperature is accompanied by two phenomena: thermal damage, which corresponds to an irreversible loss of elastic stiffness (Young's modulus), and thermal decohesion, which corresponds to an irreversible drop in compressive strength. At the microscopic level, this damage may be related to expulsion of the water from the concrete. It starts at around 100°C, and is almost total at 600 to 800°C. Diagnosis on site is made through visual inspection (colour, terracotta appearance, crazing) and by using a hammer (the tip easily penetrates into material that has lost its cohesion).

Melting

Above a certain a temperature, that varies depending on the material, the surface of the lining melts (this phenomenon has been observed during kiln tests and very locally in the Mont-Blanc tunnel, where there was an estimated temperature of 1,250°C).

Figure 1: crazed concrete [thermal limit clearly shown where soot is deposited on the crazing], at a distance of 120 m from the heavy goods vehicle that caused the fire in the Mont-Blanc tunnel [no other vehicle involved]

Figure 2: craters 30 to 60 cm deep created in the arch by the fire next to the heavy goods vehicle that caused the fire [Mont-Blanc tunnel]

Figure 3: deep spalling revealing the intrados reinforcements, following the ten-hour fire in the Channel Tunnel in 1996, involving a heavy goods shuttle. In the most affected area, at the heart of the fire in this tunnel, (formed of prefabricated reinforced concrete segments), the damage locally affected the tamping mortar.

2.12 Deteriorations associated with poor maintenance

List of deteriorations	Sheet number
Deteriorations associated with poor maintenance	
Poor maintenance	EN-1

Poor maintenance	EN-1

Description (visual appearance of the deterioration)

This sheet groups together all the deteriorations that do not affect the structure of the tunnel but that play a role in the tunnel's operation and that, in some cases, may constitute a danger to users.

These deteriorations may be quite different in nature and may be located in various areas of the tunnel.

Inspection methods

Visual inspection

Parameters to be measured

Location

Associated deteriorations or defects to be looked for

None

Origins and possible causes

Poor maintenance or workmanship – Weather-related deteriorations.

Aggravating factors

No regular maintenance.

Consequences, possible evolutions

Worsening of the deterioration – Disrupted tunnel operation – Risk of traffic incidents

Dangers to the users

Possible danger, depending on the scale of the problem (elements or equipment falling on the carriageway, presence of water and/or obstacles on the carriageway).

Risks to the tunnel and its structural elements

Blockage of drainage systems – Deterioration of portals due to vegetation

Monitoring

Visual inspection

Remedial measures

Carry out regular checks (patrolling) in the tunnel and its surrounding areas
Continuous monitoring (systematic checking of all of the equipment or facilities in and around the tunnel that may, if not correctly maintained or in poor state, become a risk to users)
Annual inspection
Maintenance of equipment and routine maintenance of structural elements

Observations

These deteriorations directly affect the tunnel's operation and sometimes the safety of users. They must be identified and mentioned in inspection and control reports. These deteriorations are often caused by lack of maintenance: it is therefore important to record them in the "actions to take" section of the inspection report and check their development during the next inspection.

The deteriorations grouped together in this sheet are diverse in nature. Others may exist but they all have one thing in common: their cause is a lack of routine maintenance of the tunnel.

For example, the following deteriorations concerning tunnel equipment and areas in the vicinity of the tunnel may sometimes be noted:

- dense vegetation that may create instabilities at portals,
- objects that may fall on the carriageway,
- faulty fixtures (cable tray hangers, cameras, power cables in the roof section),
- cast iron manhole or drain covers that are missing or that obstruct the traffic.

These deteriorations can be avoided if the tunnel operator adopts risk prevention measures.

Figures 1a and 1b: dense vegetation that may create instabilities at portals – Objects that may fall on the carriageway

Figures 2a and 2b: partially or totally severed cable tray hangers or camera fastenings

<u>Figure 2c:</u> broken plastic power cable fixture in the roof section

<u>Figure 3</u>: incorrectly positioned cover blocking the gutter

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