

Managing knowledge for future-proof tunnels in the Netherlands

K. de Haas

COB, Netherlands Knowledge Centre for Underground Space and Underground Construction, Delft, the Netherlands

W. Broere Ph.D. MSc

Delft University of Technology, Delft, the Netherlands

H. Dekker MSc

Rijkswaterstaat, Ministry of Infrastructure and Water Management, Den Haag, the Netherlands

L. van Gelder BSc

Soltegro, Capelle aan den IJssel, the Netherlands

ABSTRACT: The COB is the Netherlands Knowledge Centre for Underground Construction and Underground Space. Over sixty organisations, from government, industry and knowledge institutes, work together to learn and develop smart solutions regarding tunnels. This network has developed a long-term vision on tunnels in the Netherlands. As a result, nineteen tunnels and all stakeholders collaborate on eight research topics of our tunnel programme. We found common ground and the key issues are already being addressed in both practice and science. Topics include risks, construction failure, modular renovation, digital tunnel twin, virtual testing, virtual education and system safety. The way clients, science and industry work together within the COB network has been a major precondition to achieve these great results in such a short period of time.

1 INTRODUCTION

In December 2016 COB, the Netherlands Knowledge Centre for Underground Construction and Underground Space, published a long-term vision on tunnels in the Netherlands (COB, 2016). In 2017, two key tasks were distilled from this vision document: how to create additional value for society and how to reduce disruptions, during normal operation, in emergency situations, as well as during maintenance and renovation works. In 2018, the COB network drafted four development lines in a tunnel programme (COB, 2017a) from these key tasks: civil construction and renovation, the digital tunnel twin, tunnels and their value for their surroundings and adaptive installations. The first two development lines have already resulted in detailed work plans for 2018 to 2021. The detailing of the other two development lines will start in 2019.



Figure 1. The COB has created an online overview of Dutch tunnels. It shows that twenty-eight tunnel projects (green = new, orange = renovation) have been scheduled for the upcoming ten years.

This paper deals with the two development lines already prepared, each of which is divided into several projects. It includes a summary of the detailed projects, goals and deliverables for the coming years.

2 DEVELOPMENT LINE 1: DIFFERENT CIVIL CONSTRUCTION AND RENOVATION

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 1960s and 1970s as immersed tunnels and half their expected life-span has now passed (Bijl, 2011). Determining the scope of (civil) renovation of these tunnels is a complicated task and, as a long-term full closure of the tunnels would lead to severe public disruptions, modular renovation is becoming increasingly necessary. Changes in the scope of renovation works after contracts have been awarded, or tunnel failures due to unexpected and unscheduled maintenance during operation are undesirable for all parties.

Because of the high traffic intensities in the densely populated Netherlands and the limited available budgets, renovating tunnels is a far-reaching process with many administrative-political considerations. The complete closure of tunnels for a longer period is usually not possible because of the essential function of tunnels in the Dutch road network. Very careful planning of smart (innovative) renovations has therefore become essential.

This development line focuses on four goals:

1. Being able to better determine the complete civil scope of tunnel renovations.
2. Being able to apply predictable special and extensive maintenance works, integrated as part of the regular management and maintenance systems of tunnels.
3. Reduce the (social) nuisance (public disruption) by reducing the amount of time required for (major) maintenance and renovation with associated reduced availability of the tunnel to traffic
4. Reduce the occurrence of major renovation works by addressing 1, 2 and 3. Eventually eighty per cent of the (civil) maintenance of tunnels will have to take place as part of regular maintenance cycles. We thus achieve one of the main objectives of the tunnel programme, which is less disruption due to higher availability to end users and predictability of maintenance and availability.

These four goals have been translated into four projects:

1. Identify the risks (contributes to all goals).
2. Identify and reduce knowledge gaps regarding structural failure (contributes to all goals).
3. Modular renovation, blueprint and assessment framework (contributes to goals 3 and 4).
4. 'Know your tunnel', framework for a handbook and manual for a specific tunnel (contributes to all goals).

2.1 *Project 1: Identify the risks*

Regular inspections and preparatory research prior to a tender for renovation, are not always sufficiently substantive to really identify all the detailed aspects of the tunnel construction and its current state. After being awarded the job, the contractor usually carries out additional research, followed by a discussion about scope extensions or, in the worst case, changes to the schedule.

2.1.1 *Project goal and deliverables*

In this project, we want to conduct at least twenty interviews based on an extensive questionnaire to identify what experiences have been gained (and are being gained) in scheduled, ongoing and completed renovation projects. We also want to make use of the lessons learned from the new Rijkswaterstaat inspection programme. All this information will result in a risk checklist for tunnel renovation, management and maintenance. This checklist should become an im-

portant tool for (long-term) programming, scope assessment of renovations and planning of regular large and small maintenance works.

This risk checklist must include:

- A. The most common risks
- B. The associated failure mechanisms.
- C. The associated inspection techniques, with a distinction between effectiveness, impact on the availability, level of predictability, and amount of damage to tunnel integrity.

It is expected that this stocktaking will identify several risks for which we do not yet know the failure mechanisms and for which there are no inspection techniques yet. These knowledge gaps will be passed on to the second COB project: 'Structural failure'.

2.2 *Project 2: Structural failure*

The frequent unexpected and unscheduled reduced availability of bridges, locks and tunnels in recent years has shown that we still have gaps in our knowledge regarding (residual) lifespan, failure mechanisms and the effectiveness of control measures. For too long it has been thought that civil structures are hardly subject to ageing. More and more often, we are confronted with joint problems due to leakages, subsidence and rotations of tunnel elements and even failure of components such as tension piles, reinforcement bars and fire resistance plating. It cannot be ruled out that other unexpected failures may occur in the future.

This project will provide more fundamental knowledge of structural failure mechanisms so that unexpected failures can be kept to the absolute minimum. Determining the true lifespan of civil structures is the most fundamental knowledge goal for this project. Determining the true-life-span and the rate of ageing of structures is an issue faced by many projects worldwide, and a lot of research is being conducted in this field all around the world. We will incorporate the most recent research results when they become available.

This project foresees an approach in which the contribution of tunnel project managers and technical staff, academia and industry experts is integrated by one central steering committee on a permanent basis, like a spider in the web, below which, for the time being, three subcommittees are set up.

In addition to coordinating and connecting activities to ensure coherence in the different COB projects, the steering committee will work on a 'structural health report' and 'structural health monitoring' as tools for predictable maintenance. These instruments are used to answer questions such as: if a tunnel is subject to subsidence, how will the tunnel react, and do we need to take measures inside or outside the tunnel, or do we possibly need to apply soil improvement techniques below the tunnel?

Other knowledge gaps already identified are related to immersion joints, omega profiles, tension piles, permanent on-line monitoring systems, new monitoring techniques using sensors, inspection techniques and determining the residual lifespan of tunnels and their components.

2.2.1 *Three subcommittees*

1. Joints

The objective of this committee is to understand the failure mechanisms of a specific civil part of tunnels: the immersion joints that provide the primary flood defence in immersed tunnels. The committee put together an expert team that advises ongoing tunnel projects and other stakeholders on the inspections, control measures, and so on. that need to be carried out. Based on questions arising from the Eerste Coentunnel renovation project, this work was continued with the Heinenoordtunnel and the Kiltunnel. The experience already gained has been translated into knowledge and experience in guidelines.

After a detailed analysis of the problems associated with immersion joints, the committee has now entered the next stage. The committee's most important activities will include:

- A. Advise Rijkswaterstaat, as the national road and tunnel operator, as well as the owner of the private Kiltunnel on the scope of the studies for renovation of the Eerste Heinenoordtunnel and the Kiltunnel and critically assess the results after implementation.

These two tunnels are quite similar in construction details, geological conditions and age, and are expected to face quite similar challenges during renovation.

- B. Retain knowledge and making it available to future renovation projects. As an example, the results of endoscopic investigations into immersion joints, to obtain a detailed assessment of the current state of the joints, rubber seals and bolts, will be made public through the COB knowledge bank, as will the action plans for the Heinenoordtunnel and the Kiltunnel renovations.
- C. Investigate possible problems of all types of joints, not only immersion joints but also closure joints between concrete sections and dilation joints. This comment will be the centre of knowledge regarding joint investigation and renovation in immersed tunnels.

2. Deformation of tunnels

A second important issue that governs the overall behaviour of the civil structure is the deformation of tunnels. How do the structure and the soil below it behave, what are the associated failure mechanisms and which control measures are required and effective? At the Kiltunnel project, the Delft University of Technology together with the University of Zagreb experimented with a MASW soil scan that, in combination with a 3D model of the tunnel itself and including time dependent soil behaviour, should result in a better prediction of the tunnel behaviour over time. This MASW scan will be repeated at the Heinenoordtunnel and combined with deformation measurements obtained using optical distributed strain measurements (Broere, 2018).

This subcommittee will, just like the subcommittee on joints, carry out the supervision and interpretation of applied research projects (first the Kiltunnel and later the Eerste Heinenoordtunnel and other tunnels) and make the results generally applicable. The results of this subcommittee will be translated via the steering committee into PhD research at universities, applied in practical projects throughout the tunnel programme, and published as knowledge products in the COB knowledge bank.

3. Degradation of materials and components in tunnels

The problem of the degradation of concrete and the corrosion of reinforcement is a major issue in older tunnels. This can lead to reduced strength and leakages in tunnels, as well as damage to the integrity of the structure. There are currently also questions regarding escape doors, fire-resistant materials and fire compartmentalisation in, for example, the Piet Heintunnel.

The renovation of the Maastunnel offers an opportunity to gather more fundamental knowledge about degradation processes through monitoring. Rotterdam has indicated its willingness to allow the Delft University of Technology and COB to set up and carry out monitoring during the renovation of the second tube and use the results for scientific and practical use. The results of this subcommittee will also be translated via the steering committee into PhD research at universities, applied in practical projects through the tunnel programme, and published as knowledge products in the COB knowledge bank.

2.3 *Project 3: Modular renovation*

Choosing the right scenario for renovation works and making sure that the chosen scenario is feasible, is a major challenge for tunnel owners and renovation teams on both the client and contractor side. That is why it is wise to combine knowledge, instruments and experiences to develop a framework and blueprint for modular renovation of tunnels. The COB distinguishes three types of modularity:

1. The definition of a 'module'. What do we mean, what kind of modules can we identify? Can we find a shared language?
2. The 'time' module (weeks, weekends, nights): can the module be implemented in terms of work within this time unit?

3. The 'building blocks' module (both for the civil and installation technology): can we install a building block and are we able to open the tunnel again (technically operational and with the permission of the competent authority) within the chosen time frame?
4. The 'construction management' module: are we able to conduct the building logistics activities (supply of materials, numbers of people in the tunnel, etc.)?

2.3.1 *Deliverables*

Based on expertise from the COB network and input from completed, current and upcoming renovation projects, we want to arrive at an assessment framework and a description of scenarios with all the pros and cons. This project also aims to contribute to the design and implementation of better maintainable tunnel modules in new-build projects so that, after the catch-up effort with the existing tunnels, we can then carry out eighty per cent of the renovation task during regular maintenance.

2.4 *Project 4: 'Know your tunnel' handbook*

If we do not know exactly how our tunnel was constructed, which materials and components were used and what their current state is, we will not know how to identify the critical parts, nor what we must inspect, where we must adjust the parameters and how to interpret the results. We will not know what and how we need to record during the operating phase either, while this is important for the period thereafter. We see substantial differences in knowledge regarding their tunnels among the various tunnel managers and owners. The correct as-built information is not always available, there is no shared approach for developing a proper scope and taking a 'baseline measurement' at the start of the renovation (what are we going to monitor, inspect and/or look up?).

In collaboration with several tunnel owners with extensive experience of this process (Maastunnel, Kiltunnel, tunnels in The Hague) and with experts in completing new tunnels, the COB wants to produce a 'Know your tunnel' handbook. This can be used as a framework and form the inspiration for all tunnel owners and managers for regular management and maintenance, as well as a source document for preparatory teams for the start of a renovation and the completion file.

2.4.1 *Deliverables*

1. Creating a table of contents (TOC) for a handbook.
2. Translating the TOC into specific texts, references, and so forth for the tunnel managers involved until they can complete their own 'Know your tunnel' handbook.
3. As a result of 1 and 2, producing a recommendation for other tunnel managers on how to make their own tunnel handbook.

3 DEVELOPMENT LINE 2: DIGITAL TUNNEL TWIN

In recent years digital modelling has become much more important in tunnel projects. Building Information Modelling (BIM) is now common practice in both renovation projects and in new construction projects for tunnels. The development of digital modelling, gaming, VR, IoT, etc. requires a different approach, not only during the test phase, but especially during the design phase (model-driven design). Each tunnel project uses a combination of these tools and has its own digital strategy to build and renovate faster, smarter, with less disruption, and to open tunnels faster. This development has its own problems as all innovations relate to challenges such as filling gaps in our knowledge, reducing the time between project phases, managing discrepancies in the requirements of the various stakeholders and resolving gaps in the system. To a large extent, the market and clients can solve this individually, but there are issues for which a joint approach is needed, questions that you want to answer outside projects and challenges that require more time than an individual project allows for. That is why the COB sees it as its task to help, stimulate, exhibit, inform and streamline criticism in this process, especially since all stakeholders agree that the digitisation of every aspect of tunnels has enormous potential.

3.1.1 What is a digital tunnel twin?

The digital tunnel twin is not a thing, but a very effective tool for designing, building, commissioning, managing, renovating and adapting physical tunnels: better, faster, with fewer breakdowns and added value. The digital tunnel twin is used and developed in all phases of tunnel projects and adds value in every phase and for each stakeholder. The digital tunnel twin includes all developments in the field of virtualisation/visualisation, operating interface, modelling, simulation, testing, gaming and information provision for the tunnel system.

The first steps towards a digital tunnel twin were made by moving from a paper-based to an electronic completion file. Visualisation in 3D-BIM as part of the digital tunnel twin has already become indispensable (and in the future this will be expanded to 6D-BIM). Within the next five years the digital tunnel twin will offer even more functionality: functional and system models will be added to improve virtual testing and allowing emergency services to train and practice in virtual and/or augmented reality.

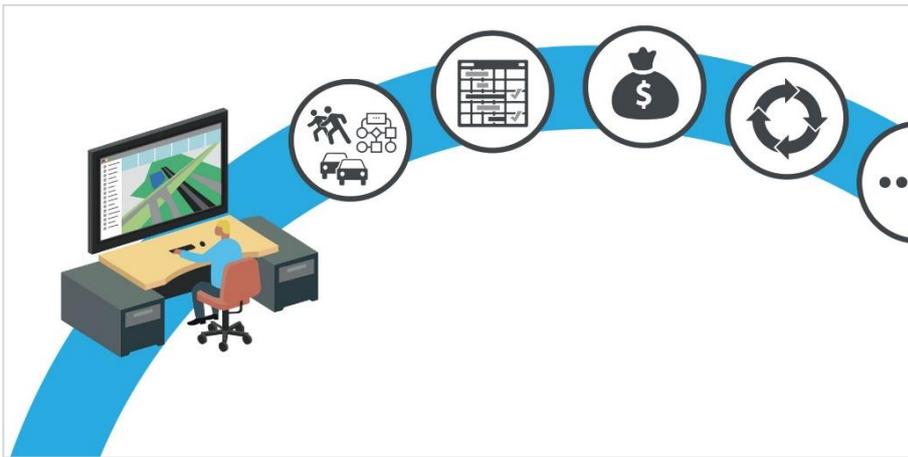


Figure 2. Digital tunnel twin is an 3D-BIM model with more functionality.

3.1.2 COB's role

The COB's role is to boost, facilitate and present information and not to develop, design or set frameworks. It aims to answer questions such as:

1. What is the significance of a digital tunnel twin in the tendering and design phases of projects?
2. How can virtual testing help to limit public disruption?
3. How can a digital twin help with the opening permit, competent authorities and emergency services?
4. How can a digital twin help keep availability as high as possible through smarter maintenance during the operational phase?
5. Which digital twin concepts are used per project and asset life phase?
6. In which phase does each concept of the digital twin originate?
7. What standards, guidelines and best practices are there for each concept of the digital twin?
8. How can a digital twin contribute to education, training and practice?

The COB has initiated four projects to support the development of the digital tunnel twin:

- Project 1: Opening tunnels without problems using the digital tunnel twin.
- Project 2: Opening tunnels faster with the help of virtual testing.
- Project 3: Virtual education, training and practice.
- Project 4: From paper-based to fully digital.

3.2 Project 1: Opening tunnels without problems using the digital tunnel twin

We want to increase the probability of problem-free opening of both new construction and renovation projects by disseminating knowledge about and making the best use of sufficiently ma-

ture digital and virtual tools: the digital tunnel twin. This project also wants to contribute to organising the dialogue about and support for (elements of) the digital tunnel twin with important stakeholders such as competent authorities, emergency services and managers.

3.2.1 *Explanation*

Opening a tunnel without problems is mainly about finding support among stakeholders such as competent authorities, being able to coordinate with all stakeholders and testing and checking (validating and verifying) long before the tunnel is operational. It is key that stakeholders must be able to trust that the digital twin corresponds to the physical tunnel to be build.

A digital tunnel twin makes it possible to test the requirements, design and operational scenarios before starting the construction or renovation of the tunnel. It is not envisioned to demonstrate (verify) the performance requirements, such as required air and water flows, overpressure, lighting levels, keeping the safe areas free of smoke, and so on. Nor can it be used to test whether all systems are installed properly. Physical testing will therefore always play a role; virtual and physical testing continue to exist side by side.

Actual meaning for a problem-free opening:

- Using a digital tunnel twin, the (operating) processes and system behaviour of tunnels can be made transparent and suitable for coordination in the early stages of a project. Tunnel managers, road traffic controllers and tunnel operators can be involved early in the process, which makes it possible to include their feedback in the final design phase. Competent authorities, safety officers and emergency services are offered insight into (tunnel) processes and can respond to and anticipate them. Feedback and early involvement would ideally lead to acceleration in the acceptance/testing of the operation. It is possible to simulate the system model and compare it with models of other projects or with a reference model. This allows for the testing of the quality and completeness and makes an important contribution to the verification, validation and acceptance even before installation work takes place at the project site.
- The use of a digital tunnel reduces testing at the project location. The on-site work has been reduced to assembly, commissioning and verification of performance requirements. The validation of processes and system behaviour takes place at an earlier stage. The regular alignment with the competent authorities, emergency services, tunnel managers and safety officers can also take place early on.
- Automated testing programmes will identify non-conformal system behaviour and human errors, especially if these programmes are enriched with experiences from previous projects, thus increasing overall quality.
- By adding gaming functionality, it becomes possible to test and tighten scenarios, and to educate, train and practice without the tunnel being physically available (and not just during the opening). It also has a positive effect on incident handling, as emergency services familiarise themselves with the specific characteristics of the tunnel and can practice their responses (in a virtual environment) before the tunnel is built and throughout the entire lifespan of the tunnel. If there is enough confidence in the simulation, the opening permit may be issued faster.

3.2.2 *Manual*

As a first deliverable, the COB will produce a manual including materials and support that will help tunnel projects understand:

1. the definition of 'hassle' for the most important stakeholders (the thirteen most important stakeholders are: competent authority and safety region, safety officers, tunnel managers, directive bodies such as LTR and Building Decree, client's internal services, traffic controllers, road managers, technical managers, client's project organisation, contractor's project organisation, parent companies and subcontractors/suppliers);
2. what stakeholders' needs are, in order not to encounter, experience or cause any hassle;
3. the available tools and systems from the digital tunnel twin that can reduce or even prevent this hassle;
4. the digital tools already used at projects;

5. how these or other elements of the digital tunnel twin can improve the process towards problem-free opening (which processes and tools are available, mature and of added value?).

This will also allow for the sharing of knowledge among the six new construction projects.

3.3 *Project 2: Opening tunnels faster with the help of virtual testing*

We want tunnels to be opened faster by making the best possible use of virtual testing. The basis for this is the 2017 exploratory study 'Shortening tunnel closures through virtual testing', which lists the possibilities and preconditions (COB, 2017b).

3.3.1 *Objectives*

This project's objectives include:

1. Formulating unambiguous expectations, definitions and a common 'framework' by the experts in the field (both clients and contractors): what exactly do we mean by virtual testing, how far are we, what do we do and when?
2. Formulating the right preconditions by all stakeholders, in particular the competent authorities.
3. Starting and facilitating a dialogue and building trust with important stakeholders such as competent authorities.
4. Supporting practical projects in thinking about, forming a vision on and presenting the possibilities of virtual testing.

We will look at the possibility of advancing virtual testing in a step-by-step approach. Each of the tunnel projects virtually tests a small element and uses this as proof that it can and does work. By involving as many clients as possible, each project will make a (small) contribution on the technical roadmap and this will benefit all parties.

3.3.2 *COB's role*

Frontrunner group

Almost all (construction and renovation) projects use virtual testing to some extent, but there is not yet a consensus on how we understand virtual testing. Do we have the same point of view? What issues do we encounter? When and how will virtual testing be acceptable for authorities? We will set up a frontrunner group with key people from clients and contractors to discuss issues such as the demarcation of virtual testing, what resources are required, how to describe a virtual model and what tools it needs, standardising test results, how to incorporate it in a digital tunnel twin, include it in contracts, and so forth. The deliverable of the group will be a written recommendation for using virtual testing in tunnel projects.

Competent authority group

Competent authorities must, in addition to their own role as independent evaluators of their tunnels, also come to understand virtual testing and the systems and working methods involved. By jointly organising this process, we can find out what they need to accept virtual testing as real testing. We can also work together to identify and remove any uncertainties. We can do this by including the group of competent authorities in the technical roadmap for the practical projects, where they can observe the process and discuss issues together with us, etc. This way we hope to garner their support. Here the deliverable will be a written recommendation of virtual testing for competent authorities.

3.4 *Project 3: Virtual education, training and practice*

Keeping everyone up-to-date and 'properly trained' for all possible scenarios is a sheer impossible task. That is why we want to encourage the use of digital tools to further the development of virtual education, training and practice based on the experiences, opinions and ideas of stakeholders (such as tunnel managers, operators, emergency services, competent authorities, security officers, etc.) and help them in formulating their vision and making strategic choices. This will

result in written recommendations for virtual education, training and practice for tunnel managers and other stakeholders.

3.5 Project 4: From paper-based to fully digital

Several tunnel owners and especially tunnel operators tell us that investing in and managing a complex digital tunnel twin does not suit the size and low complexity of their tunnel. Nevertheless, they do realise that digitisation, (big) data, IoT, sustainability objectives, and so on. can also have a very positive effect on their tunnel management and maintenance. What could be the first small but meaningful step for tunnel managers to benefit from the digital tunnel twin? And what preconditions allow tunnel managers to use the digital output produced by builders during the renovation/construction of tunnels?

3.5.1 Tunnel managers group

A group of tunnel managers will look at several issues, including predictable maintenance and, BIM-xD. The group will identify work on these and similar issues being done by clients and look at ways of how to gain access to the results of this work and share any knowledge and experiences. This is expected to lead to a report entitled: 'First exploration: From analogue to digital – the tunnel manager's perspective'.

3.5.2 Involving market parties

At a later stage we will invite market parties (and other stakeholders) to enter into a dialogue about the preconditions that tunnel managers want to set for the output from renovation/construction. We thus want to build a bridge between the (digital) information that is available from the construction or renovation of a tunnel and the needs of the asset manager and other relevant stakeholders. This is expected to result in a 'Recommendation for using the digital tunnel twin from a management perspective'.

4 CONCLUSION

The COB developed its tunnel programme for the Netherlands to add value and reduce disruptions. It was envisioned that at least three actual tunnel projects had to benefit from the COB's activities and that the resulting practical benefits are translated into precompetitive knowledge for all parties in the Dutch tunnel industry. This will be achieved through the active involvement of all current new construction and renovation projects, major clients and market parties.



Figure 3. During the COB congress in June 2018 more than 300 network members joined the 'class of 2018' to start learning in the tunnel programme. (Photo by Vincent Basler).

The COB tunnel programme is currently being implemented with the active participation of more than thirty tunnel projects and tunnel owners, who together with almost sixty market par-

ties and various knowledge institutes such as TNO and the Delft University of Technology manage the projects in the programme.

The development of a long-term vision on tunnels has resulted in a joint scope on what are considered important issues to solve. The challenges are too big and too complex for just one party and we therefore need each other. Moreover, the initial results of the tunnel programme show that collaboration pays off and brings about momentum to tackle other issues.

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