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Guide for structural health analysis (SHA)

Gaining insight into the structural condition of a tunnel

Netherlands knowledge centre for underground construction and underground space

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Contents

1 Introduction

In the coming years, the Netherlands will face a major maintenance task in the field of infrastructure. This work is important in order to be able to continue to guarantee the reliability and availability of the infrastructural networks. Many tunnels are approaching the end of their design lifespan, which increases the chance of hindrance and malfunctions. At the moment it is still very difficult to reliably determine the actual (structural) scope of a tunnel renovation reliably. More insight is needed into the condition of the tunnel. For example, which elements still comply with the design lifespan and which elements need to be repaired or renovated? Nowadays, there is no unambiguous approach for assessing the '(structural) health' of tunnels. Inspections are being carried out and monitoring is being done, but what should the tunnel manager do with this information? What do these data say about the actual lifespan of the tunnel?

Three research projects were started within the Civil (re)construction development line of the COB tunnel programme: Identify the risks, Know your tunnel and Structural failure, a steering group with three underlying expert teams, Joints, Deformation and Degradation, see FIGURE 1.1. In addition to these projects, a structural health analysis (SHA) has been developed. This guide explains the concept of an SHA and how it can be applied to a tunnel project. The steps are based on the analysis performed by Tunnel Engineering Consultancy (TEC) for the Limfjord Tunnel in Denmark.

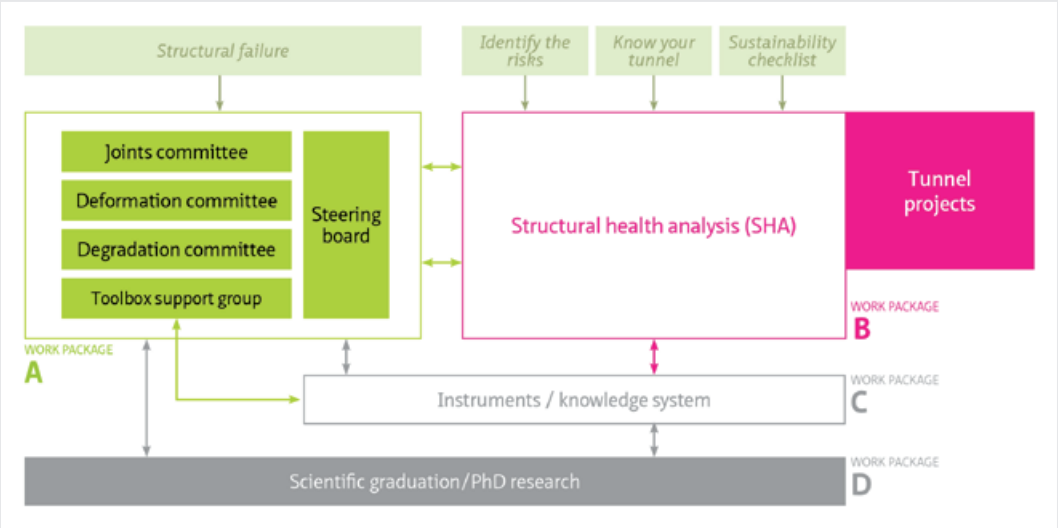


Figure 1.1 / Schematic representation of the current Civil (re)construction development line. Work package A forms the basis; these projects started already in 2018/2019. Work package B will be the main focus moving forward. The knowledge system will be developed externally as work package C. Parallel to these processes, scientific knowledge is retained through work package D. (Image: COB)

2 What is an SHA?

A structural health analysis is a process with knowledge workshops and (field) studies with which the tunnel manager gains insight into the structural condition of the tunnel and the scope for a (possible) renovation. In an SHA it is determined whether a civil engineering object still complies with the design lifespan or needs to be repaired or renovated.

Global roadmap
The SHA process starts with an inventory of available knowledge and information about the tunnel structure. All data is structured and ordered by using COB products. The information is analysed by the COB expert groups, identifying important potential risks and drawing up advice for additional research. The tunnel manager then analyses both the current and future structural status of the tunnel. Based on the results, a condition assessment is carried out and the scope for a (possible) renovation is determined. The condition assessment uses a 'traffic light model'. In case of insufficient structural health (red), repair/renovation is immediately necessary and the SHA process will be continued during the renovation phase. After the renovation has been carried out, the tunnel is 'healthy' and a health declaration can be drawn up for the tunnel.

Role of the COB network
The accuracy with which an SHA can be performed depends on the available information and the knowledge of the possible failure mechanisms. That is why each SHA is supported by the COB network with a steering group and expert teams that develop knowledge. The expert teams are available to assist the tunnel manager in interpreting the results of studies that are carried out for the SHA and the tunnel renovation. Because the steering committee includes both the chairs of the expert committees and scientists of TU Delft, this is the platform where scientific and field-oriented research can be integrated.

Platform for sustainability
In addition to the COB expert teams in the field of civil engineering, there is also the COB platform for sustainability. Here, experts in the field of sustainability come together to share knowledge and experience. A member of this platform will always participate in the SHA knowledge workshops. Renovation projects often offer good opportunities to make the tunnel more sustainable.

For more information (in Dutch): www.cob.nl/platformduurzaamheid

Instruments
For the time being, the COB wants to go through the SHA process for 22 tunnels in Europe. The method is applicable to immersed, bored, open pit or land tunnels. To record and deepen the knowledge gained, so that the SHA can be carried out with increased accuracy, instruments are also being developed. This knowledge retaining system is developed externally by TNO and Deltares. An advisory committee has been set up by the COB. This ensures that the system meets the needs of, and is of use to, tunnel managers, engineering firms and contractors.

Condition assessments
The SHA process is based on the condition assessments of the structural elements. Condition assessments point out aspects that are important when inspecting a tunnel. The criteria of the condition assessments are based on quantitative values for, for example, deformations, intensity and extent of material degradation or amount of water penetrated (leakage). If the measured value is higher than the criteria, it follows that action must be taken. This action can be repair or even replacement. A more detailed explanation per condition assessments is shown in APPENDIX B.

3 Steps

STEP 0 Introduction

Before the SHA process starts, an introduction takes place between the tunnel manager and the COB. During this meeting, the SHA roadmap is explained as well as the available COB products that can be used in (preparation for) the SHA. The COB team and the team of the tunnel manager are assembled. The COB team is specifically composed of experts frrom the various committees (Joints, Deformation and Degradation) and the platform for sustainability. The selection is based on the scope of the tunnel project and the experience of the experts.

STEP 1 Condition assessments civil engineering elements

The first step concerns the preparation by the tunnel manager. He makes all (archive) data of the tunnel available to both parties. These data concern the as-built documentation (drawings and calculations, work plans, inspection and deviation reports) and the condition assessments (material surveys performed, inspection and damage reports, monitoring data and deformation measurements). For a good overview, the missing data must also be reported. The large amount of data is organised and structured using COB products, see below. The tunnel manager can hire an engineering firm to carry out this work.

- **Manual 'Know your tunnel'**
  For tunnels, a lot of information is contained in (legally required) plans, but there is also a lot of knowledge that resides only in the heads of those involved. Such details can be bundled in a manual 'Know your tunnel' by means of this template and directions. The aim is not to give a complete, exhaustive overview of all the available data but to draw attention to some specifics.
  www.cob.nl/knowyourtunnel

- **Checklist Identify the risks**
  The risk checklist presents damage patterns that may arise in the tunnel. The publication indicates what may be the cause of these damages, what consequences may occur and how further inspection can take place. The checklist can be used in the SHA process to determine the research to be carried out and to determine the scope of the renovation.
  www.cob.nl/identifytherisks

- **Interfaces TTI-civil engineering**
  During the construction or renovation of a tunnel, it is important that the design of structural elements and tunnel technical installations are coordinated. This checklist provides an overview of important interfaces between these two disciplines.
  www.cob.nl/identifytherisks

- **Sustainable tunnel checklist**
  The sustainability checklist helps the tunnel manager to identify the opportunities to make the tunnel more sustainable as part of the SHA process. As the the questions are about very specific subjects, the checklist immediately offers practical tools.
  www.cob.nl/sustainabletunnelchecklist

For further explanation of these products, please see the action plan for the civil engineering development line of the tunnel programme.
www.cob.nl/english

The tunnel manager's team, with the support of the chairman of the COB expert team, compiles an information package of all the collected data. This information package consists of a set of characteristic drawings and a summary of the condition assessments, to provide a global picture of the condition of the tunnel structure.

Each committee/project group receives the information package, after which a meeting is scheduled to analyse the data. The main potential risks and advice for additional required research follow from this session. All comments are bundled per drawing by the secretary of the COB expert team.

STEP 2 Knowledge workshop A - Understanding risks

Step 2 includes the first knowledge workshop, possibly split into several sessions. In the workshop, the commented drawings are used as a starting point. The aim is to gain a first insight into the risks for the tunnel structure. The experts from the COB team inform the tunnel manager and his team about the possible risks and knowledge gaps that require further investigation. In this way, interaction is obtained between the COB expert team and the tunnel manager's team.

The result of the workshop is a 'shopping list' for the tunnel manager with the necessary inspections, monitoring, investigations and further information sources. To reduce knowledge gaps, it may be desirable to conduct more or more detailed research than is strictly necessary in the context of the renovation. It will be discussed with the tunnel manager how this research can be applied.

STEP 3 Research

In step 3, the tunnel manager starts with an assessment of the condition of the tunnel structure based on the 'shopping list'. The tunnel manager may approach market parties to carry out the analyses, required inspections and monitoring. The tunnel manager will determine which analyses and investigations will be carried out in this step and which will be performed after the possible renovation contract has been awarded.

On the one hand, the current condition of the tunnel structure is analysed. This includes checking each condition assessment against the design and/or as-built information. This could include comparing the deformations that have occurred to the calculated deformations in the design. If the structural condition of the tunnel meets the assessment criteria set, this phase is completed. In the event of deviating results or unknown causes of damage, additional research can be carried out as input for a further analysis.

On the other hand, the future state of the tunnel structure is being examined. For this, a prediction is made of the behaviour of the tunnel structure in the near future. In case of identified structural damage, deformations and/or leaks, the course of the degradation or increase in deformation and/or leakage over time are considered. If the tunnel's structural condition meets the assessment criteria set, this analysis has been completed. In the event of deviating results or unknown causes of damage, additional research can be carried out as input for a further analysis.

If a certain aspect of the tunnel is still assessed as 'critical' (for current or future situation) after additional research, an appropriate measure is given priority. This measure can be temporary or permanent, depending on the availability and severity of the assessment to maintain structural safety. The choice of measure also depends on the preference of the tunnel manager and contractor.

During this phase, the manual Know your tunnel will be supplemented with the results of the inspections, investigations, monitoring and analyses. If applicable, research is conducted in this phase by PhD students or PDEngs as part of the knowledge process.

STEP 4 Knowledge workshop B - Interpretation and analysis

The second knowledge workshop takes place when the results of the analyses and studies carried out in step 3 are known. The COB expert teams will receive and analyse the results before the workshop. During the workshop the possible bottlenecks and knowledge gaps in the (renovation) task are determined together with the tunnel manager's team. The knowledge gaps are transferred to the COB committees.

STEP 5 Knowledge retention

In step 5, the COB expert team, together with the tunnel manager's team, draws up a report of the knowledge and information collected so far in order to guarantee a level playing field for the tender. Based on the information in that report, the tunnel manager carries out a condition assessment of the tunnel structure and determines the scope for the renovation. The condition assessment uses a 'traffic light model':

- Green, no actions required. The structural health of the tunnel is sufficient for both the current and the future situation.
- Orange, expect maintenance in X years. The structural health of the tunnel is sufficient for the current situation. Problems may arise in the future. It is therefore important to continue monitoring the tunnel structure in order to anticipate risks.
- Red, intervene. The structural health of the tunnel is insufficient and repair/renovation is 'immediately' necessary. In this scenario, the SHA continues with steps 6-9.

The COB also ensures the transfer of knowledge/data to the instruments.

STEP 6 Tender

If a 'red light' was detected in step 5, the tunnel manager puts the tunnel renovation tender on the market in step 6; the COB expert team withdraws. The client makes clear in the tender that the project is (also) a knowledge process.

STEP 7 Knowledge workshop C - Kick-off renovation

After the renovation project has been awarded, the third knowledge workshop will take place. Prior to this workshop, the chosen party carried out (own) additional research. Possible differences in the results are discussed in the knowledge workshop. The aim of this step is to reveal knowledge gaps and to include the contractor in the knowledge process. Any additional work such as inspections and monitoring is also coordinated.

STEP 8 Knowledge workshop D - Midterm update

Halfway through the renovation, for example when one of the tunnel tubes is ready, a knowledge workshop is organised to retrieve experiences and information, share knowledge between the client, contractor and the COB expert team and interpret results. What do we see, what does this mean for the execution of the second half (of the renovation and/or the SHA process) and what input can already be included in the instruments?

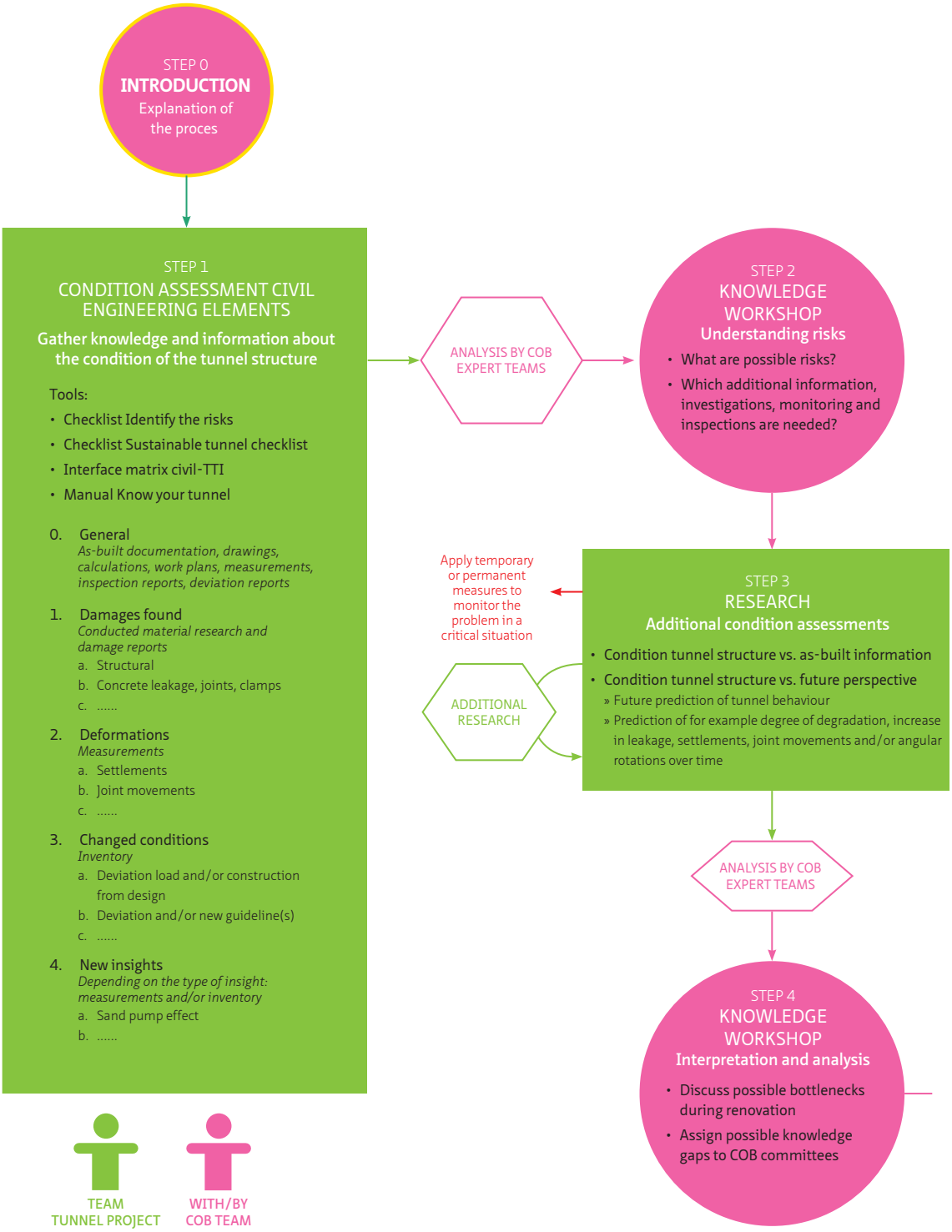
STEP 9 Knowledge workshop E - Evaluation and completion

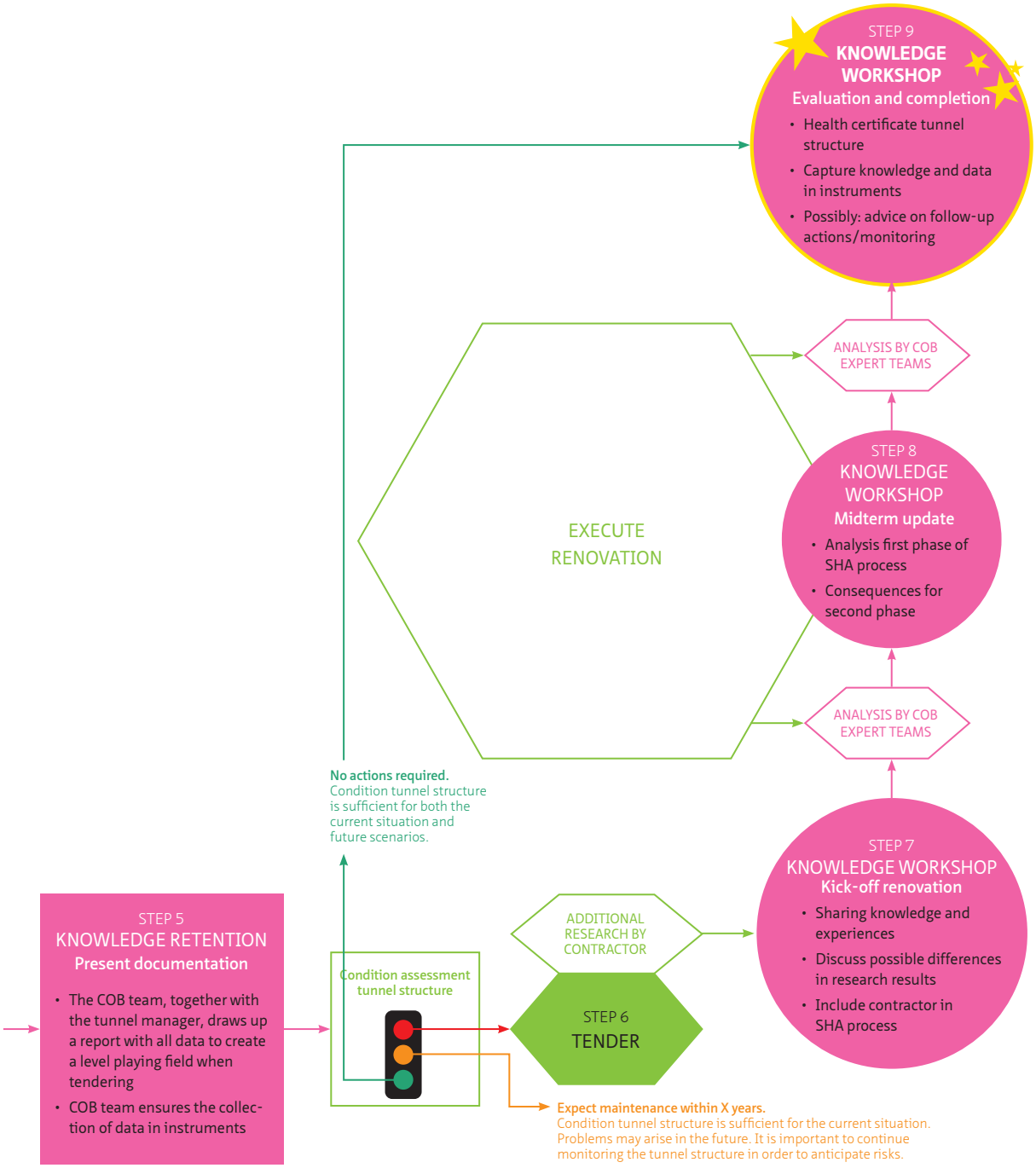
After completion of the work, the knowledge process is concluded with an evaluation. The tunnel manager has a 'health declaration' of his tunnel, advice for a monitoring strategy and a new version of his Know your tunnel manual. The newly acquired knowledge is also incorporated in the instruments.

Figure 3.1 / First knowledge workshop on July 1st, 2020 for the Drechttunnel. (Photos: COB)

Appendix A SHA roadmap

A large version of this scheme can be downloaded from www.cob.nl/sha.




STEP 9
KNOWLEDGE WORKSHOP
Evaluation and completion
• Health certificate tunnel structure
• Capture knowledge and data in instruments
• Possibly: advice on follow-up actions/monitoring
ANALYSIS BY COB EXPERT TEAMS
STEP 8
KNOWLEDGE WORKSHOP
Midterm update
• Analysis first phase of SHA process
• Consequences for second phase
EXECUTE RENOVATION
ANALYSIS BY COB EXPERT TEAMS
No actions required.
Condition tunnel structure is sufficient for both the current situation and future scenarios.
STEP 7
KNOWLEDGE WORKSHOP
Kick-off renovation
• Sharing knowledge and experiences
• Discuss possible differences in research results
• Include contractor in SHA process
ADDITIONAL RESEARCH BY CONTRACTOR
STEP 5
KNOWLEDGE RETENTION
Present documentation
• The COB team, together with the tunnel manager, draws up a report with all data to create a level playing field when tendering
• COB team ensures the collection of data in instruments
Condition assessment tunnel structure
STEP 6
TENDER
Expect maintenance within X years.
Condition tunnel structure is sufficient for the current situation. Problems may arise in the future. It is important to continue monitoring the tunnel structure in order to anticipate risks.

Appendix B Condition assessments SHA

Condition assessments of the structural elements of the tunnel form the basis of a structural health analysis (SHA). There are five parts:

Condition assessment (0) General
This assessment focuses on the 'general' tunnel information as stated in the original design and as-built information (including calculations, drawings, work plans, measurements and inspection reports). This information includes the story of the tunnel, the object description and the construction method.

Condition assessment (1) Damages found
In this assessment, any damage to the tunnel structure is registered. It is possible that damage is observed during inspections/material studies for which a cause cannot be immediately identified. There are a number of types of damage that are known to occur sporadically in immersion tunnels, namely:

- Structural damage, such as with dowels or tooth breakage in immersion tunnels.
- Leaks in the concrete construction, due to the inaccurate sealing of the connections.
- Leaks in the rubber joint profiles, for example due to chemical reactions.
- Leaks at the clamp connections due to incorrect securing of the connection.

Condition assessment (2) Deformations
In this assessment, the deformations of the tunnel structure that have occurred are registered by means of monitoring and measurements. Two known situations concern the joint movements and the subsidence of the tunnel construction. Joint movements can possibly lead to cracks in the joint profiles or connecting structures with leakage as a result. Subsidence of the tunnel construction can result in leaks or structural instability.

Condition assessment (3) Changed conditions
In this assessment, the changed conditions of the tunnel structure compared to the final design are inventoried. For example, these can be deviations in the load on the tunnel, deviations in the implementation and changes in legislation and regulations. In the latter case, this means that the applicable laws and regulations during the design phase of the tunnel are outdated compared to current laws and regulations.

Condition assessment (4) New insights
Since the construction of the first tunnel, many developments have taken place in the field of tunnel design and construction. There is a chance that these insights have not been included in the design of the tunnel in question, which means that this tunnel does not meet the current assessment criteria. An example of this is the sand pump effect in immersion joints. Depending on the type of insight, measurements and/or studies are required.

Colophon

Publisher
Netherlands knowledge centre for underground construction and underground space (COB).

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Publication date
Juni 29th 2020

Cover photo
Tunnel elements of the Drechttunnel are transported from the construction dock at Barendrecht.
(Photo: image bank RWS/Li Tan)

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This publication can be downloaded free of charge at www.cob.nl/kennisbank.

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