CSI for tunnels; no more unpredictable maintenance

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1. Introduction

Worldwide, renovation of tunnels is becoming a huge challenge. Due to the large costs and the need for accessible infrastructure, choices need to be made as to which tunnels will be renovated first, which renovations can be postponed and what should be the scope. Unfortunately, we lack the knowledge to develop a proper asset management strategy for tunnels.

Figure 1: Main road network in the Netherlands

Of course, asset management of infrastructure is a well recognized and often studied issue. Various asset management strategies have been developed for road and rail infrastructure, but specifically for tunnels the required information is lacking as we have:

a. limited fundamental and practical knowledge about the actual state and residual life span of the structure. There is a lack of information on aging behaviour and ageing models for joints, transitions and foundations. An exception is information about the aging of concrete. There is a lot of information about the aging behaviour of concrete structures and this is not a specific topic for tunnels. What is specificly tunnel related is that the concrete is often covered with promatect fire protection or ceramic tiles. This makes it difficult to directly monitor the status of the concrete.

b. limited fundamental and practical knowledge about the relationship between the (changes in) physical environment of the tunnel (soil, groundwater, changing river depths and widths, construction other structures) and the expected residual life span.

c. limited fundamental and practical knowledge about the influence of changing traffic loads, the densification of the network and of the urban environment or the behaviour of the tunnel construction and aging aspects.

d. hardly any studies establishing the relationship between these aspects and the identification of possible (as yet) unknown risks.

Small expert team to start

The ambition of the COB, the Netherlands Knowledge Center of Underground Space and Construction is to make a first step in clarifying the existing knowledge on these issues by developing a position paper. For this paper we are forming a group of experts to sketch the framework of the task at hand and to make an overview of the ten key risk areas and the extent to which we currently have control over those risks. We will use the methodology of Forensic Engineering to look at rail and road tunnels and their surroundings to establish the major failure modes and their causes. Forensic Engineering is a way to investigate the causes of failing objects (after they have failed). We will proactively use this methodology to gain fundamental insight and to establish a validated asset management strategy.

We've invited a small number of engineers, scientists and experts from the field and asked the chair of Subsurface Engineering at Delft University of Technology to chair this group. See the last page of this paper for current attendees of this group. We hope to expand this group both nationally and internationally.

2. Scope

We are limiting ourselves to tunnels in soft soils because we expect the failure mechanisms and the uncertainties to be the highest for these tunnels and they are the most relevant to Delta-areas. We do expect a difference in failure mechanisms between different kind of construction types, so we will look at bored, immersed as well as in-situ tunnels in that regard. We limit ourselves for the time being to road- and railway tunnels but we do expect the results to be applicable to other types of structures.

In general tunnels can be subdivided in large sub-systems such as Logic Function Fillers (LFVs) (i.e. the most important mechanical engineering components, such as tunnel ventilation), Operation, Controlling and Monitoring Components (i.e. the mainly electro-technical components that provide the control of the LFVs), Local Operation Components (i.e. the electrical and ICT components that interface with the operator), Road and Pavement Construction and Civil Construction (i.e. the tunnel tube and the tunnel channel). **In the scope of this study, we focus on the Civil Construction only.** Hence, we don't include the mechanical engineering components, electro-technical components and electrical and ICT components within the tunnels. Because of the relatively short lifecycle of those objects (ca. 10-15 years) the reasons for intervention are usually related to maintenance (i.e. the failure rate in relation to the required availability) and the lack of continued technical support (i.e. ending manufacturer support and limited availability of knowledge through rapid technological development). To focus the study, Road and Pavement Construction is also excluded from our scope although it is acknowledged that, similarity to Civil Construction, the primary cause of intervention lies in the technical aging of the structure (in combination with changing use.) Yet, for Road and Pavement Construction the technical service life is substantially shorter than for Civil Construction.

2.1 Approach

We aim to make a decomposition of a Civil Construction of a tunnel and its surroundings that might influence the residual life of the structure, the of failure-mechanisms that might occur (and why), the kind of mitigation and control mechanism we have and how much we know of the effectiveness of these measures. We also expect to identify failure mechanisms without proper control mechanisms Here, their likelihood times consequences will give us a scope to search for new solutions.

We don't want to spend a lot of time on a complete desk research on every previous study available, because we believe that the main problem is not the lack of detailed information, but more so the interaction of all the elements. We expect we have most puzzle-pieces, but we are missing the general picture. Finding that general picture and getting the blanks in that picture identified is our first goal for this position paper. Also we hope that with this paper we can link up with an international community of researchers, tunnel owners, maintenance-contractors and advisors, to get more focus on the blanks that need to be filled in. With this bigger picture and common goal we hope to really take a leap towards predictable asset management, a higher availability of our network and a well-used investment of (mostly) public money.

2.2 Whose problem are we solving?

In the Netherlands (see figure 2, timeline of all Dutch tunnels) RWS, the municipalities, the provinces and private owners have the following common goals: keeping the tunnels available and safe; and maintenance predictable. RWS, which is responsible for 26 road tunnels, recently[1] estimated its required investment for the period of 2017 until 2050. In this estimate the life expectancy for tunnels is based on a hypothesis of 100 years of estimated (average) technical service life for the civil structure (and estimated (average) 'midlife upgrade' renovation of the whole civil structure of a tunnel after about 50 years). RWS states that these assumptions are highly uncertain, and recent events with tunnels and other assets tell us that these estimates could be either too optimistic or too pessimistic.

But this uncertainties not only a problem for the tunnel owners. In the Netherlands the maintenance of tunnels is very often included in long term contracts with either the civil contractors or the contractors who are hired to do the renovation and replacement of the installations. They invest in monitoring and a maintenance program, often without thorough understanding of the underlying phenomena are behind failure mechanism under considerations, for example, leakage in tunnels.

[1] Prognoserapport_VenR_2016_21_ feb_2017.pdf

After the renovation of the Maastunnel (built in 1942, immersed tunnel), the Velsertunnel (built in ’57, cut and cover) and the Coentunnel (’66, immersed) COB, representing a combination of owners, contractors, engineering companies, knowledge-institutes and other experts, realised that we have a mutual problem that needs a mutual approach. This wider attention for the impact of aging on asset management grew from a small issue, namely the immersion joints of the immersed Coentunnel which were leaking and where the renovation contract demanded a 100 year guaranty after the renovation. Both the tunnel owner and the contractor contacted COB to help investigate this problem, the possible failure mechanisms and the way these problems might be solved.[2]

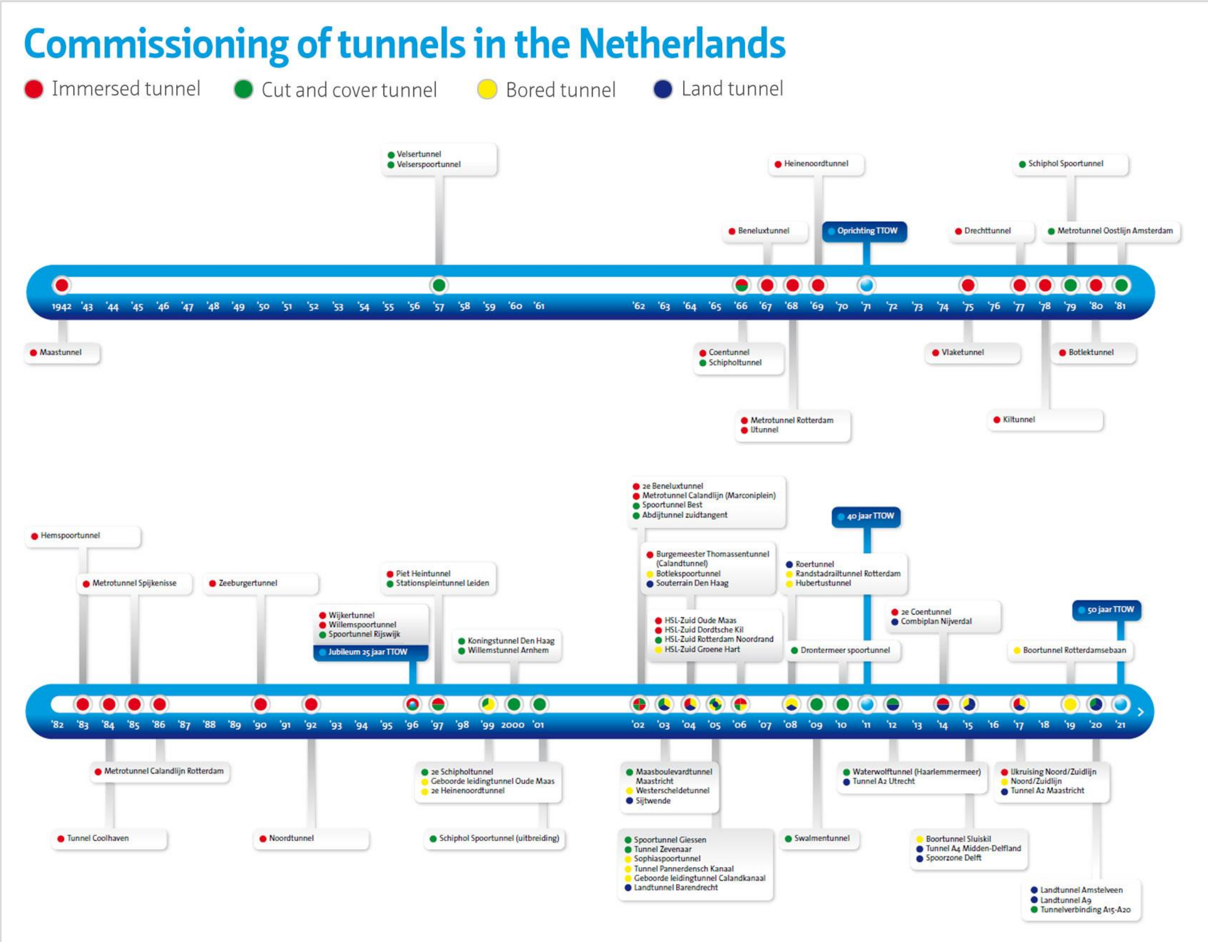

Figure 2: Timeline of the Dutch tunnels

This research project and the upcoming renovations of several tunnels in the Netherlands (Kiltunnel, Heinenoordtunnel, Maastunnel, Metro Rotterdam, Willemspoortunnel, etc.) gave COB the impulse to start with this initiative and find a group of experts to start ‘solving the puzzle’. For RWS the next step in developing an asset management strategy will be to ask the regional tunnel managers to make an estimate of the life expectancy of their tunnels and the failure mechanisms they observe. We hope to include this group into our expert team, as we expect a lot of practical knowledge from them.

2.3 First impression on the pieces of the puzzle

In order to clarify the scope (of possible problems), a mind map has been created, see figure 3 (full resolution pdf: https://drive.google.com/uc?export=download&id=0B1IflSYEoWvtcndwOHJ0b0VaczA).

[2] https://www.cob.nl/nc/kennisbank/webshop/artikel/instandhouding-zinkvoegen.html

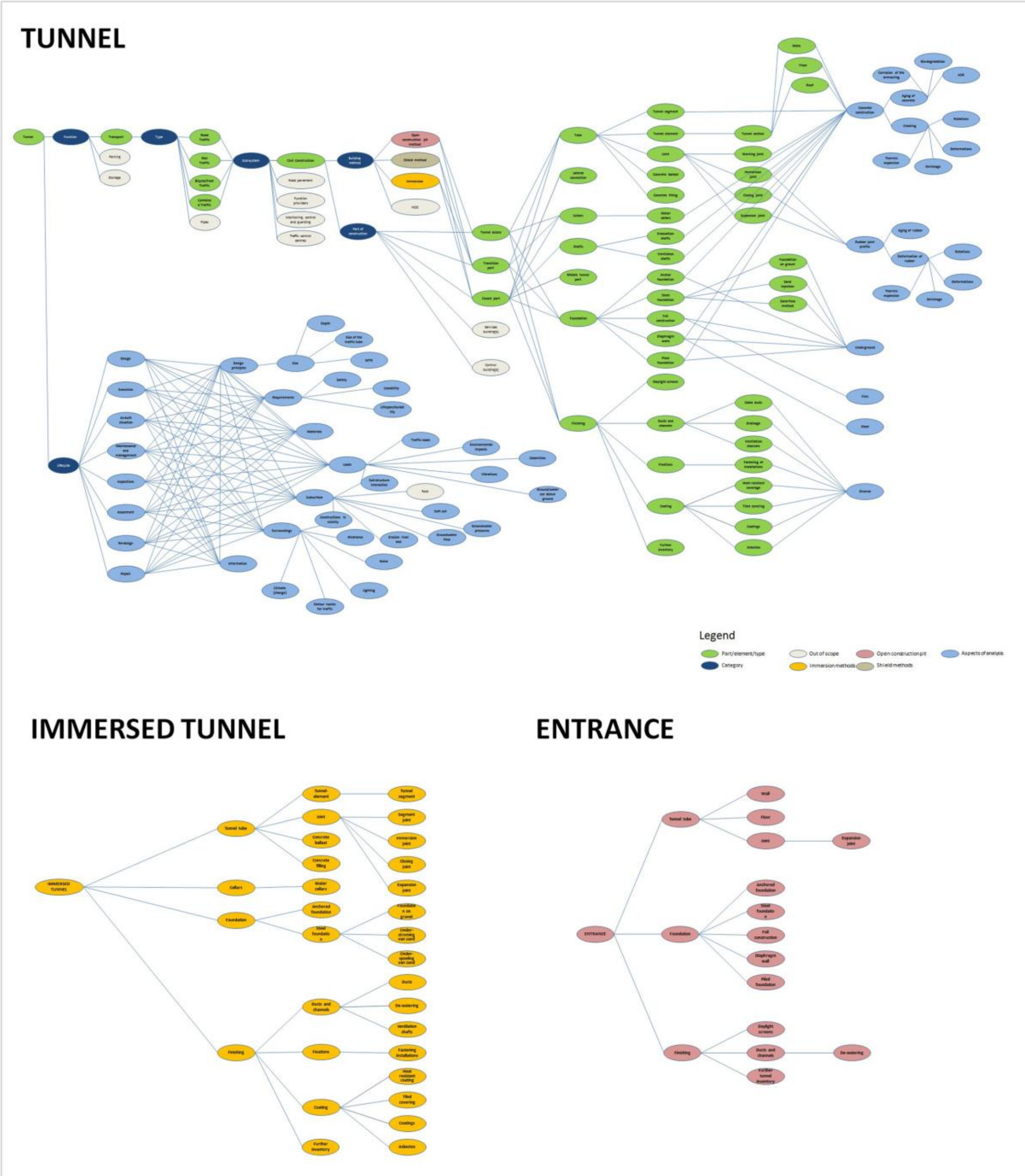

Figure 3: Mindmap scope

The main aspects of this mind map are:

- The main function of the tunnel is transport
- The design can be subdivided in the requirements, and the (calamity) loads. The difference between the as built situation (details of which are often not available any more for the existing tunnels) and the design is very important information. This information can be used to identify the “gaps” in our knowledge, and can possibly predict events that occur during the life cycle
- The entrance ramp and the transition part between the closed and open structure is a crucial component. This is the part where the tunnel is fixed and the most problematic part where shear forces come together.
- The surroundings greatly influence the behaviour of the tunnel through the years. The subsurface and the groundwater levels are important to consider, as well as the loads. Furthermore, the effect of the tunnel on the surroundings should be considered. Climate change, traffic loads, vibrations in alldirections, and erosion of the cover layer above a tunnel can cause problems.
- Special situations can occur when for instance asbestos needs to be removed.

The immersed tunnel is taken as an example to identify problems with:

- Aging and fatigue of concrete as well as leakages in the wall. The mechanisms of degradation are known. Discrepancy between how the concrete has been prepared (eg occurrence of cracks during production) and this may trigger aging. Alkali silica reactions, carbonation and corrosion of the reinforcement and the corrosion of anchors is important. Cracks reinforce these processes. Furthermore, problems such as the occurrence of fungi can be encountered when installations need to be fastened.
- For the entrance ramp, the concrete construction in this part is strongly impacted by the climate. The temperatures are different, and thus the repair approach will be different.
- The repair of the tunnel: How effective is repair? How to guarantee the safety during large scale repairs where, for instance, the complete reinforcement is exposed and separated from the concrete?
- Problems with the closure joints and the expansion joints are often encountered for this type of tunnel. Expansion joints: the rubber and its degradation is important. In the entrance ramp, degradation is worse due to penetration of UV.
- The foundation of the tunnel is an important part to consider, because it is often composed of poorly compacted sand.

3. What do we know?

Based on the experts in the group and the initial desk research we currently know:

1. In the tunnels, main degradation mechanisms of concrete and the mechanisms of influence on the life-expectancy of the c**oncrete** is well documented. Together with these, some protection measures for the concrete are known (eg. "Indicatie van de levensduur van de betonnen wand van de Westerscheldetunnel", (1999)). Internationally, standards have been developed to model the degradation processes and perform service life verification (e.g. fib "Model Code 2010 for Concrete Structures" (2013), ISO 16204:2012 "Durability -- Service life design of concrete structures"). Common shortcoming of those standards is that they are predominantly developed for the purpose of designing new structures and that they often lack precision in assessing the residual service life of existing structures affected by damage or undergoing progressive deterioration. Furthermore, information on effective renovation methods of aged concrete is lacking. Klaas van Breugel and his group of the TU Delft did extensive research on chloride-intrusion and other failure-mechanisms. Intensive research has on concrete durability also been done at TNO, which was one of the leading partners in *DuraCrete Brite-EuRam BE95-1347* (together with (from the Netherlands): CUR (coördinator), HBG, NPC, Bouwdienst RWS and Intron. During the Coentunnel renovation project, methods were established to define a definition of the global condition of the tunnel using statistical calculations, using analysis of important degradation processes of several tunnel elements. Several results(eg. Corrosion monitoring for underground and submerged concrete structures (2006)) have indicated that there are still many problems to be solved with regards to the aging of concrete, such as the problem of macrocel corrosion.

2. We have current models and guidelines to calculate the durability and the safety of underground structures, and we have made an effort to incorporate them into Eurocodes. One of the possibilities that gets particular attention in the recent decade is the use of those codes in association with data gathering and condition survey of existing structures, so to reduce model uncertainties and increase accuracy of condition assessment and service life prediction. Monitoring is becoming a fundamental tool to control the evolution in time of structural behaviour and to allow a predictive so pro-active, instead of reactive, policy to be used to control the maintenance process. The developing availability of low-cost micro-sensors (MEMS) is expected to allow their extensive use in the measurement of local behaviours (crack opening evolution, stress levels) and overall behaviour (displacements, rotations, accelerations). These processes are expected to evolve into the development of self-diagnosis procedures. While recognizing the promising perspective, it is obvious that at present knowledge is lacking about the optimal choice of performance indicators to be measure, interpretation of those data and value of the information provided by this data with respect to the assessment of structural performance and durability.

Next, the monitoring and inspection techniques should be improved, as interpretation of the current measurements is not always straightforward (eg. "Monitoring durability aspects of the Green Heart Tunnel lining"(2003), " Symposium Levensduur en onderhoud Groene Hart tunnel" (2003), "Performance evaluation of the durability monitoring system in the Green Heart Tunnel", (2006)). For instance, non-destructive condition survey and monitoring should be developed further (eg. "Niet-destructieve metingen naar corrosie in tunnelsegmenten met schadeplekken in de Westerscheldetunnel", (2002)) to get better insight in the processes that occur during the life cycle of the tunnel. Hence, the relevant questions are: What do we see, what does it mean and how can we make the right decision about what measures we should take based on the information obtained from the structures? Particular questions relate to the efficient monitoring of structures and the management of big sets of data, resulting in improved maintenance programs and asset management. A component of such condition-based asset management is the preparation and use of a database containing all the relevant data to allow effective and efficient management of the structure throughout its life cycle.

An aspect of through-life management is the implementation of the conservation and management strategies defined during design. This requires processes by which the condition of existing concrete structures can be evaluated and interventions undertaken. These activities may include measures such as possibly restricting usage, performing maintenance and undertaking interventions to extend service life and / or meet new performance requirements, as appropriate. In this respect, understanding and controlling the effectiveness of the measures is essential: What are the cost-optimal measures, do those measures really help or is the effect worse then the solution?

3. We know a lot about leakages (mostly about the Gina-profile.) Often leakage is related to poor concrete quality, especially around cast-in elements, or cracks and is treated by injection. But we cannot foresee future

leakage. We still miss a clear instruction about how to interpret leakage and how to take the right measurements but at this moment an expert group is writing an instruction manual for contractors and owners. What we don't know is what kind of mechanisms are the cause of the failure at a fundamental level. That is a problem because it gives us no clue our measurements are effective and adding to the life expectancy of the tunnel. Another COB- expert group is investigating the potential failure mechanisms causing leakage of immersion joints. Desk study and site investigation show the most likely failure mechanism is failure of the clamp connection of the watertight Omega profile. However due to position of this connection inspection and replacement are challenging. For instance, for the Coentunnuel renovation project, after risk analysis it was decided not to repair the dowel, as the risk was too large (eg. *Eerste Coentunnel - DO - Levensduur & Onderhoud - Ontwerpnota Modellering,* B.B. van den Bossche, I.J. Stork, A.A. Kirstein, C. Baduin (2013)) A thorough risk assesment is generally required in case of repair.

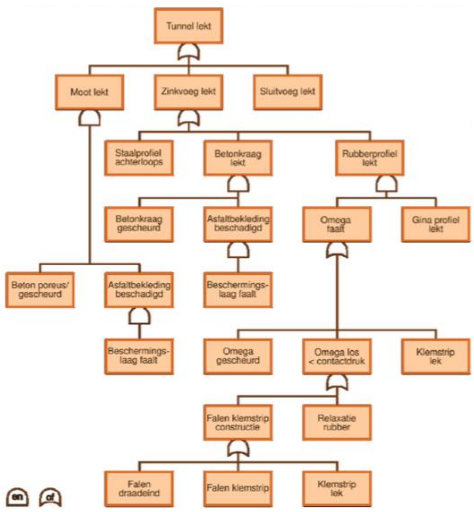

Figure 4: SEQ Figure \ Failure tree for leakages

4. We know a lot about soft soils and the mechanisms that occur over a longer period of time after you built something in that soft soil. Up until now research has been focussing on the construction stage of underground projects and we seem to have a lack of information about how structures perform during their lifecycle: only very few research projects (eg. Effect of surface loading on the hydro-mechanical response of a tunnel in saturated ground (2016), Impact of tidal level fluctuations on the structural behaviour of a segmental tunnel lining(2017)) have been carried out to identify what effects occur in the soil itself, the groundwater system and other objects that influence the tunnel itself (as waterways, dikes, large underground constructions nearby, old geological states etc.)

5. Our insights have changed a lot in the last 50 years. 50 years ago we underestimated deformations of tunnels once constructed and made calculations and designs based on very positive assumptions and now we see most of the tunnels translated, rotated, settled or becoming porous or corroded on vital parts. We have an educated guess about the reasons and failure mechanisms that occur but it remains a guess because we can only see the inside of the tunnel (and not what happens on the outside or underneath). The effect of all those aspects on the safety and durability is mostly unknown. We have some information about hidden strength in other object but the translation of that knowledge to underground objects hasn't been made yet.

6. The effect of changes in usage of tunnels (more intense traffic, changes in the surroundings) is unknown to this group. Hopefully the knowledge from the ageing center of the TU Delft will provide us with the necessary insights but otherwise we have to explore the possibility to ask people with this expertise to join us. Trends in mobility development and their effect on use of tunnels have been analysed in the Masterplan Tunnels of InfraQuest (2015).

7. If we look at future trends[3] we can see that tunnels are expected to be adaptive in the next 50 years. That adaptivity has of course the most influence on the installation and usages of tunnels and will have minor effects on the civil structure itself. But we can expect the city and the water to sneak up to the tunnel and,

[3] https://issuu.com/hetcob/docs/cob_langetermijnvisie-op-tunnels

because of that, influence the safety and stability and failure of the tunnel. For example, we see tunnels that lost half of their top pressure because of the increasing river depth; we see large windmills near tunnels and tunnels almost crossing each other in the underground because of expansion of the network capacity.
The effect of all these unexpected and complex interventions in the total system are highly unknown.

3.1 First impressions from stakeholders

On May the 30th we formed a focus group of both tunnel owners and -builders involved in renovation projects. We asked them, based on four hypotheses, to share their opinions and ideas. However limited this group and the workshop was, we did find the conclusions a good reference to the current state of perception of the main stakeholders.

By means of an interactive session four statements were given to a group of specialists, in order to identify the main gaps in the current knowledge. The following statements were proposed to the group:

1. We know very well what the state of the tunnel is.

The group replied that this is not self-evident, but depends strongly upon the managing authority. European law demands the monitoring of the state of the tunnel. However, some parts of the construction cannot be monitored, and these are often the critical parts. Generally, only in the parts of the tunnel where visual inspection can be done, the state of the tunnel is proven. Therefore, there is need for improvement of the current monitoring techniques. In order to save costs, the focus of the monitoring should be on the critical parts. Standards should be developed to record the most efficient methods of monitoring. An important factor that complicates the monitoring, is the change of building guidelines through time.

2. The failure mechanisms of tunnels are known

A majority of the group indicated that this is not on beforehand the case. Several important failure mechanisms were proposed by the group:

- Consolidation and changes in the subsurface
- groundwater flows can lead to flooding of the tunnel
- Detachment of the foundation and the concrete
- Degradation of the construction material as a consequence of for instance fire or thermic change
- Changes in the environment (effects of building, loss of tunnel cover layer after dredging)
- Mistakes made during renovation: eg. no good attachment old and new materials
- Fatigue
- Mistakes made in design or execution, loss of strength after renovation
- Failure of the GINA profile, for instance due to unexpected soil load
- corrosion of the joints

3. Repairs are proven to be effective, and increase the durability of the construction

The group replied to this statement that a repair is only a good repair if it is validated that an effective technique is chosen. The main repairs were divided in three groups: the concrete, the installations and the joints. A first step in effective repair is the indication of the current state of the element. In the repair, the guidelines should be reviewed with current knowledge, and the application of quality control is recommended. Sharing knowledge is essential to establish effective techniques of repair.

4. The scope of the renovation project can be easily determined

The group did not agree upon this statement. The difficulty is most of all to determine where the scope of the renovation project stops. Regularly this is on 150% of the original planned budget. Safety in the tunnel is however a primary driver in the definition of the scope. A method to define the scope can be to divide the tunnel up into several components. Also the future needs and sustainability should be taken up into the scope of the renovation. Hereby the full range of possibilities of future problems should be listed, and mitigation methods for for instance unexpected repair should be defined. Lessons could be learned from other renovation projects, such as buildings or bridges. Unplanned maintenance occurs quite often to unknown failure mechanism (for example the corrosion in the tension piles at the Vlaketunnel).

4. Preliminary conclusions; what do we want to focus on?

As an opening for discussion we would like to state that, based on all above, the following 7 topics are blank spaces in our puzzle:

1. Effect on the tunnel as a system
We do have fundamental knowledge and practical insight on most aspects of the tunnel but we have very little insight in the effect of all those loose aspects on the tunnel as a system (within a traffic system and within the surroundings and as a stand-alone object).

Structures shall be designed, constructed and maintained in such a way that they perform adequately and in an economically reasonable way during construction, service life and dismantlement. In this context, structures are perceived as an arrangement of interacting structural components, all together providing a solution to meeting performance requirements under a specified combination of (direct and indirect) actions. This implies that performance of a structure is a system problem and should therefore be treated taking into account structural system characteristics. This consideration is generic, hence it holds true for all performance aspects related to safety, serviceability and durability.

In the context of performance-based approach, durability refers to the fulfilment of the performance requirements during specified period of time and within the framework of the planned use and foreseen actions, without unforeseen expenditure on maintenance and repair. Considering the abovementioned system aspect of performance assessment, durability of a structure shouldl be understood as durability of a structural system composed of a number of components, adequately taking into account that a single component may also be prone to several failure modes of various importance. Therefore, the likelihood of durability loss (i.e. reaching the end of the required service life) should be assessed considering complexity of the structural system, taking into account both (1) the susceptibility of the individual components to (a number of) possible degradation mechanisms and associated failure modes and (2) the robustness of the structural system in respect to avoiding disproportional damage of a larger part of the structure. Note that the problem grows with the system size (number of system components) and degradation complexity: it shouldbe considered that system component s may interact while degradations may be related, possibly interacting or triggering each other.

2. Difference in insights then and now
The people who are responsible for the asset management of tunnels now look at those objects with the knowledge we have now. The effect of difference in insight (why was the tunnel built as it was built) and what kind of tunnel do we have now? This is a large concern but also a big chance. Looking at the tunnel now from knowledge of the past can help us make better predictions of failure mechanisms in the future.

3. Reality versus drawings
We know that almost every tunnel is not built as it was designed. Also there is very little as built-information available and often there is no well documented archive of every intervention in or around the tunnel. The basic information about the state of the soil/surroundings before the tunnel was built is also often missing. And last but not least sometimes faults are being made by constructors during building. So what do we know about our constructions, what do we own? It would be of great use to come up with a strategy to find this missing information in a way that is not only useful for an individual tunnel owner, but to get a better insight in over-object-problems and solutions.

4. What is safe?
Everything stated at 1, 2 en 3 has an influence on the aspect safety. What is safe ? What do we do when an object is not sufficient safe anymore to the current standards but isn't failing as a system? Do we know when failure occurs and how to define that risk both in investment as in consequence?

5. Does it help? Is there help?
If we have a fault tree of all the relevant failure mechanisms we hope to have options to repair. What we don't know is if these repair options really help in the long term. We also expect to find failure mechanisms without real solutions. And how to deal with the parts of the tunnel that cannot easily be reached, such as the foundation? What's the plan B?

6. Can we quantify the residual life?
If a renovation is worth the investment has a lot to do with the true life expectancy of the construction. The Maastunnel, the oldest tunnel in the Netherlands, is currently renovated for 262 million euro's. Is this a good investment ? Will we still say yes if in 50 years the construction is really failing?

7. Relationships and effects
We see that geology, climate change, different usage, pressure changes etc. all have effects but we know too little about the interaction and the effect on failure mechanism. We have interesting monitoring systems but little insight in the information behind the data and the smart way to implement a monitoring system.

Let's talk, discuss and improve. Please contact us at www.cob.nl: karin.dehaas@cob.nl or 0031 6 5429 1940.

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Appendix: Case interview at the Maastunnel

During the course of this investigation, experts of the Maastunnel renovation project were visited in order to gain information on the current state of the art methods in tunnel renovation. The Maastunnel case is unique, as it is the oldest and most drastic renovation that has occurred in the Netherlands until today. The tunnel was built around 1937, and is listed as a National monument. One of the main problems in this project was the impact of the tunnel closure on the city. No solutions to this problem were available and many compromises had to be made, leading to costs that reach far beyond the cost of the tunnel renovation itself. According to the specialists, attention should be paid to this aspect of tunnel renovation. In the Maastunnel case the concrete has been fully degraded, and needs to be removed. In this case the degradation of the material is chloride-initiated, and at a material level the current knowledge of repairs lacks severely. There are some guidelines for the chemical composition of the repair material, but there are no guidelines available on how to get this material to be attached to the old material. And there is no certainty on how with how many years this will increase the tunnel life. On these parts, more research is needed. A big problem in the Maastunnel is caused by Macrocel corrosion. Cathodic protection was not seen as a longtime solution to the problem, as the technique did not fulfill the durability requirements. Different, and more durable solutions should be developed in the future. In the case of the Maastunnel, the concrete is fully removed by hydrojetting and renewed. However, a very dangerous situation may occur when the armouring comes to lie fully free, while the water pressures remain the same. A lot of knowledge on this part is lacking as well. Another recommendation of the specialists was to develop monitoring methods for concrete whereby drilling of holes in the concrete is no longer necessary. In general, the monitoring and inspection methods of all non-visible parts of the tunnel should be improved

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