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Report on key parameters for bridge and tunnel inspections

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Review Comments

Following the In2Rail midterm review on Tuesday 28th February 2017, this deliverable was requested for revision by the European Commission in the assessment report #Ref. Ares(2017)1734456 - 31/03/2017, In2Rail can confirm that the review comments have been duly considered and this modified report contains revisions to address these specific points.

The below table provides an index to Sections of the revised document that contain the responses to the review comments.

Revision Requested from EC	**Revision Reference Number**
"Selection of KPIs needs to be better explained…"	See section 3.3 in addition to improvements in various sections
"The report will need to consider what is being done today …"	It has been further clarified that this is not in scope of deliverable nor task, and has therefore not been included in the deliverable.

Executive Summary

This document has been developed to identify and quantify inspection parameters required by Infrastructure Managers for inspection of Railway Bridges and Tunnels using innovative monitoring systems.

These parameters are developed as Key Performance Indicators to:

- Meet current and future safety and performance requirements;
- Identify early environmental factors affecting deterioration;
- Monitor visual damage;
- Develop deterioration profiles;
- Plan early intervention and repairs;
- Extend the service life of assets.

These KPIs will be used to identify, compare, evaluate and further develop the technology for new inspection methods and remote monitoring systems.

Future monitoring systems aim to reduce the requirements for physical inspection of structures by examiners, improve quality and this will reduce the need for traffic disruptions and line closures.

The key performance indicators identified can be treated separately as they are relatively independent of each other. There are 14 and 31 key performance indicators for tunnels and bridges, respectively defined to detect either latent or ongoing deterioration.

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Abbreviations and Acronyms

Abbreviation / Acronyms	Description
KPI	Key performance indicators
LCC	Life cycle cost
PI	Performance indicators

1 Background

This document is Deliverable D4.1 “REPORT ON KEY PARAMETERS FOR BRIDGE AND TUNNEL INSPECTIONS” in the framework of the Project titled “Innovative Intelligent Rail” (Project Acronym: In2Rail; Grant Agreement No 635900).

To meet In2Rail and Shift2Rail objectives, some of the current inspection methods need to be replaced. Current inspections require closure to traffic in order to obtain unrestricted access to structures and the results are generally low quality in terms of repeatability as they are often not only person dependent, but may vary over time from the same inspector. Another significant disadvantage with today’s inspection methods is evidenced in documents produced by Batman (2015) and the Standard NR/L3/CIV/006 (2012), which demonstrates that existing methods are mainly focused on detecting damage or deviations from specification drawings.

One issue with detecting already occurred damage, is that this deterioration is likely to increase until there is an opportunity to do repairs. Even more critical is damage that reduces safety requiring mitigation with the introduction of limitations on traffic until the problem is corrected, either permanently or temporarily. All repair works that cannot be planned well in advance are typically more costly and will also cause more traffic disruptions, compared to damage that is managed proactively and in due time. The quality of the repair will typically be lower the longer the damage is allowed to progress.

Typical inspections for example Fib B22 (2003), UIC 778-1 (2011), UIC 778-2 (1986) UIC 778-3 (2014) and UIC 778-4 (2009) are normally applied to the specific structures, and in many cases do not consider surroundings, track support condition, transitions zones, dynamic behaviour or performance under load conditions, such as noise emission.

With improved inspection and possible monitoring, these uncertainties can be reduced, resulting in increased load bearing capacities, increased speed and will effectively record fatigue consumption; thus extending the effective and practical use of structures.

As new inspection methods and technologies are considered, it is essential to understand the requirements that are needed to detect and register actual damage. It is also a requirement to be able to detect deterioration earlier for proactive management. In some cases it might even be possible to detect unfavourable conditions that can be eliminated and therefore prevent the occurrence of damage. In addition new methods for inspections may also detect elements of risks from surrounding environment such as erosion, flooding or similar.

Inspections of structures potentially carries risk for the people on site undertaking the inspection in the form of; attention divided between inspection and simultaneous traffic, slippery underfoot conditions, deep water, partial climbing and unsocial working hours with limited available time. These risks may be eliminated with more automated inspections.

2 Objective and Aim

This document has been prepared to provide guidance in evaluating existing and new methods for bridge and tunnel inspection that are to be studied in later research within the project. The work builds upon previous research conducted within SB-LRA (2007), SB-ICA (2007), SB-MON (2007), SB-STR (2007), PM'n'IDEA (2012), Smartrail (2014), ML-D1.3 (2015) and ML-D1.4 (2015) and the presented work has intentionally not included any evaluation of existing methods or standards. The document presents parameters that are likely to be useful for study to detect future damage or to detect damages earlier. Parameters that are introduced are intended to be more generic in describing phenomena, rather than prescribing detection method. A main aim is to describe parameters that can be studied for proactive management.

The intended use of proposed parameters will support infrastructure managers to answer more detailed questions on how long a specific structure will be safe, if any maintenance will be needed, if traffic limitations need to be considered, and adjustments to inspection programmes are needed. The proposed key parameters are in addition to existing parameters for visual inspections. Some parameters described are already inspected currently, however it is possible that these parameters may be detected or monitored in new ways with new technology and to some extent, replace existing inspections. Only indicators of significant value for project objectives will be discussed and shall be designated key performance indicators.

Defining parameters that can detect deterioration or damages at different levels of severity is considered to be important. The earlier deterioration can be recorded, the better. The aim is to identify different parameters to study without prescribing how to monitor and without considering if this data is viable to obtain. The aim of the parameters is to have ones which are not affected by today's practice, existing doubts, preferences or pre-set minds on possibility to record them.

Developing new inspection and monitoring technologies is best done by an iterative process where requirements should be allowed to evolve during the process. By introducing strict requirements from the beginning, promising technologies risk being excluded. If possible, requirements should at this stage instead be flexible and tackled by a combination of method, frequency, accuracy and precision. Introducing new philosophy of managing structures must allow for flexibility in purpose, requirements and ambition. A proper balance between these aspects is considered more important than finding an imaginary optimal method or technology. Frequency of inspections, type of inspection, and quality of results are dependent factors and should be regulated by an overarching philosophy. Such a philosophy must include type of traffic, asset condition, and desired level of safety.

In addition to presented key parameters, there are other considerations when evaluating inspection methods. To facilitate proactive management, inspections should be repeatable, with good accuracy, and quantitative in nature. In addition, inspection methods must not significantly disturb traffic, yet be safe, provide safe structures, and detect deterioration well ahead of time. In general, methods that cover surroundings should be allowed, i.e. not only structures themselves should be inspected but also latent harmful situations around them. By including presented parameters in evaluation, it should be possible to compare and grade technologies for inspection of tunnels and bridges.

2.1 Limitations

The given parameters and values are for benchmark purposes of different technologies only. All values given are not to be taken as absolute values for safety, reliability nor sustainability. This report does not present inspection methods or philosophy of management.

In the range from potential deterioration to significant physical damages, there are several dependent and independent factors that must be included in order to develop this range up to critical condition. However, this document does not intend to present a complete fault-tree or event-tree diagrams of damages.

Any description of maintenance needed in order to avoid or reduce deterioration is not included in this report.

Presented parameters will have large ranges of possible values. Presented values are deterministic values of different kinds that may be expressed as a minimum, average, or maximum depending on physical application and should be seen as an indication of what is needed for management.

3 Performance Indicators

3.1 General

For a railway system to work and fulfil its purpose - trains, infrastructure and users are needed. The infrastructure here includes track components, bridges, tunnels and embankment. The high level requirements for bridges and tunnels to function in a railway system are:

- Load Bearing capacity;
- Structural robustness;
- Clearance (Gauge).

In order to manage structures over time, the high level requirements must be further specified. The performance of structures is normally described by a set of parameters depending on the type of structure. Performance of bridges can be divided into bearing capacity, stiffness, aesthetics, clearance, durability and structural safety including robustness. For tunnels the performance can be described by, clearance, structural safety, structural integrity. As performance normally reduces over time, it is interesting from a management perspective to describe and predict the rate of deterioration. In Figure 3.1 a schematic deterioration profile is given.

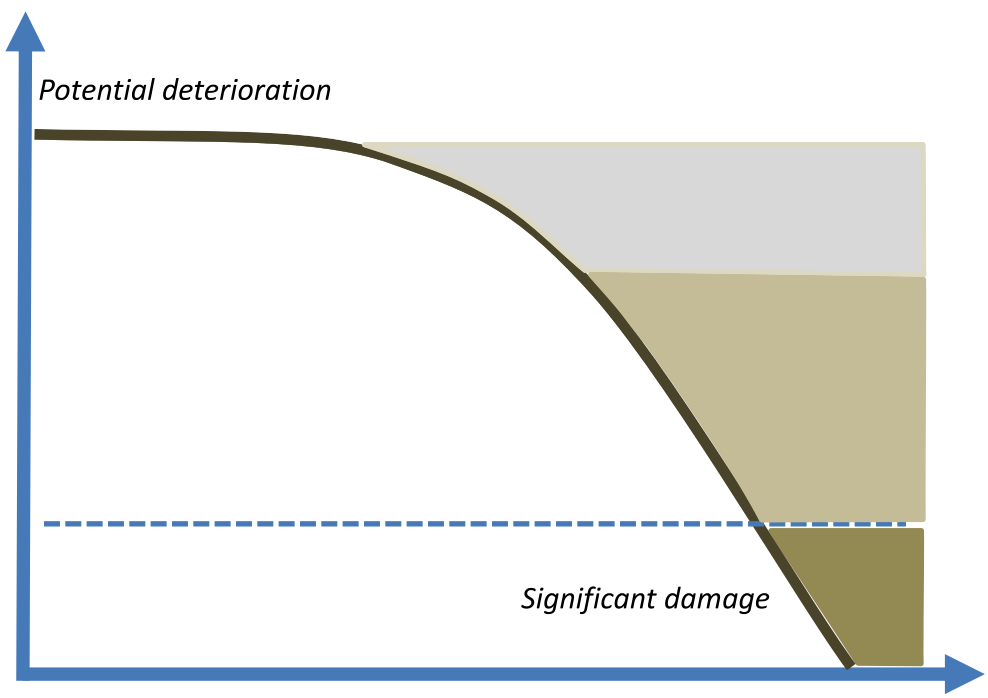

Figure 3.1: Schematic deterioration of performance of time

There are also other performance requirements for structures included in a railway system. One example is noise emission and vibrations of structures in service. In Figure 3.1, four categories of deterioration are given, three above the minimum level and one below:

- **Potential deterioration**: includes harmful environment, faulty materials, and with fulfilled combination of events or simplified just with time that deterioration takes place;
- **Minor deterioration:** non-visual deviations still affecting structural condition;
- **Major deterioration**: visual deviations and typically what can be identified by current most commonly practised inspection methods;
- **Significant damage**: Visual Deviation and severe damage that result in reduction in safety i.e. increased probability of failure or malfunction.

Minimum level: represents a stage when passage of normal traffic cannot be permitted. For an effective management at least two more levels should be applied:

- **Alarm level:** when managers become aware of something**;**
- **Maintenance level:** a level when maintenance can be implemented in order to avoid reaching minimum level.

In the following, different levels are not in focus, as the intent is to find indicators of potential or ongoing deterioration as early as possible.

The categories are not strictly chronological. Development of damage can go from potential deterioration directly to significant damage. In figure 3.2, the development of damage is schematically illustrated.

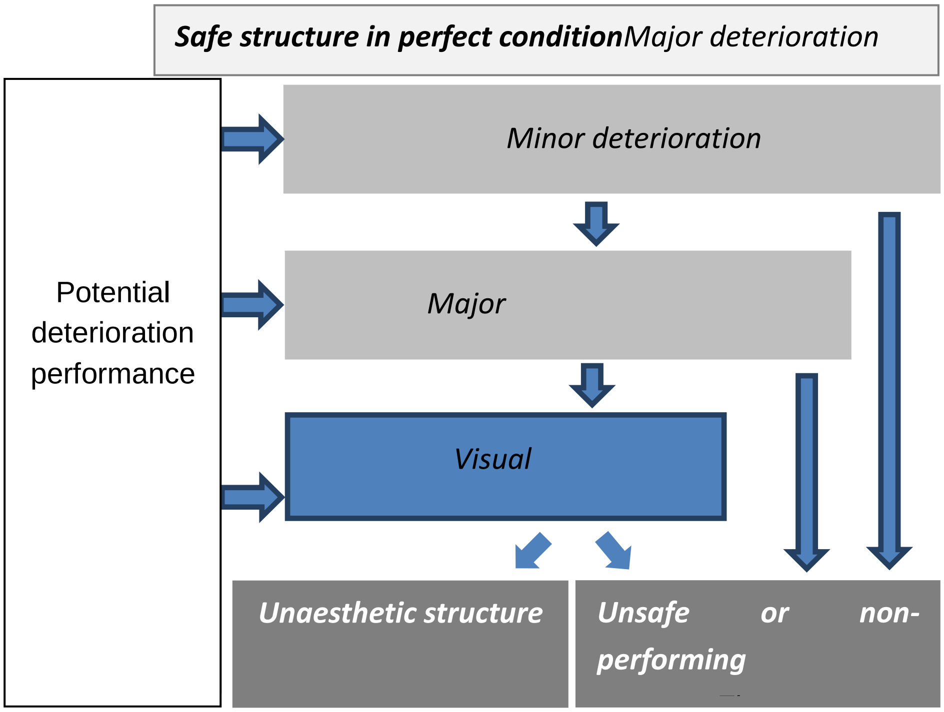

Figure 3.2: Deterioration and ways of damage development

The visual damage has been divided into aesthetic and structurally unsafe, however there are also other performance capabilities and combinations, which may be reduced by the deterioration. Typically for potential deterioration, there is a set of logical events that need to occur in order to cause deterioration or damage. Some damage will never happen, even though a potential deterioration exists, if one critical event is missing. This is important to understand when parameters for monitoring are selected. If a combination of parameters is needed for deterioration it can be enough to record one parameter, hence such parameter can be a key performance indicator to detect possible deterioration early.

The deterioration profile may have many possible shapes. For many deterioration types, the deterioration increases with damage, hence a parabolic curve is often used as example. Some deterioration will follow a linear development. Some damage developments, can be discontinuous, e.g., structures hit by vehicles can go instantly from perfect to unsafe. Deterioration curves are also very unpredictable with large differences between two apparently identical situations.

To clearly define the position in the deterioration process, several circumstances must be considered. The exact position is typically not needed for evaluating inspection methods and in the following analysis, only two parameter types will be used:

- **Early indicator:** includes Potential deterioration and Minor deterioration;
- **Visual deviation:** includes Major deterioration and Significant damage.

In addition to the deterioration profile, it is also considered helpful to study chains of cause and consequences. Such chains can have several links where one consequence from a previous cause will be the subsequent cause for another additional consequence. Performance indicators, (PI) are here defined as potential indicators describing either that performance is in perfect condition, or that performance is affected. Some performance indicators are more important than others and they will be called Key Performance indicators, (KPIs) and will be used in the following manner. When studying KPIs it is important to understand the structural behaviour of the whole structure and to differentiate between cause and indication. Some KPIs will indicate a local indication of a global occurrence, or a local occurrence elsewhere on or near the structure.

Finally some deterioration has very limited visual damage preceding a failure, e.g. shear failures, fatigue, certain joints, and brittle materials. Some of these can possibly be detected by studying the secondary effects of untraditional parameters such as acoustic emissions or changes of curvature for example.

3.1.1 Planning Process

Assets with an anticipated long life, such as bridges and tunnels need to have a long-term maintenance strategy. For all of these assets, a precise maintenance planning is scheduled which needs support from inspection results. The depth of investigations needed for assessment differs with management philosophy and asset type. Many assessment techniques need direct access to the track and influence the track availability. Inspection in tunnels is similar to construction activities and consequently often needs the same attention in pre-planning as construction works itself. Moreover special inspection vehicles or equipment is needed and the availability is limited.

Normally at a very early stage (around 5 years prior to needed work in the track environment), any activity influencing track availability should be declared. This is the only way that assessment activities, together with replacement works and corresponding track closures can be included in timetables.

Therefore the planning of extensive assessment activities with advanced equipment in the railway environment is a complex task. Different disciplines and necessary preparation of infrastructure parts (accessibility of bearings, alternative signalling etc.) have to be coordinated. Infrastructure owners have their own principles and tools to implement this assessment process into timetables. The number of assets and the age of railway infrastructure plays an important role, with more assets to maintain and the older the structure, then more traffic disturbance is caused by condition assessment.

Typically the available capacity is used to a quite high degree with limited tolerance for disturbance. To reduce the interruption of rail traffic to a minimum; here enhanced and reliable assessment techniques can play an important role. One method is to inspect and "monitor" the condition state of infrastructure assets with the possibility to prolong maintenance interval, while another method is to use faster equipment (like on-board technology) or wayside monitoring systems to enable infrastructure data collection without disturbance of normal traffic. Both methods would significantly enhance track availability and lower traffic disturbance. Here the key performance indicators and their possible guidance will be important.

3.2 Level of Requirements

When KPIs are defined and understood, the data requirements of the indicators are needed for effective monitoring. This can be divided into what is absolutely essential and what is good to know. For planning process it can also be very important to identify when information is needed. The quality of data that can be divided into precision, accuracy and repeatability, are important issues and illustrated in Figure 3.3.

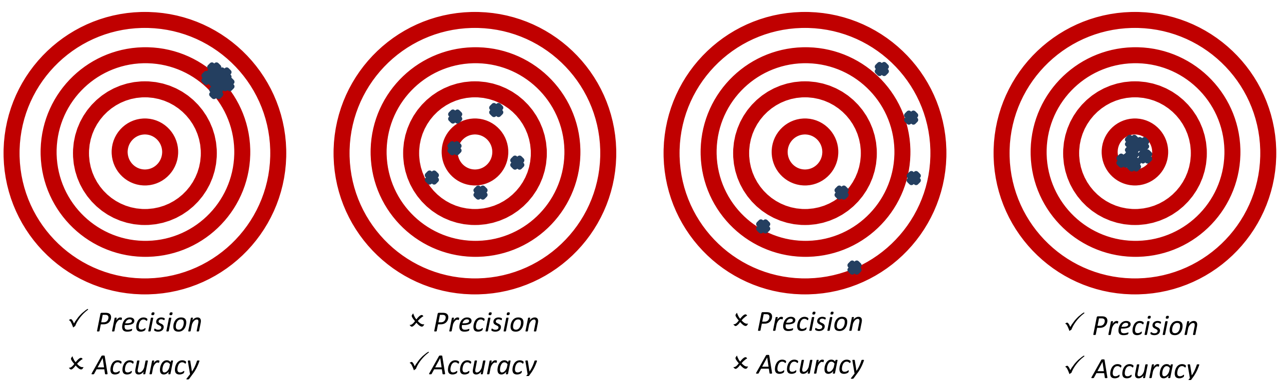

Figure 3.3: Quality aspects of data

High precision, high accuracy and high repeatability is the best basis for any prognosis and planning. This kind of data is also the most difficult and most expensive to obtain. For some variables, measurements with high precision without accuracy can be as good as previous quality if repeatability is good. With large amounts of data frequently obtained, poor precision can be overcome by trend analysis, if accuracy is good.

For relative measurements, sometimes even poor precision and poor accuracy can be meaningful in order to detect deviations in trends. When different kinds of data are used for alarm systems, it is important that data quality provides a high degree of warning and low frequency of false alarm.

The requirements of data must be selected based on costs, important KPIs and management philosophy. With the dependencies on how data can be recorded, evaluated and management philosophy, it is not possible to prescribe accuracy, precision or repeatability without limiting procedures for inspection and hence it will not be made in this document.

3.3 Identification and Quantification

Bridge and tunnel problems are well known and understood by infrastructure managers at the time when problems can be categorised as "Major deterioration" or "Significant damage" as earlier presented. Also the development of these problems are well known and can be seen as a chain of causes and consequences where one consequence also may be the cause for another consequence. When identifying PI, cause and consequence chains have been developed based on experience for common and well known bridge and tunnel problems. This work has been made by project partners' experts. The identification is focused on real structural problems, deterioration experience, structure usage and environmental actions. Particular efforts have been made to avoid influence from habits, anecdotal sources, existing Standards, costs, etc. Figure 3.4 presents an example of a cause and consequence chain for "scale deposits" in a tunnel drainage system leading to damage to the tunnel structure.

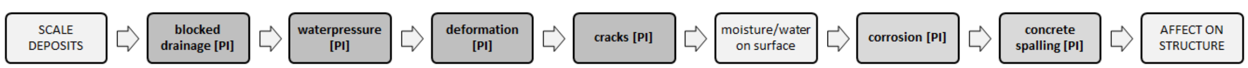

Figure 3.4: Causes & Consequences Series for scale deposits in a tunnel drainage system

By defining chains for relevant problems, i.e. traffic troublesome problems, some causes and consequences will be part of several chains. Chains can also to different degrees be interlaced and dependent on each other. Without organising chains in complicated fault and event trees, frequent common denominators cannot be quantified by existing mature technologies and hence PI's will not be correctly identified. In order to get an early warning indicators, particular efforts have been made to identify PI's early in the chains. When relevant problems are covered by at least one PI, possible monitoring of the problem is considered to be found. PI for some well-known problems can also be identified based on experience and for these cases this have been done without using cause and consequences chains.

After PIs have been identified each and every one must be quantified in terms of needing a resolution. As earlier described precision, accuracy and inspection frequency are interlinked and will all affect the required resolution. In addition maintenance philosophy, traffic intensity and environmental load will also affect the resolution. Maintenance philosophy is strongly correlated to the adopted interest rates used for calculating future costing purposes that varies between countries and oddly also to some extent over time. Traffic intensity varies significantly between different lines and focus has been given to situations with structures that are difficult to access because of high traffic levels. Environmental loads also vary significantly and additional focus has been given to structures subjected to more than normal deterioration, planned maintenance or extensive repair activity. To have effective monitoring solutions a balance between different aspects was applied when stating requirements on promising technologies, i.e. quantification of PIs.

For different PIs, expert groups from In2Rail partners have discussed values based on their experience. For different situations highest and lowest possible values were identified and each PI was given a tolerance range. In considering a probabilistic view and the likely combinations of precision, accuracy and inspection frequency, this identified ranges that were further reduced. With more refined analysis of cause and consequence chains together with different aspects of maintenance philosophy, ranges were again reduced until the highest and lowest values were considered to be of similar magnitude. This means that the same technology could be used for both upper and lower limits. With a narrow range, the resulting resolutions for the PIs were calculated as a weighted average value, considering importance for different cause and consequence chains.

Identified PI’s together with quantified thresholds and levels of precision are presented in following chapters for the different structure types.

4 Tunnel Key Performance Indicators

4.1 General Principles

For tunnels there are two general functions that must be fulfilled. First the free opening must be ensured, i.e. no parts of the tunnel nor can any installations obstruct the gauge. Second the structural integrity, i.e. bearing capacity of the tunnel itself and possible additional loads must be ensured. Tunnels may be divided into un-lined or lined tunnels.

Un-lined tunnels do however typically use some kinds of strengthening or drainage system on the rock surface. To define PI for tunnels, the focus on a system of causes and consequences is necessary. Each cause may have consequence for structure, equipment or clearance. A consequence could be the cause for the next consequence.

Causes shown in Figure 4.1 for tunnels may be divided in:

- “outside actions” are all parameters which come from the in situ rock and groundwater condition;
- “inside actions” are conditions which could be present during the operation of the tunnel;
- “within actions” are the result from processes within the construction.

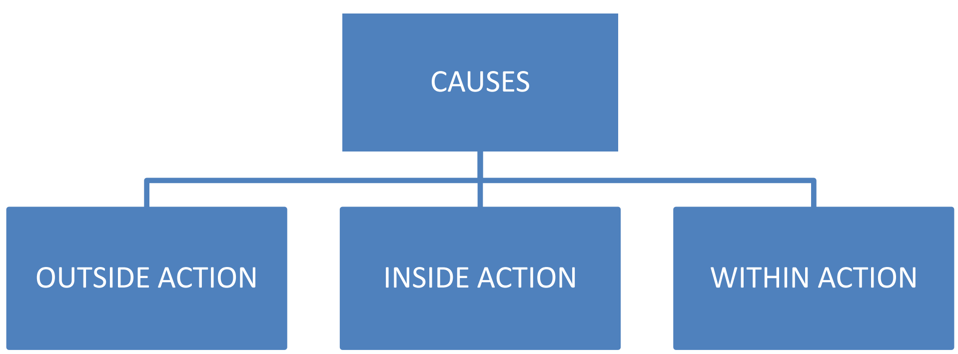

Figure 4.1: Causes on tunnel structures

Consequences shown in Figure 4.2 for tunnels may be divided in:

- Structure, consists of the structural integrity, sealing and lining.
- Equipment, e.g. signs, water supply, emergency supply, catenary.
- Clearance is the minimum profile which needed for the safe working of the train service.

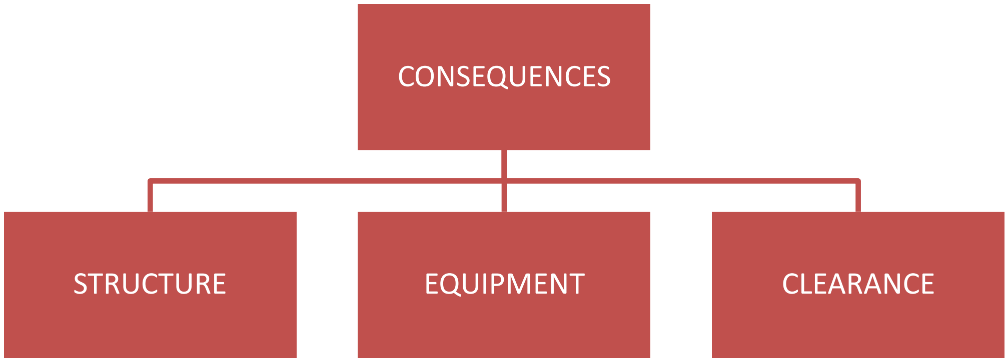

Figure 4.2: Consequences for tunnel structures

Several causes and consequences are common for many tunnel types. Performances indexes for these damages will be presented under each tunnel type as the numerical value for threshold and precision can vary and should be allowed to be discussed separately. Presence of water in track bed from faulty drainage will reduce track stability. However, this consequence is not covered by listed performance indexes even though it in turn can be a cause of derailment and severe tunnel damage. In general pressure and suction from trains passing through tunnels will give loading on linings, installations and require possible strengthening. This loading is dependent on many factors and can be used as a performance index to monitor load effect, however this is not further described.

4.2 Lined Tunnels

Lined tunnels can have lining in direct contact with surrounding material or with some space between lining and rock. When lining is in direct contact it is normally a supporting structure, such as found in soils or poor rocks, and is composed of thick linings built with good quality. When there is a space between lining and rock it is normally a protective structure composed of a thin lining with a function to protect the rails from blocks falling and to reduce icicle problems. There are also different kinds of materials used for linings which will be treated separately in the following.

4.2.1 Concrete Lining

In general a concrete lined tunnel consists of:

1. Rock mass;
2. Sealing system;
3. Concrete shell (in situ/or prefabricated),

Depending on the rock condition; there are two different ways to build the tunnel:

1. Watertight solution – watertight concrete shell (in situ/prefabricated);

2. Drained solution – with bottom and wall drainage.

Lined tunnels may be affected from various causes shown in Figure 4.3.

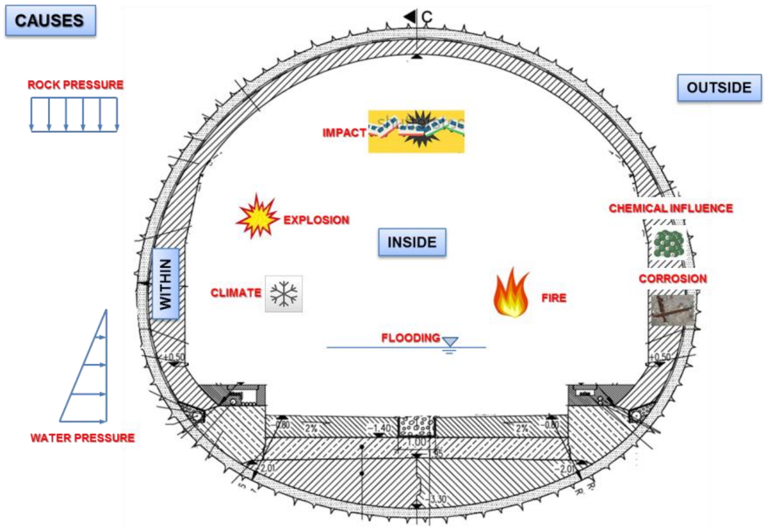

Figure 4.3: Causes on lined tunnels

This various causes may be classified in accordance to the scheme shown in Figure 4.4.

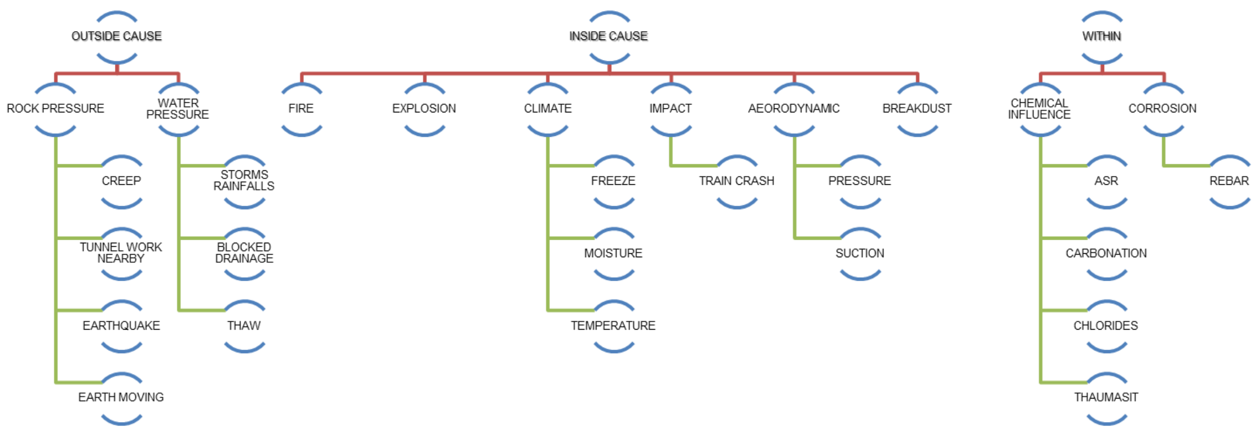

Figure 4.4: Scheme of various causes (lined tunnels

Consequences from these causes may occur on the structure, equipment or clearance, shown in Figure 4.5.

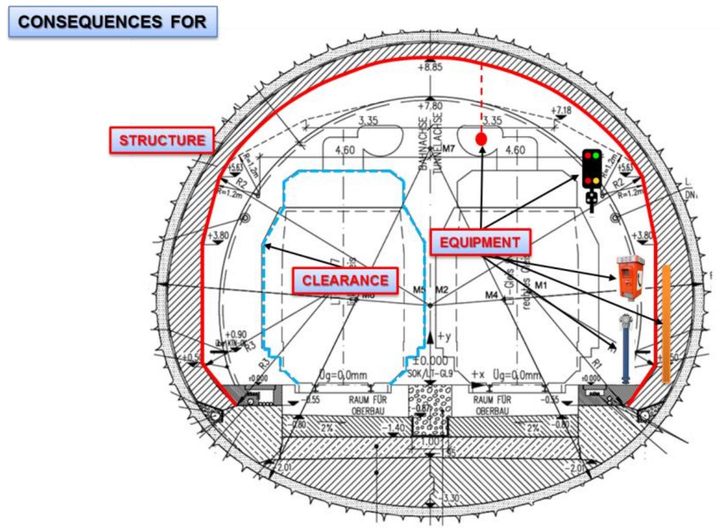

Figure 4.5: Consequences for lined tunnels

Correlations lead to various cause – consequence series shown in Figure 4.6.

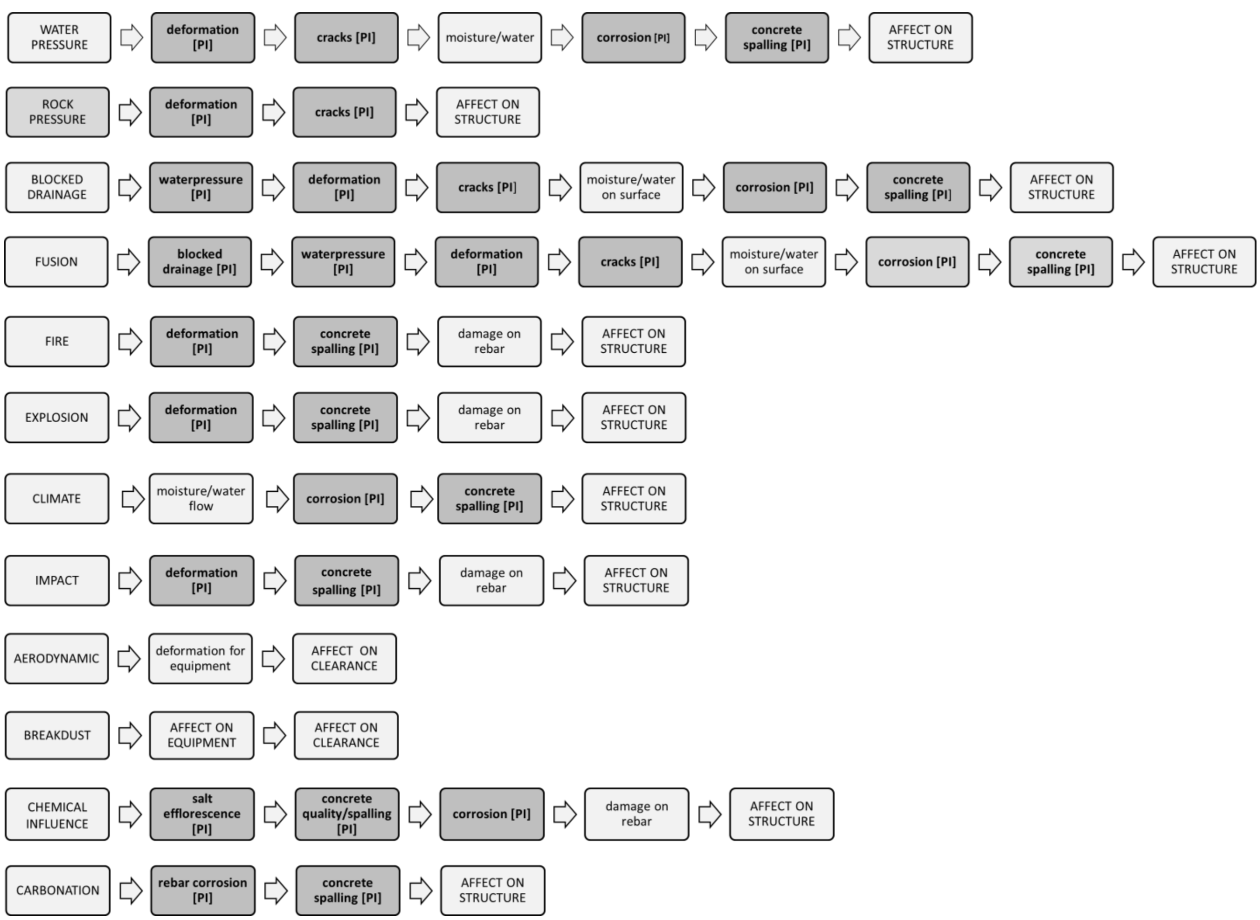

Figure 4.6: Cause/Consequence series for lined tunnels

As a result from the focus on the system of causes and consequences, the following performance indicators (PI) can be defined as in Table 4.1.

Parameter type	***Measurable Object***	***Threshold***	***Precision***	***Comments***
Early Indicator	*Rock Pressure*	*5 % or 50 kPa*	*+-2 %*	
Early Indicator	*Water Pressure*	*5 % or 50 kPa*	*+-2 %*	
Early Indicator	*Blocked Drainage*	*90 % residual cross-section*	*+-5 %*	*When applicable*
Early Indicator	*Carbonation depth*	*10 mm*	*+-2 %*	
Visual deviation	*Salt efflorescence*	*10 cm²*	*+-5 %*	
Visual deviation	*Deformation*	*1 mm*		*Small deformation can also be early indicator*
Visual deviation	*Cracking of concrete*	*0.25 mm*		
Visual deviation	*Concrete spalling*	*20 cm²*	*+-5 %*	
Visual deviation	*Rebar corrosion*	*10 % loss of cross section*	*+-2 %*	
Visual deviation	*Discoloration due to chemical influence*	*10 cm²*	*+-5 %*	

Table 4.1: PI for Concrete lined tunnels

4.2.2 Brick and Masonry Linings

Masonry tunnels belong to a common form of lined tunnel system. Tunnels with masonry lining includes brickwork, stonework and blockwork, an example is shown in Figure 4.7.

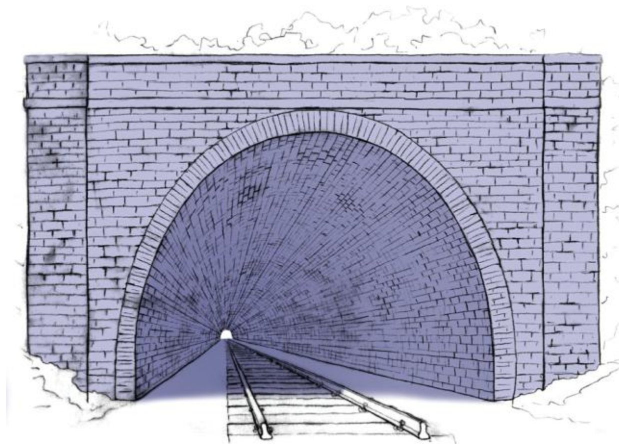

Figure 4.7: Brickwork lined tunnel

Degradation of masonry lined tunnel consists of the following:

- Impact loading resulting in cracking and crushing of masonry;
- Structural failure of spandrel walls;
- Settlement or spread of substructures;
- Wing wall or parapet wall spread.

Detailed problems include:

- Spalling;
- Open joints or perished mortar;
- Water ingress;
- Hollow sounding areas;
- Bulges or lining deformation, distortion or flattening;
- Loose or missing masonry;
- Cracks and fractures.

In Table 4.2 Performance indexes for brick and masonry lined tunnels are given.

Parameter type	***Measurable object***	***Threshold***	***Precision***	***Comments***
Early Indicator	*Vegetation*	*Any*	*Any*	*Remove, treat to prevent regrowth and standard masonry repair*
Visual deviation	*Ingress of water through lining*	*Damp or wet area > 10 %*	*Wet* *Dripping* *Damp* *Dry* *(Stained)*	*Cracking or spalling of the masonry due to mildly acidic water which dissolves the calcium carbonate which then weakens the mortars bonding properties). Potential for failure of lining leading to derailment*
Visual deviation	*Composition of construction materials and/or ground and groundwater conditions.*	*Discolouration > 2 m^2*	*1-3 m^2*	*Lining deterioration due to calcite or ochre formation or efflorescence*
Visual deviation	*Hollow sounding areas*	*1 m^2*	*0.5-3 m^2*	*Void behind lining, ring separation , drummy brickwork*
Visual deviation	*Bulges or lining deformation, distortion or flattening*	*50 mm over 1 m^2*	*30-100 mm*	*Due to:* *Created during construction.* *Since construction:* • *hollow sounding* • *solid sounding*

Parameter type	***Measurable object***	***Threshold***	***Precision***	***Comments***
Visual deviation	*Service support structures failing.*	*20 mm Movement over successive samples*	*10-50 mm*	*Trays, cables and support structures may fail, detach from lining and fall onto track*
Visual damage	*Loose or missing masonry*	*3-5 bricks or blocks*	*2-6 bricks or blocks*	
Visual damage	*Spalling (Brickwork)*	*Depth 30 mm*	*20-50 mm*	*Freeze / thaw damage. Chemical attack due to crystallisation of minerals within the brick, or long term weathering. Chloride attack*
Visual damage	*Spalling (Blockwork / Stonework)*	*Depth 60 mm*	*40-100 mm*	
Visual damage	*Open joints or perished mortar (Brickwork)*	*Depth 30 mm*	*20-50 mm*	
Visual damage	*Open joints or perished mortar (Blockwork / Stonework)*	*Depth 60 mm*	*40-100 mm*	
Visual damage	*Longitudinal Cracks and Fractures (bore)*	*5 mm Crack > 200 mm Length*	*100-300 mm*	*Structural distortion of lining, potential for infringement of tunnel gauge and/or structural failure. Bulging or cracking of tunnel lining*

Parameter type	***Measurable object***	***Threshold***	***Precision***	***Comments***
Visual damage	*Circumferential Cracks and Fractures (Bore)*	*5 mm crack over 25 % circumference*	*20-40 % circumference*	*Longitudinal Crack more severe than Circumferential crack. Cracks in single bricks / blocks not severe!*
Visual damage	*Cracks in wing walls or portals*	*Stepped crack over 3 bricks / blocks*	*2-5 bricks / blocks*	*Indicative of earth retaining wall failure.*
Visual damage	*Ground conditions*	*Subsidence > 200 mm / 2m^2* *Slope failures > 2 m length*	*150-500 mm* *1 m – 3 m*	*Evidence of soil movement nearby*

Table 4.2: PI for Brick and Masonry lined tunnels

4.2.3 Metallic Lining

Metallic lined tunnels are not very common form, however those existing are typically very old. An example is shown in Figure 4.8.

Figure 4.8: Metallic lined tunnel

Degradation of metallic lined tunnel consists of the following:

- Corrosion;
- Fatigue failure;
- Water Penetration.

In Table 4.3 Performance indexes for metallic lined tunnels are given.

Parameter type	***Measurable object***	***Threshold***	***Precision***	***Comments***
Early Indicator.	*Vegetation*	*Any*	*Any*	*Growth through lining joints - Traps moisture and encourages corrosion*
Visual deviation	*Water ingress on metallic components*	*Damp area > 10 %*	*Wet Dripping Damp Dry (Stained)*	
Visual deviation	*Corrosion*	*>10 % Loss of steel section, or 5-10 mm deep.*	*10-30 % of Area*	*Sections are typically 20mm thick.*
Visual damage	*Deformation, bulging.*	*30 mm over 0.5 m^2*	*20-50 mm*	*Needs to consider area as well.*
Visual Damage	*Longitudinal Cracks and Fractures (bore)*	*1 mm Crack > 200 mm Length*	*0.5 mm Crack 100-300 mm Length*	*Structural distortion of lining, potential for infringement of tunnel gauge and/or structural failure. Bulging or cracking of tunnel lining*
Visual damage	*Circumferential Cracks and Fractures (Bore)*	*1 mm crack over 25 % circumference*	*0.5 mm Crack 20-40 % circumference*	*Longitudinal Crack more severe than Circumferential crack. Cracks across segments more severe!*

Parameter type	***Measurable object***	***Threshold***	***Precision***	***Comments***
Visual damage	*Misalignment of segments*	*20 mm Step*	*10-50 mm*	*Similar to concrete segments. Important to record over several segments to determine trends.*
Visual damage	*Ground conditions*	*Subsidence > 200 mm / 2m^2* *Slope failures > 2 m length*	*150-500 mm* *1 m – 3 m*	*Bulging or cracking of tunnel lining. Indicators from nearby areas.*

Table 4.3: PI for metallic lined tunnels

4.3 Unlined Tunnels

4.3.1 Unlined Tunnels

This tunnel type is used in stable rock conditions. It was a typical building method in the early days of tunneling. Unlined tunnels may be affected from various causes shown in Figure 4.9.

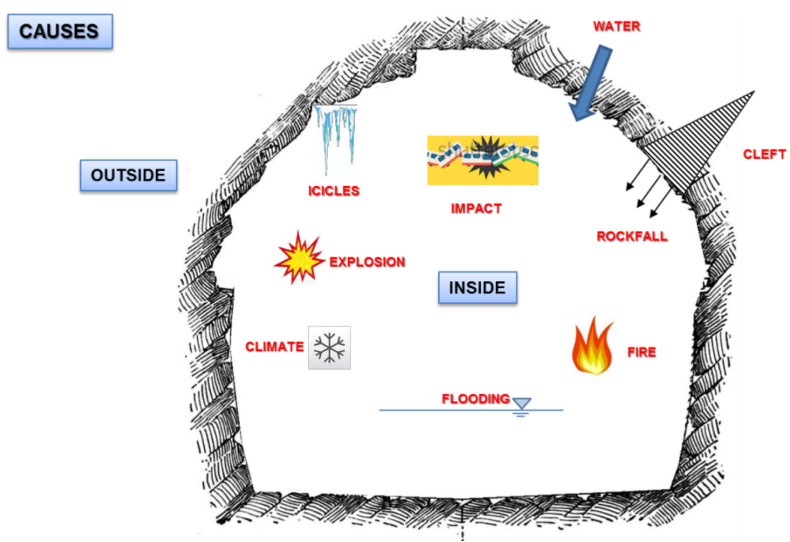

Figure 4.9: Causes on unlined tunnels

This various causes may be classified in accordance to the scheme shown in Figure 4.10.

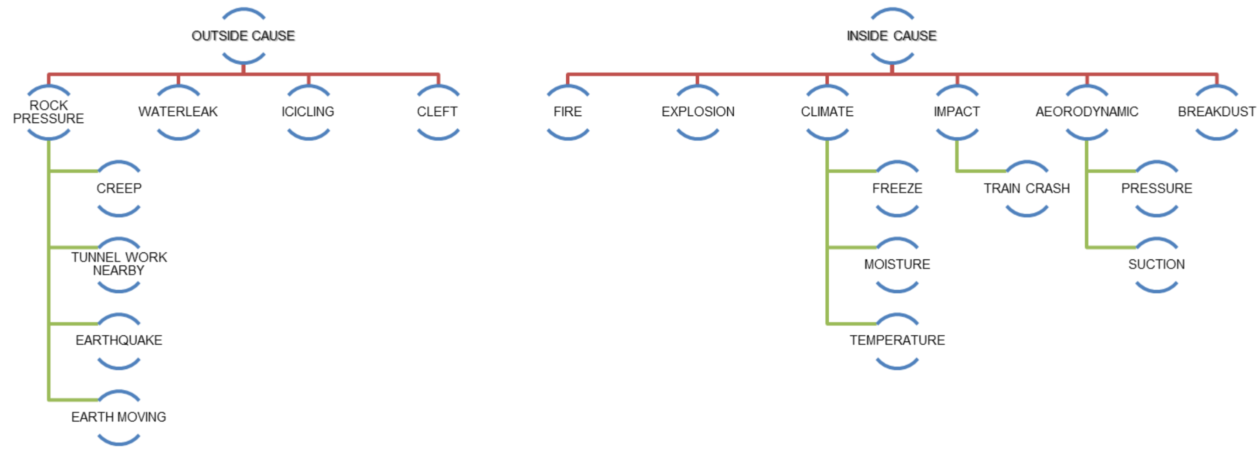

Figure 4.10: Scheme of various causes for unlined tunnels

Consequences from these causes may occur on the structure, equipment or clearance as shown in Figure 4.11.

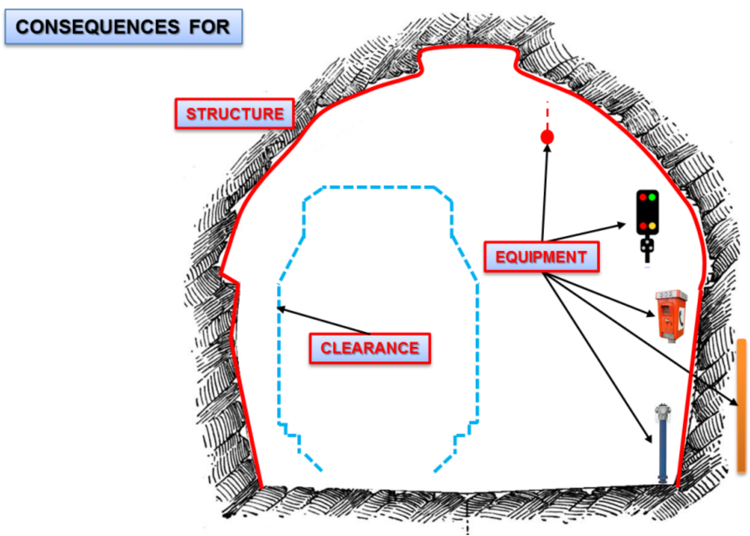

Figure 4.11: Consequences for unlined tunnels

Correlations lead to various cause – consequence series.

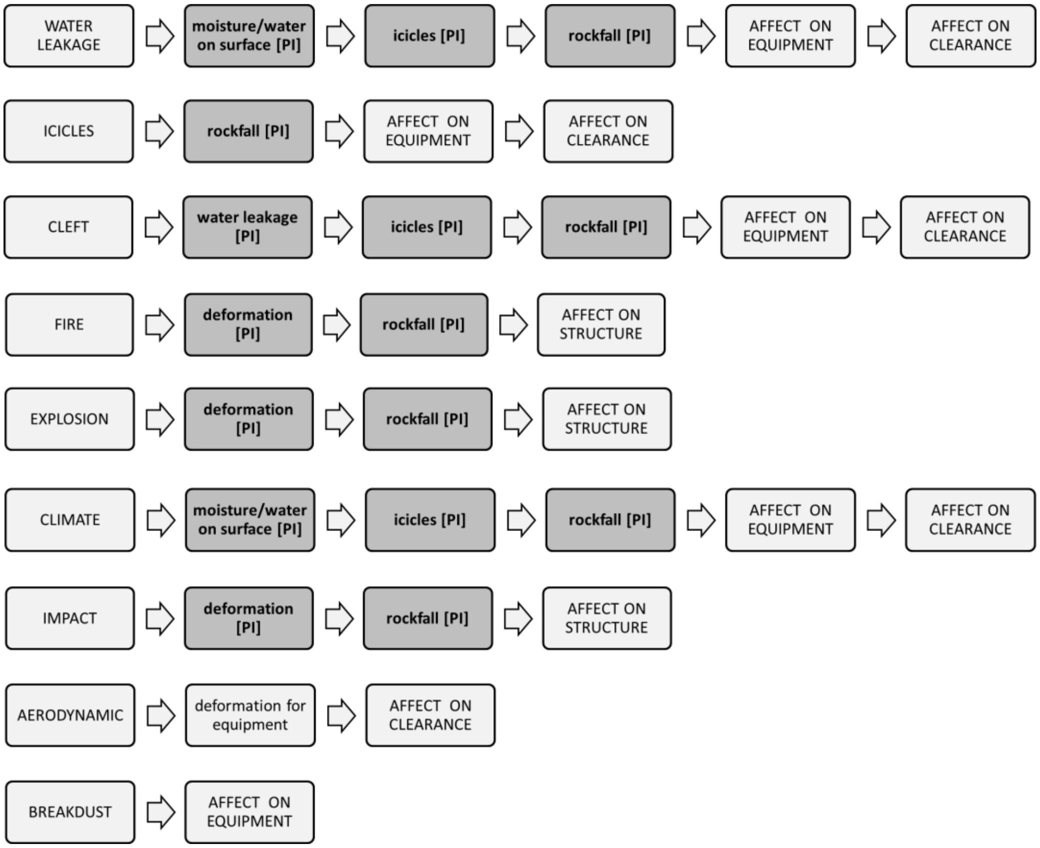

Figure 4.12: Cause/Consequence series for unlined tunnels

As a result from the focus on the complete system of causes and consequences; the following performance indicators (PI) in Table 4.4 can be defined.

Parameter type	***Measurable object***	***Threshold***	***Precision***	***Comments***
Early Indicator	*Water leak*	*0,5 m²*	*+-5 %*	
Early Indicator	*Icicles*	*Surface temperature <0˚C*		*Surface temperature*
Early Indicator	*Cleft*	*Width >1 cm*	*+-2 %*	
Early Indicator	*Rock fall*	*25 cm²*	*+-5 %*	
Early Indicator	*Climate*			*Temperature, Humidity- Additional parameter for summer and winter*
Visual deviation	*Deformation as rock movement*	*10 mm*		*Small deformation can also be early indicator.*

Table 4.4: PI for unlined tunnels

4.3.2 Strengthening of Unlined Tunnels

Unlined tunnels are often at least partially strengthened by shotcrete shell or by rock bolt anchors solely. A shotcrete shall consist of:

- Anchors;
- Reinforcement;
- Shotcrete.

Figure 4.13 shows a typical cross section through a shotcrete construction:

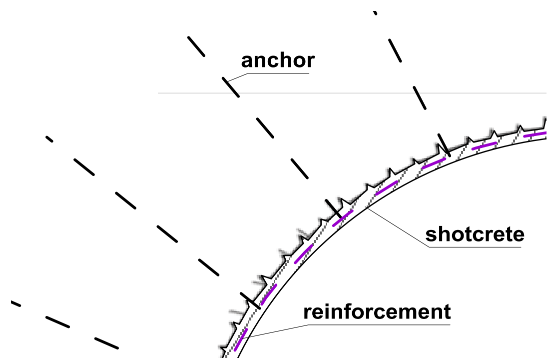

Figure 4.13: Cross section - shotcrete construction

Shotcrete is used for:

- Ensure tunnel structural integrity;
- Stabilizing the rock mass;
- Protection against rock fall;
- Protection of drainage systems.

Shotcrete may be affected from various causes shown in figure 4.14.

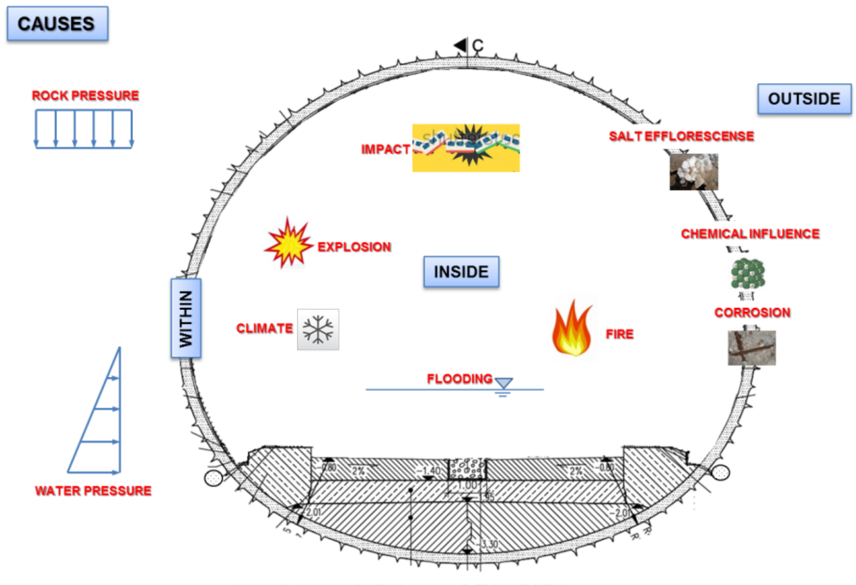

Figure 4.14: Causes on tunnel strengthening (shotcrete)

Rock anchor bolt is used to reduce weakness of the rock mass and to prevent blocks from falling out. Rock anchor bolt are mainly affected from corrosion. The various causes may be classified in accordance to Figure 4.15.

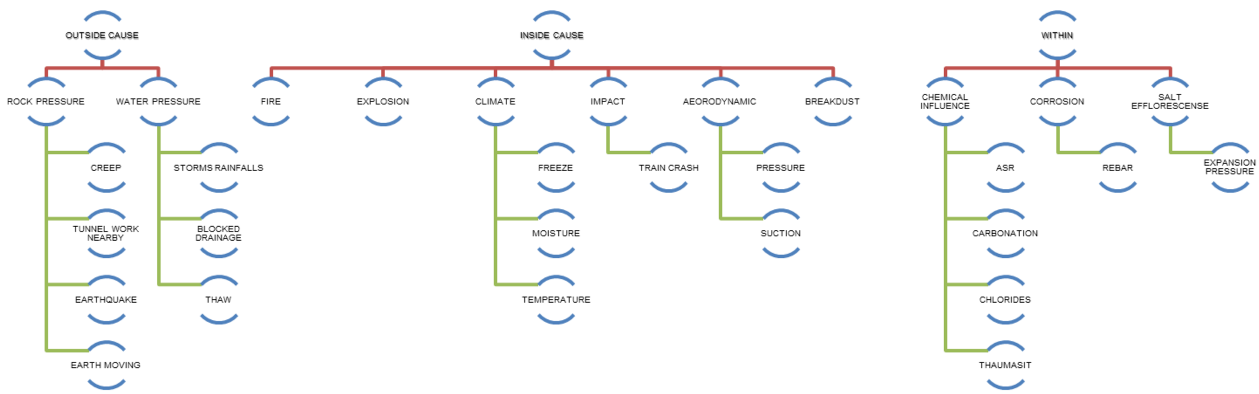

Figure 4.15: Scheme of various causes (tunnel strengthening)

Consequences from these causes may occur on the structure, equipment or clearance shown in Figure 4.16.

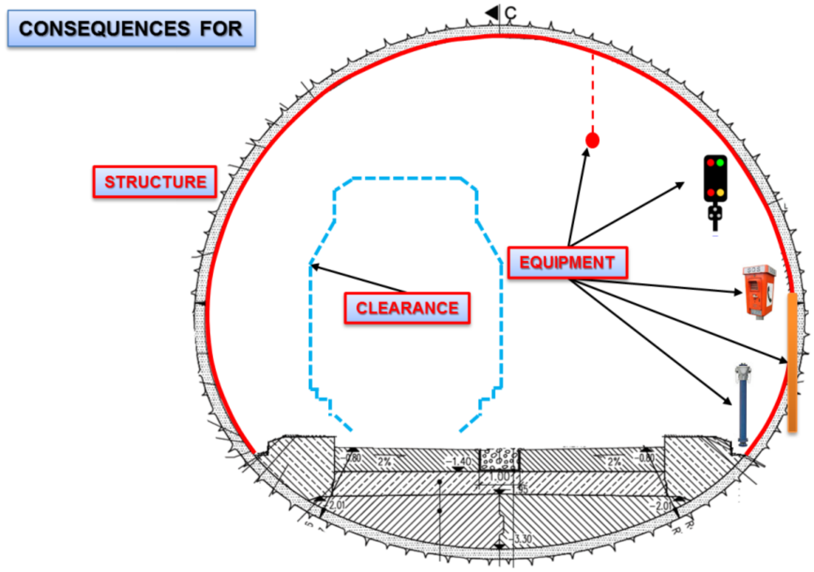

Figure 4.16: Consequences for tunnel strengthening

Correlations lead to various cause – consequence series shown in Figure 4.17.

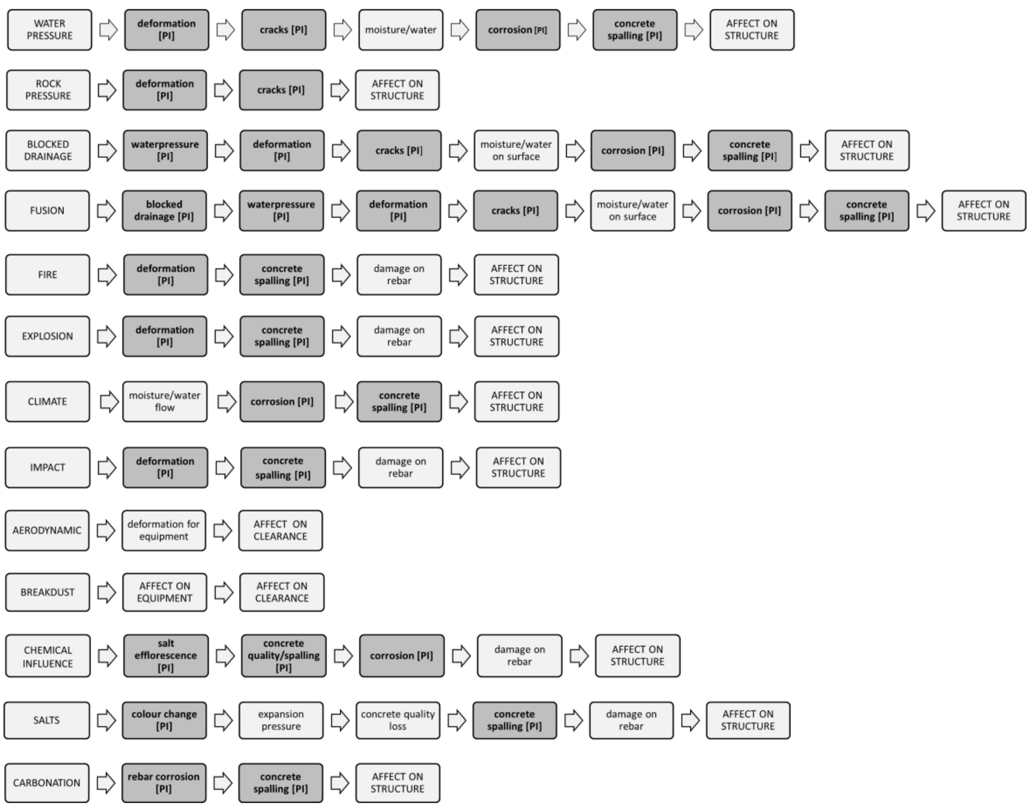

Figure 4.17: Cause/Consequence series for tunnel strengthening

As a result from the focus on the complete system of causes and consequences following performance indicators (PI) in Table 4.5 can be defined.

Parameter type	***Measurable object***	***Threshold***	***Precision***	***Comments*** *(must or nice, critical for safety, deterioration parameter,)*
Early Indicator	*Rock Pressure*	*5 % or 50 kPa*	*+-2 %*	
Early Indicator	*Water Pressure*	*5 % or 50 kPa*	*+-2 %*	
Early Indicator	*Blocked Drainage*	*90 % residual cross-section*	*+-5 %*	
Early Indicator	*Carbonation depth*	*10 mm*	*+-2 %*	
Visual damage	*Salt efflorescence*	*10 cm²*	*+-5 %*	
Visual deviation	*Rebar corrosion*	*10% loss of cross section*	*+-2 %*	
Visual deviation	*Concrete spalling*	*20 cm²*	*+-5 %*	
Visual deviation	*Deformation*	*1-2 mm*		*Small deformation can also be early indicator.*
Visual deviation	*Crack*	*0.25-0.5 mm*		
Visual deviation	*Discolouration due to chemical influence*	*10 cm²*	*+-5 %*	
Visual deviation	*Anchor bolt corrosion*	*Any Area loss*	*5 % of cross section area*	*Bolt head is less important compared by bolt itself.*

Table 4.5: PI for tunnel strengthening

5 Bridge Key Performance Indicators

5.1 General Principles

Defects on bridges can lead to reduced serviceability and in the worst cases endanger safety for the trains and the environment around the structure. Severe damage usually leads to a combination of intensified monitoring, speed restrictions or limitation of the axle load. In most severe cases, the damage can necessitate the complete interruption of the trains until the bridge is repaired temporarily or permanently. Commonly, the majority of bridge damage, is expensive to repair if not detected early. Early detection will not only give cheaper repair, it will also cause less traffic disruptions. Problems related to bridges can be tackled in different ways. One common division is to study superstructure and substructure separately. For superstructures it is feasible to further separate between structural materials.

For bridges, load bearing capacity is essential. The bridge must be able to carry dead load and loads from the trains with appropriate safety. Structural bearing component must carry the load and distribute forces to adjacent elements. The overall stiffness must meet requirements to ensure required track support. Walls and wings should not only take loads from traffic but must also a support any filling. Abutments foundation must transfer all loads to ground. Coatings must be a protection for the structural element. There are also water tight layers in order to prevent drainage and water transfer to vulnerable elements of the structure. Other solutions are also used in order to transfer water to safe places. Bridges may be affected from various causes as shown in Figure 5.1.

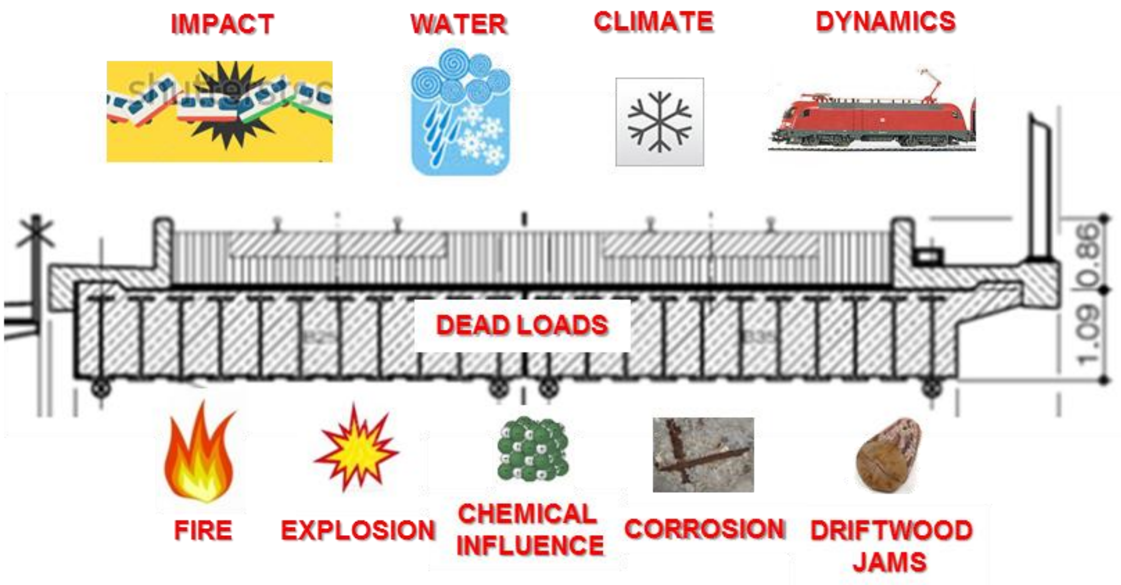

Figure 5.1: Causes on bridge constructions

5.2 Modern Steel

Modern steel bridges are made of steel that can be welded. However the full bridge can be constructed using a combination of welding and bolted joints. Various cause – consequence series have been identified and are shown in Figure 5.2.

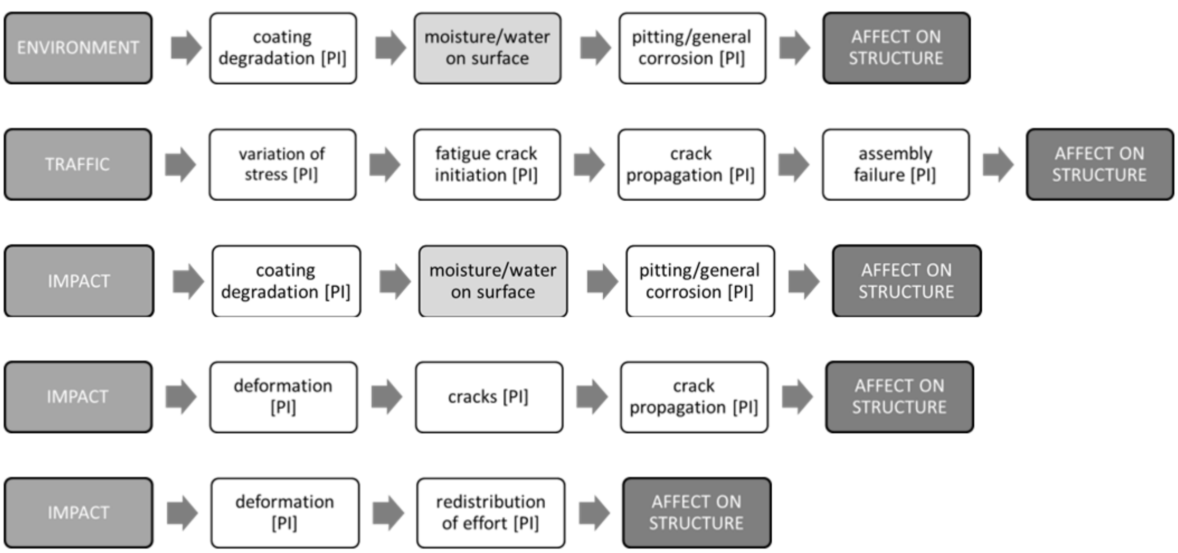

Figure 5.2: Cause and consequence chain for modern steel bridges

As a result from the focus on the complete system of causes and consequences following performance indicators (PI) in Table 5.1 can be defined.

Parameter type	***Measurable object***	***Threshold***	***Precision***	***Comments*** *(must or nice, Critical for safety, deterioration parameter,)*
Visual deviation	*Coating loss*	*10 %*	*+/- 5 %*	
Visual damage	*General or pitting corrosion*	*Presence*	*+/- 5 %*	*Evaluation according to relevant standards : ISO 4628-3, or CEPE European Rust Scale*
Visual damage	*Fatigue cracks*	*Presence*	*+/- 0.1 mm*	
Visual damage	*Cracks due to impact*	*Presence*	*+/- 1 mm*	
Visual damage	*Element deformation*	*Delta/span 1/100*	*Delta/span 1/200*	*May cause a redistribution of efforts, leading to instability phenomena*

Table 5.1: PI for Modern steel bridges

5.3 Old Metallic

Old metallic bridges are typically made of steel or other ferrous material not suitable for welding according to today's knowledge, example shown in Figure 5.3. Old metallic bridges (prior to 1960) were built mainly with riveting techniques and the use of materials with low fracture toughness. Due to the long service life, fatigue problems and corrosion are the main concern regarding this kind of structures. Cracks close to details such as stiffeners or connections being frequently identified. Flawed design and other forms of damage such as corrosion and material defects may aggravate the development of fatigue phenomena. Appropriate maintenance is essential to guarantee the security of these types of bridges, and performance indexes are needed to make inspections effective.

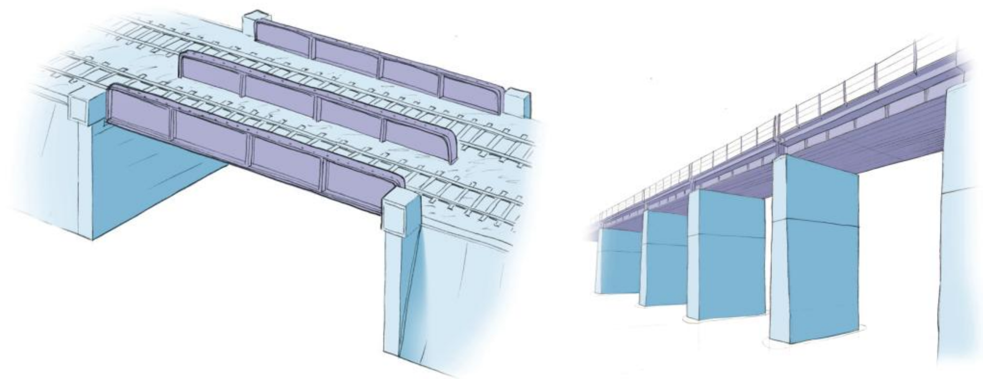

Figure 5.3: Examples of old metallic bridges

An example of structural form consists of two or more “I” girders fabricated usually from riveted wrought iron or steel plates, with a deck spanning laterally between them made from riveted cross girders and plates, metal troughs, timber decking or brick jack arches. Most were not waterproofed, but where they were, this comprised a layer of asphalt or tarmac fill. Normally comprised of the following main structural elements including those that provide the direct support to the track, and those that comprise the substructure and foundations.

These include:

- Deck: Normally comprised of metal, but may be one of the following:
  - Metal with timber e.g. decking,
  - Metal with jack arches,
  - Metal with concrete;
- Parapets or safety fences;
- Abutments or bank seats and wing walls;
- Main girders (wrought iron or early steel typically riveted).

Correlations lead to various cause – consequence series, presented in Figure 5.4.

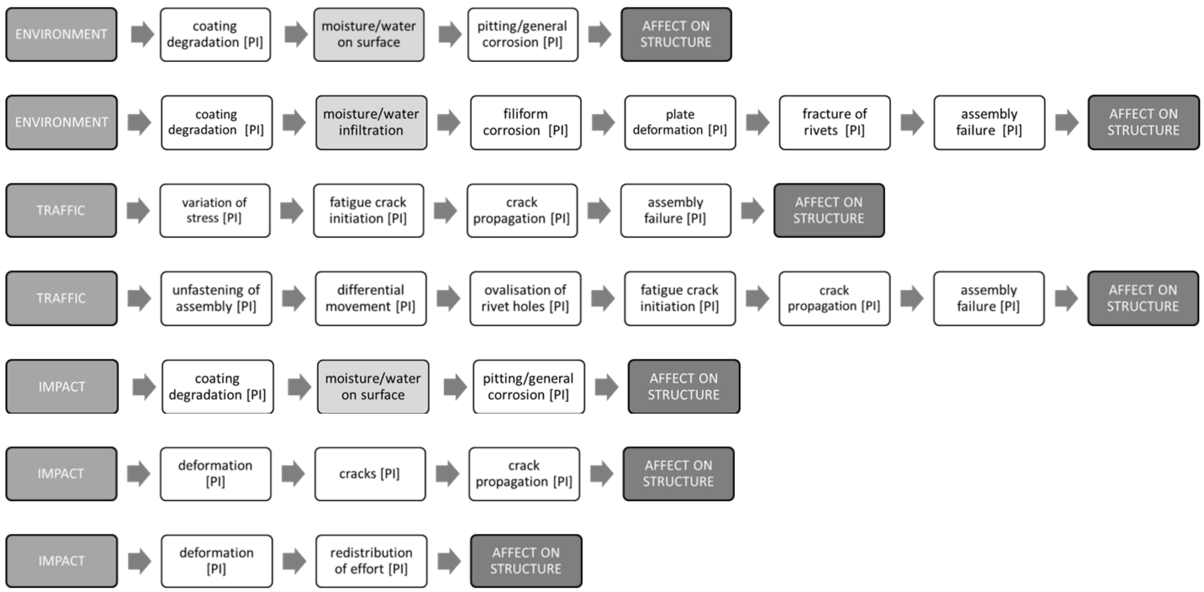

Figure 5.4: Cause and consequences for old metallic bridges

As a result from the focus on the complete system of causes and consequences following performance indicators (PI) can be defined.

Parameter type	***Measurable object***	***Threshold***	***Precision***	***Comments***
Early Indicator	*Rivet pre-stress loss*	*10 MPa*	*+/- 1 MPa*	*May lead to fatigue cracks*
Visual deviation	*Coating loss*	*10 %*	*+/- 5 %*	
Visual deviation	*Differential movement between two elements of the same assembly*	*0.1 mm*	*+/- 0.1 mm*	*May indicate an ovalisation of rivet holes, leading to fatigue cracks*
Visual damage	*General or pitting corrosion*	*Presence*	*+/- 5 %*	*Evaluation according to relevant standards :* *ISO 4628-3, or CEPE European Rust Scale*
Visual damage	*Filiform corrosion*	*Detachment 1 mm* *Length : 1 cm*	*+/- 1 mm*	
Visual damage	*Critical fatigue cracks*	*Presence*	*+/- 0,1 mm*	*The presence of cracks hidden behind an element is impossible to detect using current techniques*

Parameter type	***Measurable object***	***Threshold***	***Precision***	***Comments***
Visual damage	*Non-critical fatigue cracks*	*1 cm*	*+/- 1 mm*	
Visual damage	*Cracks due to impact*	*Presence*	*+/- 1 mm*	
Visual damage	*Element deformation*	*Delta/span 1/100*	*Delta/span 1/200*	*May cause a redistribution of efforts, leading to instability phenomena*
Visual damage	*Deformation, buckling, Fractures or tears*	*>10 mm on main members*	*-5 mm*	*Location of buckling or deformation critical.*
Visual damage	*Bolted and riveted connections*	*Any missing or corroded bolts or rivets*	*any*	
Visual damage	*Major Bridge Strike*	*Buckling of edge beams >25 mm*	*+15 mm*	*Install protection e.g bash beams, electronic warning signing.*
Early Indicator.	*Vegetation*	*Any*	*Visible*	*Vegetation growth on or obscuring structural elements.*
Visual damage	*Seized Bearings*	*<50 % of design movement.*	*-20 %*	*No measured movement, due to thermal effects, or braking / traction forces.*

Table 5.2: PI for Old metallic bridges

5.4 Reinforced Concrete

Concrete bridges normally require very little preventive maintenance. Damages from vehicles passing under the bridge are common, however not very critical. Settlements of supports are an increasing problem with increased loads also for the superstructure. Secondary parts such as handrails and ballast supports tends to call for most of the attention. Over-amounts of ballast from track adjustments are an increasing problem related to additional dead load. Alkali Silica Reaction (ASR) related problems have started to show up, however still relatively rare. Reinforcement corrosion, freeze-and-thaw scaling, and theoretical lack of fatigue capacity exists. Corrosion of reinforcement will after a period of time cause concrete cover to spall off, cause splitting of concrete and miscolour the concrete. Performance indexes for concrete bridges are shown in Table 5.3.

Parameter type	***Measurable object***	***Threshold***	***Precision***	***Comments***
Early Indicator.	*Water presence in wrong place*	*Damp areas*		*Especially when freeze-thaw cycles applies*
Early Indicator.	*Carbonation*	*10 mm depth*	*5 mm*	
Early indicator	*Fatigue loading*	*More loads than design*	*No. of cycles*	*Load cycles must be studied per component.*
Early indicator	*Chlorides*	*Elevated presence*		
Early indicator	*Stiffness change*			
Early indicator	*Reinforcement corrosion*	*Onset*		*Will be visual if continues*
Early indicator	*Poor track foundation*	*Stiffness change*		*Jump and bump will give increased DAF*
Early indicator	*Insufficient clearance under bridge*	*Any below normal*	*0.1 m*	*Will cause damage from trucks.*
Visual deviation	*Shear Crack*	*Presence*	*20 mm of length*	*Especially for fatigue critical components*
Visual deviation	*Flexural cracks*	*0,4 mm*	*0.1 mm width*	
Visual deviation	*Surface scaling*	*Any*		
Visual damage	*Deformation*	*Delta/span 1/600*	*1/100*	
Visual damage	*Irregular crack pattern*	*1 m^2*	*0.1 m^2*	*To detect Alkali Silica Reaction (ASR)*
Visual damage	*Water leakage*	*Leakage of portlandite*		

Table 5.3: PI for reinforced concrete bridges

5.5 Steel Concrete Composite

Steel-concrete composite are typically part of the newer bride stock, a typical example is shown in Figure 5.5. Uncertainties on composite action and durability of early solutions are arising. Otherwise these bridges perform and have similar problems to pure concrete or metallic bridges.

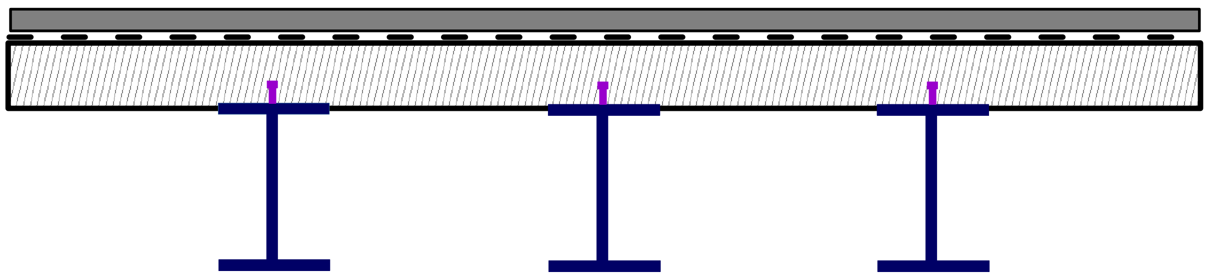

Figure 5.5: "Ordinary steel concrete composite cross section

Various causes and consequences may be classified in accordance to the scheme in Figure 5.6.

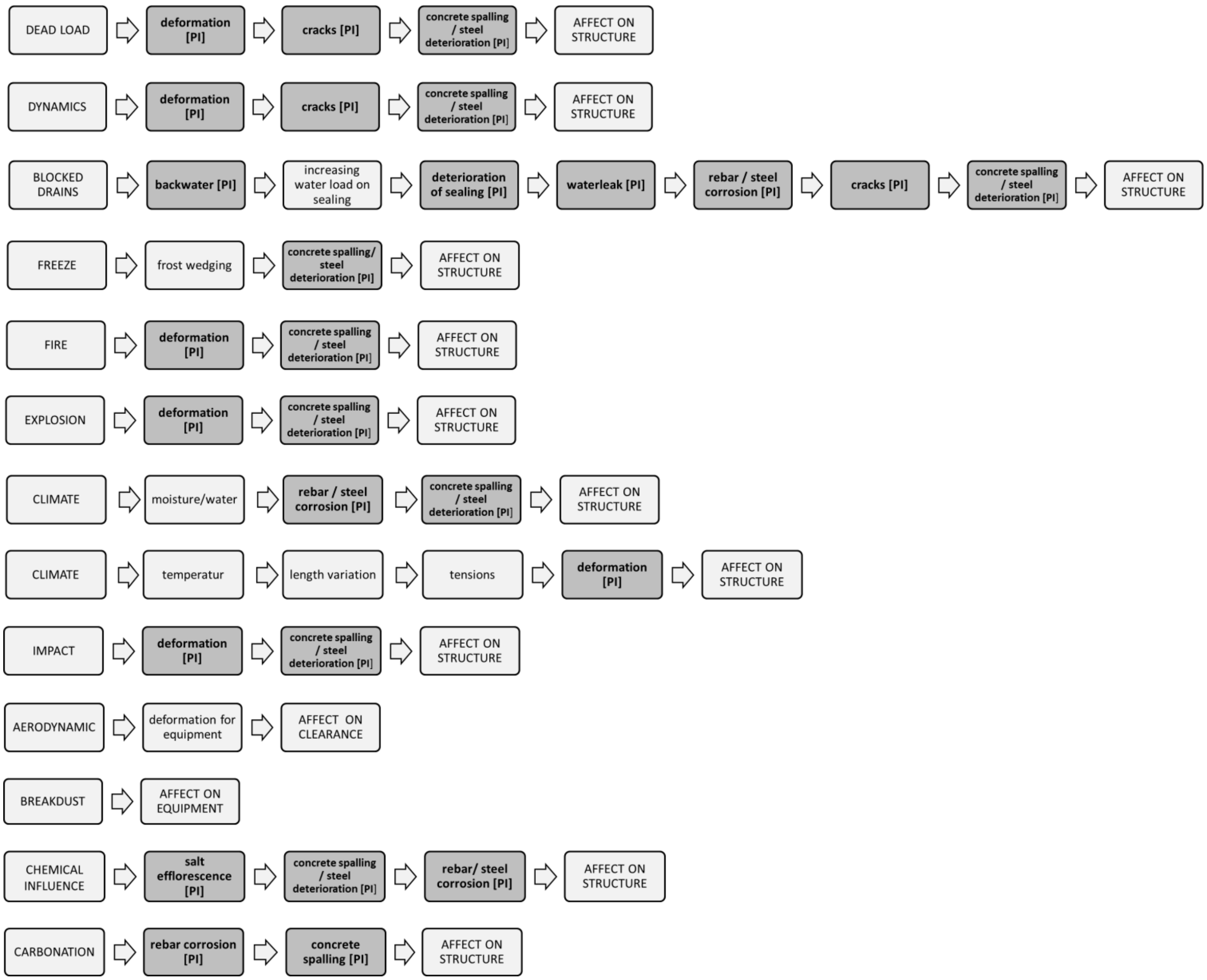

Figure 5.6: Cause/Consequence series for steel concrete composite bridges

As a result from the focus on the system of causes and consequences performance indicators (PI) in Table 5.4 can be defined.

Parameter type	***Measurable object***	***Threshold***	***Precision***	***Comments***
Early Indicator	*Blocked drains / backwater*	*40 % residual cross-section*	*+-5 %*	
Early Indicator	*Deterioration of sealing*	*0,5 cm²*		
Early Indicator	*Water leak*	*0,5 cm²*		
Early Indicator	*Carbonation depth*	*10 mm*	*+-2 %*	
Early Indicator	*Steel corrosion*	*10% of surface*		
Early indicator	*Fatigue loading*	*More than designed*		
Early indicator	*Reduced composite*	*Any*		

Parameter type	***Measurable object***	***Threshold***	***Precision***	***Comments***
	action			
Visual damage	*Concrete spalling*	*10 cm²*	*+-5 %*	
Visual damage	*Concrete cracks*	*>0,4 mm*		
Visual damage	*Salt efflorescence*	*5 cm²*	*+-2 %*	
Visual damage	*Steel corrosion*	*10 % of surface*	*+-2 %*	
Visual damage	*Rebar corrosion*	*10 % loss of cross section*	*+-2 %*	*Also early indicator before visual*
Visual deviation	*Support settlement*	*>50 % of design value settlement*	*+-20 %*	

Table 5.4: PI for steel concrete composite bridges

5.6 Post-tensioned and Pre-stressed Concrete

Pre-stressed concrete bridges modes of deterioration are not well understood currently. For this types of bridge, all inspections as for “normal concrete bridges” are mandatory, but in addition, very special attention is needed for water proofing and cracks. These bridges are far more critical than “normal concrete bridges”. Water ingress and corrosion are not necessarily a natural consequences in pre-stressed concrete bridges. A very strange phenomena is often encountered, where corroded tendons can be detected near to un-corroded tendons.

Quality of grouting around tendons is very important. A lack of grouting leads to corroded steels and tendons and good grouting system and good workmanship in this process is necessary. Any inspection methods to verify an intact grouting system is currently semi-destructive. Additional performance indexes for pre-stressed concrete are presented in Figure 5.7 and in Table 5.5.

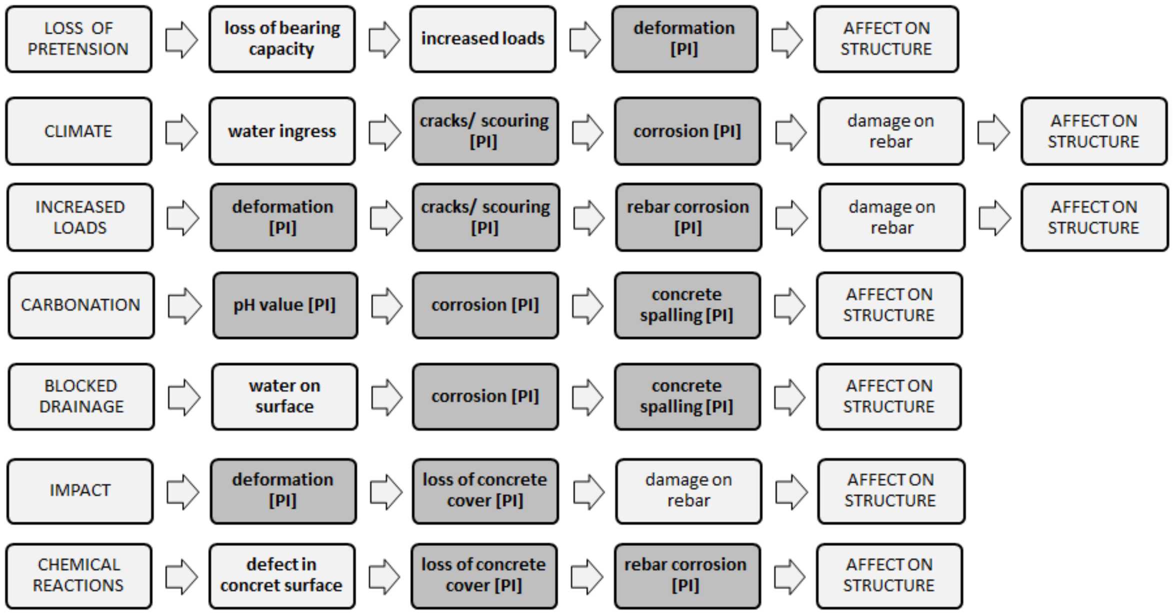

Figure 5.7: Cause/Consequence series for steel concrete composite bridges

Parameter type	***Measurable object***	***Threshold***	***Precision***	***Comments***
Early Indicator	*Carbonation of concrete*	*⩾9 pH*		*If doubts occur*
Visual deviation	*Flaking on the surface*	*25 % of concrete surface*		*Must*
Visual deviation	*Cracking in concrete*	*0.3 mm*	*+0.1 mm*	*Must*
Visual deviation	*Any corrosion of pre-stressed steel.*	*0 %*	*1 %*	*Must*
Significant deviation	*Loss of pretension*	*0.1 mm*	*+0.1 mm*	*Must*

Table 5.5: Additional PI for pre-stressed concrete

5.7 Brick and Masonry

Masonry structures are actually a combination of brick and soil interaction, examples shown in Figure 5.8. Problems are related to transversal or longitudinal cracks, losses of consolidation, block disorganisation, opening of voids and infiltrations due to the bad state of the waterproof layer. With water present, problems with scaling from freeze and thaw action arises.

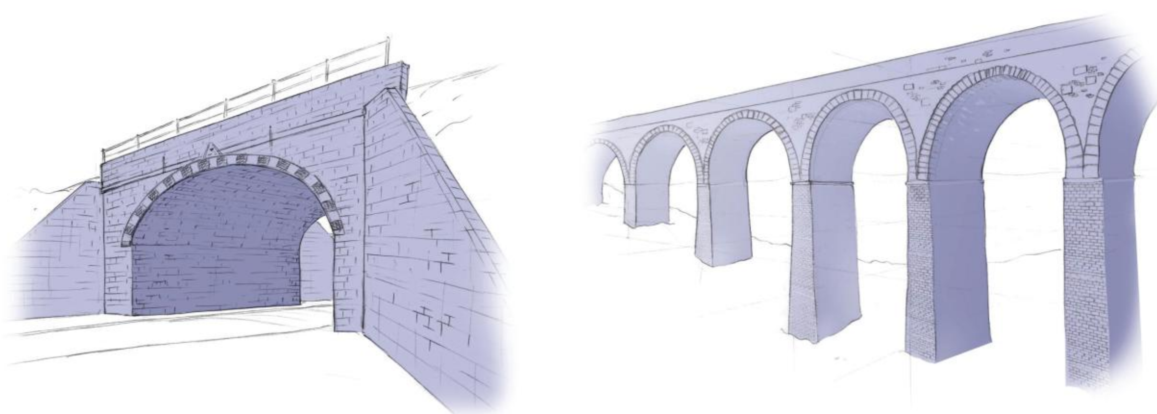

Figure 5.8: Examples of masonry bridges

The bridge type is common in some regions and quite rare in others. They are in general a very durable construction, tolerant of defects and can in general be easily repaired. Key issues include separation of spandrel walls from the arches and degradation of the masonry from vegetation, lime mortar is particularly prone to this. High skew bridges need special attention and can develop defects that are critical to the safety of the structure and need to be recognised.

The following main structural elements, including those that provide the direct support to the track and those that comprise the substructure and foundations, include:

- Arch formed from multi-ring brick arches or voussiors stone arches in a variety of shapes: parabolic or elliptical arch etc.;
- Spandrel walls support the fill and parapet walls;
- Structural backing and fill above the arches is highly variable and can be: concrete, masonry, rubble or clay. Ribs were sometimes constructed and spandrels from structures that have been widened were often buried;
- Abutments walls, piers and wing walls are usually of the same masonry as the arches;
- Stone or brick walls provide the parapets over the bridge.

Some of these can be seen in Figure 5.8. In Table 5.6 performance indicators are presented.

Parameter type	***Measurable object***	***Threshold***	***Precision***	***Comments***
Early Indicator	*Failure of waterproofing, drainage*	*>20% Consistently wet areas, moss growth*	*+10 %*	
Early Indicator	*Vegetation*	*Stem thickness > 10mm > 30% Area*	*+2 mm, +10 % Area*	*Remove, treat to prevent regrowth and standard masonry repair*
Visual deviation	*Loose masonry*	*Any*	*Any*	*Changed Load and / or Frequency or Train Impact Loading*
Visual deviation	*Cracking*	*Transverse Crack 4mm wide < 20% of Arch*	*1 mm*	*Cracks on single blocks can be ignored*
Visual damage	*Local crushing of masonry*	*Wedged/ loose/ missing bricks > 5%*	*3 %*	
Visual damage	*Loose masonry*	*Displaced or Missing - > 5% Area*	*3 %*	
Visual damage	*Cracking*	*Transverse Crack 4mm wide > 50% of Arch width*	*>4 mm*	*Location important – may indicate ring separation (Front face), bending failure (Vertical face, Transverse underside)*

Parameter type	***Measurable object***	***Threshold***	***Precision***	***Comments***
Visual damage	*Distortion or bulging of Arch*	*Bulging or distortion > 20mm over >10% area*	*+10 mm*	
Visual damage	*Cracking or displacement to parapet*	*Crack > 5mm, over > 20mm*	*+2 mm*	
Visual damage	*Cracking or crushing of masonry in obtuse corner of skew arch (BAR) and/or diagonal cracks in barrel*	*Wedged / loose / missing masonry > 10% or transverse arch crack >5mm over 10% Span/width*	*+5 %, +2 mm*	*Skew Construction - Failure of arch barrel*
Visual damage	*Spandrel Wall – Lateral displacement*	*Crack > 5mm*	*+2 mm*	*Spandrel Wall in distress*
Visual damage	*Ring Separation*	*Crack on front face, >5mm over 30% Span Drumminess > 50% Area*	*+2 mm, +10 %*	*Penetration or absorption of water*
Visual damage	*Loss of bedding mortar*	*Pointing loss >50% Area*	*+10 %*	*Penetration or absorption of water*
Visual damage	*Degradation to masonry, cracking and eroding of joints*	*Wedged / loose / missing brick >5%*	*+5 %*	*Penetration or absorption of water*
Visual damage	*Spalling of masonry, and fracturing of components*	*Spalling > 10mm deep > 50% Area*	*+10 mm, 10 %*	*Freeze / Thaw damage*
Visual damage	*Minor Bridge Strike to spandrel wall or arch ring*	*Any Debris below*	*Any*	*Urgent action required.*
Visual damage	*Major bridge strike to spandrel wall or arch ring*	*Any Missing or damaged blocks above carriageway*	*Any*	*Immediate Action required.*

Table 5.6: PI for brick and masonry bridges

5.8 Soil Steel Composites

Metallic soil interaction arches typically have problems with corrosion at water or road surface level and deformation to banana shape. PIs are presented in Table 5.7.

Parameter type	***Measurable object***	***Threshold***	***Precision***	***Comments***
Early Indicator	*Blocked drains / backwater*	*50% residual cross-section*	*+-5 %*	
Early Indicator	*Water leak*	*5cm²*		
Visual damage	*Steel corrosion*	*10% of surface*		*Almost exclusively at water surface level.*
Visual damages	*Deformation into banana shape*	*1/100 of width*	*1/200*	

Table 5.7: PI for soil steel composites

5.9 Substructures

Bridge substructures are an essential part of the bridge and are typically difficult to replace. For many bridges the superstructure has been replaced on existing substructure. Considering the substructures importance and long term use, existing inspection technology gives un-proportional attention to this bridge part. Problems for substructures often relate to poor foundation, lowered ground water table or increased loads. The deterioration is often slow, it can go on for 10 years without being noticed by current practiced methods. When damages are detected it is often too late to take any counteractions. Settlements, rotations and displacements are common problems especially in combination with increase of loads. It is expected that problems with scour and erosion may increase with more extreme weather. Older stone masonry substructures may have problems with splitting or separation of stones, and banana shaped deformation with the lowest part in the middle, hence reducing support for the superstructure in the same position. Figure 5.9 shows torsional cracks in superstructure which relates to non-uniform settlement of substructure.

Figure 5.9: Torsional cracks in superstructure from uneven substructure settlement

There can be many reasons for problems with erosion for bridges not formerly showing any of such problems. In Figure 5.10 and Figure 5.11 two examples of erosion are shown. Once started erosion progress quite fast and sometimes exponential. Without counteractions the consequences can be very severe. However, if detected in time it is normally quite easy to do repair without disturbing traffic at all.

Figure 5.10: One bridge downstream, 2 years' time difference

Figure 5.11: One bridge cone, 2 years' time difference

Parameter type	***Measurable object***	***Threshold***	***Precision***	***Comments***
Early Indicator.	*Stone movement*	*2 mm*	*1 mm*	
Early indicator	*Stone cracks*	*1 pc.*	*1 mm opening*	
Early Indicator.	*Erosion*	*10 dm^3*	*5 dm^3*	*For local erosion*
Early Indicator.	*Support settlement or rotations*	*20 mm*	*10 mm*	*For uneven settlements, for uniform larger can*
Early indicator	*Deformation of stone supports*	*2 mm/m*	*1 mm/m*	*Banana shape*

Table 5.8: PI for substructures

5.10 Specific High Speed Concerns

For high speed bridges all of the above criteria for the specific bridge type are mandatory. With high speed operating trains the track geometry becomes very important. Allowed failures or values for track quality limits become more onerous and the surveillance of high speed tracks is more frequent than on conventional lines. To ensure these track parameters, high speed bridges are often stiffer and the transition zone between embankment and bridge is an important part of the structure.

For bridge end movement due to bending in the middle of the bridge, it is important to ensure that this movement is within the allowed range of track imperfection for high speed. In combination with the embankment behind this stiffness variation need to be monitored. Additional PI regarding high speed concerns are shown in Table 5.9.

Parameter type	***Measurable object***	***Threshold***	***Precision***	***Comments***
Early Indicator	*Uneven settlements*	*2 mm*	*+/- 1 mm*	*Critical for safety*
Early Indicator	*Lateral movement*	*2 mm*	*+/- 1 mm*	*Critical for safety*
Early indicator	*Vertical acceleration*	*4* m/s^2	*0.5* m/s^2	*6 for slabtrack*
Early indicator	*Poor damping*	*Less than designed*		*Critical for durability and safety*
Early indicator	*Poor track foundation*	*Changes*		*Will affect DAF, load effect and comfort.*
Early indicator	*Track geometry*	*Changes*		

Table 5.9: Specific PI for high speed bridges

6 Conclusions

A number of performance indexes have been defined within this report that are independent of the method of measurement. Parameter thresholds and the levels of measurement precision have been established for evaluation purposes for both existing and new examination methods. This document will serve as guidance on requirements when further developing inspection methods and strategies.

The KPI parameter threshold and precision values are to be the subject of ongoing analysis and may change in future work, and are also dependant on quality and frequency of measurements.

The key performance indicators identified can be treated separately as they are relatively independent of each other. There are 14 and 31 key performance indicators for tunnels and bridges, respectively defined to detect either latent or ongoing deterioration.

This report has emphasised the importance of developing KPIs that provide early indicators of significant structural deterioration that has no visible syntoms.

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