RESEARCH PROGRAMME

Future proof tunnels

Supporting maintenance and renovation decisions by tunnel owners

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Abstract

The overarching goal of this research programme is to provide tunnel owners with a set of tools to allow them to make rational and cost-effective decisions related to maintenance and renovation of the structural parts and safety systems. Advances in sensor technologies, IoT and data analytics offer unique opportunities to make tunnels intelligent, allowing them to provide real-time updates on the condition and (resulting) performance of components and the safety of the system. In order to apply these techniques, we must understand the mechanisms controlling the reliability, availability and safety level of our tunnels and implement technologies to gather all relevant data to allow optimal maintenance planning. Application is foreseen in both the assessment and renovation of existing tunnels as well as in the construction of new tunnels.

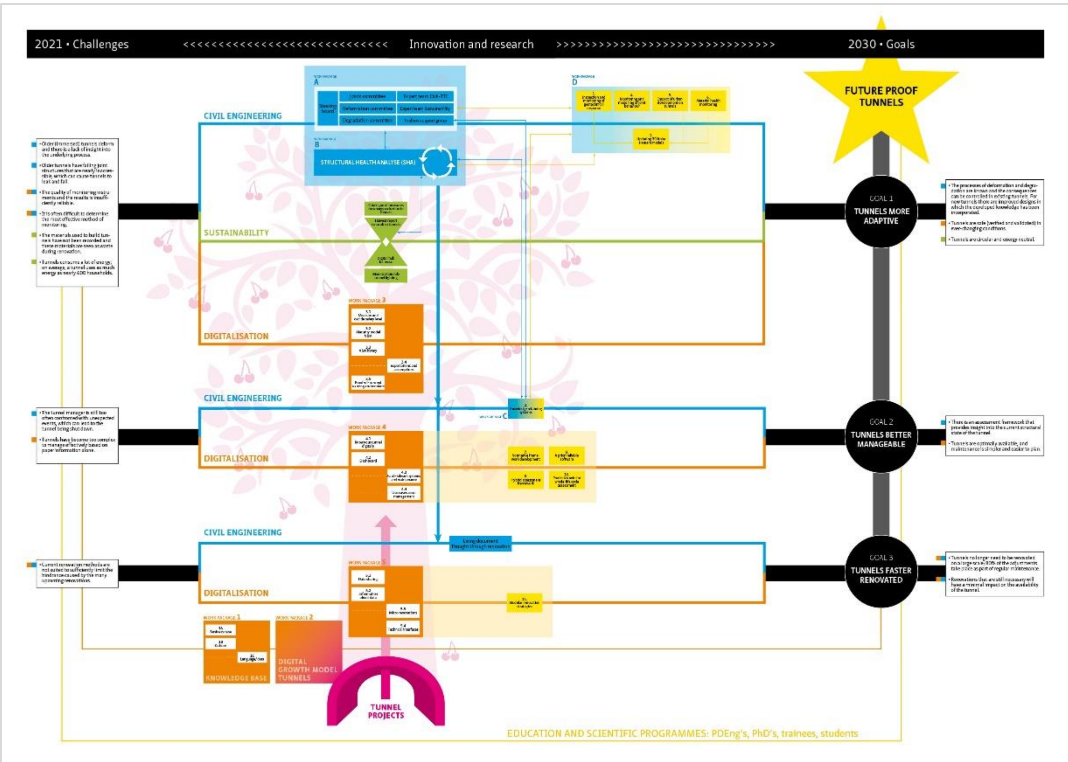

Figure 1: Impression of the schedule in Attachment A, where the projects of the COB tunnel programme and the projects of this research programme are combined. (Source: COB)

Contents

1. Tunnel renovations: a necessary and challenging assignment

1.1 Background

Tunnels form a critical component of our transport infrastructure network. Many existing tunnels in Europe are in urgent need of major renovation works, which will lead to extended tunnel closures. Postponing renovations will increase the probability of structural failure and failure of installations and systems, which could lead to reduced reliability, availability and safety. At the same time technological developments and societal changes regarding risk acceptance are foreseen that have still uncertain impacts on the required tunnel construction, installations, operation and safety.
A serious problem for tunnel asset owners is the complexity of the present safety regulation that makes an integral safety assessment difficult.

The estimated costs for all foreseen renovation projects exceed the currently available budgets, and initial cost estimates show large uncertainties, up to 50% of the initial estimates, due to uncertainties in project scope. To reduce the impact of the upcoming portfolio of renovation projects, improved integrated tunnel construction, monitoring, inspection and renovation asset management approaches are needed.

1.2 Research goal

The main objective of the COB tunnel programme is to support tunnel owners in their strive to maintain, operate, renew or renovate their tunnels in the most efficient, cost-effective and least hindering way in order to obtain a fully functioning, reliable, available, safe and future-proof transport infrastructure network.

1.3 Current obstacles

The biggest obstacle now is a lack of resources combined with too many simultaneous projects, with many unknown and unforeseen choices to be made. The are many questions: which knowledge gaps to investigate, how to assess the projects to be prioritized, which technologies to use, what technological and environmental requirements and expectations to prescribe for tunnels in the future and how to weigh all these aspects to achieve to the most optimal outcome.

1.4 How to decide

An important part of the solution can be found in guiding frameworks that allow assessment of all relevant parameters, such as which new technological developments should be used, or when proven technologies would be preferred, or what the impact on safety and (non-)availability of the infrastructure will be, and which improvements, given specific criteria and boundary conditions, will contribute most to the required goals.

In alignment with this objective, measures can be designed based on the technical, functional and economic lifespan of a tunnel. The key issues to be considered in the decision making process are (1) Cost – economic lifespan, (2) Degradation – technical lifespan, (3) Performance – functional lifespan, (4) Benefits – network reliability and (5) Sustainability – minimizing footprint.

1.5 The human capital as a resource issue

The resources problem focusses foremost on the human capital. The group of people that designed, constructed and operates our tunnels is aging and retiring, while the influx of young people in the network is limited as technology is no longer a very popular field of study. More work is to be done with less people, so new accretion and smart use of the limited resources is required.

This research programme focuses both on coping with this issue with less people by using more and advanced digital technology as well as extending the knowledge network by offering challenging and exciting research programmes in national and international cooperation of universities, research institutes as well as actual tunnel projects.

Key item in supporting technology is the further development of the predictive digital twin. This will comprise an expert system that combines tunnel data and permanent monitoring data on its condition and performance, tunnel behaviour models and life expectancy models to derive optimal maintenance and renovation strategies. The ability to use a digital twin will enable faster and more efficient storage, analysis and exchange of information, needing fewer experts to achieve faster and less error prone design and construction of our renovation tasks.

1.6 Research projects

Our programme is for research projects that use a multi-disciplinary approach to develop innovative asset management techniques for tunnels that support an owner to assess the current structural health and performance, and develop life expectancy models to optimize asset management strategies for the tunnel in its entire network and environment.

- A first step is to better fundamentally understand and model the behaviour of aging tunnels, which will reduce the uncertainty in maintenance and renovation by more accurately predicting the aging behaviour and life expectancy of elements and fill knowledge gaps regarding specific elements of soil-structure interaction **(Projects 1 to 4)**.
- Secondly, we develop data intensive tools that aid in the maintenance of an entire tunnel (new or existing) considering the impact on the surrounding environment **(Projects 5 and 6)**. An example of the use of satellite data in quantifying tunnel impact is shown in figure 1.
- Also, tools are needed to establish whether the safety of current tunnels in changing conditions meets the required standards. An integrated safety assessment framework for operational safety is developed in **Project 7**, whereas **Project 8** develops a framework to assess the structural safety aspects of existing and aging tunnels.
- Subsequently, we will develop methods and tools to ensure the reliability of tunnels during and after renovation. **Project 9** focuses on the development of a-priori reliable control software, and tools to prove the correct functioning of tunnel control software prior to site implementation. It would be interesting to add the posteriori data to improve the decision making system.
- We deliver a proof of concept for a predictive twin for tunnels: **Project 10**. This will comprise an expert system that combines tunnel data and permanent monitoring data on its condition and performance, tunnel behaviour models and life expectancy models to derive optimal maintenance and renovation strategies. Such a system is intended to reduce the overall cost of renovation projects, as well as the uncertainty in cost estimates, with a projected reduction in uncertainty margin from the current 50% down to 20%.
- **Project 11** focuses on the renovation, maintenance and replacement of tunnel installations, with the development of modular renovation methods and modular asset management strategies.

The fundamental research projects will be performed in close collaboration with the COB expert committees and the owners of the tunnels to ensure that research aims remain in line with project needs, and will be linked with specific tunnel reference projects, to ensure that intermediate research results will be tested, demonstrated and incorporated in practice as soon as possible. Each of the projects is accompanied by at least one applied project, to ensure the quick uptake of the results and integration with practice.

Project overview
1. Inspection and monitoring of the geotechnical response of tunnel structures
2. Knowledge retaining systems
3. Updating 3D finite element models – physics based approach for tunnel monitoring
4. Monitoring and modelling of cyclic deformation modes of joints in immersed tunnels
5. Enhanced assessment of impact of urban development on existing a tunnels using remote monitoring
6. Material health monitoring
7. Normative framework development
8. Hybrid assessment framework
9. A priori reliable control software
10. A predictive twin for whole-life cycle assessment of tunnels
11. Modular renovation strategies

The schedule in attachment A shows how the projects of the COB tunnel programme and the projects of this research programme fit together. An impression can be seen below in figure 1.

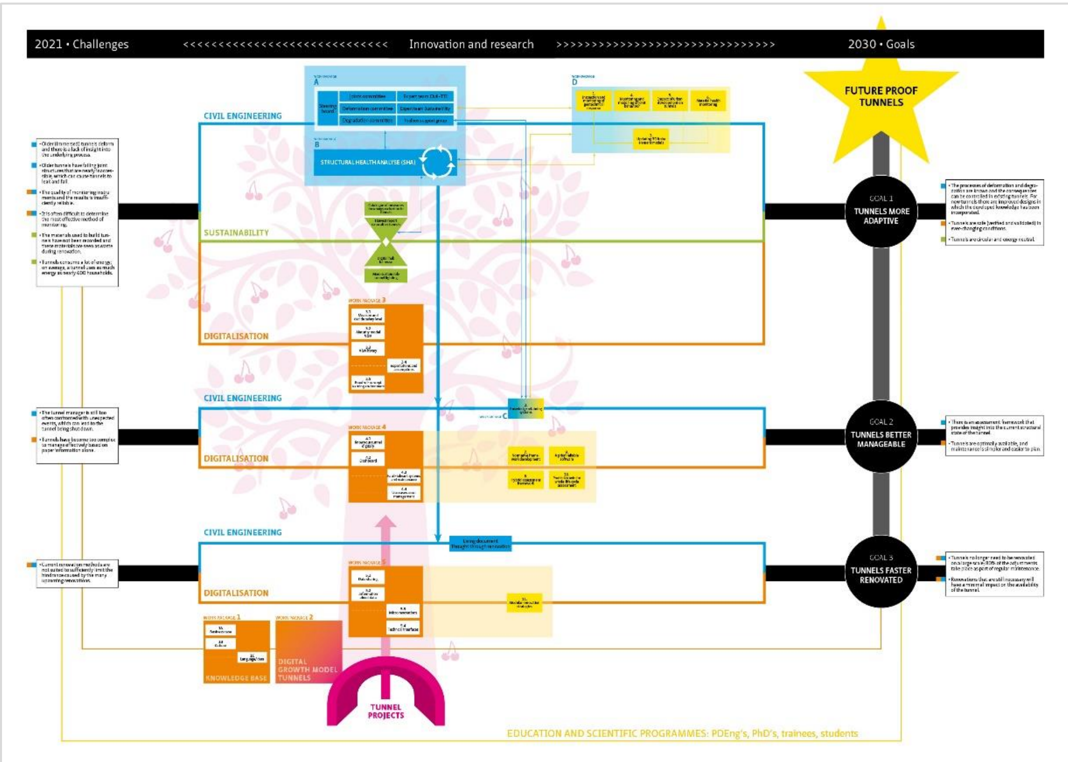

Figure 1: Impression of the schedule in Attachment A, where the projects of the COB tunnel programme and the projects of this research programme are combined. (Source: COB)

1.7 Aimed for impact

The renovation and replacement process of tunnels becomes a transparent, data driven process supported by the sector data and own assumptions. By having insight into the complexity of and coherence in all functions and technical aspects of the asset, costs for renovation and replacement of tunnels can be minimized whilst objectives (e.g. cost, environmental impact) are optimised. The decision making framework will deliver timely and efficient interventions.

This programme will make a significant contribution to the competitiveness of the Dutch private sector. Data-driven decision making provides both an unambiguous approach for renovation and replacement decisions, incorporating expert knowledge and an attractive environment for the next generation of tunnel engineers and managers. The added value of the high level knowledge of the Dutch tunnel sector on (technical) detailed processes can be shown in terms of saving costs and decreasing uncertainties and therefore risks. By applying the framework for replacement, the added value of innovative designs (object or system oriented) on different functions can be visualized.

2 Progress beyond state-of-the-art

The current project-based approach of renovation projects leads to a narrowly focused approach to fill the knowledge gaps for that specific tunnel renovation project. The structural health analysis (SHA) methodology initiated by COB as part of the tunnel programme has been started at two tunnels and, combined with the research needs already identified by the experts in COB committees, has led to an overview of knowledge gaps. We foresee that progress beyond state-of-the-art can be achieved, most efficiently, in an integrated research programme that transcends the individual projects.

Activities within the research programme can be divided into short-term activities (1-2 years), medium-term research (1-4 years) and long-term fundamental research needs (4-7 years). Short-term activities include activities that have been identified from the SHA for specific projects, as well as applied research activities that follow up from the ongoing activities in the COB tunnel programme. Medium-term research builds upon these activities, but focuses on aspects that can be approached more efficiently in an integrated (beyond the individual project) manner. Long-term research includes aspects where input from the medium-term research needs is needed to progress, and which integrate tools and results from these projects into a predictive digital twin.

2.1 Short-term activities

Activity	Project(s)
Continue the SHA approach at multiple tunnels. This will further identify the knowledge gaps and the issues which are common to multiple tunnels, which enables (further) aggregation of tunnels that exhibit similar aging behaviour.	• *Steering board SHA*
The initial SHA-s have shown that data on the original construction, the geotechnical site conditions and the current state of the tunnel are incomplete. As a result, each of the SHA projects has initiated a data gathering exercise. This includes archive research and additional site investigation (both geotechnical and structural assessments). Similar data gathering exercises are foreseen for the other SHA-s.	• *Steering board SHA*
An inventory is made of usable and available data sources, metrics and data. The development of a knowledge retaining system is needed to store the data obtained for the SHA and to ensure this remains available long-term. A semantic convention will be developed to support the uniformity and retrievability of data.	• 2 • *Tunnel programme WP 1C, WP 5.1, WP 5.2*
Deformations at several immersed tunnels (e.g. Heinenoord, Kil) locally exceed the original design limits. Large local deformations occur as well as leakages, and the potential that these ultimately lead to failure of the tunnel construction is initially being assessed. Different mechanisms that can lead to tunnel deformation have been identified, and the likelihood can be assessed using simplified analytical and empirical methods.	• 1 and 2 • *Tunnel programme Deformations committee*
An inventory of different monitoring techniques related to the condition and/or performance of tunnels (bored and immersed) is needed, in order to design appropriate monitoring systems for tunnels. A monitoring wiki is under development, which will assist in evaluating the usefulness of different monitoring approaches.	• 1 and 2

More useful monitoring of tunnel deformations, focused on specific locations and/or at shorter intervals (or continuous), is needed to obtain insight in seasonal and other cyclic deformation behaviour.	• 1, 2 and 8
An assessment framework will be developed that allows tunnel owners to make a trade-off between various digital tools. Guidelines for the behavioural and cultural aspects of digitization will be developed based on behavioural analysis.	• *Tunnel programme WP 1A and 1B*
Criteria for reliable safety levels and scenarios will be explored. This is needed for the development and verification of a maturity model for safety systems.	• *Tunnel programme WP 3.1 and 3.2*
An inventory is needed of the components needed for a verification and validation library for storing test systems, simulators and protocols, to ensure reliable control systems.	• *Tunnel programme WP 3.3*
An inventory is needed of the information required for an effective dashboard for tunnel owners and operators. This is linked to an exploration of the increased usage of the 'Know your tunnel' manual.	• *Tunnel programme WP 4.1 and 4.2*
A proof of concept will be developed for a tunnel component inventory (tunnel hub), that stores availability and potential reuse opportunities for components. Potential integration in a digital twin will be explored.	• *Tunnel programme expert team Sustainability*

2.2 Medium-term research activities

Activity	Project(s)
Once several SHA-s have been started at different tunnels and Camino data has been acquired, the issues common to multiple tunnels can be identified.	1 and 2
Degradation models (regarding the condition and resulting performance) will be developed for the most common structural parts of the tunnels based on the analysis of the SHA-s	5
Starting with the most common or probable deformation mechanisms of tunnels, 3D numerical models of the tunnel settlement behavior and interaction with the surrounding soil should be built. Including a detailed structural model will allow prediction of the impact of deformation on structural integrity. This will also form the basis for more detailed design of a monitoring strategy.	3
Models to assess proven structural capacity for tunnels will be developed, to probabilistically assess the remaining lifespan. These models take past loading conditions and the construction sequence into account and, thereby, come to more proportional renovation measures for existing tunnels.	8
Combining structural and positional data on tunnel construction and installations will form the basis for a digital twin for tunnels. Including geological models into these twins will allow for generation of 3D numerical soil-structure interaction models.	3

Continuous monitoring of tunnels is needed to validate the 3D tunnel models. The impact of various cyclic (tidal) and seasonal (temperature) effects as potential driver for tunnel deformation needs to be validated, which requires more frequent monitoring than available.	1
This requires the development and field testing of permanent sensors to continuously monitor the performance (e.g. structural behaviour) and material health of tunnel structures.	1
Additional external sources of data (such as installations or traffic data) can be integrated in an automated sensor fusion system, to optimize the inspection process and form the basis for a predictive structural health model. For rail tunnels rail condition data (Camino) can be gathered as well.	10
Immersion joints experience cyclic seasonal loads, potentially leading to an increasing non-reversible joint deformation over time. If this occurs it will increase the likelihood of leakages and tunnel failure. The precise conditions at which these cyclic deformations occur and become non-reversible need to be elaborated, and potential measures to counter or stop this for existing tunnels be designed.	4
Inspection and renovation techniques for immersion joints need to be developed. As critical elements of the tunnel construction, the joints need to remain intact, but are difficult to access for inspection and near impossible to replace.	4
Renovation strategies for tunnels need to be developed. These should focus on maximizing the availability of the tunnels during the renovation period and minimizing hindrance for the infrastructure network.	10 and 11
Software for tunnel control systems needs to be delivered and approved in a reliable and automated manner. This will require implementing a-priori verification based on instance model checking.	9
Assessing the impact of technological and social changes in a safety framework will require developing scenarios for mixed usage conditions and modelling the impact of such scenarios.	7
Development of an assessment framework for tunnels for technical, functional and economic lifespan.	6, 8 and 10

2.3 Long-term fundamental research

Activities	Project
Results from tunnel-structure-soil interaction models and life expectancy models, the continuous real-time monitoring of tunnel deformations, structural health sensors and external data sources will all be integrated in a sensor fusion system. This will extend a digital twin model of a tunnel to become a predictive twin.	10

Dashboards need to be developed to present essential information – this probably requires to translate the interpretation of current condition and performance data and corresponding predictions of those – to support maintenance and operation, as well as prepare for future renovation cycles. In order to filter the extensive data sets foreseen, AI supported tools will be needed.	10
In order to limit the impact of future renovation cycles modular installation and renovation strategies need to be developed, by which components and installations for tunnels can be replaced in a modular manner, further reducing the need for extended tunnel closures.	11

3. Organisation

The activities presented in this research programme are aimed at continuous delivery over time, with constant interaction between the scientific research, the applied research and engineering practice. It is anticipated that throughout the research program, new results will become available, with a strong emphasis on implementation of new results in the engineering practice.

We envisage that the research objectives can be addressed by topics distributed over a number of coherent projects. The work will be arranged across eleven research projects, with a total duration of seven years.

Projects 1, 3 and 4 address fundamental aspects of tunnel behaviour, Project 5 develops frameworks for interpretation of data intensive solutions on tunnel impacts and geological modelling. Project 6 addresses material health aspects, whereas Project 7 addresses integral safety aspects and Project 9 addresses reliability of tunnel control systems. Project 10 delivers the predictive twin environment and Project 11 develops modular renovation strategies.

Two projects support all others: Project 2 further develops the knowledge retaining systems for tunnel monitoring and Project 8 builds the basic framework for a hybrid assessment model for tunnel maintenance and renovation based on actual material and load conditions.

Staffing requirements are as follows:
1 The short-term activities are delivered by the existing COB committees supported by knowledge institutes (Deltares, TNO), PDEng and master students and interns. They will inform and support the six research projects that deliver the medium and long-term objectives.
2 The medium-term activities are delivered primarily by PhD students with accompanying projects by the knowledge institutes, supported by the existing COB committees.
3 The long-term predictive / cognitive twin will be delivered by a PhD and PDEng working closely with all COB partners.

Each project / work package will be linked to an existing or new COB committee, in which the parties from all backgrounds (asset owners, engineering firms, knowledge institutes, contractors, monitoring suppliers and universities) are represented and knowledge exchange is facilitated.

Preliminary time schedule							
Year:	**1**	**2**	**3**	**4**	**5**	**6**	**7**
1 Monitoring tunnel deformations							
2 Knowledge retaining systems							
3 Modelling soil-structure interaction							
4 Modelling of joint behaviour							
5 Impact of urban development							
6 Material health monitoring							
7 Normative framework development							
8 Hybrid assessment framework							
9 Control software							
10 Tunnel predictive twin							
11 Modular renovation							

4. Projects

The overall aims of this research programme can be separated into a number of projects. These will be described below.

4.1 Project 1: Inspection and monitoring of the geotechnical response of tunnel structures

This project aims to monitor the inside of existing tunnels using SHM approaches such as fibre optic and distributed mesh sensors, to continuously monitor the deformation and movement of the tunnel structure, whilst not impeding traffic flow during monitoring. In addition geotechnical and geophysical techniques will be deployed to provide insight into uncertainties pertaining to the geological settling.

Monitoring of (immersed) tunnel long-term deformations is currently done using standard geodetic surveys of a limited number of measurement bolts mounted on the tunnel wall, and only data on relative vertical deformation of these bolts is collected. This limited data set does not extend to relative deformation over all dilation joints, and does not hold information on horizontal displacements or rotations. Moreover, these surveys are performed at multi-year (3 to 10 year) intervals as they require short-term closures of the tunnel to allow surveyors' physical access to the tunnel. Even though exact data on lateral and axial deformation of the tunnel is missing, it has become clear that the tunnels deform (and twist) in these directions. Causes can be seasonal temperature differences shrinking and expanding the concrete structure of the tunnel and the underlying geotechnical conditions, leading to opposing highly localized deformations occurring in the tunnel joints that result in damage including leakage.

Measuring these seasonal (and shorter term) deformations of the tunnel and joints requires sensors on the tunnel structure and all individual tunnel joints, to record deformations and rotations on a daily basis. The required free profile in the tunnel for traffic, the requirement for the sensors to be non-distracting for (road) users, and requirements from the tunnel operators to limit the amount of cabling, limit the use of many traditional sensors. Therefore, the use of unobtrusive sensors, including fibre optic based sensors using distributed strain sensing along the entire tunnel, where needed complemented by wireless sensors, is investigated. Although Brillouin (BOTDA) distributed strain sensing fibre optic measurements have been applied for other applications, these techniques have not been used to measure localized deformations and rotations of immersed tunnel elements, and the combination of measuring both small strains and relatively large localized deformations is challenging. A pilot is currently underway at the First Heinenoord tunnel and is expected to provide first data in 2021. This project aims to continue monitoring at multiple tunnels, to prove the reliability and applicability of the fibre optic sensors also under different loading conditions and deformation modes.

Various seismic and geo-electric geophysical methods exist to measure difference sin density and strain behaviour of soil layers in a three-dimensional manner. Preliminary results have shown the feasibility to obtain additional soil investigation data from the inside of the tunnel, to add to existing (localised) site investigation data and build a more detailed geological model that can be sued to predict the response of the tunnel to geological conditions.

The project contains the following activities:

1. Survey of wireless and distributed mesh sensors
2. Continuation of monitoring at the First Heinenoord tunnel
3. Installation of sensors in a second tunnel (t.b.d.), localised design of sensor and optic fibre layout, BOTDA system, setup of data-acquisition and storage.

4. Data acquisition over multiple seasonal cycles.
5. Identifying uncertainty in the geological model and in-situ investigation to fill-in knowledge gaps.
6. Interpretation of data, analysis of deformation modes and initial modelling of tunnel deformation.

4.2 Project 2: Knowledge retaining systems

To facilitate the asset management process, condition-based (and in the longer term risk-based) maintenance strategies shall be embedded in infrastructure management systems. In such systems, assessment of the structural condition is based on the integration of asset lifecycle information and information from inspections, monitoring and testing. More specifically, ‘static information’ produced among the asset lifecycle (design, construction, operate and maintain) and data gathered from inspections, monitoring and testing is used to assess information about the condition of the structure, which is then processed with the models to obtain the actual safety and the risk levels of the structure and to predict the future development of safety and risks.

As a basis, this requires 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 the COB project Toolbox structural health analysis a start has been made with the development of such a knowledge retaining system. This project continues that work, and brings together:

1. information on existing monitoring systems and their applicability for tunnels, based on which a monitoring design template will 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 firm framework for organizing the information and knowledge on the past and current state of tunnels, where a PhD will develop a shared semantic basis for storing and retrieving existing data in a uniform manner and advanced tools and methodologies for extracting more information from existing and new tunnel data, which in turn will be needed to feed a predictive twin (Project 10);
3. a data platform to process and retain the high-frequency monitoring data of tunnels, which will be needed for the development and validation of data-enhanced modelling strategies.

A digital tunnel twin integrates different kinds of information and data and can be combined with predictive models. A twin may offer important benefits such as enhanced collaboration and visualisation for stakeholders, easy retrieval and storage of information and data and support of monitoring, decision-making and communication.

However, we can distinguish many types of digital tunnel twins varying from very sophisticated to relatively simple ones. Moreover, not every tunnel needs the same advanced digital twin and not all needed information is always available or of the right quality. This may for example result from poor recording of data in the past, but this can also occur because parties are unwilling or unable to share this information. So, what type of digital tunnel twin is needed in which situation and under which organisational and behavioural conditions can these twins be used successfully?

In this project a PhD will develop a typology of digital tunnel twins based on typical (a) stakeholder needs, (b) tunnel characteristics and available datasets. The PhD will also analyse the organisational and behavioural conditions for using these digital twins successfully. This typology can be used for existing and new tunnels to support decision making about the most appropriate digital tunnel twin in a specific situation.

4.3 Project 3: Updating 3D finite element models – physics based approach for tunnel monitoring

This project will develop models to analyse the behaviour of the immersed tube and TBM tunnels in the soft, heterogeneous soils encountered in deltaic zones in the Netherlands. Building on the data collected by the PhD in Project 1, the objective of this PhD will be to combine observed temporal effects (settlement measurements, water level, temperature, geotechnical site conditions to develop improved constitutive models for implementation in finite element / FEM analyses. Specifically attention will be given to quantifying cyclic loading and soil and concrete creep in the models, tunnel design and construction. In order to separate these effects, soil-structure interaction models will be developed. These three-dimensional models will include joint behaviour and construction interaction between tunnel segments and go beyond the current mostly one-dimensional settlement models. The PDEng will focus on assessment of the impact of forces generated on the structural response on joint behavior.

The project contains the following activities:
1. Three-dimensional modelling of tunnel deformation modes.
2. Integration of soil-structure interaction behaviour for specific tunnels.
3. Calibration on long-term tunnel monitoring data sets and updating FE models.
4. Development of appropriate models for considering cyclic loading and creep effects on soft soil.
5. Generalization of deformation models to be usable for generic tunnel types.

4.4 Project 4: Monitoring and modelling of cyclic deformation modes of joints in immersed tunnels

Immersion joints are subjected to (longitudinal) load cycles due to the seasonal expansion and contraction of the tunnel elements themselves, which in turn leads to increased local stresses in the tunnel construction, and which in some cases can lead to extreme compaction of sand in the joints (the sand pump effect). Tidal variation in waterways can lead to net vertical load if sludge layers cause retardation of the tidal wave in the permeable layer around the tunnel. This project will model the impact of such cyclic loads on the durability of the immersion joints. Assessing the impact of the joints on the overall structural integrity of the tunnel is essential for developing improved renovation strategies, as well as input for structural health and remaining life-span assessments. This project will involve a series of scale model tests to model the behaviour of immersion joints under cyclic loading at lab scale. These model tests serve as input and validation for a detailed 3D numerical model of the soil-structure interaction in and around the joint.

Furthermore, the immersion joint is difficult to access from the inside, and near impossible to inspect from the outside. Preliminary endoscopic inspections from inside the tunnel have proven difficult to perform, as large sections of the joint could not be reached for inspection. Improved inspection tools and strategies are needed to assess the current state of the existing joints. State parameters, such as forces in bolts and remaining clamping forces due to ongoing creep of the seals' rubber, are necessary input for a probabilistic failure model that can be used to establish the current safety levels. We will need to establish a complete fault tree and a probabilistic failure model for an immersed tunnel, as neither the probabilistic failure model nor the detailed input data is available. Based on inspections and lab model tests, the detailed soil-structure interaction model of the joint can be developed and validated, and the remaining structural capacity of the joints assessed. This input is needed to design renovation strategies for these joints.

The project contains the following activities:
1. Development of inspection strategy, joint inspections, joint components sample retrieval, lab testing of joint component samples.

2. Lab and pilot tests of the impact of cyclic deformation on immersion joints.
3. 3D numerical soil-structure interaction modelling of joint behaviour.
4. Construction of probabilistic failure models for immersion joints.

4.5 Project 5: Enhanced assessment of impact urban development on existing tunnels using remote monitoring

Construction activities at the surface in case of new urban developments close to and above existing tunnels can lead to structural damage of existing tunnels, which can be especially severe for older tunnels. This impact needs to be carefully assessed in the preliminary stage of project design. Methods exist to assess the potential damage for surface structures, but the intrinsic simplifications of these methods lead to neglect soil-structure interaction effects that have been proven to be relevant to the tunnel response. The development and validation of new assessment procedures requires high quality field data which are expensive and difficult to obtain from traditional ground-based monitoring but could be made available by recent advances in interferometric synthetic aperture radar (InSAR) techniques. InSAR can currently provide day-and-night, weather-independent ground settlement measurements with millimetre accuracy that can be used to monitor deformations over large areas. This allows the direct use of InSAR measurements as an input for a quantitative assessment of structural damage.

This project will develop a fully automated framework which will use InSAR monitoring data to assess the settlement-induced damage to tunnels due to surface construction activities. InSAR-based building displacements and models of the building impact towards existing tunnels will be combined to provide an accurate estimate of tunnel deformation, and a corresponding level of expected damage.

The project contains the following activities:
1. The development of an algorithm to integrate geographical information system (GIS) building inventories and InSAR-based displacement data.
2. To creation of InSAR-based fragility curves correlating ground settlements and surface deformations for selected tunnel typologies.
3. The development of relationships between structural typologies and soil-structure interaction effects.

4.6 Project 6: Material health monitoring

Health monitoring for structures is becoming more and more mature and is used already for several applications. Monitoring of the health of materials inside a structure on the other hand is new. It is believed that the degradation mechanisms and deformation and damage of a structure start at the level of the material. The properties and behaviour of the material changes over time. This can be due to thermal, hygral chemical or mechanical changes inside the material or of the environment. It is not a steady state but rather a process that develops in time and leads to internal deformations in the material and as a consequence deformation or damage of (part of) the structure. Material health monitoring aims at monitoring the different mechanisms that impact structures using various types of innovative, self-powered and wireless sensors.

The figure below gives an overview of the conditions and activities in which performance (for this example of the human body) can be monitored. Furthermore it indicates the changes in environment (mechanical, thermal, hygral) and the internal changes in the local material/body (temperature, pressure, pH, chemical, and the coupling between all, etc).

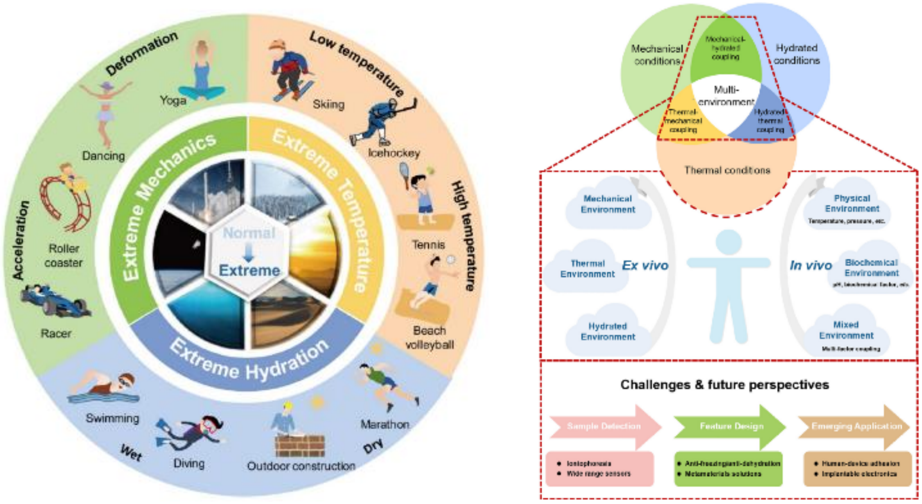

Figure 2. Example of health monitoring for humans. (Source: Materials Today, volume 41, december 2020)

The project Material health monitoring aims to develop, similar to these sensors for human body, sensors that can be put inside materials and provide us with the change in state, property and 'well-being' of the material. This should ideally be done automatic, self-powered, and wireless. In the figure at the right the human in the centre can be just replaced by a material like concrete or a concrete element or structure. This will require fundamental research to develop the sensors, although we will benefit from parallel research in other areas (primarily human health) and can adapt the sensors to fit the behaviour of construction materials. The sensors will be tested in lab conditions in specimens under various load and environmental conditions. Furthermore, they will be implemented in-situ in real structures to measure change in behaviour and couple it to real degradation in time.

The project contains the following activities:

1. Survey of possible damage mechanisms on material level that have structural consequences. Selecting sensors for material degradation monitoring.
2. Modelling and testing material degradation and structural consequences.
3. Developing structural health monitoring strategy based on measurements and modelling data.

4.7 Project 7: Normative framework development

This project will define a robust and objectifiable framework on a meta level to provide a practical guidance for an integral safety assessment of tunnels. This framework should address adequately to which extent efforts are necessary to create a situation that is acceptable regarding safety risks, durability, and the complexity of densely populated areas. Integral refers here to also to cost-benefit considerations and the feasibility of consequential efforts to preserve the availability of tunnels on the long term.

A notable feature in Dutch regulation that further burdens the safety analysis at this point, is the use of 'group risk' as a prescribed method to measure unsafety. Originally intended as a 'reference value', it has gained a place in some specific regulations. However, legislative maturation increasingly abandons this approach, and rightly considers it inadequate to provide a workable and justifiable scope.

Note that recent and upcoming developments in regulation, such as the Omgevingswet (environmental code), have a broader perspective on weighting environmental safety. As an example: the Wet lokaal spoor (local rail law) rightly doesn't only consider fire safety issues, but also factors in noise pollution that as we know these days also is a safety risk.

The project design follows an approach in which stakeholders such as civilians, users and owners are brought together in a pre-phase that is used for determining what should be valued when a system reform is considered and what mechanisms can be revealed to better understand the overall complexity. This should lead to a conceptual framework that can be developed further by a first practical implementation in a real case. During this implementation, the developed set-up is envisaged for approximately three years. In the practice of construction and renovation of tunnels, the concept will be tested and refined in consultation with the relevant actors. After the testing period, the results are recorded in detail in various publications such as a manual and a dissertation.

4.8 Project 8: Hybrid assessment framework

This project aims to collect the components needed for a hybrid condition assessment model, that integrates structural and material health degradation models and links these with performance and availability criteria, to derive remaining life-span predictions and to improve the maintenance decision making processes. Ultimately, when integrated in a digital twin of a tunnel, and combined with sufficient quality monitoring data, this will allow the operation of a predictive twin (developed in Project 10).

Integrating structural health models in a hybrid assessment framework will allow to link the (civil) engineering knowledge and expertise on the structural, geotechnical and geo-hydrological behaviour of tunnels in an appropriate manner to the impact of policy-related decisions by asset managers in light of future scenarios on climatic, socio-economic and policy developments (e.g. sustainability goals).

This project starts with the development of the overall assessment framework, and identifying and quantifying the various performance indicators and benefits to be considered, as well as developing the various scenarios that need to be considered. This is followed by broadening the (fundamental) knowledge of various geotechnical and structural degradation processes relevant to tunnels and tunnel joints (e.g. Omega profiles, see Project 4). This includes the use of existing data and developing techniques to gain insight into the actual loads and condition of tunnel components (including components that are not directly accessible such as immersion joints).

When considering the actual loading conditions of tunnels in the context of replacement and renovation decisions, there is also sufficient potential and added value in the reduction of uncertainties regarding the actual load conditions. By improving the forecasting of actual occurring forces on tunnel structures - through combining monitoring, data analysis and tools such as advanced numerical methods - more economic assessments of the (residual) lifespan of tunnels can be made, using more precise safety factors to cover uncertainties in effects of loads and conditions, and therefore leading to more proportional measures being considered. To enable such an improved forecasting, a time-dependent reliability analysis is needed, and reliability requirements and calculations must be defined on an annual basis instead of on a fixed lifespan of e.g. fifty years. These methods would be in line with common international (ISO2394) and European (CEN) standards for assessing existing structures, but are not widely validated for tunnel structures.

To effectively use this reliability analysis approach, also further development of numerical models, combined with field measurements and scale models to improve the simulation of the tunnel structures in their system is needed, to achieve data enhanced modelling. This approach quantifies and decreases the uncertainty in material strength and (resulting) overall structural behaviour (e.g. tunnel segments, joints, 3D deformations etc), and models tunnels as a system of interacting elements. It brings monitoring (Project 1), modelling (Project 3) and detailed structural behaviour aspects (e.g. immersion joint in Project 4) together to fill the knowledge gaps related to soil-tunnel interaction and soil related hazards.

This project will bring together:

1. a hybrid framework for condition assessment considering future development scenarios and the impact of policy decisions;
2. relevant inspection techniques for mapping the current condition of (parts of) tunnel structures and the surrounding soil, including degradation to date;
3. knowledge and the derivation of degradation functions (tools), in order to be able to determine the residual life of (structural components in the) infrastructure;
4. development of time-dependent reliability functions for tunnels and;
5. an improved understanding of the vulnerability due to aging in view of the proven strength and actual loading conditions of tunnels using data enhanced modelling.

4.9 Project 9: A priori reliable control software

Past experience shows that introducing additional sensors and installations in the tunnel control system increases the number of short-term tunnel closures due to (control software) glitches and interoperability issues. Therefore, research is needed for the predictable delivery of renovated intelligent and safe tunnels, which combines both technological and organizational aspects. In order to reliably integrate modular and embedded systems in existing tunnels, techniques need to be developed for the delivery and approval of the automated systems inside tunnels. This will require constructing mathematical models for the control software for the first time and implementing a-priori verification based on instance model checking, and the subsequent inclusion of model-based testing against verified models in tunnel acceptance tests.

A tunnel's software landscape consists of many individual components, running in parallel, that have to work together flawlessly. As a result, many communication interactions between components will exist that are directly or indirectly dependent on one another. Instead of investigating all the correct functioning of all components individually, we look at the tunnel's software from a system's perspective.

Defining up front what the intended behaviour in interaction between components is will provide better ways of managing the actual implementation of the software landscape. To do this, we want to design a software reference architecture for tunnel installations with two goals in mind. Firstly, such a reference architecture will allow efficient design of component interfaces, interactions and requirements to establish a notion of correct cooperation behaviour before installation of actual components. Secondly, such a reference architecture of correct cooperation behaviour can be used to enable model-based testing of the actual components and their software after installation.

We set up a model based testing framework to test that implemented components adhere to the prescribed behaviour of the reference model before they are installed. When installed we want to quantify the benefits of this software framework in terms of design and maintenance costs, as well as the reduction in unavailability of tunnels due to software issues or software testing obligations.

The project starts with the design of an information architecture. This must converge into the reference model for the software infrastructure, and the cooperating components in tunnels. The behaviour of all components will be mathematically characterized using the mathematical behavioural specification formalism mCRL2. As both safety and flawless operation of tunnels is paramount, we want to formulate and standardize behavioural requirements that govern the correct behaviour of the tunnel software. These requirements must be formulated in a precise and unambiguous way and they must be proven to hold on the defined architecture to guarantee that the software components in the tunnel work well prior to installation. Finally, we want to use the reference architecture to enable model-based testing, therewith establishing that the installation and especially the testing time of tunnel equipment can be substantially reduced, while obtaining a higher quality.

4.10 Project 10: A predictive twin for whole-life cycle assessment of tunnels

The predictive twin aims to combine condition assessment data with structural and material health degradation models in a predictive digital twin, to derive remaining life-span predictions and to improve the maintenance decision making processes.

The continuous measurements of the tunnel structure in Project 1 will add to the huge amount of condition-monitoring data that can be collected from a wide variety of sources. This includes external sources such as static road-side traffic sensors, as well as sensors that can be incorporated in the tunnel structure itself, to detect material deterioration and changes in the state of the material (for instance moisture and chloride content, corrosion potential of the reinforcement or deformation and delamination of surface layers and previous repair works.) Combining this data with models predicting the material state will lead to the development of hybrid structural health assessment models. These models estimate material and structural degradation and remaining life span based on specific knowledge of failures and system dependencies, and the data-driven approach can identify yet unknown patterns and relate these to underlying causes. This will reduce the uncertainty in both the condition of an asset and the residual lifespan in a targeted manner. Furthermore, this can help to determine which additional information collected by monitoring and sensoring systems will lead to the greatest added value.

From this assessment framework we derive key performance indicators (KPI) for the future availability and reliability of the tunnel, in a way that considers differences in construction method and functionality of the tunnel. Such a framework will allow tunnel owners to decide how to optimally operate and renovate tunnels as part of the infrastructure network and to timely plan maintenance actions, which will result in a significant improvement in performance and safety and a significant reduction of total operation costs.

This project will develop the open data standards for the components of a predictive twin, and subsequently build an open-source proof-of-concept from on these standards, such that this allows third parties to further develop the digital twin as well as extend this to include virtual learning and training environments.

4.11 Project 11: Modular renovation strategies

This project will define and optimize modular asset management strategies, which subdivide full renovations in smaller projects in time and space, whilst simultaneously establishing that the tunnel remains safe to operate in all phases and that the final renovated tunnel delivers at least the same quality as a traditional renovation. Such an asset management strategy will be based on the 3C-concept (centralize, cluster, calculate) proposed by Wolfert and Koenders (2010), which has not yet been applied in an integral manner.

For the current and future renovation cycles, modular concepts for the tunnel interior and the technical installations are expected to reduce the overall renovation period and to allow partial renovation or upgrading of the tunnel installations with limited tunnel closures. To allow modules to be upgraded later, flexible and universal connection standards for future sensor connections need to be designed now, that allow future modules to connect and integrate with the tunnel control system. Naturally, these modular and adaptive interiors and installations are to be used in newly built tunnels as well.

A challenge will be to design modules that can be exchanged in a regular service and maintenance period, and will be operate as plug-and-play systems, i.e. have universal connectors and be mostly self-contained, as not to require extensive changes to other tunnel components (such as connection cables or location of fixtures) in order to swap them. An added goal here is to design components that do not lead to a temporary doubling of similar systems in a tunnel during the exchange periods. For tunnel renovations this challenge extends to the design of asset management and renovation strategies that combine renovating both the structural and installation components, in a manner that each sub-step of the process is limited in time and space, to ensure that hindrance due to tunnel closures can be minimized. Such a renovation approach, based on the 3C-concept, will require development of detailed virtual tunnel models to design and verify the asset management strategy, which include integrated structural behaviour and life-expectancy models. Such a model is needed to validate the safety and soundness of the partial renovation strategies, to proof that the resulting partially renovated structure is structurally and operationally safe, but equally to prove whether parts of the renovation process can justifiably be delayed in time, as this will be an essential component of the modular asset management strategy.

Attachment A – Projects combined

The schedule below shows how the projects of the COB tunnel programme and the project of this research programme fit together. This schedule can also be downloaded from www.cob.nl/futureproof.