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ABSTRACT: Determining the scope of (structural) renovation of aging tunnels is a complicated task and modular renovation is becoming increasingly necessary. The COB Tunnel Programme aims at developing the knowledge necessary to renovate these tunnels in a modular fashion, to reduce hindrance as much as possible. Part of this program is the development of a Structural Health Analysis (SHA) for collecting data on the condition of the civil structure of tunnels, which will give tunnel owners insight in the need for research on structural parts of the tunnel, refurbishment and the risks for the tunnel performance in the future. As a lot of knowledge will be gathered and generated, structurally securing of this knowledge is also necessary. To meet this need, the tunnel program also started development of a knowledge management system. This paper describes the aims of the knowledge management system in relation to the overall tunnel program, as well as the tools and methods devised to gather all necessary information for tunnels constructed several decades ago, where not all required information is readily available in digital form, or even in paper archives.

KEYWORDS: Immersed tunnels, Renovation, Maintenance and Operation, Knowledge Management, Structural Health Assessment

1. INTRODUCTION

At least twenty road and rail tunnels are scheduled to be renovated in the Netherlands in the next ten years. Many of these tunnels have been constructed in the '60-ies and '70-ies as immersed tunnels and have passed half their expected life span. Determining the scope of (structural) renovation of these tunnels is a complicated task and, as long-term full closure of the tunnels would lead to severe hindrance for society, modular renovation is becoming increasingly necessary.

The COB Tunnel Programme aims at developing the knowledge necessary to renovate the tunnels in a modular fashion, both in space and time, to reduce hindrance as much as possible. An overview of knowledge gaps has been detailed and a research strategy outlined, in developing the Tunnel Programme.

Part of this program is the development of a Structural Health Analysis (SHA) for collecting data on the condition of the civil structure of tunnels. This SHA is a new method that will give tunnel owners insight in the need for research on structural parts of the tunnel, the need for refurbishments and the risks for the tunnel's performance in the future. This SHA will help to realize predictive maintenance of the tunnels in the Netherlands.

Because a lot of knowledge will be generated in the future, structurally securing of this knowledge is also necessary. To meet this need, the Tunnel Programme started development of a knowledge management system. This paper describes the aims of the knowledge management system in relation to the overall Tunnel Programme, as well as the tools and methods devised to gather all necessary information for tunnels constructed several decades ago, where not all required information is readily available in digital form, or even in paper archives.

2. STRUCTURAL HEALTH ASSESSMENT PROCESS

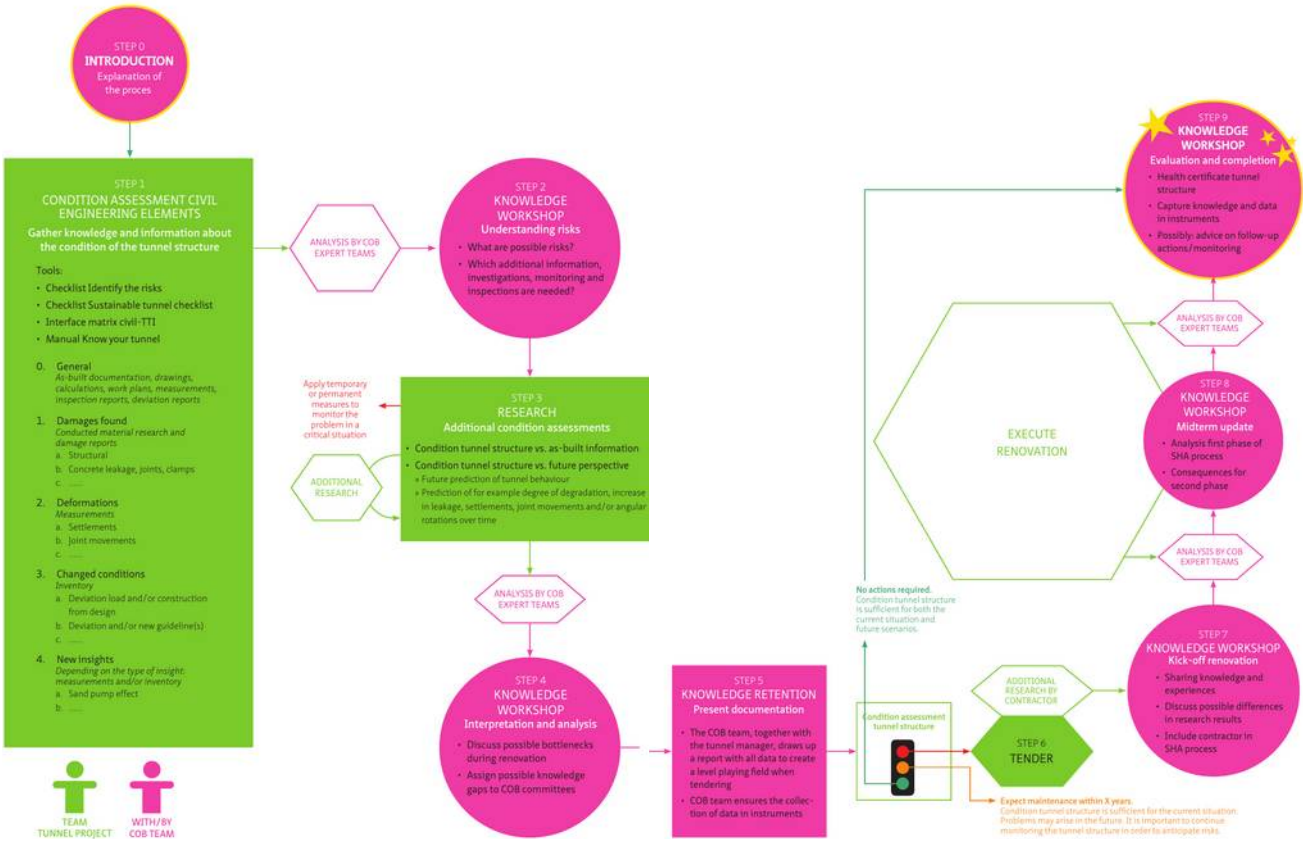
In general in an SHA it is determined whether a civil engineering object still complies with the design lifespan or needs to be repaired or renovated. To this end, information about the original and current state of the object is needed, and often extensive inspections will be needed to gather the required data. At the start, it may not always be clear exactly what information may be needed or available, and which experts should be consulted or involved to most efficiently fulfil the process.

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? With this in mind, the structural health analysis process as organized by COB is a collaborative 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 (de Wit et al., 2020).

The SHA process starts with an inventory of available knowledge and information about the tunnel structure. This is primarily a task for the tunnel manager. The safety management plan and its underlying plans, the 'as built' dossier and technical construction dossier are storehouses of information for road tunnels. The tunnel safety management plan defines the processes of operating the tunnel, and the roles and responsibilities of all stakeholders and is required the by (Dutch) law on road tunnel safety to be approved and implemented before the tunnel can be put in operation. Therefore, at least this information will be available. However, a lot of information is often not specifically set down and thus exists only as implicit as opposed to explicit knowledge. This is often the case for specific starting points, design decisions, matters relating to how the work is performed, operational aspects, interesting facts, occurrences, etc. In addition, it is not always obvious where, or in which documents, specific information can be found and which people are involved (now or in the past).

The checklist 'Know your tunnel' developed by COB provides a structured template of aspects to consider when compiling all available data (Bras et al., 2020.) In addition a risks checklist has been developed that presents common damage patterns that may arise in the tunnel, and indicates what may be the cause of these damages, what consequences may occur and how further inspection can take place (Kirstein et al., 2020). This checklist also provides an overview of important interfaces between the design of structural elements and tunnel technical installations, as during the construction or renovation of a tunnel it is important that the interfaces between these two disciplines are continuously coordinated. Finally, although not strictly necessary for an SHA inventory, a sustainability checklist is available to help the tunnel manager to identify the opportunities to make the tunnel more sustainable as part of the SHA process (Gijzel et al., 2020).

Incidentally, these checklists also highlight the (probably obvious) fact that significant differences exist between different types (or families) of tunnels, depending on construction methods used and ground conditions encountered, and that the aspects or renovation methods that are for instance most relevant for renovation of bored tunnels in rock such as repair methods ensuring the water-tightness of the lining (see ITA WG6, 2001) can be less relevant or applicable



to for instance immersed tunnels,whereas aspects like fire safety are more generically applicable.

Using these tools and checklists, the tunnel manager's team, if so desired supported by an expert from the COB Committee on Structural Aspects of Tunnels, 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.

Once this initial information package is available, an expert team is convened by COB to analyse the data. This expert team will remain involved for the following steps of the SHA process and consists of members of the various standing committees on structural aspects of tunnels, tunnel joints, deformations, degradation and sustainability, where necessary complemented by experts on other aspects. In one or more workshops they will identify the main potential risks and formulate advice for additional required research. For the aspects where a standing COB committee is present (e.g. tunnel joints, deformation, degradation, digitalization, sustainability, tunnel technical installations), this will be preceded by meetings of the full committees where all committee members will study the information package, identify the issues the see as relevant and provide the member taking part in the workshops with their input.

In this way all relevant aspects and input from all parties involved in the committees is taken into account. Subsequently, the workshops result in an overview for the tunnel manager of the necessary inspections, monitoring, investigations and further required information sources. To reduce knowledge gaps that are possibly more generic than a single tunnel renovation project, also detailed additional research goals can be specified and discussed with the tunnel manager to see how this research can be applied.

Once this overview is available, the tunnel manager starts with the actual assessment of the condition of the tunnel structure. He can involve external parties for this as desired and is always in charge to determine the scope of the analyses and investigations, and can always determine which part will be carried prior to the renovation contract negotiations with potential contractors and which part will only be performed after the potential 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.

Once this condition assessment is finished, the expert team reconvenes to analyse he results and assess if any new knowledge gaps have surfaced. Similar expert sessions are also organized just prior to the actual start of renovation, approximately midway through the renovation process and finally once after at the renovation has been completed to collect all experiences and make sure that future projects can take advantage of any new insights developed by the tunnel manager and project teams. The entire process is visualized in Figure 1.

One aspect to highlight is the perceived impact on market conditions and the potential to impact tender qualifications. As the initial information package is shared with all standing committee members in the preparation process, and all market parties can (and mostly do) take part in these committees, there is no perceived information advantage for committee members at this stage. Moreover, the information package and all results of the workshops become part of the overall tender documents to further ensure that all market parties have equal access to the relevant information during a tender stage. To date this process has functioned well for both publicly (state) owned as well as privately owned tunnels, although it has been noted early on that clearly outlining the SHA process and the fact that the SHA process and workshops are to be part of the contract between client and contractor, and that therefore there will be a required information exchange from contractor to the expert team, in the tender documents will help to reduce issues during subsequent contract negotiations.

3. KNOWLEDGE MANAGEMENT

From the first step of the SHA process onwards a significant amount of data is compiled by the tunnel manager and the expert team. This data needs to be stored, structured and ordered in such a way that it is easily retrievable during the entire SHA process as well as the following renovation process. Numerous platforms of course exist to store information in a wide set of data formats, and the data obtained during an SHA can include written reports, recent drawings in digital format as well as old paper drawings (scanned at varying quality or even available as paper only) as well as snippets of information obtained from interviews and other sources. Structuring the data for a single SHA is already a significant task.

When considering the entire renovation challenge of over 20 tunnels of somewhat similar type and construction date, it is evident that there will be issues common to different tunnels, and a platform that allows for a structured storage as well as search and retrieval across multiple renovation projects would allow the expert teams to extract more knowledge on common issues and identify research needs.

Additionally, to enable condition-based or in the longer run even risk-based asset management strategies to be employed, there is a need for an integration of information from inspections, monitoring and testing of the tunnels. More specifically, data gathered from inspections, monitoring and testing will be used to assess the condition of the structure, which is then processed with the models to obtain the actual safety levels and the risk levels of the structure and to predict the future development of safety and risks. As a basis, this require data retaining structures that can hold the data gathered from different sources and in vastly different formats, and make this data accessible in a straightforward and consistent manner, such that the information that is encapsulated in the data sets can be extracted.

In short, there is a need for information and knowledge management systems for all tunnel related data for firstly the immediate SHA process, secondly for optimizing the combined task of all upcoming renovation projects, and thirdly for the longer term goal of optimizing the asset management processes and strategies. Such a system should capture and safeguard not only reports, drawing and measurement data, but also knowledge and past experiences, and make all tunnel-related knowledge continuously accumulated over time available in a flexible, adaptable, user-friendly and future-robust way.

A start has been made with the development of such a knowledge retaining system. This system takes the form of a semantic wiki-based platform that brings together

1: available information on existing monitoring systems and their applicability for tunnels, based on which a monitoring design template can be developed that assists in setting the appropriate monitoring strategy needed to facilitate proactive maintenance, considering the a-priori available information on the tunnel condition;

2: a knowledge retaining system that provides a framework for organizing the information and knowledge on the past and current state of tunnels, where a shared semantic basis for storing and retrieving existing data in a uniform manner is being developed, as well as advanced tools and methodologies for extracting more information from existing and new tunnel data, which in turn could be used to develop the long-term asset management strategies or feed a predictive twin;

3: a data platform to process and retaining high-frequency monitoring data of tunnel, which will be needed for the development and validation of data-enhanced modelling strategies.

Central to this system is the development of a list of well-defined knowledge attributes such as tunnel as management object, building elements components, risks, loads, damage types, degradation mechanisms, measures, inspection techniques etc., that can be used by the experts to determine and agree on what is to be known per attribute and what data and information is to be obtained. Establishing these attributes in a systemic manner will also allow to define relations among knowledge attributes and between their properties, and will allow to capture the semantic relationships between concepts with their properties and make it possible for computer-aided searches to be made over the entire data sets, where these combine written reports, drawings as well as trends observed in monitoring data.

4. CONCLUSION

The oncoming large number of tunnel renovation projects in the Netherlands requires a structured process to assess the current and future structural integrity of the tunnels. An SHA process has been developed by COB to assist the tunnel manager in this task prior to the start of the actual renovation. The accuracy with which an SHA can be performed depends on the available information and the knowledge of possible failure mechanisms. That is why each SHA should be supported by a network of experts, and COB provides a cornerstone for this process by establishing a steering group and a number of expert teams that hold the specialized knowledge to efficiently assess the wide range of aspects involved in tunnel construction and renovation. These 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.

As these SHA processes will gather a large amount fo information, a stable and user-friendly information management system is needed for easy retrieval of all knowledge on the tunnel during the SHA and renovation. If this information is made available and accessible across multiple tunnel projects, it will also serve as a platform that allows experts to identify common issues between tunnels and identify the existing research needs more clearly. Given the wide range of formats that the data on tunnels comes in, a flexible, robust, and user-friendly platform is needed that allows easy cross-referencing between diverse data sources. Such a system is currently in development by COB in the form of a semantic wiki-based knowledge management system.

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