Insufficiency of immersion joints in existing immersed tunnels

Case study on functioning of Gina-seal and Omega-seal in the Kil Tunnel

Ruben van Montfort
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Saevis tranquillus in undis (“Rustig te midden van woeste golven”, lijfspreuk Willem van Oranje)

Insufficiency of immersion joints in existing immersed tunnels

Case study on functioning of Gina-seal and Omega-seal in the Kil Tunnel

by

Ruben van Montfort

to obtain the degree of Master of Science in Civil Engineering
at the Delft University of Technology,
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Graduation committee:	prof. dr. ir. S.N. Jonkman	TU Delft, chairman
	ir. K.J. Reinders	TU Delft
	dr. ir. W. Broere	TU Delft
	ing. J. Kloosterman	Nebest B.V.

Preface

This report is the result of the research performed to finish the Master Civil Engineering (specialisation Hydraulic Engineering) at the faculty of Civil Engineering and Geosciences at Delft University of Technology. The research is carried out at Delft University of Technology and for a small part at Trelleborg Ridderkerk. The report gives a complete overview of the research on the insufficiency of immersion joints in existing immersed tunnels.

For the reader who is not familiar with immersed tunnels, it is attempted to explain all relevant information on immersed tunnels in Paragraph 2.1. Tunnel managers are advised to read Chapter 6 (Application of results) and Chapter 7 (Conclusion and recommendations).

Finishing this research was not possible without the necessary guiding and critical notes of my graduation committee during the period of research. I would like to thank Bas Jonkman, Kristina Reinders and Wout Broere from Delft University of Technology and Jan Kloosterman from Nebest B.V. for their effort. I would also like to thank Joel van Stee (Trelleborg Ridderkerk) for his help. He offered me some important information about Gina-seals and Omega-seals and was always keen to answer my questions. Besides, I would like to thank Arie Bras (Wegschap Dordtsche Kil) for providing me all information on the Kil Tunnel. Also, I thank the members of the *Werkgroep Zinkvoegen* for their input to my research. The discussions of the team of tunnel experts were very valuable and gave me a better understanding on the problem. Besides, I would like to thank my family and friends. They encouraged me to pass this final project.

Delft, Wednesday the 31th of January 2018
Ruben van Montfort

Abstract

In 2009 and 2010, two leakages through immersion joints occurred in the First Coen Tunnel near Amsterdam. From the study on t-he cause of these leakages, it followed that there was a potential problem for existing immersed tunnels: failure of the temporary Gina-seal combined with corrosion on the clamping structure of the definitive Omega-seal. It is unknown whether the immersion joints of existing immersed tunnels in the Netherlands will still function during the remaining design lifetime. There is lack of calculations on the governing watertight parts (Gina-seal and Omega-seal) in immersion joints. The main goal of this research is to become both qualitative and quantitative insight into the watertightness of existing Gina-seals and Omega-seals in immersed tunnels. It is applied to the Kil Tunnel (case study).

Leakage through immersion joints can only take place when both the Gina-seal and the Omega-seal fail. The Gina-seal consists of a rubber gasket (the Gina-gasket) and a clamping structure that connects the Gina-gasket with the tunnel element. It can fail due to widening of the joint (due to seasonal temperature changes) combined with relaxation, increased soil pressure and differential movements of the tunnel elements. The Omega-seal consists of a rubber gasket (the Omega-gasket) and a structure that connects the flange of the Omega-gasket with both tunnel elements (the clamping structure). It can fail if the clamping structure is affected by differential movements, relaxation, corrosion and widening of the joint (due to seasonal temperature changes).

The Kil Tunnel (case study, finished in 1977, below Dordtsche Kil) consists of 3 tunnel elements, so it has 3 immersion joints (1A, 2E and 3A). Immersion joint 1A and 2E connect the tunnel to both abutments and are exactly the same. Immersion joint 3A connects two tunnel elements to each other. The Gina-seal and the Omega-seal are slightly different for 1A/2E and 3A.

The Gina-seal has to meet all of the following requirements in order to be watertight:

- Requirement G1 – Enough pressure in the Gina-gasket to stop water: The available pressure of the Gina-gasket should to be larger than the water required pressure to stop the water.
- Requirement G2 – Force equilibrium: The amount of friction force in the Gina-gasket should be larger than the sum of the water force and the soil force, in order to prevent that the Gina-seal is pushed away.
- Requirement G3 – Contact between Gina-gasket and opposite tunnel element: The Gina-gasket must press against the opposite tunnel element.
- Requirement G4 – Cracks in the Gina-gasket: When the Gina-gasket is compressed heavily for a long time, cracks could occur.

The result of the case study on the Gina-seal in the Kil Tunnel is the following:

- Joint 1A/2E may not meet Requirement G2 roof (Force equilibrium in the roof). This check requires attention. Therefore, it is recommended to do visual inspections in the roof of joint 1A/2E. All the other requirements are met with large margins.
- Joint 3A meets all requirements with large margins. It is expected that this Gina-seal fulfils its function over the entire lifetime.
- It is recommended to measure the value of maximum difference between winter and summer of the immersion joint in longitudinal direction (Δx) in all immersion joints.

The Omega-seal has to meet all of the following requirements in order to be watertight:

- Requirement O1: Enough pressure to stop water – The flanges of the Omega-gasket should be pressed strongly enough to both tunnel element in order to create a watertight layer.
- Requirement O2: Prevention of pulling out flange Omega-gasket – When differential displacements take place and hydrostatic pressure works on the Omega-gasket, horizontal loads act on the flange of the Omega-gasket. This should be prevented.
- Requirement O3: Cracks in the Omega-gasket – Strain of the curved part of the Omega-gasket, as a result of differential movements, can lead to cracks. This should be prevented.
- Next to the three requirements, there is also the requirement that the Gina-gasket may not be pushed away, because this could lead to damage to the Omega-seal.
- The bolt forms a crucial link within in the clamping structure. Therefore, the bolt also needs to meet a few requirements.

The result of the case study on the Omega-seal in the Kil Tunnel is the following:

- The compression of the flange of the Omega-gasket (c_O) determines strongly whether the requirements on watertightness are met. When the compression of the flange of the Omega-gasket is smaller than 5 mm, the

requirements are not met. This means that leakages through the immersion joint can occur. It is recommended to measure this value.

- The maximum allowed penetration depth of the corrosion is 2 mm of the core of the bolt. If this value is exceeded, the functioning of the bolt is not guaranteed anymore. It is recommended to remove a bolt at the "splash zone" in order to see how far the corrosion has penetrated the bolt. Besides, it must be checked whether the corrosion is an on-going process.
- When one bolt fails, the clamping plate will deform. As a result the forces on the adjacent bolts will be lower. It depends on the state of the bolt whether this is able to take the loads. This will determine whether the 'zipper effect' will occur.

This study has created a theoretical description of the state of existing Gina-seals and Omega-seals. However, visual inspections and measurements are also needed to judge whether the seals will function during the remaining lifetime.

Table of Contents

Nomenclature

α	thermic expansion coefficient of concrete	[K^{-1}]
γ_{B1}	safety factor of the surface in the bolt	[-]
γ_{B2}	safety factor of the clamping capacity	[-]
γ_{B3}	safety factor of the surface tension	[-]
γ_{G1}	safety factor of Requirement G1	[-]
γ_{G2}	safety factor of Requirement G2	[-]
γ_{O1}	safety factor of Requirement O1	[-]
γ_s	density of the soil	[kN/m^3]
γ_w	density of the water	[kN/m^3]
ΔL	elongation of a tunnel element	[m]
ΔT	temperature difference	[K]
Δx	maximum difference between winter and summer of the immersion joint in longitudinal direction	[mm]
Δy	differential movement of the immersion joint in y-direction	[mm]
Δz	differential movement of the immersion joint in z-direction	[mm]
μ	friction coefficient of rubber on steel	[-]
ρ_w	density of water	[kN/m^3]
$\sigma(t)/\sigma(t=0)$	part of the initial force that is still left after relaxation	[-]
φ	angle of the curved part of the Omega-gasket	[radians]
φ_1	angle in point A	[radians]
φ_2	angle in point B	[radians]
a	coefficient for seasonal temperature changes	[-]
A_{nut}	surface of the nut	[mm^2]
$A_{T,pr}$	surface bolt present	[mm^2]
$A_{T,req}$	surface bolt required	[mm^2]
A_{washer}	surface of the washer	[mm^2]
c_G	compression of the Gina-gasket	[mm]
c_O	compression of the flange of the Omega-gasket	[mm]
d	diameter bolt	[mm]
d_{pcp}	distance between the plate and the clamping plate	[mm]
$d_{n,max}$	diameter of the outer side of the nut	[mm]
$d_{n,min}$	diameter of the inner side of the nut	[mm]
d_p	penetration depth of the corrosion	[mm]
$d_{w,max}$	diameter of the outer side of the washer	[mm]
$d_{w,min}$	diameter of the inner side of the washer	[mm]
d_3	core diameter	[mm]
F_b	force in bolt	[kN]
$F_{rf,pr}$	reaction force present per bolt	[kN]
F_{sp}	clamping capacity	[kN]
F_v	vertical force Omega-gasket per bolt	[kN]
F_{VM}	prestressing force	[kN]
$h_{O,fl,or}$	original height of the flange of the Omega-gasket	[mm]
$h_{O,fl,pr}$	present height of the flange of the Omega-gasket	[mm]
k_A	tightening factor	[-]
l_c	distance between point A and point B	[mm]
$l_{c,0}$	initial distance between point A and B	[mm]
$l_{c,1}$	absolute distance between point A and point B (by calculation method 1)	[mm]
$l_{c,2}$	absolute distance between point A and point B (by calculation method 2)	[mm]
L_0	length in the beginning	[m]
n_f	friction force of the flange of the Omega-seal	[N/mm′]
n_h	force in the flange of the Omega-seal working in horizontal direction	[N/mm′]
$n_{G,fr}$	friction force in the Gina-gasket	[N/mm′]
$n_{G,in}$	amount of force that is present in the Gina-gasket when it is completely new	[N/mm′]
$n_{G,pr}$	force with which the Gina-gasket presses onto the opposite tunnel element	[N/mm′]
n_0	force in the curved part of the Omega-gasket	[N/mm′]
$n_{rf,pr}$	reaction force of the flange of the Omega-gasket (accounted for relaxation)	[N/mm′]
n_{soil}	force caused by the soil	[N/mm′]
$n_{soil,roof}$	force of the soil working on the Gina-seal in the roof	[N/mm′]
$n_{soil,wall}$	force of the soil working on the Gina-seal in the wall	[N/mm′]
n_{total}	total force working on the Gina-seal	[N/mm′]
n_v	force in the curved part of the Omega-gasket, working in vertical direction	[N/mm′]
n_{water}	force caused by the water column	[N/mm′]
p_G	maximum surface pressure below nut that is allowed	[N/mm^2]
$p_{G,pr}$	resistance pressure of the Gina-gasket against the opposite tunnel element	[N/mm^2]

p_{nut}	present surface pressure below nut	[N/mm^2]
$p_{O,pr}$	resistance pressure of the Omega-gasket	[N/mm^2]
p_{washer}	present surface pressure below washer	[N/mm^2]
p_{water}	pressure caused by the water	[N/mm^2]
p_{ws}	calculation value of water pressure	[N/mm^2]
r_{Gina}	relaxation per decade of the Gina-gasket	[%]
r_{Omega}	relaxation per decade of the flange of the Omega-gasket	[%]
R	present radius of the Omega-gasket	[mm]
R_{Omega}	initial inner radius Omega-gasket	[mm]
R_0	initial radius Omega-gasket	[mm]
s_{bof}	distance between bolt and outside flange Omega-gasket	[mm]
s_{bop}	distance between bolt and outside plate	[mm]
s_{bsb}	distance between bolt and steel bar	[mm]
s_{cb}	distance between the end of the clamping plate and the steel bar	[mm]
s_{cw}	width of the surface of the Gina-gasket that is pushed against the opposite tunnel element	[mm]
s_{cp}	length curved part Omega-gasket	[mm]
s_{ctc}	centre-to-centre distance bolts	[mm]
s_{dp}	deepest point joint (relative to NAP)	[m]
s_{jwp}	joint width that is present in the joint	[mm]
s_{jws}	joint width during the warmest point in summer	[mm]
s_{jww}	joint width during the coolest point in winter	[mm]
s_{gwt}	height governing water table below dike	[m]
s_{hd}	height dike (relative to NAP)	[m]
s_{ht}	height of the tunnel	[mm]
s_{mf}	distance between the middle of the flange of the Omega-gasket and the steel bar	[mm]
s_{mo1}	distance between Gina-gasket and Omega-gasket	[mm]
s_{omf}	distance between outside and middle flange Omega-gasket	[mm]
s_{sc}	height of the sand cover of the tunnel	[mm]
s_{wc}	height of the water column	[m]
s_{ws}	width clamped flange	[mm]
t	time after immersion	[years]
t_{Omega}	thickness curved part Omega-gasket	[mm]
$u_{y,1}$	movement in y-direction of tunnel element 1	[mm]
$u_{y,2}$	movement in y-direction of tunnel element 2	[mm]
$u_{z,1}$	movement in z-direction of tunnel element 1	[mm]
$u_{z,2}$	movement in z-direction of tunnel element 2	[mm]

List of figures

List of tables

1

Chapter 1 – Introduction

In this chapter, the research is introduced. First, the cause is stated. Then the goals of the research are described by means of the research question and the working method. Then, an overview of the report structure is presented.

1.1. Cause of the research

In this paragraph, the research is introduced. Firstly, the cause is clarified (1.1). Secondly, the goals of the research are stated (1.2). Afterwards, an outline of the report structure is given (1.3).

1.1.1. Background

Immersed tunnels form, next to bridges, land tunnels and bored tunnels, important links within the railway and road network in the Netherlands. They form a fixed link to cross waterways. Since these tunnels are below the water table, there is the potential of leakages.

Leakage on itself is not a problem, as long as it does not hinder the traffic in the tunnel or decrease the structural integrity of the structure. Water in the tunnel may freeze in winter, leading to dangerous situations. When water hinders the traffic, the tunnel needs to be closed, leading to economic damage. It is assumed that maintaining the watertightness is the only way to prevent hindrance from leakage water. When all elements that keep the tunnel watertight maintain their function, the amount of leakage water that enters the tunnel is so small, that hindrance will not take place.

There are basically two ways for water to leak into an immersed tunnel: via the concrete case and via the joints. Leakage via the concrete does happen. However, the amount of leakage water is rather small, since the walls of an immersed tunnel are about 1 meter thick. Cracks did occur during construction, but most of them could directly be repaired.

There are three types of joints in an immersed tunnel: expansion joints, closure joints and immersion joints. In the expansion joints, leakages have taken place. Research is done (Leeuw, 2008), and the procedures to deal with these leakages are known. In closure joints, there have not been any problems with leakages in the past (Berkhout, 2014).

Watertightness of immersion joints is provided by two watertight rubber layers: the Gina-seal (temporary seal) and the Omega-seal (definitive seal). When both seals fail, leakage occurs.

However, in 2009 and 2010, two leakages through one and the same immersion joint occurred in the First Coen Tunnel near Amsterdam. In order to find out how these leakages could happen, a team of experts, the *Commissie Zinkvoegen* ('Committee on immersion joints') was founded. Although it is not fully proven, the committee agrees that the leakages in the First Coen Tunnel were caused by cracks in the concrete frame of the immersion joint.

Next to that conclusion, it followed that there was another potential problem. Corrosion on the clamping structure of the Omega-seal (an important watertight layer in the immersion joint) was detected, which could lead to leakages in immersed tunnels. In the First Coen Tunnel, this was considered not severe enough to be replaced. However, in other tunnels this corrosion can be present too, possibly leading to failure of the Omega-seal.

1.1.2. Problem

Apart from the First Coen Tunnel, no major leakages through the immersion joints are known. However, it is unknown whether the immersion joints of existing immersed tunnels in the Netherlands will still function during the remaining lifetime. There is a lack of a detailed description of the qualitative failure mechanisms of the governing watertight parts (Gina-seal and Omega-seal) in immersion joints. Besides, there is lack of a quantitative assessment of the remaining capacity of the Gina-seal and the Omega-seal.

1.1.3. Relevance

Two immersed tunnels (First Heinenoord Tunnel near Barendrecht and Kil Tunnel near Dordrecht) will have large scale maintenance scheduled within 5 years. After maintenance of these tunnels, some more tunnels will follow, since there are 23 immersed tunnels in operation in the Netherlands. Maintenance or repair of immersion joints is a rather costly operation, since the joints are hard to access.

Because of the importance of the availability, the immersed tunnels need to be closed as short as possible for maintenance or repair. Knowledge of the problem leads to optimisation of the maintenance or repair period. This will reduce the costs and the hindrance.

1.2. Goal of the research

In this paragraph, the goal of the research is stated. The research question, following from the problem, is given. Once knowing what to find out, focus will be on how to find this out. Also, some boundary conditions and starting points are given to create the scope of the research.

1.2.1. Research question

The main goal of this research is to obtain both qualitative and quantitative insight into the remaining capacity of existing Gina-seals and Omega-seals in immersed tunnels. This is translated into a research question that reads:

"When is the condition of the Gina-seal and the Omega-seal of existing immersed tunnels considered insufficient against leakages?"

The research question is divided into some key questions. The key questions read:

- How can leakages in existing immersed tunnels occur?
  This question covers "existing immersed tunnels" and "against leakages" and is answered in Chapter 2.

- What are the characteristics of the Kil Tunnel (case study)?
  This question does not cover any term from the research question and is answered in Chapter 3.

- When does the Gina-seal fail?
  This question covers "Gina-seal" and is answered in Chapter 4. It is applied to an existing tunnel (case study).

- When does the Omega-seal fail?
  This question covers "Omega-seal" and is answered in Chapter 5. It is applied to an existing tunnel (case study).

- How can the information from this study be used for the Kil Tunnel and other existing tunnels in the Netherlands?
  This question does not cover a word from the research question and is answered in Chapter 6.

1.2.2. Working method

In order to judge whether the state of an immersion joint is still sufficient, two approaches are needed:
- Theoretical: Make calculations / considerations in order to determine remaining capacity.
- Practical: Open the joint, make visual observations and measurements.

In this report, the theoretical part is treated. However, to judge whether the immersion joint still functions, observations are important, too. The observations can also be used to improve the theoretical model.

In order to follow this theoretical approach, a first analysis of the problem is made by performing a literature study. This contains an overview of immersed tunnels, immersion joints and leakages. Since every tunnel is slightly different, one tunnel needs to be chosen as a case study. Choice of this tunnel and description of this tunnel will follow.

Afterwards, the two watertight seals of this tunnel are considered. That is done with basically the same approach. The steps are:
- First, the requirements of the seals are stated.

- Afterwards, the calculation method of this seal is described. With this method, the input values of the requirements can be found.
- Then, it is assessed which factors decrease the functioning of the seals. It is described how these values are quantified.
- This is applied to a case study (Kil Tunnel). The requirements are checked. It is judged whether the immersion joints will still function.

1.2.3. Boundary conditions and starting points

In order to define the scope, some boundary conditions and starting points are needed.

The following boundary conditions are used:
- The tunnels that are considered are road and railway tunnels in the Netherlands. Tunnels that are used for pipelines are not considered. It is assumed that the design lifetime of these tunnels is 100 years.
- The tunnels that are considered are concrete immersed tunnels. Tunnels that have a steel shell are not considered (Grantz, 1993). Therefore, the Maas Tunnel in Rotterdam is not considered.
- The tunnels that are considered use the expansion joint concept. Tunnels that use the waterproofing membrane concept are not considered (Grantz, 1993).
- The case study is related to the Kil Tunnel near Dordrecht. This is one of the Dutch immersed tunnels that will have large-scale maintenance within a few years.
- The focus is on the functioning of the Gina-seal and Omega-seal. The concrete parts of the immersion joints are not considered.

The following starting points are used:
- The work of the Commissie Zinkvoegen is continued. The results of the report 'Instandhouding zinkvoegen' and the reports on (endoscopic) research by Nebest (Leo Leeuw and Jan Kloosterman) play an important role in the research.
- For the calculations, the design methods of Trelleborg Ridderkerk, the supplier of Gina-gaskets and Omega-gaskets, are used. Since these are used for new seals, a transfer of these methods for existing seals is made. Therefore, some equations had to be adapted to the situation of an existing immersion joint.

1.3. Report structure

After knowing the cause and the goal of the research, the literature study is performed in Chapter 2. In the literature study, background information on the topic is found and filtered. Goal of this chapter is to present relevant information related to the topic. First, some general information on immersed tunnels is given. Later, information becomes more specific, focussing on the immersion joints and leakages.

In Chapter 3, a description of the Kil Tunnel (case study) is made. First, it is explained why this tunnel is chosen. Then a description of its design and location is presented. The relevant information from the design and the present state are described. This information will be used in the calculations of Chapter 4 (on the Gina-seal) and Chapter 5 (on the Omega-seal).

In Chapter 4, one of the two conditions for leakage through an immersion joint is considered: failure of the Gina-seal. After a description of the requirements of the Gina-seal in general, the mechanisms that determine the watertightness are explained. Then, calculation methods of the watertightness and functioning are explained. Afterwards, a case study on the Kil Tunnel is performed. It is calculated whether the Kil Tunnel meets the prescribed requirements.

In Chapter 5, the second of the two conditions for leakage through an immersion joint is considered: failure of the Omega-seal. After a description of the requirements of the Omega-seal in general, the mechanisms that determine the watertightness are explained. Then, the calculation methods of the watertightness and functioning are explained. Afterwards, a case study on the Kil Tunnel is performed. It is calculated whether the Kil Tunnel meets the prescribed requirements.

In Chapter 6, the Kil Tunnel is compared with some other existing tunnels. It is judged whether the model can be used for these tunnels. Furthermore, some recommendations how to improve the model are presented.

In Chapter 7, conclusions and recommendations are presented.

2

Chapter 2 – Leakages through immersion joints

In this chapter, background information on the topic is presented. Goal of this chapter is to present relevant information related to the topic. First, some general information on immersed tunnels is given. Later, information becomes more specific, focussing on the immersion joints and leakages. It is stressed that in this chapter standard procedures on the immersion process and the design of an immersed tunnel are described. Per project, other options can be chosen when this is needed in the specific situation.

2.1. Immersed tunnels

In order to understand the problem, some background information on immersed tunnels is needed. This information is provided in this paragraph.

2.1.1. Principle of immersed tunnels

An immersed tunnel is a type of tunnel that is mainly used to cross a river or a channel. It provides a fixed connection between both sides of the river or the channel. The tunnel can be used for roads, railway or pipelines.

When a river needs to be crossed, there are several options to do this. When the volume of the traffic is significant, a fixed connection is needed. A tunnel is amongst others one of the option. The advantage of a tunnel is that it does not harm the landscape. There are three construction methods for tunnels (Bakker, 2014):

- Immersed tunnel – An immersed tunnel is placed in a trench on the bottom of the waterway. It is appropriate when the river or channel is rather wide and when navigation is important. Construction of an immersed tunnels leads to little hindrance to the waterway.
- Bored tunnel – A bored tunnel is bored from one side of the waterway to the other side of the waterway. It lies relatively deep and is therefore expensive. However, it does not hinder the navigation in the waterway at all.
- Cut and cover tunnel – A cut and cover tunnel is built using a building pit and is relatively cheap. However, during construction it hinders the navigation.

In Figure 1, it is shown how an immersed tunnel and a bored tunnel are located compared to a bridge.

Figure 1: Depth and length of an Immersed tunnel compared to a bored tunnel and a bridge (ITA, 2011)

2.1.2. Construction method

An immersed tunnel consists of prefabricated elements. These elements are constructed in a dry dock. The element is prestressed and the element is floated to the site (Bakker, 2014). At the site, the elements are immersed and connected to each other and to the abutment (in this case the land tunnel). Afterwards, the foundation is placed and the prestress is removed. A schematic view is shown in Figure 2. An immersed tunnel always consists of an immersed part ("closed part" in Figure 2), a land tunnel ("transitional part" in Figure 2) and an inclined access route.

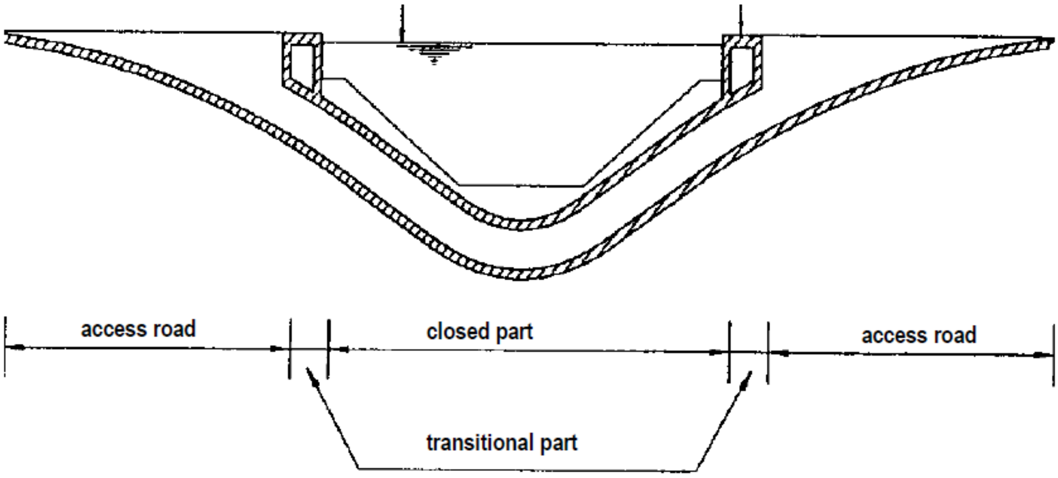

Figure 2: Schematic longitudinal of an immersed tunnel (ITA, 2011)

2.1.3. Maintenance of immersed tunnels in the Netherlands

Immersed tunnels are very important structures in the Netherlands. These tunnels are part of the network of railways and roads. The tunnels form important road links for the accessibility of the cities Amsterdam and Rotterdam and the province of Zeeland. In the Netherlands, 23 immersed tunnels are in operation (KIVI-TTOW, 2011).

A significant part of these tunnels, 9 tunnels in total, are built in the period from 1961 until 1980. An overview of these tunnels is shown in Table 1 (Molenaar, 1993). These tunnels have reached lately or will in a few years reach the age of 50 years. This is half of the planned design life time. Around this milestone, large-scale maintenance is needed. The First Coen Tunnel has recently had the large-scale maintenance (2013-2014). Large-scale maintenance of both the First Heinenoord Tunnel and the Kil Tunnel is on the agenda and will take place within a couple of years. Maintenance of immersed tunnels will remain an important topic, because of the large amount of immersed tunnels that are in operation in the Netherlands.

After certain period of use the quality of a structure may have decreased. There are a few actions that can be executed to bring the quality back to the required level:

- Replace (parts of) the structure;
- Repair (parts of) the structure;
- Maintain (parts of) the structure, such as cleaning and painting.

From now on, replacing, repairing and maintaining will all be called 'maintenance' in the rest of the report. This word covers the activity of improving the quality when it is insufficient the best.

Maintenance of immersed tunnels can be split into two categories:

1. Structural maintenance: Maintenance of the rough, concrete structures, such as foundation, tunnel tube and connections.
2. Operational maintenance: Maintenance of the finishing parts, such as installations and asphalt. Also, improvement of the tunnel safety is part of this kind of maintenance.

The emphasis during large-scale maintenance is on operational maintenance. However, since the tunnel is closed, it is also possible to do (preventive) structural maintenance. Preventive structural maintenance will in case of tunnels always be preferred above corrective maintenance, since it will most probably be cheaper and more predictable, leading to less traffic hindrance.

Name	Year of opening	Location	Function	Status	Design drawings available
First Coen Tunnel	1966	Below North Sea Channel, Amsterdam	Highway, part of Amsterdam Ringways	Large scale maintenance done, 2013-2014	Yes
First Benelux Tunnel	1967	Below New Meuse, Vlaardingen / Schiedam	Highway, part of Rotterdam Ringways	Unknown	Yes
Rotterdam Metro Tunnel	1968	Below New Meuse, Rotterdam	Metro	Unknown	Yes
IJ Tunnel	1969	Below IJ, Amsterdam	City route (vehicles)	Unknown	No
First Heinenoord Tunnel	1969	Below Old Meuse, Barendrecht	Highway	Large scale maintenance on the agenda (Berkhout, 2017)	Yes
Vlake Tunnel	1975	Below Channel South Beveland, Schore	Highway	Unknown	Yes
Drecht Tunnel	1977	Below New Meuse, Dordrecht	Highway	Unknown	No
Kil Tunnel	1978	Below Dordtsche Kil, Dordrecht	(Toll) provincial road	Large scale maintenance on the agenda (Berkhout, 2017)	Yes
Botlek Tunnel	1980	Below Old Meuse, Port of Rotterdam	Highway	Unknown	Yes

Table 1: Overview of the 9 immersed tunnels in the Netherlands that are built between 1961 and 1980 (Molenaar, 1993)

2.1.4. Leakages in immersed tunnels

Since immersed tunnels are built under water, there is a risk of leakages. Leakage on itself is not a problem, as long as it does not hinder the traffic in the tunnel or decrease the structural integrity of the structure. When water hinders the traffic, the tunnel needs to be closed, leading to economic damage. It is assumed that maintaining the watertightness is the only way to prevent hindrance from leakage water. When all elements that keep the tunnel watertight maintain their function, the amount of leakage water that enters the tunnel is so small, that hindrance will not take place.

There are four potential leakage routes for water to enter the tunnels:
- Through the concrete in the roof, wall or floor;
- Through the expansion joints;
- Through the immersion joints;
- Through the closure joints / final joints.

In Figure 3, it is shown where the joints are located in the immersed tunnel.

Significant leakage through the concrete does not occur. During production, some cracks occurred. However, most of them were repaired. Concrete keeps a bit porous, so small amounts of water may pass this layer. However, the quantities are too small to cause problems.

Leakage through the expansion joints is a common leakage route. Research has already been done and solutions for this problem are available. Therefore, these kinds of leakages are out of the scope of this research (Leeuw, 2008). Leakage through final joints has never taken place in the past. Therefore, this is not taken into account in this report.

Leakage through immersion joints did happen in the past, for example is the First Coen Tunnel. Although some research and inspections are done on this subject, there is still relatively little known about this topic. Therefore, the immersion joints have the focus when it comes to the functioning of immersed tunnels.

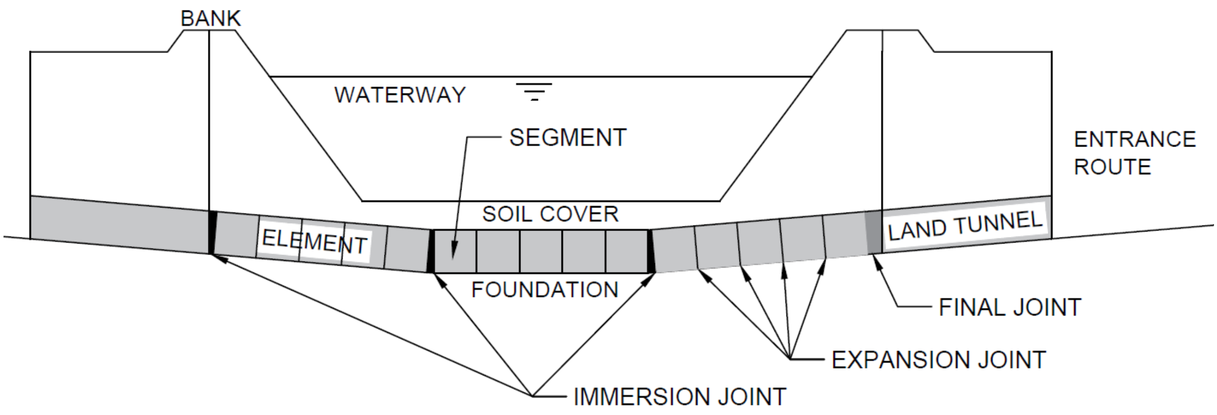

Figure 3: Longitudinal cross section of a tunnel, showing the location of the joints (not on scale, based on (Rijkswaterstaat, 1974))

2.2. Functioning of immersion joints

Now it is known what immersed tunnels are, when they are used and where leakages may occur, the focus will be on the immersion joints. The design of the immersion joint is written about.

2.2.1. Construction method of immersion joints

As described in Section 2.1.2, immersion joints form the connection between two tunnel elements. In this section, it is described how these joints are constructed.

During transportation, temporary walls are built at the other ends of the tunnel elements. These are called bulkheads. They are important, since the tunnel element can float because of these walls. However, the bulkheads need to be taken out in order to create an ongoing tube.

Immersion joints are the connections between tunnel elements. The outer ends are placed on tiles that lie at the bottom of the river. When two elements need to be connected, the element with the Gina-gasket on it is pushed onto the other element by a tugboat (step 1, Figure 4). It is pushed so strongly onto the other element, that a watertight chamber (filled with water) in between both tunnel elements is created. Then, the water on the inside of the chamber is pumped away (step 2, Figure 4). Now, one tunnel element is pushed even stronger to the other one, since the water on the other outer end pushes against it (step 3, Figure 4).

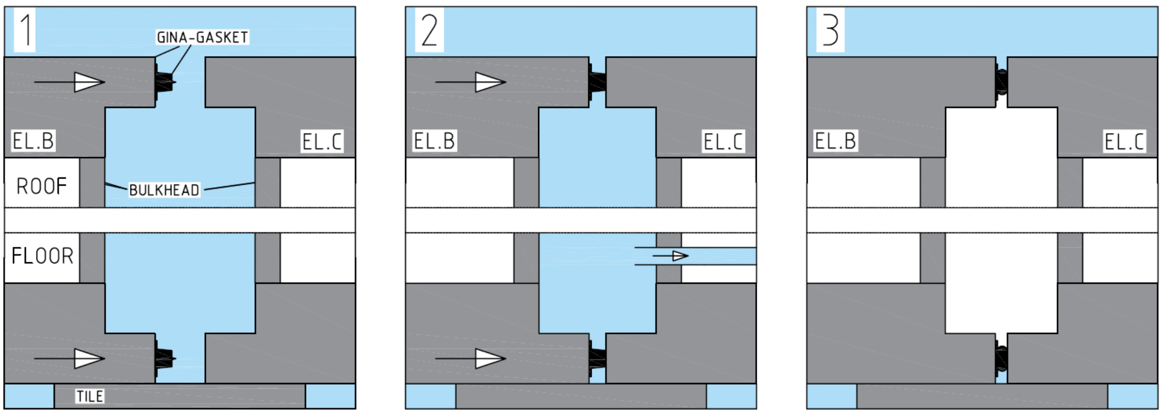

Figure 4: Schematic view of step 1 until 3 of the construction process (based on (Schols, 2012))

During connection of the tunnel elements, the tunnel lies on temporary tiles. The definitive foundation still needs to be made. The first step is to pump sand under the tunnel elements ("sandflowing"). Then, the tiles need to be removed. There are basically two procedures to install the Omega-seal then. These are:

A. The Omega-seal is installed before the consolidation period. The bulkheads are taken away and the Omega-seal is placed. The tiles and the prestress are removed, so the tunnel segments can find their position. During the consolidation period (about 4 weeks), the tunnel elements settle. This could lead to differential settlements of both tunnel elements. As a result, the shape of the Omega-gasket will change.

B. The Omega-seal is installed after the consolidation period. The bulkheads are kept intact. The tiles and the prestress are removed, so the tunnel segments can find their position. During the consolidation period (about 4 weeks), the tunnel elements settle. When this period is finished, the bulkheads are taken away and the Omega-seals are placed. It is important that both tunnel element are at the same height. Otherwise, the Omega-gasket cannot be installed.
   When difference in settlement between the two tunnel elements is expected, the element that is going to settle more is placed on a higher bed. This is done in order to compensate for the expected settlement, and to get both tunnel elements at the same level after the consolidation. If they are not at the same level, the Omega-gasket cannot be placed. However, when it is expected that both tunnel elements will have the same amount of settlement, this procedure is not necessary.

Procedure A is shown in Figure 5. Procedure B is shown in Figure 6. They are described as steps 4 and 5. Step 4 is just before the consolidation period. Step 5 is just after the consolidation period.

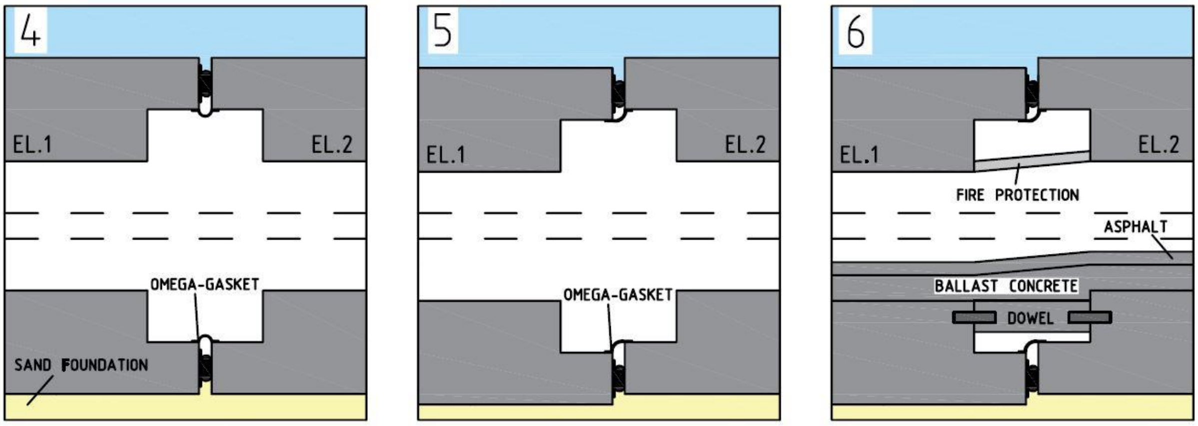

Figure 5: Schematic view of procedure A, showing that the Omega-gasket is placed before the consolidation period, resulting in possible differential settlements (based on (Schols, 2012))

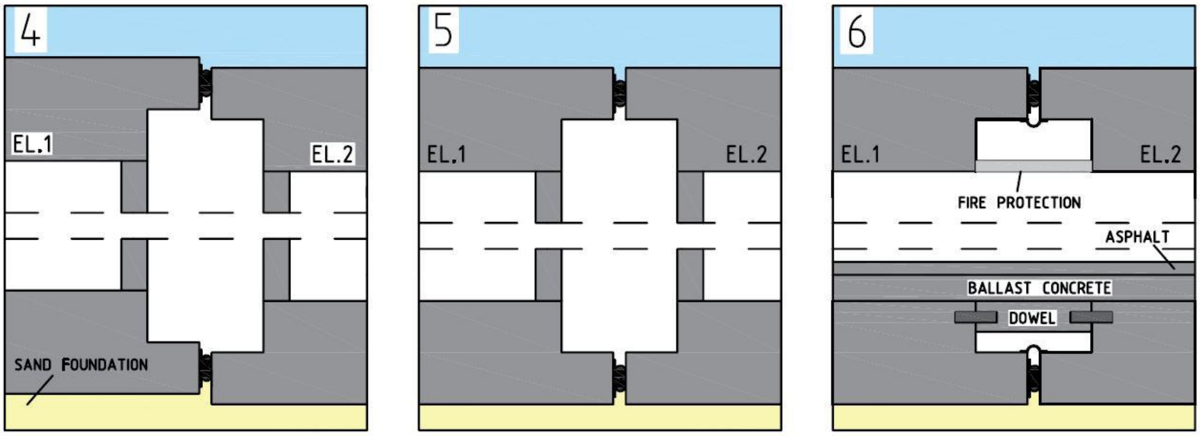

Figure 6: Schematic view of procedure B, showing that the Omega-gasket is placed after the consolidation period, resulting in an immersion joint without differential settlements (based on (Schols, 2012))

When the consolidation period is finished, the dowels are placed. This is shown in step 6 of Figure 5 and Figure 6. In procedure A, the execution procedure could lead to differential settlements. This has an effect on the forces that can occur in the Omega-seal. This will be treated in Chapter 5.

2.2.2. Components of the immersion joints

One of the requirements of an immersion joint is that it needs to create a watertight layer. Besides, the elements should be able to limitedly rotate and move. The joints should therefore be able to take the loads from the small displacements and rotations of the tunnel elements. Before the dowels are placed, the flexibility is very important because significant settlements of the tunnel elements take place. However, still tunnels move slightly during the period of use. The dowels are able to take these settlements.

In Figure 7, a detail of the cross section of an immersion joint is shown. Some components are in every immersed tunnel. These are the Gina-seal, the Omega-seal and the concrete frame. The Gina-seal and the Omega-seal form the watertight layer. The concrete frame is a strong element that transfers loads of the joint to the foundation. It can be reinforced with steel on the outside in order to have a higher strength. Some components differ over the cross sections. These are the dowel, ballast concrete, concrete fill and fire protection. In Table 2, the functions are presented.

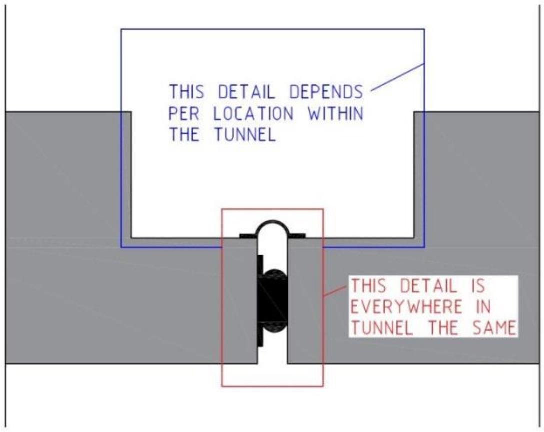

Figure 7: Schematization of the locations where the detail differs over the cross section

	Component	**Function**
This detail is everywhere in the tunnel the same	Gina-seal	Watertight layer during construction
	Omega-seal	Watertight layer during use
	Concrete frame	Strong element that can transfer the loads from the joint to the foundation
This detail depends per location within the tunnel	Dowel	Strong element that hinders differential settlement
	Ballast concrete	Add mass to prevent floating of the tunnel
	Concrete fill	Protect the Omega-seal, add mass to prevent floating of the tunnel
	Fire protection	Protect the Omega-seal against fire in the inside of the tunnel

Table 2: Components in the immersion joint with their function

It is important to note that in between the Omega-seal and the concrete layer on top of the immersion joint, there is a hollow space. This forms a 'chamber' over the whole cross section. In case of road tunnels, this chamber is filled with water from the road. The water table is at about the level of the road, since the water comes from the road. Over time, it has somehow found a way through the concrete. The water in this chamber contains de-icing salts (Leeuw, 2015). The location of this chamber is shown in Figure 8. Corrosion could take place at this location.

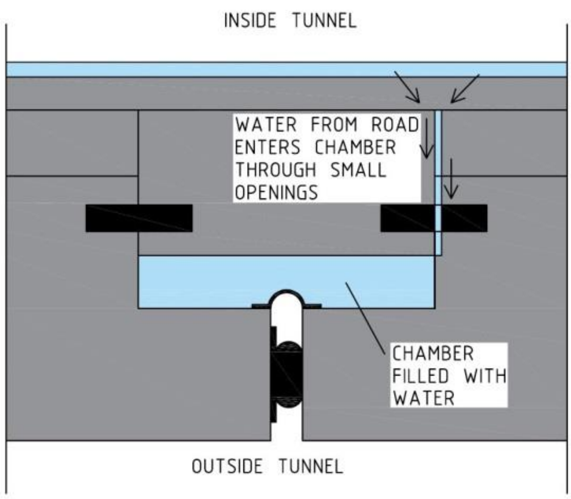

Figure 8: Location of the chamber that is filled with water

2.2.3. Design immersion joints over the cross section

As shown in Table 3, the joints consist of several components that all have a specific function. In this section, it is shown where these components are used over the cross section.

The details differ over the cross section. Basically, there are three different details. These are at the following locations:

- In the floor;
- In the wall;
- In the roof.

In Section 2.2.2, it was described that the Gina-seal, the Omega-seal and the concrete frame are the same over the entire cross section. However, there are also components that differ over the floor, wall and roof. In Table 3, it is shown where the components can be used over the cross section of the tunnel. A few examples are shown below.

Location	**Component**			
	Dowel	Ballast concrete	Concrete fill	Fire protection
Floor	Common location	Common location	Common location	Possible, but not common
Wall	Possible, but not common	Possible, but not common	Lower part of the wall: common location Upper part of the wall: possible, but not common	Common location
Roof	Possible, but not common	Possible, but not common	Possible, but not common	Common location

Table 3: Overview of where the components of an immersion joint can be used over the cross section of the tunnel

Detail of the floor

In the detail in Figure 9, dowels are used. Ballast concrete is placed next to the concrete fill. On top, a layer of asphalt is placed since this a road tunnel.

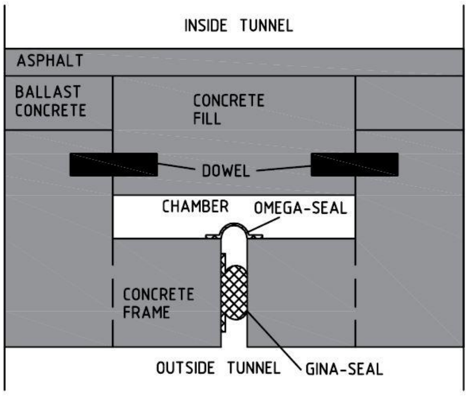

Figure 9: Example of the detail of the immersion joint in the floor

Detail of the wall

In the detail in Figure 10, no dowels are used. There is only a concrete fill that needs to protect the joint when a car or train hits the immersion joint. Although it is not shown in Figure 10, fireproofing is present in the wall of an immersed tunnel.

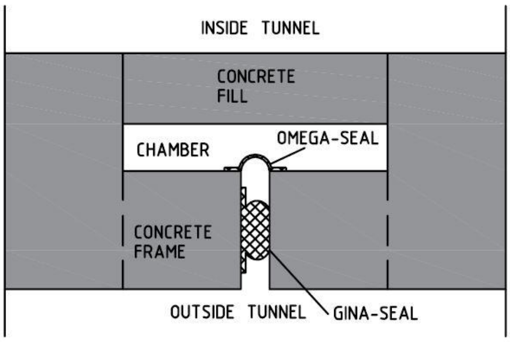

Figure 10: Example of the detail of the immersion joint in the wall

Detail of the roof
In the detail in Figure 11, no dowels are used. A layer of shotcrete is used, combined with fire-resistant material. When a fire in the tunnel occurs, this layer will protect the immersion joint.

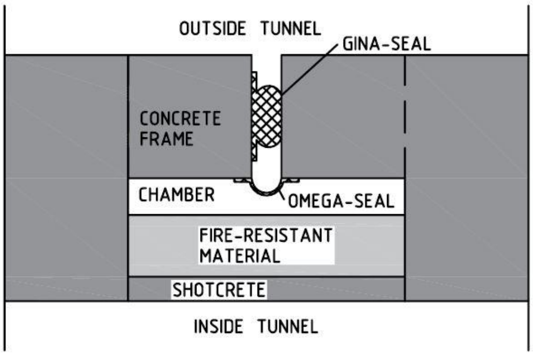

Figure 11: Example of the detail of the immersion joint in the roof

2.2.4. Movements in the immersion joint

Movements of the tunnel elements take place over the lifetime. As a result, the immersion joints may lose their watertight function. The movements can basically take place in three directions: the x-direction (longitudinal), the y-direction (sideways) and the z-direction (vertically). In Figure 12, an overview of the directions is presented. The immersion joint needs to keep functioning when these movements occur.

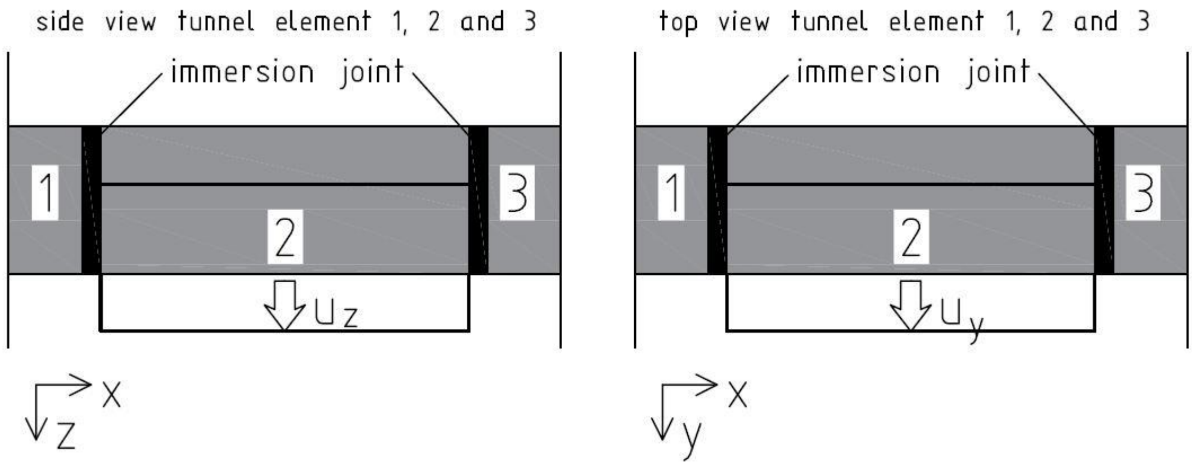

Figure 12: Overview of the x, y and z direction and movement of the element in y and z direction

In y-direction and z-direction, the differential movements are important. For example, two tunnel elements have the same amount of settlement. In that case, this is no problem since the joint still functions in the same way.

However, when one tunnel element settles and the other one does not settle, the forces in the immersion joint changes. This phenomenon is called differential settlement.

Movement in x-direction
When temperature rises materials start to expand. In the summer, tunnel elements are larger than in the winter. Due to these differences, there are deformations in longitudinal direction of the tunnel over the year.

The differential settlement in x-direction is expressed as Δx. It can be calculated by Equation 2.1. In Figure 13, the joint width between winter and summer is shown.

$$\Delta x = s_{jww} - s_{jws} \tag{2.1}$$

With:
Δx = maximum difference between winter and summer of the immersion joint in longitudinal direction [mm]
s_{jww} = joint width during the coolest point in winter [mm]
s_{jws} = joint width during the warmest point in summer [mm]

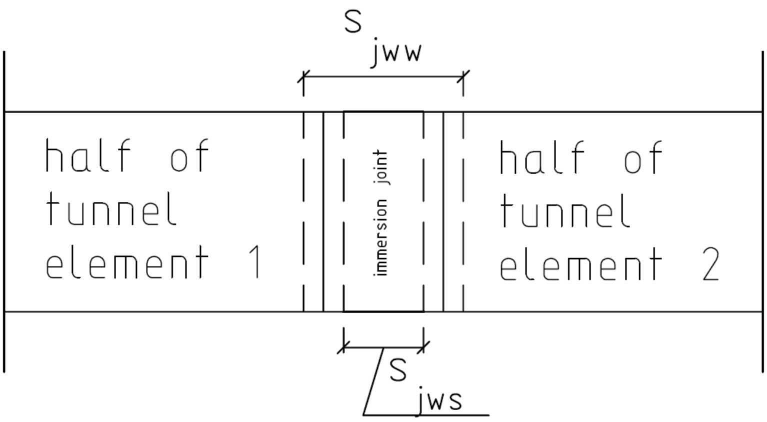

Figure 13: Schematic top view of an immersion joint, showing the width in summer (s_{jws}) and winter (s_{jww})

<u>*Movement in y-direction*</u>

Due to groundwater flow, it may be possible that the tunnel moves in y-direction. Although this displacement does not seem to be large, it needs to be taken into account. The differential settlement in y-direction is expressed as Δy. It is calculated the following.

$$\Delta y = |u_{y,1} - u_{y,2}| \tag{2.2}$$

With:

Δy = differential movement of the immersion joint in y-direction [mm]
$u_{y,1}$ = movement in y-direction of tunnel element 1 [mm]
$u_{y,2}$ = movement in y-direction of tunnel element 2 [mm]

<u>*Movement in z-direction*</u>

Tunnels can experience vertical displacement over the lifetime. These are also called settlements. They can be caused by the quality of the foundation and by the amount of loads on the structure. Settlements need to be taken into account when the immersion joints are designed. The settlement is largest in the conservation period. Afterwards, settlement continues, although the amount is small. The differential settlement in z-direction is expressed as Δz. It is calculated the following. An example is shown in Figure 14.

$$\Delta z = |u_{z,1} - u_{z,2}| \tag{2.3}$$

With:

Δz = differential movement of the immersion joint in z-direction [mm]
$u_{z,1}$ = movement in z-direction of tunnel element 1 [mm]
$u_{z,2}$ = movement in z-direction of tunnel element 2 [mm]

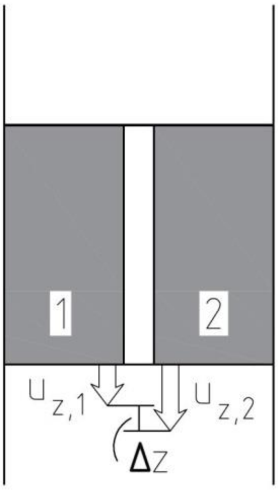

Figure 14: Differential settlement within an immersion joint in z-direction

2.3. Causes of leakages in immersion joints

Since it is known that leakages occur, it should be found out how these occur. In this paragraph, first some background is given how the causes of leakages are found. Then the leakage mechanisms are described.

2.3.1. Known leakages

In the First Coen Tunnel, two leakages through one and the same the immersion joints took place in 2009 and 2010. When large-scale maintenance was done in 2013 and 2014, this problem had to be solved. However, the causes of the leakages were unclear. Apart from the First Coen Tunnel, no major leakages through the immersion joints were known.

Therefore, a team of experts was formed to analyse the problem. Members of this team were tunnel experts from engineering companies, contractors, university, suppliers and Rijkswaterstaat (Berkhout, 2017). This team operated as *Commissie Zinkvoegen* ('Committee on immersion joints'). This team of experts wrote a report on how to prevent leakages in immersion joint, which was finished by the end of 2014.

After finishing the first study, the team continued. Some research was done by engineering company Nebest B.V. The research related to this problem was discussed during the meetings that took place about 4 times per year. Since the team was quite large (more than 30 members), it was decided at the end of 2016 to set up a smaller team, the *Werkgroep Zinkvoegen* ('Working group on immersion joints'). The frequency of the meetings increased. Over time, the knowledge on this subject has increased.

2.3.2. Leakage mechanisms

The committee determined the possible leakage mechanisms (Berkhout, 2014). These can basically be divided into two categories:

- Leakages *around* the immersion joint (shown in Figure 15):
    - Mechanism 1 – Cracks in the concrete frame: Large differences in vertical shear, eccentric forces or a combination of both caused the cracks in the concrete frame. This leads to a bypass route around the Gina-seal and Omega-seal.
    - Mechanism 2 – "Piping": Concrete behind the steel plate opposite of the Gina-gasket becomes loose. A bypass route around the Gina-seal and Omega-seal is created.

- Leakages *through* the immersion joint (shown in Figure 16):
    - Mechanism 3 – Failure of Gina-seal and leakage through the Omega-gasket: The Gina-gasket is not pressed enough onto the opposite steel profile, and the Omega-gasket is damaged. Water may pass both layers and a leakage route is created.
    - Mechanism 4 – Failure of Gina-seal and corrosion of the clamping structure of the Omega-seal: The Gina-gasket is not pressed enough onto the opposite steel profile, and the clamping structure of the Omega-gasket does not function because of deterioration due to corrosion. Water may pass both layers and a leakage route is created.

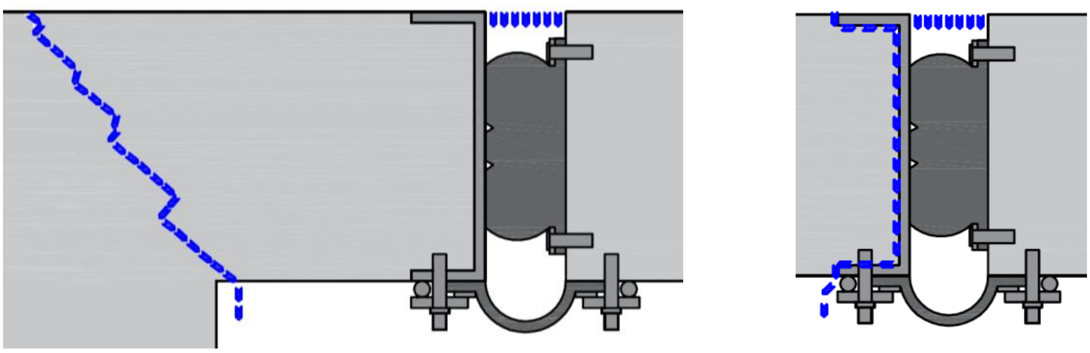

Figure 15: Leakage around the immersion joint: mechanisms 1 (left) and 2 (right) (based on (Berkhout, 2014))

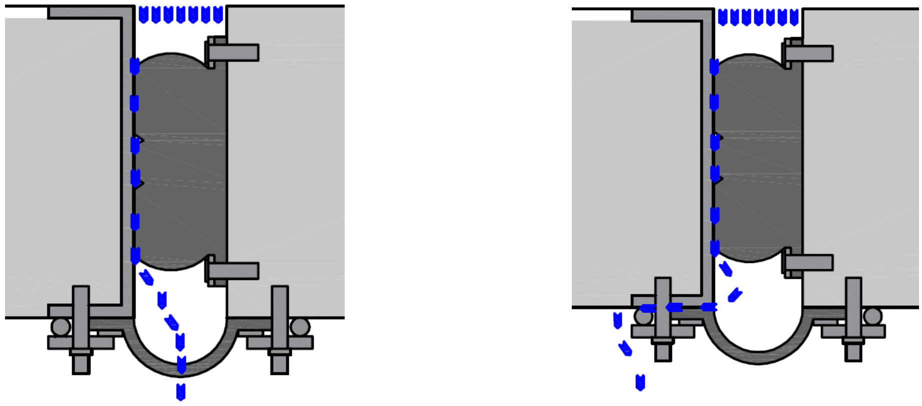

Figure 16: Leakage through the immersion joints: mechanism 3 (left) and 4 (right) (based on (Berkhout, 2014))

In case of the First Coen Tunnel, mechanism 1 was most likely cause of this leakage (Berkhout, 2014). It is considered whether to solve the entire problem or to take measures against the leakages. Solving the entire problem was considered too risky. Therefore, robust drainage that could drain leaked water was placed.

Leakage mechanism 2 can take place, but this will lead to small discharge that will not cause problems. Therefore, this is not further studied.

Although it is not expected that the Omega-gasket is damaged, leakage mechanism 3 could occur (Berkhout, 2014). Due to large differential movements, cracks could have happened in the Omega-gasket. Therefore, this is leakage mechanism is taken into account.

Leakage mechanism 4 could take place, too. Inspections of the quality of the clamping structure were done in the First Coen Tunnel (Berkhout, 2014). Bolts of the clamping structure of the Omega-seal were corroded. This could lead to deterioration of the structure, leading to leakages. In case of the First Coen Tunnel, it was considered not severe enough to take action. However, it became a point of attention. In other tunnels (Drecht Tunnel, Noord Tunnel, Kil Tunnel, Vlake Tunnel and First Heinenoord Tunnel) inspection was done as well. Corrosion in the clamping structure of the Omega-seal was detected there, too.

Leakage mechanisms 3 and 4 can only take place when both the Gina-seal and the Omega-seal do not function. Failure of one of these seals occurs more or less separately. Therefore, these parts will be treated separately in this report.

2.4. Main leakage mechanism: leakage through the immersion joint

In Paragraph 2.3, it is found out in which ways the immersion joint can leak. In this paragraph, the focus is on how these leakages can take place.

2.4.1. Occurrence of the leakage mechanism

Immersed tunnels have two watertight layers. The Gina-seal is the seal during construction, while the Omega-seal provides a watertight layer during use. Although strictly speaking, the Gina-seal becomes unnecessary after construction, it is still beneficial if it creates a watertight layer during use.

The situation is shown in a failure tree in Figure 17. As it is shown by the AND-gate, leakage can only occur if both the Gina-seal and the Omega-seal fail.

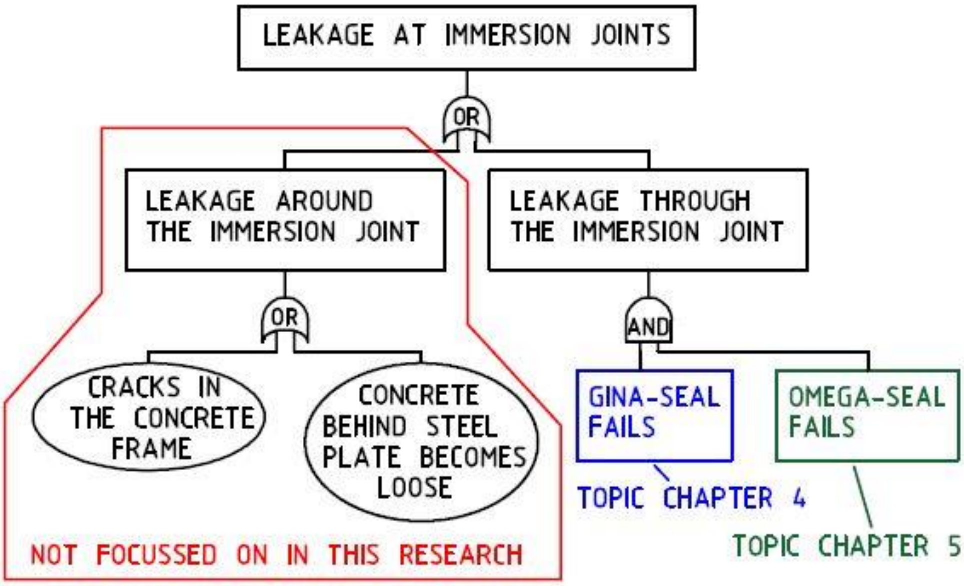

Figure 17: Failure tree of possible leakage mechanisms at immersion joints, showing the parts that is focussed on

2.4.2. Failure Gina-seal

The Gina-seal consists of a rubber gasket (the Gina-gasket) and a clamping structure that connects the Gina-gasket with one the tunnel element. This is shown in Figure 18. The Gina-gasket consists of rubber and is flexible. Therefore, it keeps functioning when limited deformations take place. It has a long lifetime (> 100 years), when is not exposed to UV and ozone.

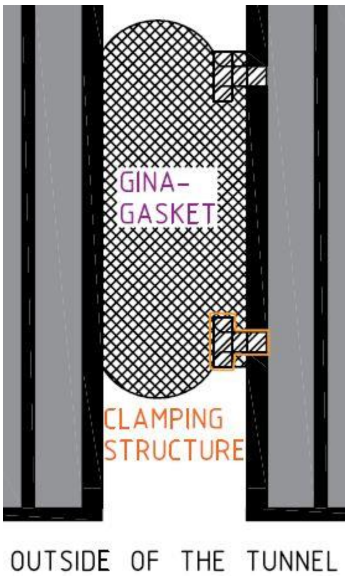

Figure 18: Cross section of the Gina-seal, showing the outside of the tunnel, and the difference between the clamping structure and the Gina-gasket

Watertightness of a Gina-seal is provided by the Gina-gasket. The Gina-gasket is pushed towards the other tunnel element. There should be enough pressure in the Gina-gasket to prevent water from passing this layer. If the pressure in the Gina-gasket is insufficient, water may find a way to pass this layer.

Initially, the Gina-seal was designed as a temporary seal (Bakker, 2014). The Omega-seal is considered as the main watertight layer during use in an immersion joint in the Netherlands. However, over time the opinion has slightly changed. Although it strictly does not need to function anymore, it is beneficial if it works. In that case, repair of the Omega-gasket is much easier. The Omega-seal may even be superficial if the Gina-seal functions.

The Gina-seal can basically fail in four ways. These are described below. In Figure 19, an example is shown.

1. Water is able to pass the layer due to a lack of pressure
This could happen due to a combination of relaxation and widening of the immersion joint. When relaxation occurs, the pressure of the Gina-gasket decreases. When the joint becomes wider, the pressure of the Gina-gasket decreases, too.

2. The Gina-seal is pushed away
When the Gina-seal is pushed away, there is no watertight seal present anymore. This could happen due to an increased soil pressure. When the soil pushed strongly on the Gina-seal, it might move. Also, relaxation may play a role. When this happens, there is an extra load on the Omega-seal, too.

3. The Gina-seal loses contact with the opposite tunnel element
When the Gina-seal loses contact with the opposite tunnel element, there is no watertight seal present anymore. This could happen due to movements of the tunnel elements in y-direction and in z-direction.

4. Water is able to pass the layer due to cracks in the gasket
When cracks in the Gina-gasket occur, water could pass the layer. These cracks can occur if the Gina-gasket is compressed very strongly for a longer time. This can only happen when the immersion joint has become narrow.

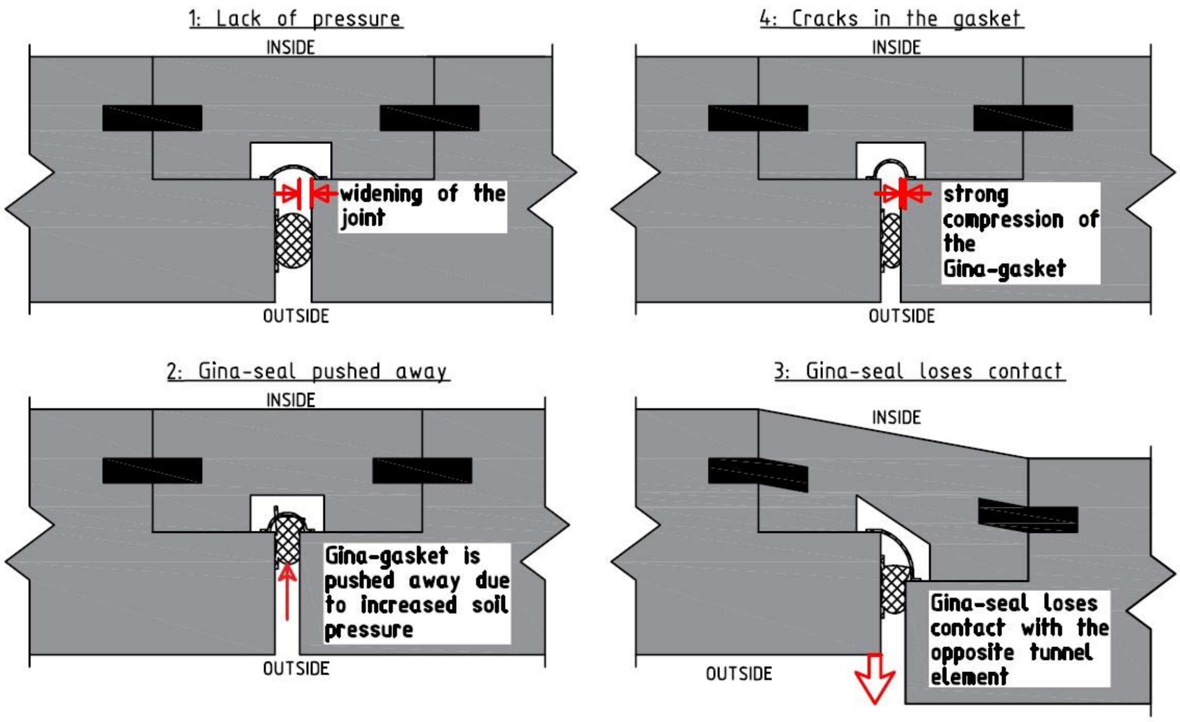

Figure 19: Visualisation of the 3 ways how the Omega-seal can fail

2.4.3. Failure Omega-seal

The Omega-seal consists of a rubber gasket (the Omega-gasket) and a structure that connects the Omega-gasket with both tunnel elements (the clamping structure). This is shown in Figure 20. The Omega-gasket consist of rubber and is flexible. Therefore, it keeps functioning when limited deformations take place. It has a long lifetime (> 100 years), when is not exposed to UV and ozone.

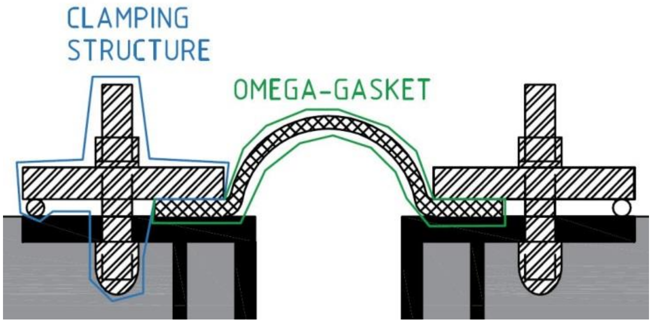

Figure 20: Cross section of the Omega-seal, showing the difference between the clamping structure and the Omega-gasket

Watertightness of an Omega-seal is provided by the Omega-gasket. The flanges of the Omega-gasket are pushed towards both tunnel elements. There should be enough pressure in the flanges of the Omega-gasket to prevent water from passing this layer. If the pressure in the Gina-gasket is insufficient, water may find a way to pass this layer.

When the Gina-seal functions well, the Omega-seal is not exposed to water pressure. This raises the question whether the Omega-seal needs to be maintained, if it can be proven that the Gina-seal is watertight.

The Omega-seal can basically fail in three ways. These are described below. In Figure 21, an example is shown.

1. Water is able to pass the layer due to lack of clamping pressure
This could happen due to insufficient clamping pressure of the flange of the Omega-seal. This could be the results of relaxation or insufficient compression of the flange of the Omega-seal. When the flange is not compressed enough, this is caused by failure of the clamping structure. The main cause will be corrosion of the clamping structure.

2. The flange of the Omega-gasket is pulled out
When pulling out of the flange of the Omega-gasket occurs, there is no watertight seal present anymore. An important aspect that plays a role is the movement of the tunnel elements. These could lead to increased forces that pull out the flange of the Omega-gasket. This could also happen due to insufficient clamping pressure of the flange of the Omega-seal. This could be the results of relaxation or insufficient compression of the flange of the Omega-seal. When the flange is not compressed enough, this is caused by failure of the clamping structure. The main cause will be corrosion of the clamping structure.

3. Water is able to pass the layer due to cracks in the gasket
When cracks in the Omega-gasket occur, water could pass the layer. The cracks can occur if there are movements within the joint. When these become so large that the Omega-gasket will strain, cracks will occur. The movements can be in all directions.

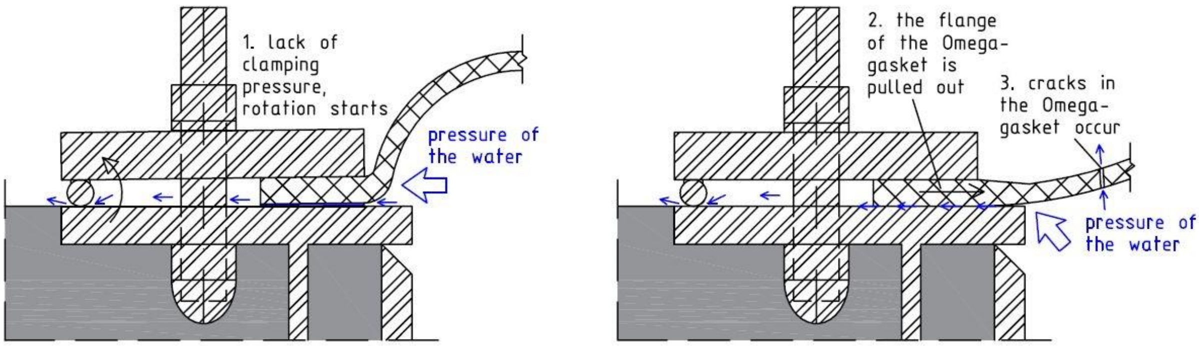

Figure 21: Visualisation of the 3 ways how the Omega-seal can fail

Influence of the Gina-seal: The Gina-seal is pushed away and delivers a force to the Omega-seal
When failure mechanism 2 (Gina-seal is pushed away) from Section 2.4.2 takes place, there is an extra force working on the Omega-seal. Therefore, in order to check the Omega-seal, the Gina-seal needs to be considered, too. This is not taken into account in the further analysis of the Omega-seal, but it plays a role. This effect is shown in Figure 22.

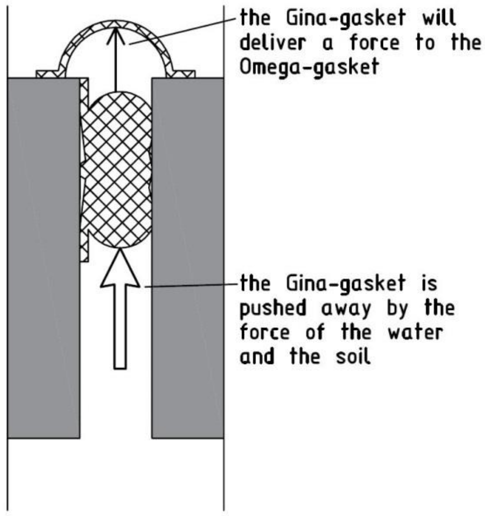

Figure 22: Gina-seal is pushed away and delivers a force to the Omega-seal

2.4.5. Main causes of leakage

As described in Sections 2.4.2 and 2.4.3, the main causes of failure of the Gina-gasket and the Omega-gasket are corrosion, relaxation, movements of the tunnel elements and increased soil pressure. In this section, these causes are further explained.

Corrosion of the clamping structure of the Omega-seal
Corrosion can lead to failure of the clamping structure. When corrosion attacks certain parts of the clamping structure, the effective amount of strong and useful steel decreases. This may lead to loss of strength.

The main part of the clamping structure is the bolts. When one bolt fails, the pressure on the adjacent bolt increases. When the adjacent bolt fails, too, the force on the bolt next to it increases. The chance of failure of the next bolt also increases. This is called the 'zipper effect' (Berkhout, 2014). When this occurs, a leakage that is not drainable may take place. Further research on the probability of the 'zipper effect' is needed. At the moment, it is not clear whether the 'zipper effect' is likely to happen. From this research, it should follow how much margin is still left, before the 'zipper effect' occurs.

Relaxation of both the Gina-gasket and the Omega-gasket
In both the Gina-gasket and the Omega-gasket, relaxation can take place. Relaxation is a process of time. This means that the force per unit of compression decreases. As a consequence, the amount of reaction force of the flange of the Omega-gasket decreases. This could lead to a loss of watertightness in the Omega-seal.

Movements of the tunnel elements
Movements of the tunnel elements take place over the lifetime. As a result, the immersion joints may lose their function. The movements can basically take place in three directions: the x-direction (longitudinal), the y-direction (left / right) and the z-direction (up / down).

Increased soil pressure
Every year, the tunnel elements increase a bit in length (in summer) and decrease a bit in length (in winter). The soil that is in between the elements could be compressed. This leads to an increased soil pressure on the Gina-gasket. This may lead to a force that is strong enough to push the Gina-seal out (Rahadian, 2017).

A combined failure tree is shown in Figure 23. It is also shown that the Omega-seal can fail due to failure of the Gina-seal.

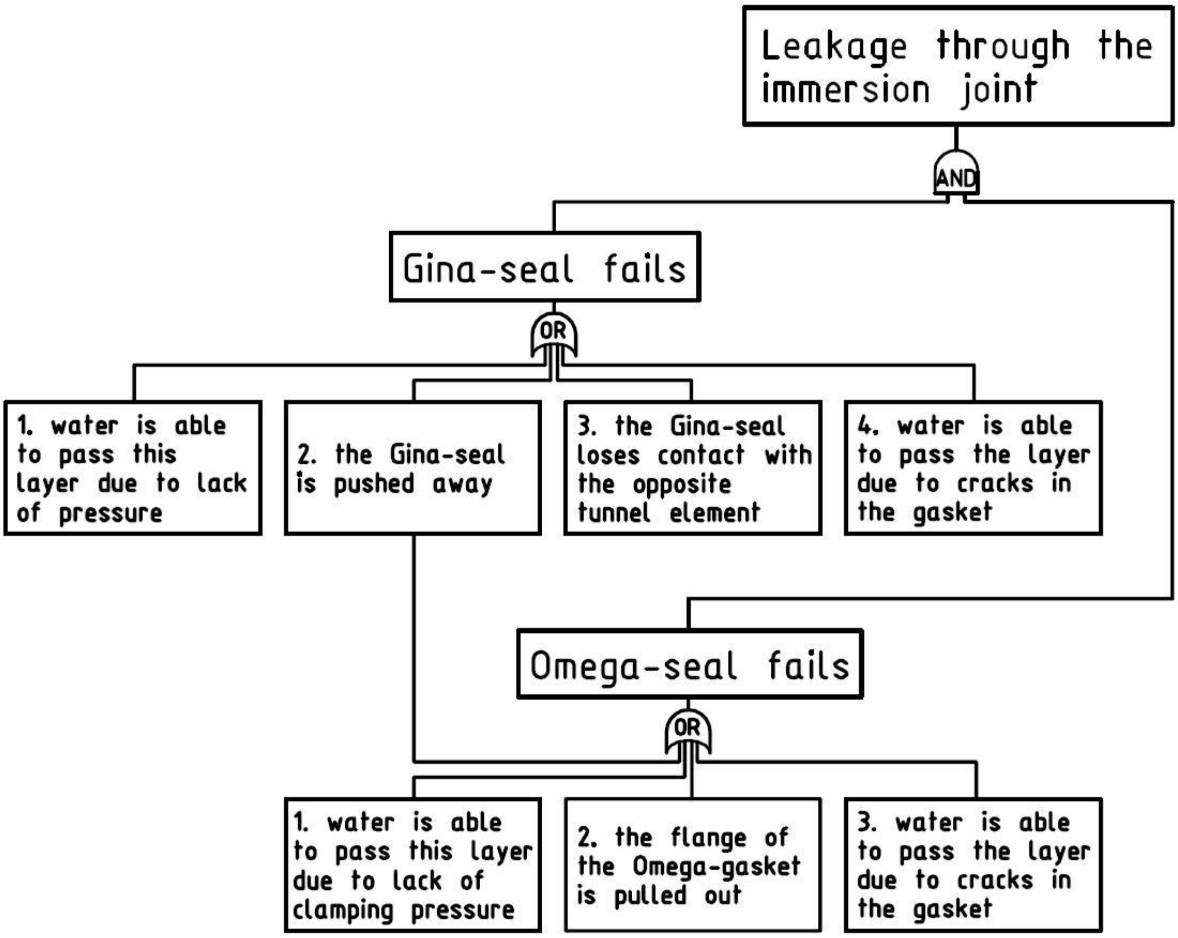

Figure 23: Failure tree of leakage through the immersion joint

2.5. Difficulties of inspection and maintenance

It seems obvious: when a component of the tunnel does not function, you repair it. However, for immersed tunnels is not that convenient. In this paragraph, the difficulties of maintenance in immersed tunnels will be explained.

2.5.1. Difficulties inspection

Insufficiency of the state of the immersion joint is very difficult to demonstrate. The Omega-seal can be reached, although it is a rather time consuming task. This can be done in two ways that are described below.

The Gina-seal can only be reached if the Gina-seal is watertight. However, the Omega-seal must be removed, so it can be a risky operation. Also, it is a rather costly and time consuming task.

Endoscope

The method to reach the Omega-seal that is most economical is by using an endoscope (a small camera with light). From the tunnel tube, a hole is drilled. This hole connects the tunnel tube with the part of the joint that needs to be inspected. The camera records its observations. From a few pictures with limited sight, it is hard to judge on the amount of corrosion of the bolts. The condition of the bolds is not always visible from these pictures, since the water or the bolds are regularly polluted. If it is visible, only the outside of the bolt and clamping structure can be seen. This is not the most crucial part when it comes to the functioning of the clamping structure. In Figure 24, an example of such a picture is shown. When the water is polluted, it is drained. When the bolds are polluted, water can be pumped through the cavity to clean the bolts. Both techniques are time-consuming and do not always have the right result.

Figure 24: Example of a picture taken by the endoscope (Leeuw, 2015)

Opening of the joint
Another method to inspect the Omega-seal is by removing the concrete cover. This is the best way to inspect the Omega-seal. It provides useful information. However, this only tells something about the state of that part of the Omega-seal. Besides, traffic in the tunnel tube will be hindered largely. An example of the view is shown in Figure 25.

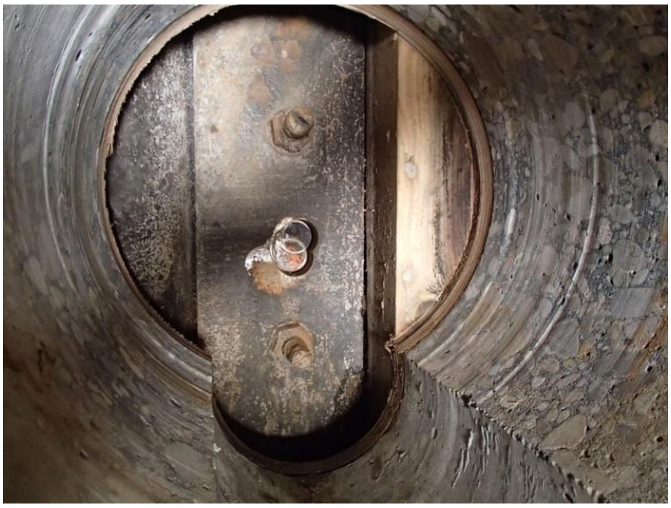

Figure 25: Picture of the clamping structure of the Omega-seal in the Kil Tunnel, which can only be seen by making a large hole in the concrete fill (COB, 2017)

2.5.2. Difficulties maintenance

There are a few reasons why maintenance on immersion joints is rather difficult. These are described in this section. First of all, it is not possible to reach the immersion joints from the outside of the tunnel. The tunnel is completely covered with soil.

Accessibility
When it is demonstrated that the immersion joints do not function well, research needs to be done which parts within the immersion joints need to be maintained. However, replacement is not that easy because of the many obstacles in the tunnel. The following obstacles can hinder standard maintenance work:

- Ballast concrete: Ballast concrete can have a thickness of more than 1 meter, so removal is a time consuming and costly activity.
- Asphalt: On the floor, asphalt needs to be removed. In case of railway or metro tunnels, railway and gravel need to be replaced.
- Walls within the tunnel: Parts of a joint near a wall are difficult to reach. In some cases, the wall needs to be removed to reach the location where maintenance needs to be done.
- Installations: On several locations, there are installations (such as ventilation, cables, light, etc.). This mainly holds for the walls and the roof.

The locations of the obstacles are shown in Figure 26.

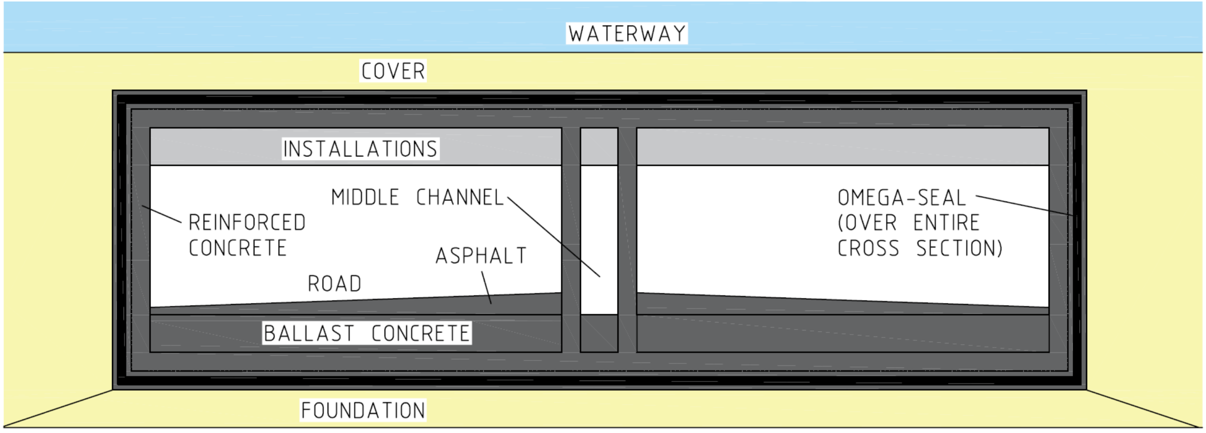

Figure 26: Cross section of a tunnel element, showing the functions

Limited possibilities of tunnel closure
In Paragraph 2.4, it is explained that corrosion in the Omega-seal can cause leakages. Demonstration of this corrosion is a difficult task. A joint cannot be opened anytime, because opening of a joint takes much time and hinders the traffic. Tunnels cannot be closed for research, unless it is urgent. An exception is the Kil Tunnel that has a slow traffic lane that can be used for research.

Risks when crucial parts are removed temporarily
Some parts of an immersion joint do have an important function. It is risky to remove them, in order to repair or replace. These parts are:

- Dowels: In order to prevent differential settlements of two tunnel elements, dowels are used. They form a strong connection, made of either steel or concrete. When the dowels are replaced, settlements can take place. The unpredictability of this action makes it difficult. A solution is to build temporary dowels and replace the original dowels.
- Omega-seal: It is risky to replace an Omega-seal. This seal is still an important watertight layer, in case the Gina-seal is not watertight. Therefore, it must be proven that the Gina-seal is watertight, before it can be taken out and replaced.

Presence of asbestos
In the older tunnels, asbestos is often used. This is a dangerous material in terms of health. Removal of asbestos needs to be done by a certified company.

Lack of data
There is limited data of settlements and horizontal movement of elements in tunnels. In many tunnels, the measurements that are made are lost. This information would be helpful to explain the behaviour of immersed tunnels.

2.6. Possible measures

Earlier in this chapter, an analysis of the problem is made. In the report of *Commissie Zinkvoegen*, written in 2014, it was advised not to touch parts of the Omega-seal. However, it was advised to prevent further deterioration of the clamping structure or to install a third seal (Berkhout, 2014). In this paragraph, all possible measures are described.

2.6.1. Possibilities maintenance Gina-seal

Maintenance on the Gina-seal is rather difficult. Seen from the inside of the tunnel, the Gina-seal is placed behind the Omega-seal. Behind the Gina-seal, there is a water column with a large hydrostatic pressure. In order to replace (parts of) the Gina-seal, a temporary watertight layer is needed to replace the Gina-seal. The only option to do this would be by freezing the surrounding soil. Since there is very limited space at this location, it is does not seem feasible to repair or replace the Gina-seal. However, if this is crucial for the functioning of a tunnel, a solution will be found.

2.6.2. Possibilities maintenance Omega-seal

There are possibilities to maintain the Omega-seal. When it is found out that the state of the Omega-seal is critical, there are basically three options for maintenance:

1. Conserve the current state: When the clamping structure is in a state that is acceptable now but may not be acceptable in the future, one could try to conserve the current state. This means that a substance that prevents further corrosion is added. This would be an inhibitor (a liquid substance).
2. Replace parts of the Omega-seal: When parts of the Omega-seal do not function anymore, these can be replaced. However, the Gina-seal should be watertight. Otherwise, water could enter the tunnel. If it is proven that the Gina-seal is watertight and replacement is feasible, this is a good option.

In case of option 1, it is a rather cheap solution. However, it is difficult to prove that it works in practice. In case of option 2, it is a rather costly solution. It does add reliability though.

2.6.3. Third watertight seal

If it is not possible to reach the required level of safety by maintenance of the Omega-gasket, an additional watertight layer is an option (Berkhout, 2014). This layer is placed near the Omega-seal. In Figure 27, a conceptual idea of this third layer is shown.

The advantage of this technique is that no further maintenance on the Gina-seal and the Omega-seal is needed. However, over the entire cross section, this layer needs to function well, which is technically a difficult task. Besides, it is a rather costly operation, of which it is questionable whether it is actually needed. Therefore, it is not seriously considered for existing immersed tunnels. One condition is that the Omega-seal may not be pressed towards the third watertight seal, because this could lead to damage.

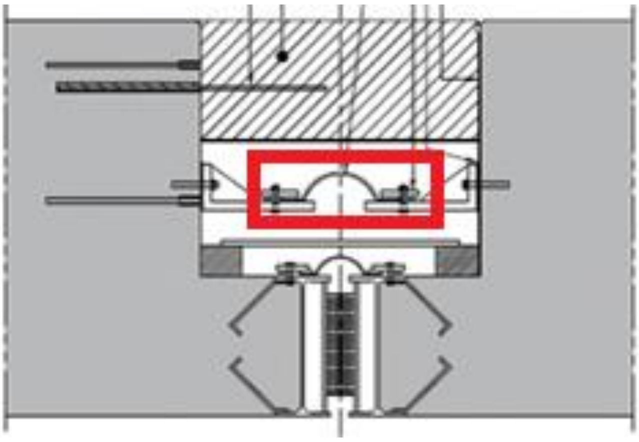

Figure 27: Detail of an immersion joint with in the red box the third watertight layer (Berkhout, 2014)

2.7. Summary

An immersed tunnel provides a fixed connection between both sides of a river or channel. An immersed tunnel consists of prefabricated elements that are floated to the site, immersed and connected. There are 23 immersed tunnels in operation in the Netherlands. Large-scale maintenance of both the First Heinenoord Tunnel and the Kil Tunnel will take place within a couple of years. Leakage through immersion joints happened in the past. This has the focus when it comes to the functioning of immersed tunnels.

The Gina-seal is the watertight layer of an immersion joint during construction. The procedure to create a foundation and when to install the Omega-seal determines the final shape of the cross section of the immersion joint. The Omega-gasket is the watertight layer during use. Further, dowels are installed to prevent differential settlements. The detail of the immersion joint differs over the cross section. The tunnel elements can move in x-direction (longitudinal), y-direction (sideways) and z-direction (vertically). The immersion joint needs to keep functioning when these movements occur.

The *Commissie Zinkvoegen* ('Committee on immersion joints') was founded as a result of the leakages in the First Coen Tunnel in 2009 and 2010. This team of experts determined four leakage mechanisms. Although it was most likely that mechanism 1 (cracks in the concrete frame) occurred in the First Coen Tunnel, mechanism 4 (failure of Gina-seal and corrosion of the clamping structure of the Omega-seal) became a point of attention for other immersed tunnels.

Immersed tunnels have two rubber watertight layers: the Gina-seal (during construction) and the Omega-seal (during use). When they both fail, leakages could occur. The Gina-seal and Omega-seal could fail in several ways. The main causes of leakages are corrosion of the clamping structure of the Omega-seal, relaxation of the Gina-gasket and the Omega-gasket, movements of the tunnel elements and an increased soil pressure.

Inspection of the immersion joint is rather difficult. The two ways to do this are with endoscope (cheap, but limited information) and by opening of the joint (useful information, but much hindrance). Maintenance is difficult because of accessibility, many obstacles in the tunnel that hinder the works and the limited possibilities of closure of a tunnel. Next to that, some elements that need to be replaced have an important function (such as the dowels and the Omega-seal) and cannot be removed temporarily.

Due to the water pressure it seems not feasible to replace the Gina-seal. There are more options for the Omega-seal: conservation of the current state and replacement of parts of the Omega-seal. The third option is to add a third watertight layer, on top of the Gina-seal and the Omega-seal.

3

Chapter 3 – Immersion joints case Kil Tunnel

In Chapter 3, a description of the Kil Tunnel (case study) is made. First, it is explained why this tunnel is chosen. Then a description of its design and location is presented. The design of the immersion joints in presented in Paragraph 3.3. Then, it is described what is known about the present state of the immersion joints. The information from this chapter will be used in the calculations of Chapter 4 (on the Gina-seal) and Chapter 5 (on the Omega-seal).

3.1. Choice of this tunnel

As mentioned earlier, each tunnel is slightly different. Therefore, it is not possible to research one immersed tunnel and judge on all immersed tunnels. Instead, one representative tunnel is taken into account. The chosen tunnel is the Kil Tunnel, an existing immersed tunnel near the city of Dordrecht.

There are several reasons to use the Kil Tunnel for a case study, such as:

- In the Kil Tunnel, endoscopic research is done on the quality of the clamping structures (Leeuw, 2015). Another research, aiming to get more insight into the possibility of maintenance, is planned (Berkhout, 2017). This tunnel is suitable for this kind of research, since each tube has a slow traffic lane. This lane can easily be partly closed for research.
- There are many settlement measuring points within this tunnel (Schols, 2012). Also, relatively many measurements on settlements over the lifetime of the tunnel are executed, and these still go on.
- Large-scale maintenance of the Kil Tunnel is planned for 2020 until 2022. This means that every bit of extra information on this tunnel may be useful for this maintenance.
- There is much documentation on the design available. For some tunnels, this has somehow disappeared over the years, but at the Kil Tunnel, very specific cross sections and dimensions are available.

3.2. Tunnel description

In this paragraph, a description of the Kil Tunnel is given. The location, time of construction, longitudinal cross section and cross section are treated.

The Kil Tunnel is an immersed tunnel located below the river Dordtsche Kil. Construction started in September 1974 and the structure was finished in August 1977. In Paragraph B.1, more information about the function and construction is presented. The tunnel is therefore 40 years in use. Although it is not described in the design documents, the design lifetime of this tunnel is not reached yet.

The Kil Tunnel consists of three tunnel elements that are produced in the dry dock of Barendrecht. These elements all consist of 5 segments. In Figure 28 and 29, the location of the 3 tunnel elements is shown. Also, the location of the 3 immersion joints (1A, 2E and 3A) and the location of the closure joint is shown. The number of the tunnel elements corresponds with the placement of them. Tunnel element 1 was the first element that was placed. In Figure 29, it is shown that elements 1 and 2 are inclined.

There are three immersion joints in the Kil Tunnel: 1A, 2E and 3A. Two of them have exactly the same design, namely immersion joints 1A and 2E. These will be considered equally. Later in this report, it is referred to as "1A / 2E". The other immersion joint is 3A. Joints 1A and 2E both form a connection between the tunnel element and the abutment. Joint 3A forms a connection between two tunnel elements. The depth of 1A/2E and 3A is different. Therefore, the design of 1A/2E and 3A differs.

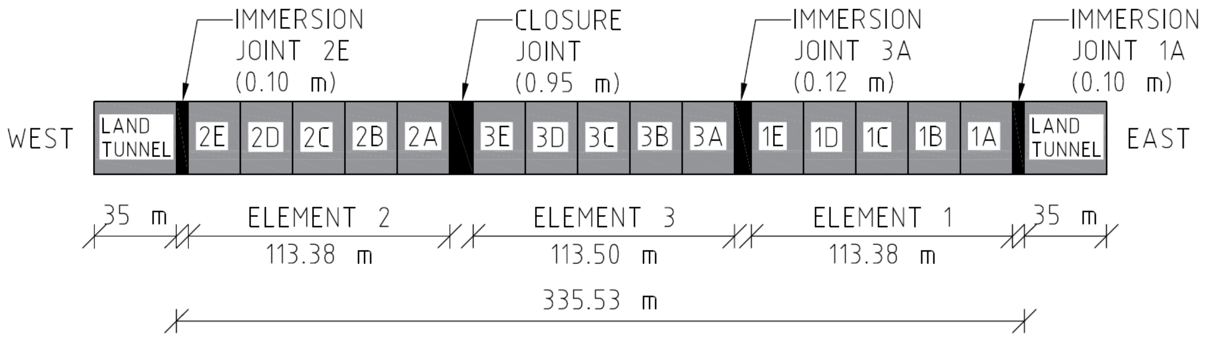

Figure 28: Schematic top view of the longitudinal cross section of the closed part of the Kil Tunnel, showing the location of element 1, 2 and 3 and the location of the immersion joints and the final joint (not on scale, based on (Rijkswaterstaat, 1974))

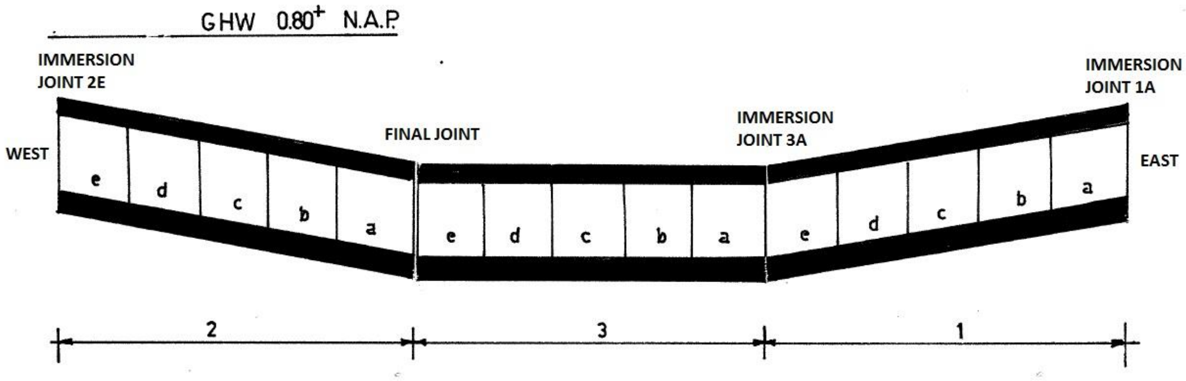

Figure 29: Schematic side view of the longitudinal cross section of the closed part of the Kil Tunnel, showing that elements 1 and 2 are inclined (not on scale, based on (Rijkswaterstaat, 1974))

The tunnel has two lanes in both directions. Also, there is a cycling lane in both tunnel tubes. Both functions are separated by a barrier. This tunnel does not have a middle tunnel channel, since it is rather short tunnel. A wall in the tunnel separates the traffic in different directions. Below the roof, there are installations (fans) that for example blow away gasses and smoke. An overview of the cross section with all functions is shown in Figure 30.

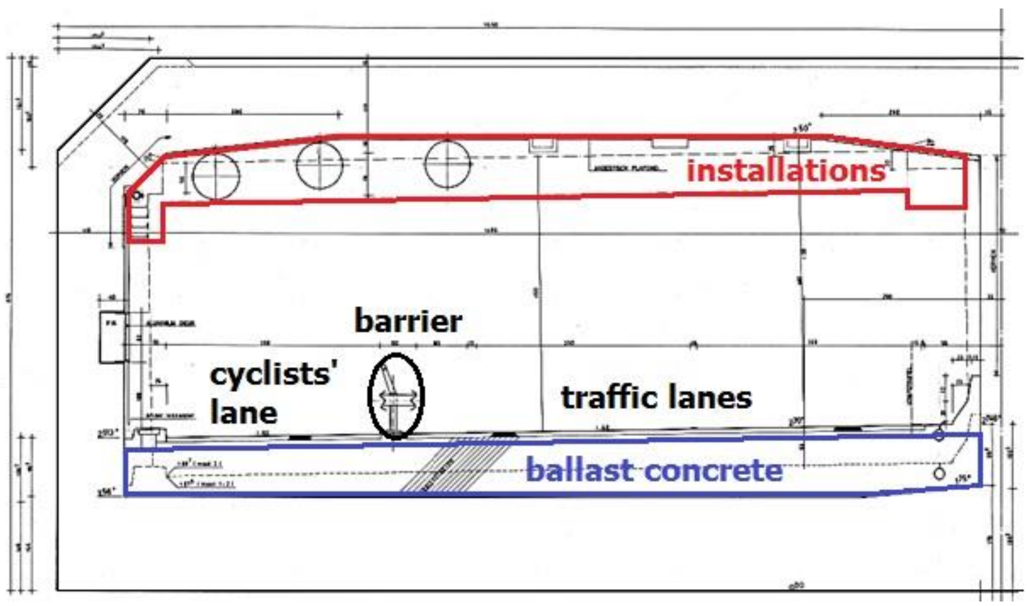

Figure 30: Cross-section of one half of the Kil Tunnel after finishing, showing the functions over the cross section (on scale, based on (Rijkswaterstaat, 1974))

3.3. Design immersion joints

As described in Paragraph 3.2, In this paragraph, a description of the design of 1A/2E and 3A is made.

3.3.1. Construction method

The three tunnel elements of the Kil Tunnel were produced in the dry dock in Barendrecht (Burger, 1978). From there, they were piece by piece (while floating) transported to the site and immersed. The tunnel elements were placed at the bottom of the river on temporary supports. The procedure of connection between two elements or an element with the abutment, as described in Section 2.2.1, was followed. Afterwards, the bulkheads were removed and the Omega-seal was installed. Then, the definitive foundation is placed by sand flowing. The temporary foundation is removed and the prestress of the tunnel elements is removed. The consolidation started.

In Section 2.2.1, it was described that there are two different procedures to install the Omega-seal. In the Kil Tunnel, procedure A (Omega-seal installed before consolidation period) is used. There is a relatively large difference in settlement between the land tunnel and the immersed tunnel. It is expected that the settlements of the sand bed made by sand are about 100 mm. The expected settlements of the land tunnel are much smaller, since this is placed on a pile foundation. Procedure A does not compensate for these differential settlements. Therefore, it is expected that the differential settlements are approximately 100 mm (Burger, 1978). The forces in the Omega-gasket will therefore change. This will be further explained in Chapter 5.

3.3.2. Dimensions immersion joint

The dimensions of the immersion joints differ for joint 1A/2E and 3A. Therefore, these are described separately. More details of the immersion joint can be found in Paragraph B.2.

Joint 1A/2E

An overview of the important dimensions of immersion joints is shown in Figure 31. The values of joint 1A/2E are described in Table 4. There is a difference between the design of the roof and the wall / floor. In the roof, the joint is a bit higher than in the wall / floor. The reason for this is unclear. However, this has significant influence on the increased soil pressure. This is further explained in Section 3.4.3.

On top of immersion joint 1A/2E, a dike is located. This means that on top of the immersion joint, a large soil column is present. On top of the immersion joint, there is a water column. It is assumed that the governing water table is a little below the crest of this dike. A schematic overview is shown in Figure 32. The values are shown in Table 4.

The width of the immersion joint is on average 100 mm. This means that the Gina-gasket needs to be compressed from 167 mm (the original height) to 100 mm (the compressed height).

Joint 3A

An overview of the important dimensions of immersion joints is shown in Figure 28. The values of joint 1A/2E are described in Table 4. Like joint 1A/2E, there is a difference between the design of the roof and the wall / floor. In the roof, the joint is a bit higher than in the wall / floor. The reason for this is unclear. However, this has significant influence on the increased soil pressure. This is further explained in Section 3.4.3.

On top of immersion joint 3A, there is a rather small sand cover. This means that the loads from the soil are limited. On top of the immersion joint, there is also a water column. It is assumed that the governing water table is a little below the crest of this dike. A schematic overview is shown in Figure 32. The values are shown in Table 5.

The width of the immersion joint is on average 120 mm. This means that the Gina-gasket needs to be compressed from 205 mm (the original height) to 120 mm (the compressed height).

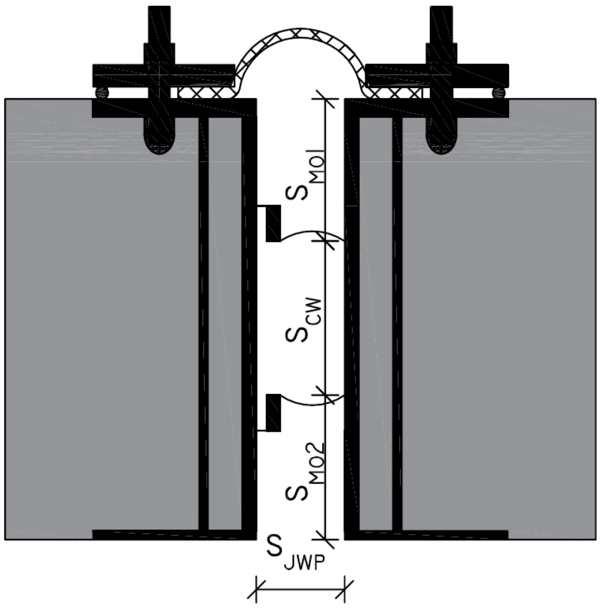

Figure 31: Cross section of Gina-seal and Omega-seal in the joints 1A/2E (left) and 3A (right) (based on (Rijkswaterstaat, 1974))

Description	**Symbol**	**Dimensions [mm]**			
		Joint 1A/2E		Joint 3A	
		Floor / Wall	Roof	Floor / Wall	Roof
Distance between Gina-gasket and Omega-gasket	s_{mo1}	161	161	134	135
Distance between Gina-gasket and outside tunnel	s_{mo2}	164	314	136	286
Clamping width compressed Gina-gasket	s_{cw}	175	175	230	230
Joint width present	s_{jwp}	90 – 110	90 – 110	110 – 130	110 – 130

Table 4: Overview of the dimensions of the soil and water around the immersion joints 1A/2E and 3A

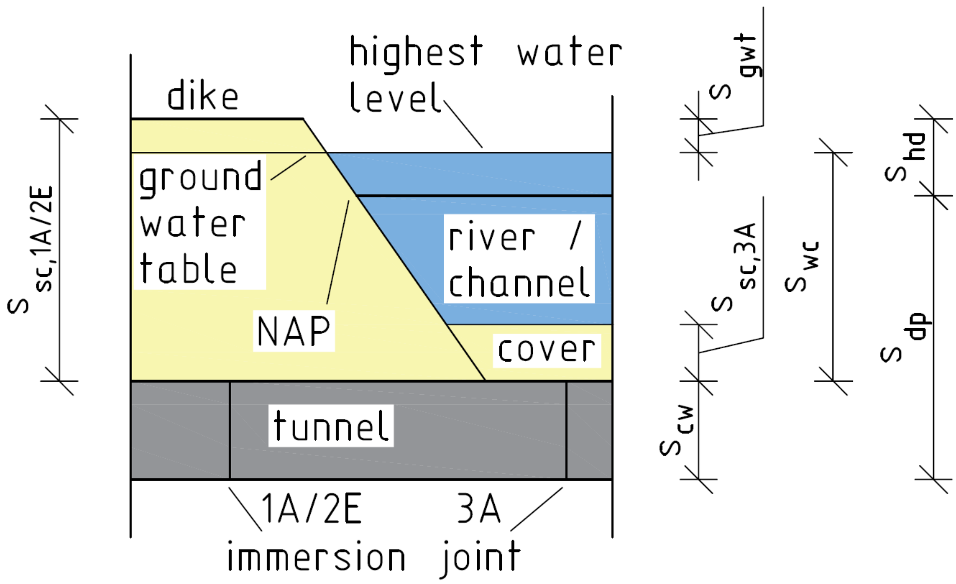

Figure 32: Schematic cross section (not on scale) of the dimensions around the immersion joints 1A/2E and 3A (based on (Rijkswaterstaat, 1974))

Description	Symbol	Dimensions [m]	
		Joint 1A/2E	Joint 3A
Deepest point of the tunnel (relative to NAP)	s_{dp}	-14.12	-19.19
Height tunnel element	s_{ht}	8.75	8.75
Height dike (relative to NAP)	s_{hd}	5.10	5.10
Height governing water table below dike	s_{gwt}	1.00	1.00
Height sand cover	s_{sc}	10.47	2.00
Height water column	s_{wc}	18.22	23.29

Table 5: Overview of the dimensions of the soil and water around the immersion joints 1A/2E and 3A

3.3.3. Design Gina-seal

The Gina-seal design of the immersion joints differ for joint 1A/2E and 3A. Therefore, these are described separately.

Joint 1A/2E
The Gina-gasket that is used in this joint is type G 155-109-60. It is smaller than the Gina-gasket in joint 3A. In Figure 33, an example is shown.

The Gina-gasket is fixed to a tunnel element by a clamping structure. An example is shown in Figure 34. The clamping structure basically consists of a bolt and a clamping plate. The bolt is connected to the tunnel element. This bolt clamps the clamping plate that keeps the side of the Gina-gasket at its place.

The force-compression curve is described in Paragraph C.1.

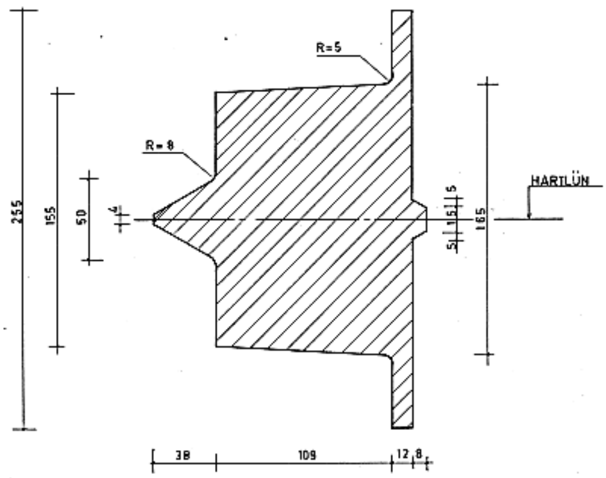

Figure 33: Cross section of Gina-gasket G 155-109-60 (initial shape, dimensions in mm) (Rijkswaterstaat, 1974)

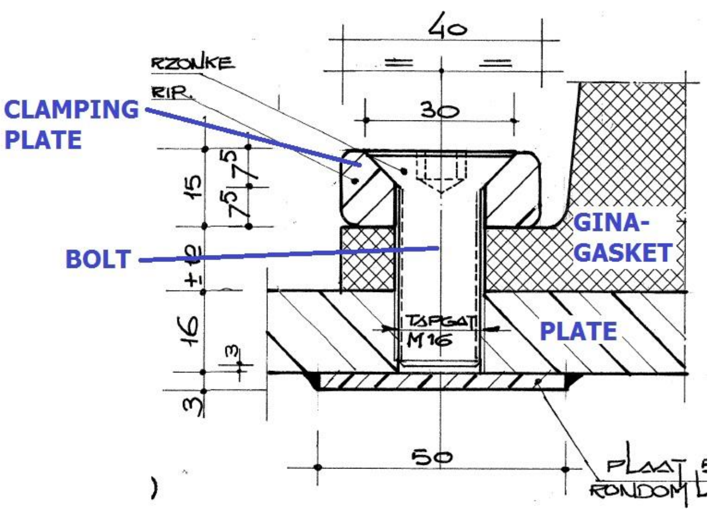

Figure 34: Detail of the clamping structure of joint 1A/2E (dimensions in mm, based on (Rijkswaterstaat, 1974))

Joint 3A

The Gina-gasket that is used in this joint is type G 190-148-50. It is larger than the Gina-gasket in joint 1A/2E. In Figure 35, an example is shown.

The Gina-gasket is fixed to a tunnel element by a clamping structure. An example is shown in Figure 36. The clamping structure basically consists of a bolt and a clamping plate. The bolt is connected to the tunnel element. This bolt clamps the clamping plate and the side of the Gina-gasket.

The force-compression curve is described in Paragraph C.1.

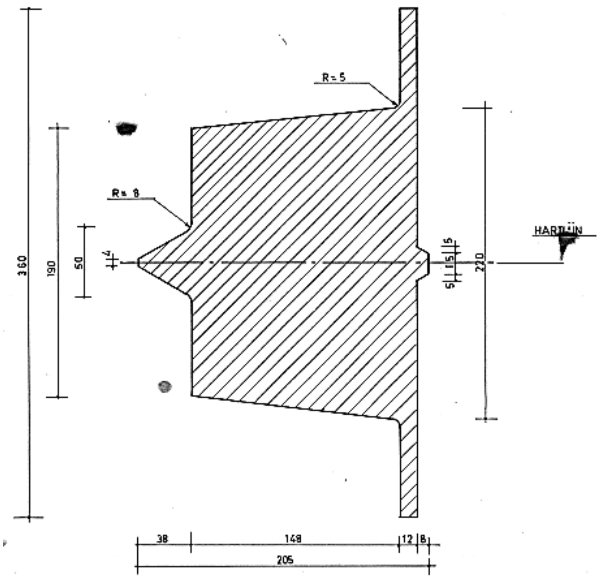

Figure 35: Cross section of Gina-gasket G 190-148-50 (initial shape, dimensions in mm) (Rijkswaterstaat, 1974)

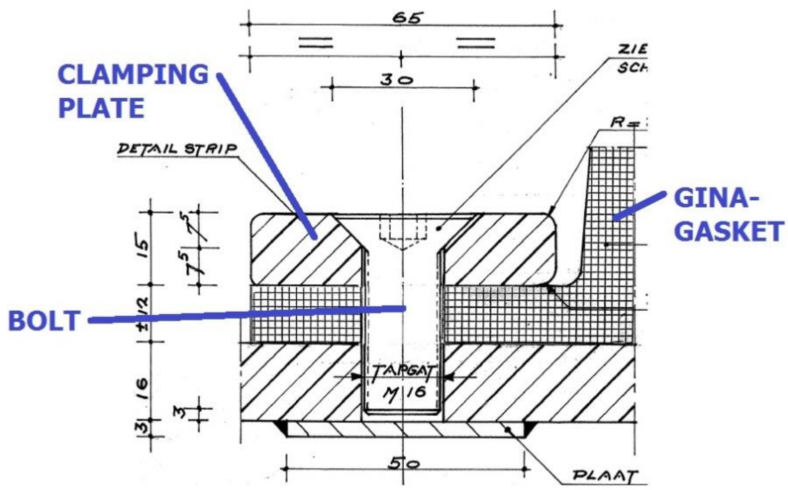

Figure 36: Detail of the clamping structure of joint 3A (dimensions in mm, based on (Rijkswaterstaat, 1974))

3.3.4. Design Omega-seal

The Omega-seal design is almost the same in joint 1A/2E and 3A. First, the similarities are explained. Then, the differences are explained.

The Omega-gasket that is used in both joints is of the type B 277-70. An example is shown in Figure 37. This drawing shows that the radius of the Omega-gasket (R_{Omega}) is 70 mm. The thickness of the curved part (t_{Omega}) is 10 mm.

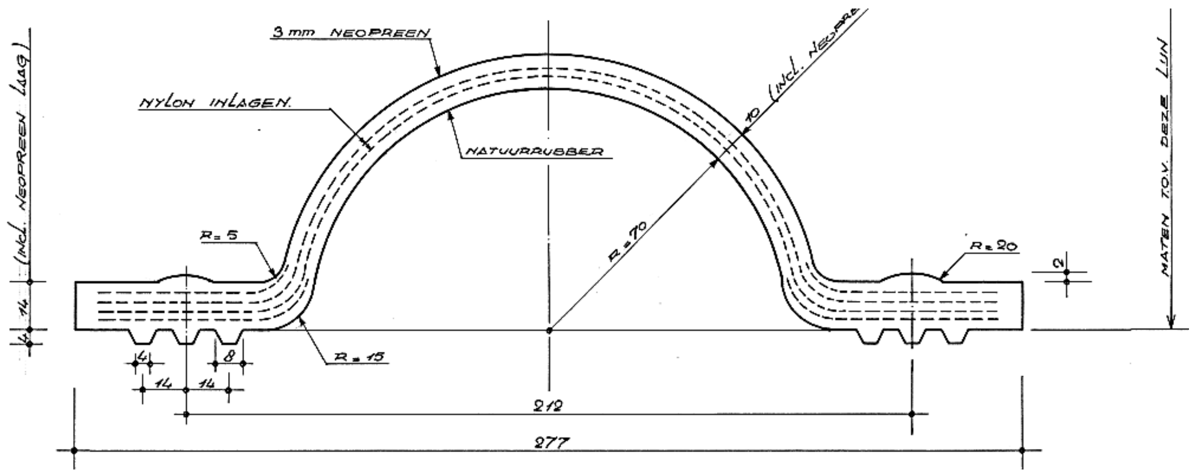

Figure 37: Cross section of Omega-gasket B 277-70 (initial shape, dimensions in mm)

The Omega-gasket is clamped to both tunnel elements with a clamping structure. In order to keep watertight a clamping structure is needed. The clamping structure consists of the following parts:

- Bolt: A cap nut is surrounded by concrete. A stud (diameter: 24 mm) is attached to this cap nut. A nut is spanned in order to generate a clamping force. Together it is referred to as a bolt, although it is strictly taken not a bolt. A ring (or 'washer') is added to spread the load over a larger surface.
- Clamping plate: This steel plate (thickness: 25 mm) is pushed towards the flange of the Omega-gasket.
- Steel bar: The steel bar (14 mm diameter) is placed to keep enough distance between the clamping plate and the plate. It is welded to the clamping plate before installation.
- Plate: The plate (thickness: 20 mm) is part of the tunnel element. It is used as formwork during production of the tunnel element and has a definitive function. The flange of the Omega-gasket is pushed against this surface. It must therefore be smooth, in order to have predictable friction.
- Flange Omega-gasket: This rubber part is pushed towards the plate by the clamping plate. Due to the compression, a force upwards and downwards is created. This results in friction forces.

The centre-to-centre distance of the bolts is important for the calculations. This is 200 mm. In Paragraph B.3, this is explained.

In Figure 38, an overview of the elements within the clamping structure is shown.

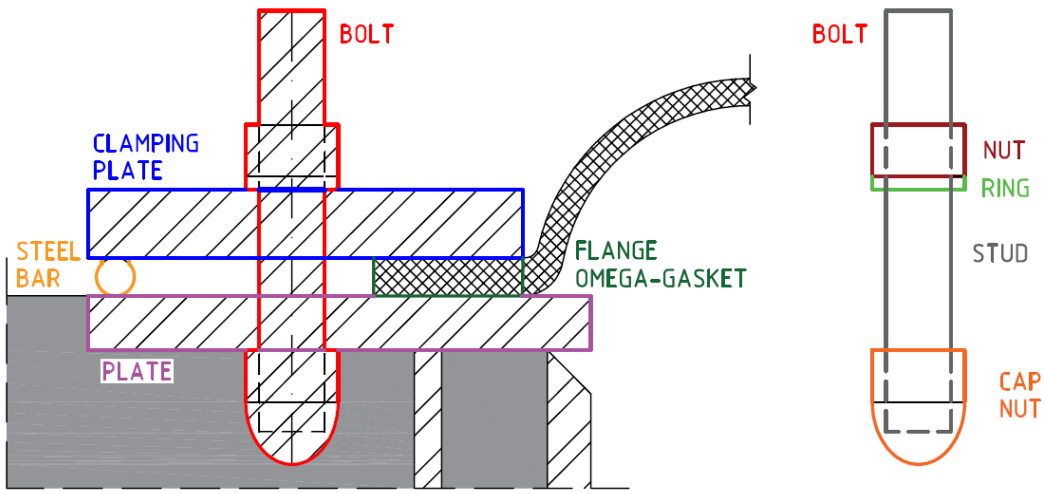

Figure 38: Cross section of the clamping structure of the Omega-gasket showing all components

The only difference between the Omega-seal of 1A/2E and 3A is the position of the Omega-gasket. Since the joint width differs (1A/2E: 100 mm; 3A: 120 mm), it is positioned slightly different. In joint 3A, it is positioned a bit more to the centre of the joint. The dimensions of the Omega-seal are shown in Figure 39 and 40.

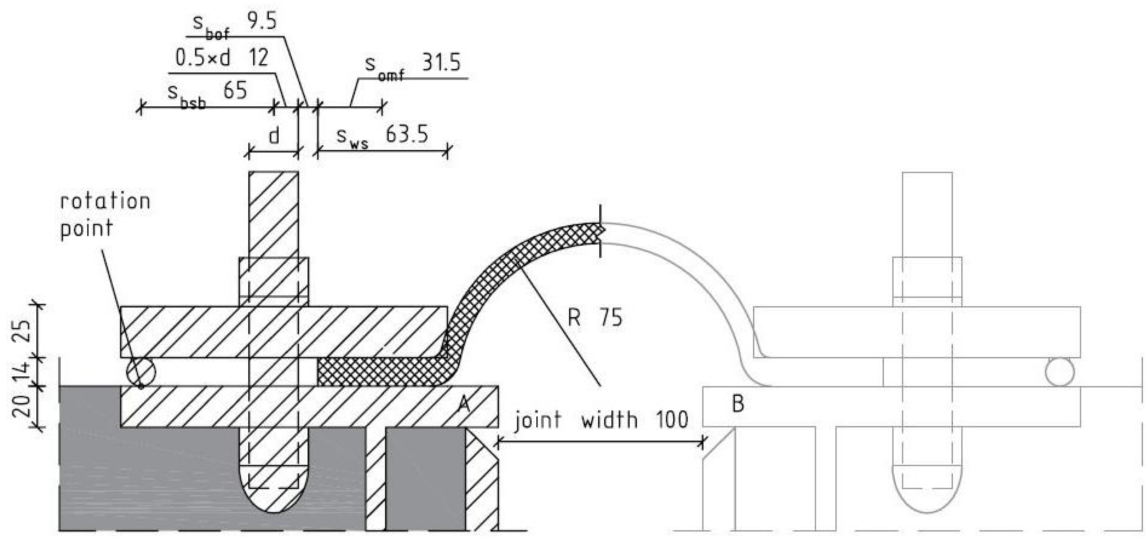

Figure 39: Cross section of the clamping structure of the Omega-gasket of joint 1A/2E with dimensions (initial shape, dimensions in mm)

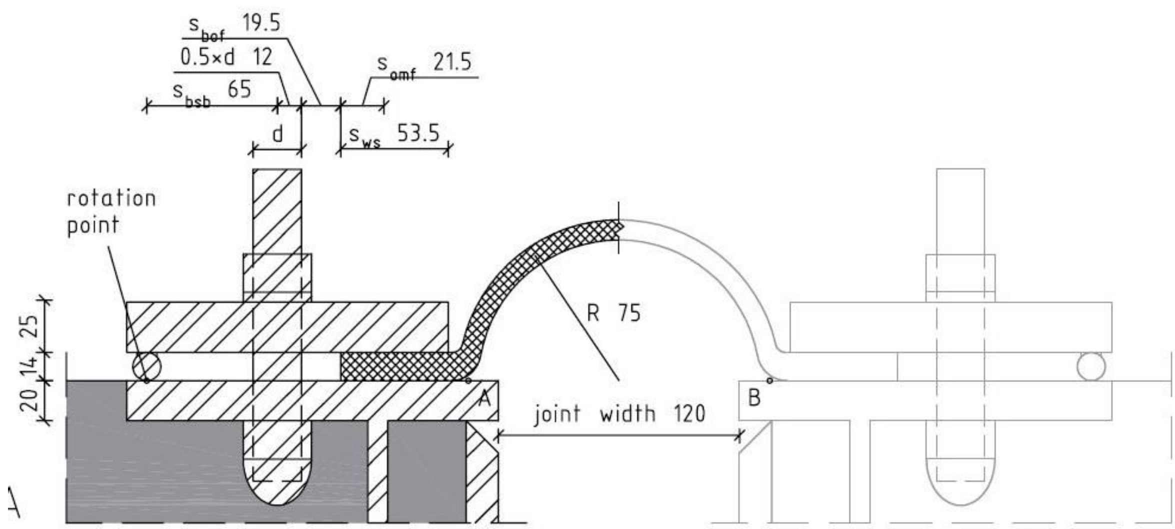

Figure 40: Cross section of the clamping structure of the Omega-gasket of joint 3A with dimensions (initial shape, dimensions in mm)

3.4. Present state of the immersion joints in the Kil Tunnel

In Paragraph 3.3 it is explained what the immersion joints should look like according to the design drawings. However, over the lifetime deterioration may have taken place. In this paragraph it is explained which measurements and observations are done in the Kil Tunnel. From the increased soil pressure relatively little is known. However, it can be calculated with a rule of thumb. This will be explained in Chapter 4. Relaxation can be calculated with a formula. This will be explained in Chapter 4 (Gina-seal) and Chapter 5 (Omega-seal).

3.4.1. Movements of the immersion joints

The movements are important for further calculations in Chapter 4 and 5. These are estimated in this section. An estimation is made for the following moments in time:

1. Completion Kil Tunnel – ± ¾ years after completion of the immersion joint
2. Present situation – ± 40 years after completion of the immersion joint
3. Design lifetime – ± 100 years after completion of the immersion joint

Movements in x-direction
This value depends of the seasonal temperature changes. In immersed tunnels, this phenomenon was observed. However, these values cannot be copied for the Kil Tunnel. Therefore, these values should be estimated.

The amount of longitudinal displacement depends of the shrinkage and elongation of the tunnel elements. They can be calculated when the temperature difference, the material and the dimensions of the tunnel elements are known by Equation 3.1. It is assumed that the average temperature of the tunnel is 10 °C. The minimum temperature of the concrete in the winter is assumed to be 2,5 °C and in the summer 17,5 °C. This means that the temperature difference is 15 K (Kelvin).

The value of the temperature difference will differ per tunnel. In closed tunnels, where the influence of the weather is less, this value will be lower than in the Kil Tunnel.

$$\Delta L = \alpha \times L_0 \times \Delta T \qquad (3.1)$$

With:
ΔL = elongation of a tunnel element [m]
α = thermic expansion coefficient of concrete [K^{-1}]
L_0 = length in the beginning [m]
ΔT = temperature difference [K]

Knowing the thermic expansion coefficient of concrete (being 12×10^{-6} K^{-1}), it follows that the maximum difference between winter and summer of the immersion joint (Δx) is 20 mm, taken into account the length of a tunnel element (being 113.5 m). This is an extreme value. In practice, this will probably not be reached, due to friction of the sand around. Besides, expansion joints will also take some of the deformations.

Equation 2.1 is used to calculate the value of Δx. It is calculated that the extreme value is 20 mm. The extreme value is 20 mm. However, it is estimated that the expected value of Δx is half of this, being 10 mm. The values are presented in Table 6.

Moment in time	Time after installation Omega-seal (years)	Expected value of Δx [mm]		Extreme value of Δx [mm]	
		1A / 2E	3A	1A / 2E	3A
Completion Kil Tunnel	0,75	10	10	20	20
Present situation	40	10	10	20	20
Design lifetime	100	10	10	20	20

Table 6: Expected and extreme values of Δx at different moments in time (estimated)

Movements in y-direction
This value depends of the differential horizontal movement of two tunnel element, in the direction perpendicular to the longitudinal axis of the tunnel. Since no measurements are made, these values need to be estimated.

These movements seem relatively limited in tunnels. The expected value is 0 mm. In case of extreme loading, it is expected that these movements are about 20 mm in that direction. The values are presented in Table 7.

Moment in time	Time after installation Omega-seal (years)	Expected value of Δy [mm]		Extreme value of Δy [mm]	
		1A / 2E	3A	1A / 2E	3A
Completion Kil Tunnel	0,75	0	0	20	20
Present situation	40	0	0	20	20
Design lifetime	100	0	0	20	20

Table 7: Expected and extreme values of Δy at different moments in time (estimated)

Movements in z-direction
This value depends of the differential settlements of the two parts that are connected. Measurements are made, but these are only available from the period after consolidation. In the consolidation period, the main settlements have occurred. Therefore, the measurements are not so useful. An estimation on the settlements must be made.

During the consolidation period (after the Omega-seal is installed) settlements certainly occurred. In the report about the construction of the Kil Tunnel, it is said that these settlements of the tunnel elements between 0 and 100 mm are expected. After the consolidation period, steel dowels are constructed in the immersion joints. These dowels prevent against differential settlements. In the period after placement of these dowels, measurements of differential settlements are performed. The maximum expected value of these settlements is 10 mm. This is based on measured the settlement data that is available. After completion of the tunnel, settlements are measured. There are 47 measuring points in the tunnel. This was first done in the period September 1977 until April 1978. Then, from July 2001 the measurements were continued as a consequence of a leakage that occurred. An overview is presented in Figure 41.

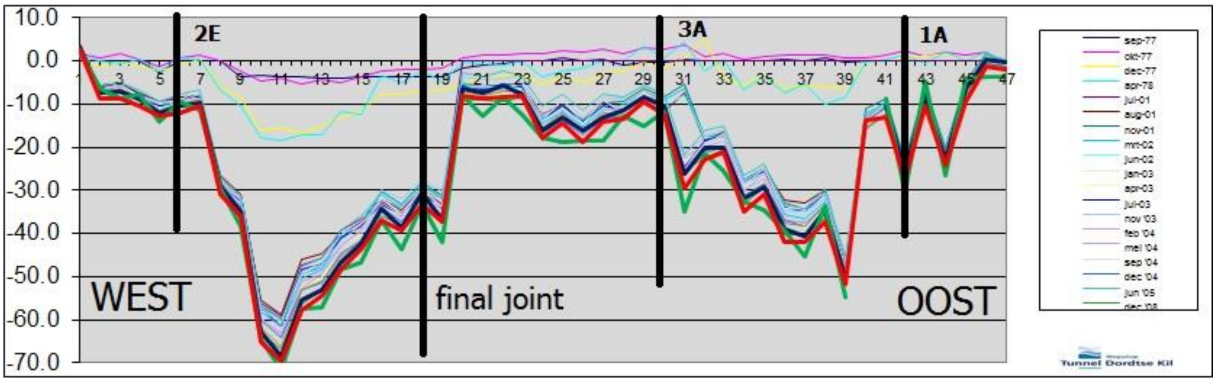

Figure 41: Absolute settlement data (dimensions in mm) at different points in the Kil Tunnel between 1977 and 2005 (based on (Leeuw, 2016))

The differential settlements differ per joint. In the joints 1A and 2E, the tunnel element (which settles heavily) is connected to the abutment (which settles slightly). Therefore, it is expected that the differential settlements are large in joint 1A/2E. In joint 3A, two tunnel elements are connected to each other. The differential settlements are expected to be small. An overview of the expected values is shown in Table 8.

Moment in time	**Time after installation Omega-seal [years]**	**Expected value of Δz [mm]**		**Extreme value of Δz [mm]**	
		1A / 2E	3A	1A / 2E	3A
Completion Kil Tunnel	0,75	100	50	110	70
Present situation	40	105	55	120	80
Design lifetime	100	110	60	130	90

Table 8: Expected and extreme values of Δz at different moments in time (estimated)

3.4.2. Corrosion

In the Kil Tunnel, endoscopic fieldwork is done. Besides, the joint was opened. Since the Kil Tunnel has a cyclists' lane from which measurements can be done, the tunnel did not need to be closed. In other tunnels, lanes have to be closed in order to make measurements. In this section, the results of the fieldwork are explained. In Section 2.5.1, a description is made.

Endoscopic research was done in four tunnels in the Netherlands: Drecht Tunnel, Noord Tunnel, Kil Tunnel, Vlake Tunnel and First Heinenoord Tunnel. Since it was not possible to reach the chamber to do visual observations, endoscopes were used. A hole was bored from the tunnel tube to the chamber, at the floor of the tunnel. The main results of the research were:

- All chambers were (at the floor of the tunnel) filled with water. This water contained de-icing salts.
- It was difficult to judge on the state of the bolts, since the majority was heavily polluted. The visible bolts in the floor were hardly corroded (Figure 42).
- Since it was known that all chambers were filled with water, there would be a region in the tunnel where corrosion was most likely. This was the so called "splashzone", where both water and air were present. This location was at about the same level as the road.
- In the same four tunnels, endoscopic research was done at the "splashzone". At a few locations, corrosion in the bolts was discovered (Figure 43). It was hard to judge how severe this corrosion was, since observations only show the outside of the clamping structure.

Figure 42: Clean clamping structure at the floor of the Kil Tunnel, from research in 2014 (Leeuw, 2015)

Figure 43: Corroded clamping structure at the wall of the Kil Tunnel, from the research in 2015 (Leeuw, 2015)

Therefore, the clamping structure can be divided into three zones in terms of corrosion:

- The wet zone: This area is in the floor of the chamber. Corrosion is limited, since water prevented air from entering.
- The "splashzone": This area is at about the same level as the water table in the chamber. This is at about the height of the road. Corrosion is large, since water and air are present in this area.
- The dry zone: This area is above the "splashzone". Corrosion is small, since there is no water present.

In Figure 44, an overview of the location of these locations is shown.

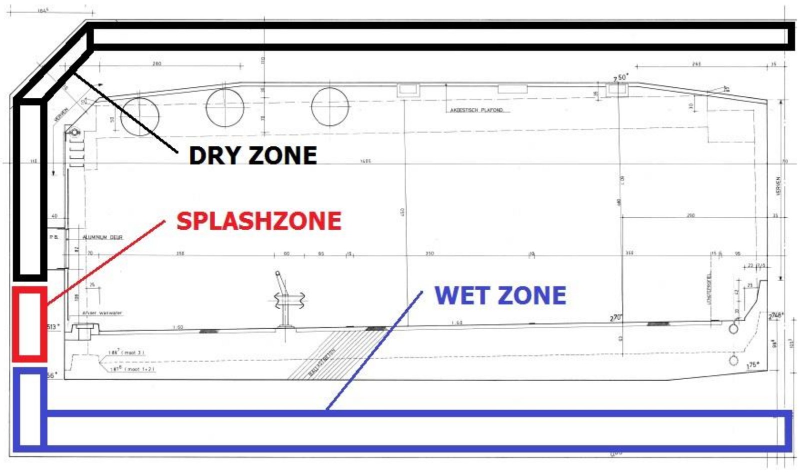

Figure 44: Cross section of half of the Kil Tunnel, showing the location of the different zones

Since the "splashzone" seems most critical, it was decided to do inspections in that zone. Joint 3A was opened. During this research, part of the concrete was removed by digging a hole, in order to do visual observations. Also, a hole was made into the clamping plate, in order to enable the endoscope to see the space in between the clamping plate and the plate. The main results were (Leeuw, 2016):

- The clamping plate was slightly corroded at the side of the plate. Since the clamping plate is relatively thick in many immersed tunnels, this would not lead to problems.
- The bolts / studs were considered at the location in between the clamping plate and the plate. There is no relation between corrosion at that location, and corrosion at the cantilevering part of the bolt or stud. This means: if corrosion occurs at the cantilevering part of the bolt or stud, it is not known what the state of the bolt or stud in between the clamping plate and the plate is.
- The extent of the corrosion was hard to judge from the visual observations. The depth of the penetration of the corrosion is hard to determine.
- The Gina-seal is watertight in this joint. Since it was possible to compress the curved part of the Omega-gasket, it was concluded that there was no water in between the Gina-gasket and the Omega-gasket.

The bore hole and the clamping plate are shown in Figure 45.

Figure 45: Clamping plate, with stud through it, seen from the tunnel tube (COB, 2017)

It is known where the corrosion is most severe. However, the extent is hard to determine. Further research on the corrosion is needed to become the required insight. For further calculations, assumptions must be made.

3.5. Summary

The Kil Tunnel is used as a case study, since there is relatively much information available on the design, construction and current state. Also, large-scale maintenance is planned for 2020 until 2022.

The Kil Tunnel is an immersed tunnel that is located below the river Dordtsche Kil that is constructed from September 1974 until August 1977. It consists of three tunnel elements and has three immersion joints: 1A, 2E and 3A. Immersion joints 1A and 2E connect the tunnel with the abutment. These joints are exactly the same. Immersion joint 3A connects two tunnel elements with each other.

Procedure A (install Omega-seal before consolidation period) was used during the construction of the immersion joints. Significant differential settlement will occur in joint 1A/2E. The joints are a bit higher in the roof (compared to the wall / floor). Joint 1A/2E has a larger soil cover due to the dike that is located on top. The joint width of 1A/2E and 3A are respectively 100 and 120 mm. In joint 1A/2E, the Gina-gasket is of the type G 155-109-60. In joint 3A, the Gina-gasket is of the type G 190-148-50 and therefore a bit larger. The Omega-gasket that is used in 1A/2E and 3A is exactly the same.

The expected and extreme values of the movement of the tunnel elements are determined (for a lifetime of ¾, 40 and 100 years):

- Movements in x-direction: This depends of the seasonal temperature changes. The values of the differential movement (Δx) range between 10 mm (expected) and 20 mm (extreme).

- Movements in y-direction: This depends of the differential horizontal movement of two tunnel elements. The values of the differential movement (Δy) range between 0 mm (expected) and 20 mm (extreme).
- Movements in z-direction: This depends of the differential vertical moment of two tunnel elements. The values of the differential movement (Δz) range between 50 mm (expected, ¾ years, joint 3A) and 130 mm (extreme, 100 years, joint 1A/2E).

Endoscopic research is done in the Kil Tunnel. The most critical zone of the corrosion is in the "splashzone". This area is at about the same height as the road. Corrosion is large, since water from the chamber and air are present in this area. In the other zones (wet zone and dry zone) the corrosion is limited. Joint 3A was also opened at the "splashzone". Corrosion was detected there, too. However, it was not possible to state the extent of the corrosion.

4

Chapter 4 – Failure of the Gina-seal

In Chapter 4, one of the two conditions for leakage through an immersion joint is considered: failure of the Gina-seal. After a description of the requirements of the Gina-seal in general, the mechanisms that determine the watertightness are explained. Then, calculation methods of the watertightness and functioning are explained. Afterwards, a case study on the Kil Tunnel is performed. It is calculated whether the Kil Tunnel meets the prescribed requirements.

4.1. Requirements Gina-seal

The main goal of the Gina-seal is to prevent water from entering the tunnel. This paragraph, it is explained which requirements need to be met in order to achieve this goal. From the design documents by Trelleborg, four requirements of the Gina-seal are prescribed. These correspond to the failure mechanisms described in Section 2.4.2. Leakage through the Gina-seal takes place when at least one of the requirements is not met. This means that the situation can be schematized as an OR-gate in a failure tree.

4.1.1. Requirement G1: Enough pressure to stop water

The Gina-gasket should be pressed strongly enough to the opposite tunnel element in order to create a watertight layer. If the pressure from the Gina-gasket on the opposite tunnel element is strong enough, water is not able to pass the layer. This mechanism is shown in Figure 46 (left). It should be taken into account that over the time, the clamping force in the Gina-gasket decreases due to relaxation.

Requirement G1 is quantified by Equation 4.1. This requirement is used by Trelleborg Ridderkerk in the design of Gina-seals (Coentunnel Construction, 2009). It is assumed that if the pressure of the Gina-gasket is at least 2.5 as large as the local water pressure, the Gina-seal forms a watertight layer over the lifetime. In case the clamping pressure is (slightly) larger than the water pressure, the water pressure is not able to push the Gina-gasket away. This value of 2.5 contains some margin, for inaccuracies of production of the Gina-gasket, displacement of the tunnel elements in x-direction, deterioration, imperfection of the model and safety. The governing situation of this requirement is always in the floor, since the water pressure is highest there.

$$p_{G,pr} > 2.5 \times p_{water} \tag{4.1}$$

$$2.5 \times p_{water} = p_{ws} \tag{4.2}$$

With:

$p_{G,pr}$ = resistance pressure of the Gina-gasket against the opposite tunnel element [N/mm^2]
p_{water} = pressure caused by the water [N/mm^2]
p_{ws} = calculation value of water pressure [N/mm^2]

In order to know how much margin is left, the remaining safety of Requirement G1 is calculated. This is done by Equation 4.3. In case γ_{G1} is smaller than 1, Requirement G1 is not met, so there is no remaining safety. In case γ_{G1} is larger than 1, the requirement is met. The larger the value of remaining safety is on top of 1, the more reliable the seal is against leakages of this mechanism.

$$\gamma_{G1} = \frac{p_{G,pr}}{2.5 \times p_{water}} = \frac{p_{G,pr}}{p_{ws}} \tag{4.3}$$

With:

γ_{G1} = safety factor of Requirement G1 [-]
$p_{G,pr}$ = resistance pressure of the Gina-gasket against the opposite tunnel element [N/mm^2]
p_{water} = pressure caused by the water [N/mm^2]

4.1.2. Requirement G2: Force equilibrium

When water and soil press to the compressed Gina-gasket, the gasket may be pushed away causing leakage. Therefore, there should be enough resistance, so displacement of the Gina-gasket is prevented. An example is shown in Figure 46 (right). In order to prevent this, there should be enough clamping force in the Gina-gasket, so enough friction force is created. If this requirement is not met, the Gina-seal is pushed in the direction of the Omega-seal. When this happens severely, the Gina-gasket will touch the Omega-seal. In that case, an extra load acts on the Omega-seal.

Requirement G2 is quantified by Equation 4.4. This requirement is used by Trelleborg Ridderkerk in the design of Gina-seals. The friction force of the compressed Gina-gasket should be larger than the force caused by the water column and the soil. In this calculation, the capacity of the clamping structure is not taken into account. Only the friction of the Gina-gasket is taken into account in this calculation. In reality, the clamping structure will also hinder displacement the Gina-gasket and provide some additional capacity.

$$n_{G,fr} > n_{total} \tag{4.4}$$

$$n_{G,fr} = n_{G,pr} \times 2 \times \mu \tag{4.5}$$

$$n_{total} = n_{water} + n_{soil} \tag{4.6}$$

With:

$n_{G,fr}$ = friction force in the Gina-gasket [N/mm′]
$n_{G,pr}$ = force with which the Gina-gasket presses onto the opposite tunnel element [N/mm′]
n_{total} = total force working on the Gina-seal [N/mm′]
n_{water} = force caused by the water column [N/mm′]
n_{soil} = force caused by the soil [N/mm′]
μ = friction coefficient of rubber on steel [-]

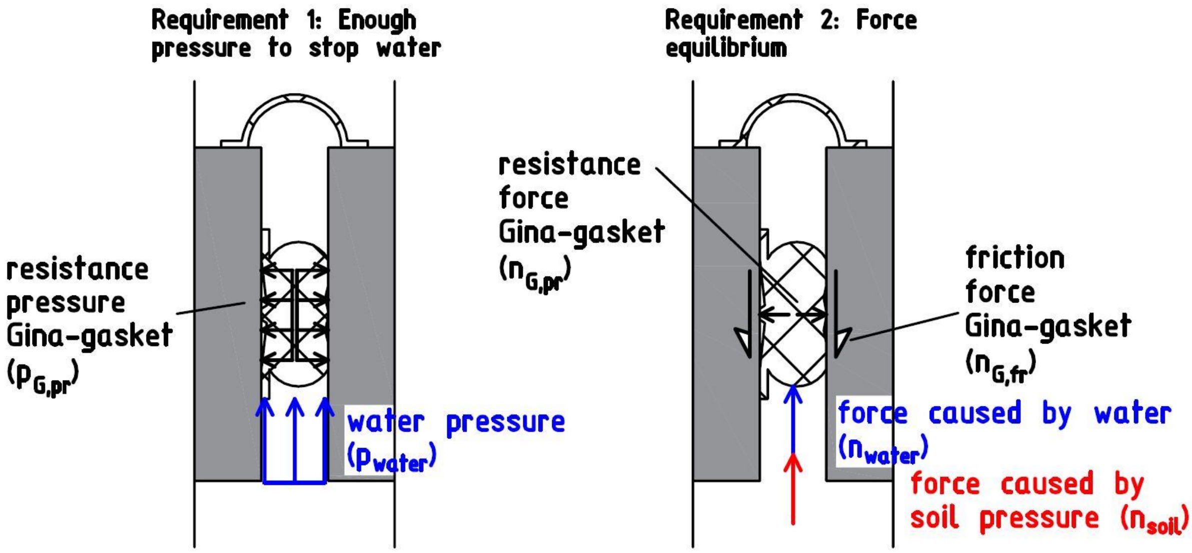

Figure 46: Force schedule of Requirement G1 (left) and Requirement G2 (right)

In the calculations, the remaining safety of Requirement G2 is calculated. This is done with Equation 4.7. In case safety factor γ_{G2} is smaller than 1, Requirement G2 is not met, so there is no remaining safety. In case γ_{G2} is larger than 1, the requirement is met. The larger the value of remaining safety is on top of 1, the more reliable the seal is against failure of this mechanism.

$$\gamma_{G2} = \frac{n_{G,fr}}{n_{total}} = \frac{n_{G,pr} \times 2 \times \mu}{n_{total}} \tag{4.7}$$

With:

γ_{G2} = safety factor of Requirement G2 [-]
$n_{G,fr}$ = friction force in the Gina-gasket [N/mm′]
n_{total} = total force working on the Gina-seal [N/mm′]
$n_{G,pr}$ = force with which the Gina-gasket presses onto the opposite tunnel element [N/mm′]
μ = friction coefficient of rubber on steel [-]

There will be three safety checks: from the roof, the wall and the floor, since the loads are different in all situations.

4.1.3. Requirement G3: Contact between Gina-gasket and opposite tunnel element

In order to create a watertight layer, the Gina-gasket must press against the opposite tunnel element. This mechanism is shown in Figure 47. Movements of the tunnel in y-direction and in z-direction can lead to lack of connection between the Gina-seal and the opposite tunnel element.

Requirement G3 is quantified by Equation 4.8 and 4.9. Equation 4.8 holds for the wall of the tunnel. Equation 4.9 holds for the floor and the roof of the tunnel. The margin is not calculated. When this requirement is not met, it is assumed that the Gina-seal is not watertight.

$$\Delta y < s_{mo1} \tag{4.8}$$
$$\Delta z < s_{mo1} \tag{4.9}$$

With:

Δy = differential movement of the immersion joint in y-direction [mm]
Δz = differential movement of the immersion joint in z-direction [mm]
s_{mo1} = distance between Gina-gasket and Omega-gasket [mm]

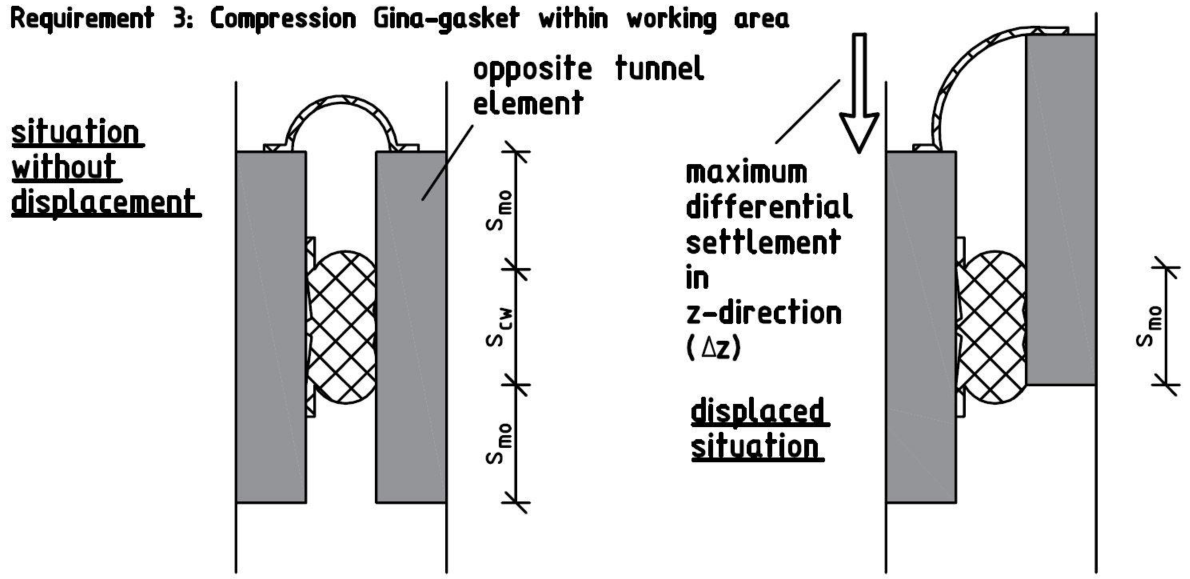

Figure 47: Overview of the maximum allowed differential settlement that is allowed in z-direction

4.1.4. Requirement G4: Cracks in the Gina-gasket

When the Gina-gasket is compressed heavily for a long time, cracks could occur. As a consequence water could pass this layer. This can only happen when the immersion joint has become narrow.

Requirement G4 is quantified by Equation 4.10. This requirement is used by Trelleborg Ridderkerk in the design of Gina-seals (van Stee, 2017). This requirement needs to be met, in order to be watertight.

$$c_G \leq \frac{1}{2} \times h_G \tag{4.10}$$

With:

c_G = compression of the Gina-gasket [mm]
h_G = original (uncompressed) height of the Gina-gasket [mm]

4.2. Calculation method Gina-seal

Once it is known what the requirements are, they need to be calculated. A few formulas are needed to come to the values that can be inserted into the checks stated in Paragraph 4.1. These calculation methods are described in this paragraph.

4.2.1. Capacity Gina-seal

There are basically three values that are important related to the capacity of the Gina-seal: the reaction force, the pressure and the friction force of the Gina-gasket. The procedure to determine these values is described in this section.

Reaction force of the Gina-gasket

When the Gina-gasket is compressed, a reaction force occurs. This force from the Gina-gasket depends on the amount of compression. When knowing the compression, the reaction force can be obtained from the force-compression curve. An example is shown in Paragraph D.1. Compression is on the x-axis, while the reaction force is on the y-axis.

The compression is calculated with Equation 4.11. The original (uncompressed) height of the Gina-gasket (h_{Gina}) is known from the type of Gina-gasket that is used. This is obtained from the design drawings. The average joint width (s_{jwp}) is known from the design drawings, too.

$$c_G = h_G - s_{jwp} \tag{4.11}$$

With:

c_G = compression of the Gina-gasket [mm]
h_G = original (uncompressed) height of the Gina-gasket [mm]
s_{jwp} = joint width that is present in the joint [mm]

The joint width that is present is still unknown. This can be calculated by Equation 4.12. The joint width depends over the year. This is taken into account in this tunnel.

$$s_{jwp} = s_{jwa} + \frac{1}{2} \times a \times \Delta x \tag{4.12}$$

With:

s_{jwp} = joint width that is present in the joint [mm]
s_{jwa} = average joint width in the joint [mm]
a = coefficient for seasonal temperature changes [-]
Δx = maximum tightening and widening of the immersion joint in longitudinal direction according to the average [mm]

Pressure of the Gina-gasket

From the force of the Gina-gasket, the pressure of the Gina-gasket ($p_{G,pr}$) can be calculated. In order to calculate this, the width of the surface of the Gina-gasket that is pushed against the opposite tunnel element (s_{cw}) needs to be known. With Equation 4.13, the pressure of the Gina-gasket can be calculated. It is assumed that the pressure is equally spread over the surface.

$$p_{G,pr} = \frac{n_{G,pr}}{s_{cw}} \tag{4.13}$$

With:

$p_{G,pr}$ = pressure of the Gina-gasket [N/mm^2]
$n_{G,pr}$ = amount of force that is present in the Gina-gasket [N/mm']
s_{cw} = width of the surface of the Gina-gasket that is pushed against the opposite tunnel element [mm]

Friction force of the Gina-gasket

The friction force that the Gina-gasket creates can be calculated with Equation 4.14. The force of the Gina-gasket ($n_{G,pr}$) is multiplied with the friction factor (μ) of the material against which the Gina-gasket pushes. It must be multiplied by 2, since the Gina-gasket pushes in two planes: one on both tunnel elements.

$$n_{G,fr} = n_{G,pr} \times 2 \times \mu \tag{4.14}$$

With:

$n_{G,fr}$ = friction force in the Gina-gasket [N/mm']
$n_{G,pr}$ = force with which the Gina-gasket pushes against the opposite tunnel element [N/mm']

μ = friction coefficient of the material against which the Gina-gasket pushes [-]

4.2.2. Loads on Gina-seal

Basically, there are two (external) loads that act on the Gina-seal: water and soil. The procedure to determine these values is described in this section. It is stressed that the calculation is executed with expected values. This means that no probabilistic calculations are made. The result of the calculations is expectations whether leakages will occur.

Loads from water

The water on top of the immersed tunnel forms a column. The own weight of this column will create a hydrostatic pressure on the Gina-seal. Therefore, it is important to know what the density of the water is, and what the height of the water column. The pressure and the force of the water that acts on the Gina-gasket can be calculated with Equation 4.15 and 4.16. The value of 2.5 is explained in Section 4.1.1.

$$p_{ws} = 2.5 \times s_{wc} \times \gamma_w \tag{4.15}$$
$$n_w = s_{wc} \times \gamma_w \times s_{jwp} \tag{4.16}$$

With:

p_{ws} = calculation value of water pressure [N/mm^2]
n_w = force of the water that acts on the Gina-gasket [N/mm']
s_{wc} = height of the water column [m]
γ_w = density of the water [kN/m^3]
s_{jwp} = joint width that is present in the joint [mm]

An important parameter from in Equation 4.15 and 4.16 is the height of the water column. The procedure to calculate this is presented in Equation 4.17. The author proposed this equation.

$$s_{wc} = |s_{dp}| + |s_{hd} - s_{gwt}| \tag{4.17}$$

With:

s_{wc} = height of the water column [m]
s_{dp} = deepest point joint (relative to NAP) [m]
s_{hd} = height dike (relative to NAP) [m]
s_{gwt} = height governing water table below dike [m]

Loads from soil

The soil in the roof and the soil in the wall create a load on the Gina-seal. In the roof, the vertical force is calculated by Equation 4.18. In the wall, the horizontal force is calculated by Equation 4.19. In the floor, the soil does not work on the Gina-seal, since soil force cannot act in upward direction.

The value of α depends per situation. The design of the joint, the time and the movements in x-direction play a role. This will be further explained in Section 4.3.2 for the situation of the Kil Tunnel.

$$n_{soil,roof} = s_{sc} \times (\gamma_s - \gamma_w) \times \alpha \times s_{jwp} \tag{4.18}$$
$$n_{soil,wall} = K_0 \times (s_{sc} + s_{ht}) \times (\gamma_s - \gamma_w) \times \alpha \times s_{jwp} \tag{4.19}$$

With:

$n_{soil,roof}$ = force of the soil working on the Gina-seal in the roof [N/mm']
$n_{soil,wall}$ = force of the soil working on the Gina-seal in the wall [N/mm']
K_0 = neutral earth pressure coefficient [-]
s_{sc} = height of the sand cover of the tunnel [mm]
s_{ht} = height of the tunnel [mm]
γ_s = density of the soil [kN/m^3]
γ_w = density of water [kN/m^3]
α = multiplication factor due to the cyclic compression [-]
s_{jwp} = joint width that is present [mm]

4.3. Mechanisms that influence the functioning over the lifetime

There are a few mechanisms that influence the watertightness over the lifetime. These are described in this paragraph, both qualitative and quantitative. Also, ways to calculate the influence are described.

4.3.1. Movements in the immersion joints

There are basically two different mechanisms that play a role. Movement in x-direction influences Requirements G1, G2 and G4. Movement in y-direction and in z-direction influences Requirement G3.

Movement in x-direction

Due to movements in x-direction (caused by seasonal temperature changes), the immersion joints become a bit narrower in summer and a bit wider in winter, as a consequence of thermal expansion or shrinkage. This is a very important phenomenon for functioning of the Gina-gasket. A schematization is shown in Figure 48. It influences the compression that is present in the Gina-gasket (c_G). A lower compression leads to a lower value of the friction force, resulting in a lower capacity.

When the joint becomes wider, the risk of leakage occurs. Requirements G1 and G2 may not be met, since the friction becomes smaller. When the joint becomes narrower, this may lead to cracks of the Gina-gasket. In that case Requirement G4 may not be met.

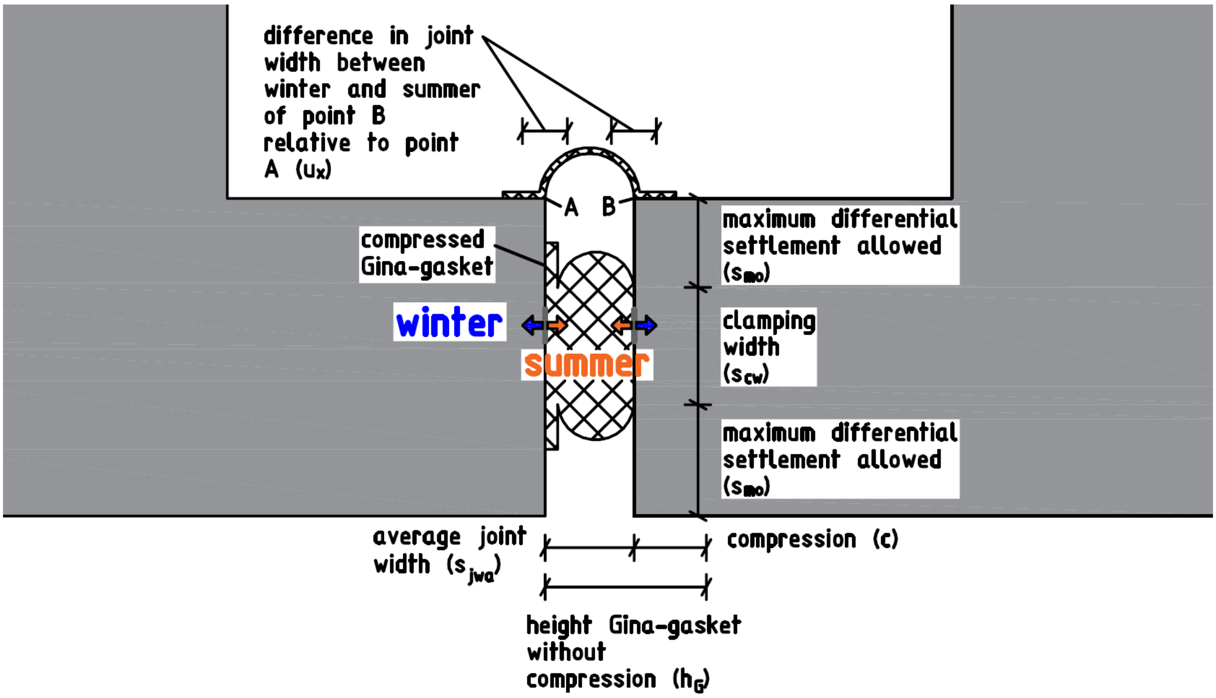

Figure 48: Schematization of the effect of seasonal temperature changes

Movement in y-direction and in z-direction

Differential movement (as shown in Figure 49) can occur in two directions:

- y-direction (Δy) – These settlements are in horizontal direction (perpendicular to the longitudinal direction of the tunnel). In the wall, this can lead to loss of contact between the Gina-gasket and the opposite tunnel element.
- z-direction (Δz) – These settlements are in vertical direction. In the roof and in the floor, this can lead to loss of contact between the Gina-gasket and the opposite tunnel element.

The risk is that the Gina-gasket will lose its connection with the opposite tunnel element. It is checked whether this happens in Requirement 3. The capacity is referred to as distance between Gina-gasket and Omega-gasket (s_{mo1}) and holds for both y-direction and z-direction. The amount of differential movement (Δy and Δz) should be lower than the capacity.

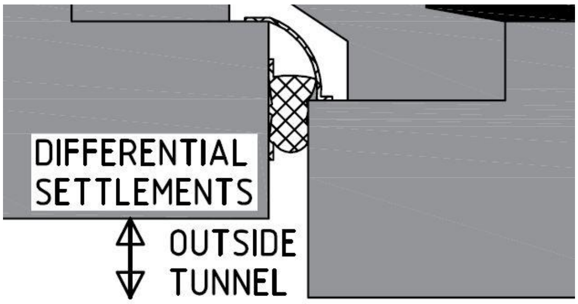

Figure 49: Effect of differential settlements in immersion joints

4.3.2. Increased soil pressure

Soil causes a pressure on the Gina-gasket. This effect occurs in the wall and the roof. The soil in the joint compresses when the joint becomes narrow (in summer). The pressure decreases when the joint becomes wider (in winter). When this happens cyclically, soil pressure can increase due to the plentiful times of compression. In that case, the multiplication factor due to cyclic compression (α) that is part of Equation 4.18 and 4.19 increases. There is a risk of pushing out of the Gina-gasket which is shown in Figure 50. The influence of the soil pressure is checked in Requirement 2.

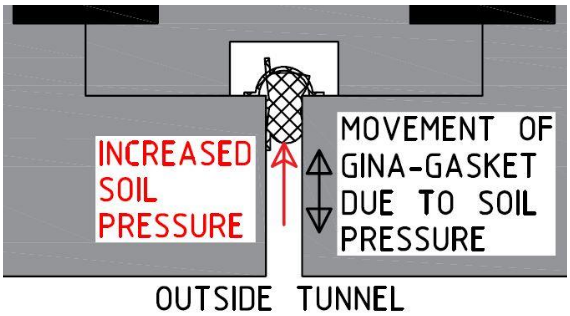

Figure 50: Schematization of the movement of the Gina-gasket due to increased soil load

Increase of soil pressure can take place, as a rule of thumb, when the width of the joint (s_{jwp}) is smaller than the height of the joint (s_{mo2}) (Taffijn, 2016). This described in Equation 4.20. The outcome of this check determines the multiplication factor due to cyclic compression (α).

$$s_{jwp} < s_{mo2} \tag{4.20}$$

With:
s_{jwp} = joint width that is present in the joint [mm]
s_{mo2} = distance between Gina-gasket and outside tunnel [mm]

Further, there are three mechanisms that play a role:

- The shape of the immersion joint: When the corners of the tunnel element are straight, the increase of soil pressure will earlier take place than when there is a gradual or rounded corner.
- The amount of soil on top of the joint (s_{sc}): When the soil column is large, the increase of the soil pressure will be larger.
- The age of the immersion joint (t): This mechanism increases over time. The soil is compressed more, when it is cyclically compressed over a longer time.

4.3.3. Relaxation

Over time, the stress in the Gina-gasket and Omega-gasket decreases. This phenomenon is called relaxation. It influences the amount of force that is present in the Gina-gasket and Omega-gasket. The amount of stress that remains can be calculated with Equation 4.21 (Coentunnel Construction, 2009). Relaxation decreases the capacity of the Gina-seal and the Omega-seal. It is taken into account in the Requirements G1 and G2.

$$\frac{\sigma(t)}{\sigma(t=0)} = 1 - 0.01 \times r \times \log(t \times 365 \times 24 \times 60) \tag{4.21}$$

With:

σ(t)/σ(t=0)	= part of the initial force that is still left after relaxation [-]
r	= relaxation per decade [%]
t	= time after immersion [years]

The remaining force in the Gina-seal can be calculated by Equation 4.22.

$$n_{G,pr} = \frac{\sigma(t)}{\sigma(t=0)} \times n_{G,in} \tag{4.22}$$

With:

$n_{G,pr}$	= amount of force that is present in the Gina-gasket [N/mm′]
σ(t)/σ(t=0)	= part of the initial force that is still left [-]
$n_{G,in}$	= amount of force that is present in the Gina-gasket when it is completely new [N/mm′]

4.4. Calculation watertightness case Kil Tunnel

The case study Kil Tunnel is considered. In this paragraph, the calculations on the watertightness of the Omega-seal in the Kil Tunnel are presented. First of all, the system is described. Then, the calculated situations are explained and the input values are described. Then, the results of the calculations are presented.

4.4.1. Input values

As described in Chapter 3, there are three immersion joints in the Kil Tunnel. Two of them are exactly the same, namely immersion joints 1A and 2E (type 1A / 2E). The other immersion joint is 3A (type 3A). The input values from these two types are described in Section 3.3.2 and 3.3.3. The other relevant parameters are described in this section.

Location and time

There are many locations in the tunnel where failure of the Gina-seal can occur. The following locations are checked in the Kil Tunnel:

- Roof of the tunnel: The soil pressure acts on the roof of the tunnel. The forces are approximately equal over the roof.
- Wall of the tunnel: The soil pressure acts on the wall of the tunnel. Within the wall, the forces are highest in the lower sections, so close to the floor.
- Floor of the tunnel: In the floor, the differential settlements may play a role. However, the soil pressure is not present since it cannot deliver forces ‘upward’. Therefore, this part needs to be checked.

The clamping structure is considered at three moments in time: at completion of the Kil Tunnel, in the present situation and at the design lifetime. The determined values for the movements of the tunnel are used.

Multiplication factor of soil compression

Another important parameter is the multiplication factor of soil compression (α). When increase of the soil pressure does not occur, this value remains 1. However, when increase of the soil pressure occurs, the value will become larger than 1. First, a check needs to be made to state whether increase of soil pressure is likely to happen. Equation 4.20 is used. Besides, the amount of soil on top of the joint is taken into account. The results are shown in Table 9.

Joint	Location	s_{jwp} [mm]	s_{mo2} [mm]	s_{sc} [m]	Presence of increase of soil pressure
1A/2E	Roof	90 – 110	314	10.47	This phenomenon will probably occur. The difference between s_{jwp} and s_{mo2} is very large and the amount of soil cover (s_{mo2}) is large, so the multiplication factor will be significant.
	Wall	90 – 110	164	10.47	This phenomenon will probably occur. The amount of soil cover (s_{mo2}) is rather small, so the multiplication factor will be rather small.
3A	Roof	110 – 130	286	2.00	This phenomenon will probably occur, but will not be significant because the amount of soil cover is rather small.
	Wall	110 – 130	136	2.00	This phenomenon will probably occur, but will not be significant because the amount of soil cover is rather small.

Table 9: Consideration whether the increase of soil pressure is likely to take place in the immersion joints of the Kil Tunnel

Based on the thesis report of Rheza Rahadian, multiplication factors are determined (Rahadian, 2017). The chosen values are shown in Table 10. Since there is relatively little known about this phenomenon, these values are rather stochastic.

Joint	Description	Symbol	t = 0.75 years		t = 40 years		t = 100 years	
			Expected	Extreme	Expected	Extreme	Expected	Extreme
1A / 2E	Multiplication factor due to the cyclic compression roof [-]	α_{roof}	1.5	2	2	3	2.5	4
	Multiplication factor due to the cyclic compression wall [-]	α_{wall}	1.2	1.4	1.4	1.8	1.6	2.2
3A	Multiplication factor due to the cyclic compression roof [-]	α_{roof}	1.1	1.2	1.2	1.4	1.3	1.6
	Multiplication factor due to the cyclic compression wall [-]	α_{wall}	1	1	1	1	1	1

Table 10: Determined multiplication factors in different situations in the tunnel

Other parameters
There are a few calculation parameters that are the same for all calculations. These are presented in Table 11. The relaxation per decade (r) and the friction factor (μ) are both standard design values that are used by Trelleborg. The density of wet sand (γ_s) is assumed. The density of water is assumed too, based on the fact that the water in the Dordtsche Kil is fresh water.

Besides, there is the coefficient for seasonal temperature changes (a). This value is always -1 for the summer, 0 for the average and +1 for the winter.

Description	Symbol	Value	Unity
Relaxation per decade	r	5	%
Friction factor	μ	0.3	(-)
Wet density sand	γ_s	19	kN/m^3
Density water	γ_w	10	kN/m^3

Table 11: Calculation parameters that do not change throughout the tunnel and over time

4.4.2. Results calculations

The calculations are made. The complete calculations can be found in Paragraph C.2. In this section, the main values are presented with an explanation.

Joint 1A/2E
In Table 12, the results of the checks are presented. Below, an analysis is made.

Requirement G1 is met in every case. However, the margin is not very large. At its smallest, the margin is 22%, under extreme conditions, in the winter at design life time (100 years). Requirement G2 roof is not met in every case. Under extreme conditions during design lifetime, the requirement is not met. Requirement G2 wall is met in every case, although not with too large margins. At its lowest, the margin is 42%. Requirement G2 floor is met in every case, with very large margins. Requirement G3 and G4 are met in every case.

Requirement G2 roof requires attention. Within the immersion joint of 1A/2E, this is the location where compression of the soil is expected to be the largest. Visual inspection is needed to see if the Gina-seal is still at the right location.

Re-quire-ment	**Description**	**Loca-tion**	**t = 40 years**				**t = 100 years**			
			expected		extreme		expected		extreme	
			W	S	W	S	W	S	W	S
G1	Enough pressure to stop water (γ_{G1})	Floor	1.44	1.88	1.26	2.17	1.39	1.83	1.22	2.10
G2	Force equilibrium (γ_{G2})	Roof	1.77	2.56	1.18	2.48	1.52	2.20	0.95	2.00
		Wall	2.16	3.13	1.62	3.42	1.98	2.87	1.42	3.00
		Floor	3.60	5.21	3.00	6.33	3.49	5.04	2.91	6.14
G3	Contact between Gina-gasket and opposite tunnel element	Wall	OK	OK	OK	OK	OK	OK	OK	OK
		Floor	OK	OK	OK	OK	OK	OK	OK	OK
G4	Cracks in the Gina-gasket	Floor	OK	OK	OK	OK	OK	OK	OK	OK

Table 12: Results of the checks of joint 1A/2E (W: winter; S: summer)

Joint 3A
In Table 13, the results of the checks are presented. Below, an analysis is made.

Requirement G1 is met in every case. The margins are rather large. At its smallest, the margin is over 100%, even under extreme conditions, in the winter at design life time (100 years). Requirements G2 is met in every case, with margins larger than 100%. Requirement G3 and G4 are met in every case.

According to the calculations, it seems that this immersion joint is still functioning well. However, visual inspection is needed to check whether this is the case in practice.

Re-quire-ment	**Description**	**Loca-tion**	**t = 40 years**				**t = 100 years**			
			expected		extreme		expected		extreme	
			W	S	W	S	W	S	W	S
G1	Enough pressure to stop water (γ_{G1})	Floor	2.81	4.01	2.31	4.73	2.72	3.89	2.23	4.58
G2	Force equilibrium (γ_{G2})	Roof	4.50	7.00	3.32	8.06	4.21	6.55	3.02	7.33
		Wall	5.27	8.19	4.16	10.09	5.10	7.94	4.03	9.78
		Floor	7.74	12.04	6.12	14.83	7.50	11.66	5.93	14.37
G3	Contact between Gina-gasket and opposite tunnel element	Wall	OK	OK	OK	OK	OK	OK	OK	OK
		Floor	OK	OK	OK	OK	OK	OK	OK	OK
G4	Cracks in the Gina-gasket	Floor	OK	OK	OK	OK	OK	OK	OK	OK

Table 13: Results of the checks of joint 3A (W: winter; S: summer)

4.4.3. Conclusions and recommendations

The following can be concluded:

- The Gina-seal of immersion joint 1A/2E could experience problems related to check G2 roof. Due to a large soil cover, the design of the joint and cyclic deformation of the tunnel elements, this could lead to pushing out of the Gina-seal. The other checks (G1, G2 wall, G2 floor, G3 wall, G3 floor and G4) are all met. This joint requires special attention.

- The Gina-seal of immersion joint 3A seems to be in good condition. All requirements are met with significant margins.
- About the requirements, the following can be said:
    - Requirement G1 is checked easily. The loads do not change over the lifetime. The resistance changes, but can easily be calculated. The values of Δx would make the consideration more reliable.
    - Requirement G2 is difficult to check. Increased soil pressure needs to be taken into account in this calculation. It is the mechanism that forms the highest risk in the Kil Tunnel. There is a rather large uncertainty in the used values for this calculation.
    - Requirement G3 is checked easily. However, the values of the differential settlements are not present. In order to be sure, the differential settlements in y-direction and in z-direction need to be measured.
    - Requirement G4 is checked easily. The values of Δx would make the consideration more reliable.
- The calculations only give an indication whether the Gina-seal functions. In practice, it must be proven by visual inspections whether the Gina-seal still functions. It is advised to do these inspections in the roof of joint 1A/2E, because damage is most likely in that area.

4.6 Summary

The Gina-seal has to meet all of the following requirements in order to be watertight:

- Requirement G1 – Enough pressure in the Gina-gasket to stop water: The available pressure of the Gina-gasket should to be larger than the water required pressure to stop the water.
- Requirement G2 – Force equilibrium: The amount of friction force in the Gina-gasket should be larger than the sum of the water force and the soil force, in order to prevent that the Gina-seal is pushed away.
- Requirement G3 – Contact between Gina-gasket and opposite tunnel element: The Gina-gasket must press against the opposite tunnel element.
- Requirement G4 – Cracks in the Gina-gasket: When the Gina-gasket is compressed heavily for a long time, cracks could occur.

The joint width depends how much the compression of the Gina-gasket is. From the force-compression curve, the force in the Gina-gasket can be determined. With the friction coefficient (μ), this can be translated into a friction force. With the dimensions of the Gina-gasket, the force can be transferred into a pressure.

The water pressure depends on the height of the water column. The soil pressure depends on the direction (horizontal or vertical) and the height of the soil. With the joint width, the water pressure and the soil pressure can be transferred into a force.

During the lifetime, the capacity of the Gina-seal changes, due to the following reasons:

- Movements in the immersion joints:
    - Movement in x-direction: When the joints become a bit wider in winter, friction force will decrease.
    - Movement in y-direction and z-direction: In the wall (y-direction) and the floor (z-direction) this can lead to loss of contact between the Gina-gasket and the opposite tunnel element.
- Increased soil pressure: The joint narrows in summer and widens in winter. Due to this cyclical effect, the soil pressure can increase, leading to larger loads on the Gina-seal. This effect is dependent on the design of the joint, the amount of soil on top and the age of the immersion joint.
- Relaxation – The stress in the Gina-gasket decreases in time as a result of relaxation.

The case Kil Tunnel is considered. The input values determined in Chapter 3 are used. The checks are executed at three different locations: the roof, the wall and the floor. The multiplication factor of soil compression is determined, and some general other assumptions are made.

The result of the case study on the Gina-seal in the Kil Tunnel is the following:

- Joint 1A/2E is, due to the application of a smaller Gina-gasket and the height of the soil, most critical. Requirement G1 (Enough pressure to stop water) is met easily. However, Requirement G2 (Force equilibrium in the roof) requires special attention. Requirements G2 wall, G2 floor, G3 wall, G3 floor and G4 are met.
- Joint 3A meets all requirements easily. It is expected that this Gina-seal fulfils its function over the entire lifetime.
- It is recommended to measure the maximum difference between winter and summer of the immersion joint in longitudinal direction (Δx) in all immersion joints.
- Requirement G1, G3 and G4 are easy to check. However, Requirement G2 is hard to check because of the increased soil pressure is hard to determine. Requirement G2 is hard to check because measurements of the differential settlements are not available. There is a rather large uncertainty in the used values for this calculation.

- The calculations only give an indication whether the Gina-seal functions. In practice, it must be proven by visual inspections whether the Gina-seal still functions. It is advised to do these inspections in the roof of joint 1A/2E, because damage is most likely in that area.

5

Chapter 5 – Failure of the Omega-seal

In Chapter 5, the second of the two conditions for leakage through an immersion joint is considered: failure of the Omega-seal. First the requirements will be described. Then, the way to calculate all forces in the Omega-seal is described, followed by the mechanisms that influence the watertightness over time. Afterwards, calculations on the case Kil Tunnel are performed.

5.1. Requirements Omega-seal

The main goal of the Omega-seal is to prevent water from entering the tunnel. In this paragraph, it is explained which requirements need to be met in order to achieve this goal. This is basically split up into two parts. First, the requirements of the watertightness of the entire Omega-seal are described. From this calculation, the forces in the bolt are determined. Secondly, the most important part of the Omega-seal, the bolt, is focussed on. It is checked whether the bolts are able to take the forces.

5.1.1. Requirements watertightness

Three requirements related to the watertightness of the Omega-seal are prescribed. These correspond to the failure mechanisms described in Section 2.4.3.

There are two conditions for leakage through the Omega-seal: 1) There is water behind the Omega-seal, because the Gina-seal is not watertight; 2) One of the requirements is not met. Condition 1 means that if the Gina-seal functions, the Omega-seal is theoretically not needed. Condition 2 means that this event can be schematized as an OR-gate in a failure tree. The requirements are based on the design documents by Trelleborg.

Requirement O1: Enough pressure to stop water

The flanges of the Omega-gasket should be pressed strongly enough to both tunnel elements in order to create a watertight layer. If the pressure of the Omega-gasket on the both tunnel elements is strong enough, water is not able to pass the layer. This mechanism is shown in Figure 51. It should be taken into account that over time, the clamping force in the Omega-gasket decreases due to relaxation.

Requirement O1 is quantified by Equation 5.1. This requirement is used by Trelleborg Ridderkerk in the design of Omega-seals (Coentunnel Construction, 2009). It is assumed that the pressure of the Omega-gasket is at least 2.5 as large as the local water pressure, the Omega-seal forms a watertight layer over the lifetime. In case the resistance pressure is (slightly) larger the water pressure, the water pressure is not able to push the Omega-gasket away. This value of 2.5 contains some margin, for inaccuracies of production of the Omega-gasket, displacement of the tunnel elements in x-direction, deterioration, imperfection of the model and safety.

$$p_{O,pr} > 2.5 \times p_{water} \tag{5.1}$$

$$2.5 \times p_{water} = p_{ws} \tag{5.2}$$

With:

$p_{O,pr}$ = resistance pressure of the Omega-gasket [N/mm^2]

p_{water} = pressure caused by the water [N/mm^2]

p_{ws} = calculation value of water pressure [N/mm^2]

The resistance pressure of the Omega-gasket can be calculated with Equation 5.3 and 5.4.

$$p_{O,pr} = \frac{n_{rf,pr}}{s_{ws}} \tag{5.3}$$

$$s_{ws} = s_{bop} - s_{bof} - 0.5 \times d \tag{5.4}$$

With:

$p_{O,pr}$	= resistance pressure of the Omega-gasket [N/mm^2]
$n_{rf,pr}$	= reaction force of the flange of the Omega-gasket (accounted for relaxation) [N/mm']
s_{ws}	= width clamped flange [mm]
s_{bop}	= distance between bolt and outside plate [mm]
s_{bof}	= distance between bolt and outside flange Omega-gasket [mm]
d	= diameter bolt [mm]

In order to know how much margin is left, the remaining safety of Requirement G1 is calculated. This is done by Equation 5.5. In case γ_{O1} is smaller than 1, Requirement O1 is not met, so there is no remaining safety. In case γ_{O1} is larger than 1, the requirement is met. The larger the value of remaining safety is on top of 1, the more reliable the seal is against leakages of this mechanism.

$$\gamma_{O1} = \frac{p_{O,pr}}{2.5 \times p_{water}} = \frac{p_{O,pr}}{p_{ws}} \tag{5.5}$$

With:

γ_{O1}	= safety factor of Requirement O1 [-]
$p_{O,pr}$	= resistance pressure of the Omega-gasket [N/mm^2]
p_{water}	= pressure caused by the water [N/mm^2]

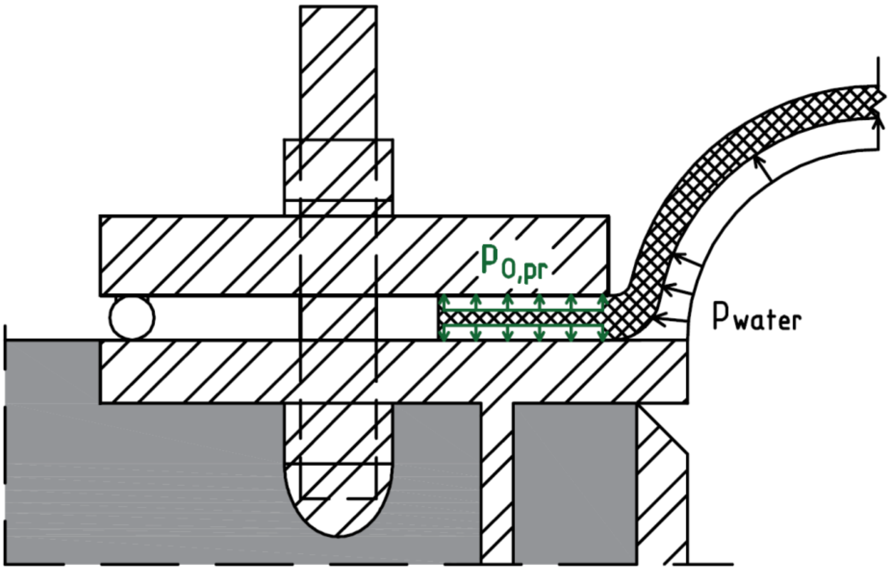

Figure 51: Force schedule of Requirement O1

Requirement O2: Prevention of pulling out flange Omega-gasket

When differential displacements take place and hydrostatic pressure works on the Omega-gasket, horizontal loads act on the flange of the Omega-seal. When the flange is loaded in horizontal direction, there is the possibility that the flange of the Omega-gasket is pulled out from the clamping structure. In order to prevent this, there should be enough friction in the flange of the Omega-gasket. Friction is caused by the reaction force of the compressed flange of the Omega-gasket.

Requirement O2 is quantified by Equation 5.6. This requirement is used by Trelleborg Ridderkerk in the design of Omega-seals. The horizontal force of the Omega-gasket should be smaller than the friction force. The friction force doubled, since it works in two planes (on the top side and bottom side of the flange). The friction force can be calculated with Equation 5.7. The force schedule is shown in Figure 52.

$$n_h < 2 \times n_f \tag{5.6}$$
$$n_f = n_{rf,pr} \times \mu \tag{5.7}$$

With:

n_h	= force in the flange of the Omega-seal working in horizontal direction [N/mm']
n_f	= friction force of the flange of the Omega-seal [N/mm']
$n_{rf,pr}$	= reaction force of the Omega-gasket that is present [N/mm']

μ = friction factor [-]

In the calculation, the remaining safety of Requirement O2 is calculated. This is done with Equation 5.8. In case γ_{O2} is smaller than 1, Requirement O2 is not met, so there is no remaining safety. In case γ_{O2} is larger than 1, the requirement is met. The larger the value of remaining safety is on top of 1, the more reliable the seal is against failure of this mechanism.

$$\gamma_{O2} = \frac{2 \times n_f}{n_h} \tag{5.8}$$

With:

γ_{O2} = safety factor of Requirement O2 [-]
n_f = friction force of the flange of the Omega-seal [N/mm']
n_h = force in the flange of the Omega-seal working in horizontal direction [N/mm']

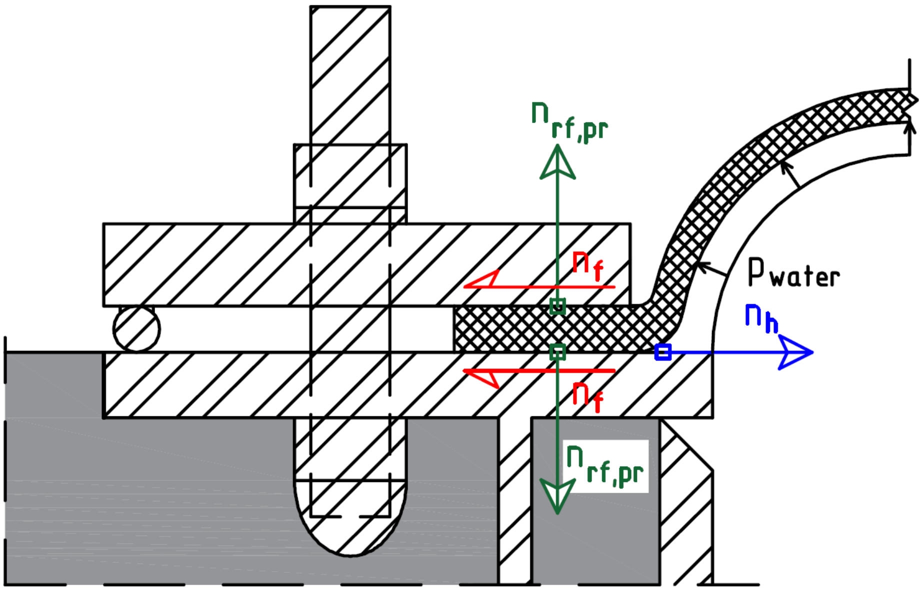

Figure 52: Force schedule of Requirement O2

Requirement O3: Cracks in the Omega-gasket

Due to differential movements of the tunnel elements, the shape of the curved part of Omega-gasket will change. When the distance between one tunnel element (point A) and the other tunnel element (point B) is larger than the length of the curved part of the Omega-gasket, strain will occur. However, the strain capacity of Omega-gasket is rather small. Strain will lead to cracks. Since the Omega-gasket should form a safe watertight layer, cracks are not allowed.

Pont A is the point where the centre line of the curved part of the Omega-gasket intersects with the plate. Point B is the same, but then on the right side of the immersion joint.

Requirement O3 is quantified in Equation 5.9. The length of the curved part of the Omega-gasket (s_{cp}) is a characteristic related to the design. The distance between point A and point B (l_c) depends on the movements of the tunnel elements. It is calculated in Equation 5.10. A margin of 10% is used in this calculation. This is taken for inaccuracies of the production of the Omega-gaskets, deterioration and imperfection of the model. The governing situation is during the winter, since the value of the movement in x-direction is largest. In Figure 50 and 51, the dimensions and the displacement is shown.

$$0.9 \times s_{cp} \leq l_c \tag{5.9}$$

$$l_c = \sqrt{(\Delta x)^2 + (\Delta y)^2 + (\Delta z)^2} \tag{5.10}$$

With:

s_{cp} = length curved part Omega-gasket [mm]
l_c = distance between point A and point B [mm]
Δx = maximum difference between winter and summer of the immersion joint in longitudinal direction [mm]
Δy = differential movement of the immersion joint in y-direction [mm]
Δz = differential movement of the immersion joint in z-direction [mm]

The length of the curved part of the Omega-gasket (s_{cp}) is shown in Figure 53. Calculation of this value is explained in Appendix D.2.

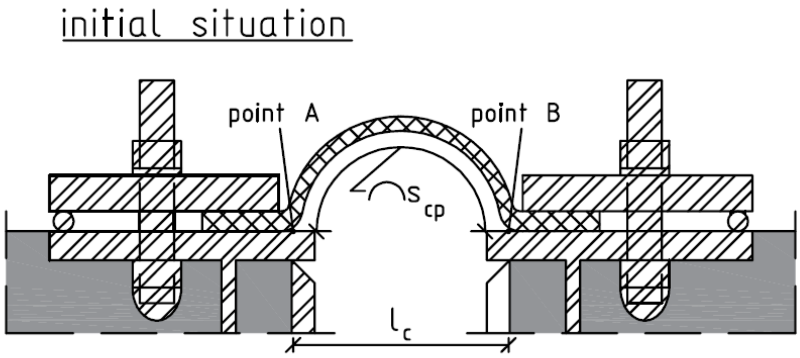

Figure 53: Schedule of the initial situation of the Omega-gasket

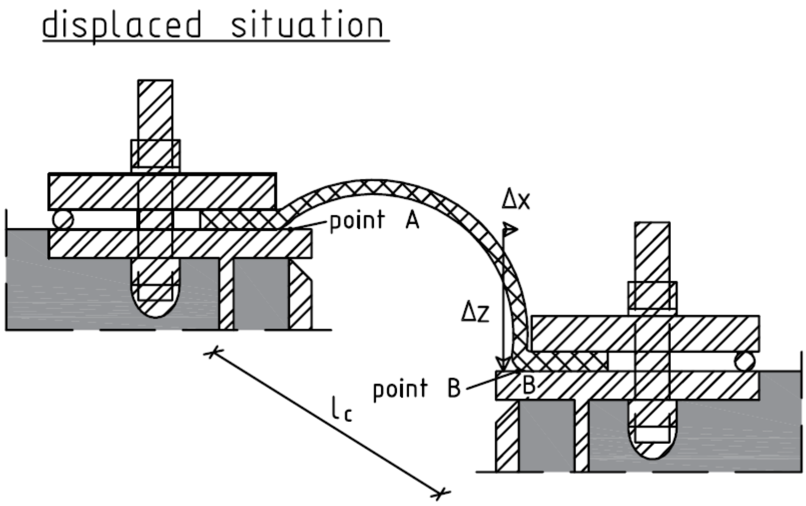

Figure 54: Schedule of the displaced situation of the Omega-gasket, that could possibly lead to cracks

Influence of the Gina-seal: The Gina-seal is pushed away and delivers a force to the Omega-seal
Next to the three requirements, there is also the requirement that the Gina-gasket may not be pushed away, because this could lead to damage to the Omega-seal. However, this is treated in Section 4.1.2. Since this could also lead to failure of the Omega-seal, this must be taken into account in the consideration.

5.1.2. Requirements bolt

The focus will now be on a part of the Omega-seal: the bolt. The bolt forms a crucial link within the clamping structure. Since it mainly determines whether the clamping structure functions, some checks need to be performed. The requirements are described in this section. The bolt consists of a stud, a nut and a washer, as described in Section 3.3.4.

In Section 5.2.1, the way to calculate the force in the bolt (F_b) was explained. It must be calculated if the individual bolt is able to take these loads. The calculations are made with the book of Roloff Matek (Muhs, 2005). Basically, three elements of the bolt need to be checked. They are explained in this section. An overview of the location of all loads is shown in Figure 55.

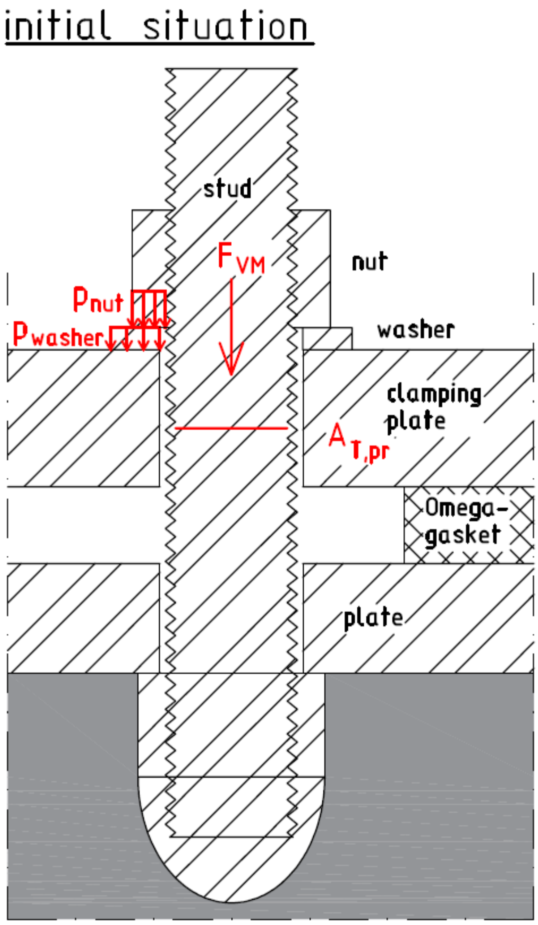

Figure 55: Cross section of an individual bolt, showing where the forces described in Section 5.1.2 act

Requirement B1: Amount of surface in the bolt
This is a check whether the surface of the bolt is large enough to transfer the loads. The requirement is quantified in Equation 5.11. The capacity is determined in Equation 5.12. This value is dependent on the design of the bolt, and the penetration of the corrosion. The required surface, to be able to take the loads, is determined in Equation 5.13. This is rather a complex formula and will therefore be explained in Paragraph D.1.

$$A_{T,pr} \leq A_{T,req} \tag{5.11}$$
$$A_{T,pr} = 0.25 \times \pi \times (d_3)^2 \tag{5.12}$$
$$A_{T,req} = \frac{F_B + F_b}{\frac{R_{p0,2}}{\kappa * k_A} - (\beta * E * f_z)/l_k} \tag{5.13}$$

With:
$A_{T,pr}$ = surface bolt present [mm^2]
$A_{T,req}$ = surface bolt required [mm^2]
d_3 = core diameter [mm]

In order to know how much margin is left, the remaining safety of this requirement is calculated. This is done with Equation 5.14. In case γ_{B1} is smaller than 1, this requirement is not met, so there is no remaining safety. In case γ_{B1} is larger than 1, the requirement is met. The larger the value of remaining safety is on top of 1, the more reliable a bolt is.

$$\gamma_{B1} = \frac{A_{T,pr}}{A_{T,req}} \tag{5.14}$$

With:
γ_{B1} = safety factor of the surface in the bolt [-]
$A_{T,pr}$ = surface bolt present [mm^2]
$A_{T,req}$ = surface bolt required [mm^2]

Requirement B2: Clamping capacity
This is a check whether the clamping capacity is not exceeded by the clamping force that is present in the bolt. The check is performed in Equation 5.15. The value of the prestressing force (F_{VM}) can be calculated with Equation 5.16. The value of the clamping capacity (F_{sp}) is provided by one of the tables in Roloff Matek and depends on the friction of the bolt.

$$F_{VM} \leq F_{sp} \tag{5.15}$$
$$F_{VM} = F_b \times k_A \tag{5.16}$$

With:
F_{VM} = prestressing force [kN]
F_{sp} = clamping capacity [kN]
F_b = force in bolt [kN]
k_A = tightening factor [-]

In order to know how much margin is left, the remaining safety of this requirement is calculated. This is done with Equation 5.17. In case γ_{B2} is smaller than 1, this requirement is not met, so there is no remaining safety. In case γ_{B2} is larger than 1, the requirement is met. The larger the value of remaining safety is on top of 1, the more reliable a bolt is.

$$\gamma_{B2} = \frac{F_{sp}}{F_{VM}} \tag{5.17}$$

With:
γ_{B2} = safety factor of the clamping capacity [-]

Requirement B3: Surface tension
This is a check whether damage to the surface of the clamping place caused by the nut or the washer occurs. Both parts will be checked in Equation 5.18 and 5.19. In order to have the values Equation 5.20 and 5.21 are needed.

$$p_{nut} \leq p_G \tag{5.18}$$
$$p_{washer} \leq p_G \tag{5.19}$$
$$p_{nut} = \frac{F_b}{A_{nut}} \tag{5.20}$$
$$p_{washer} = \frac{F_b}{A_{washer}} \tag{5.21}$$

With:
p_{nut} = present surface pressure below nut [N/mm^2]
p_{washer} = present surface pressure below washer [N/mm^2]
p_G = maximum surface pressure below nut that is allowed [N/mm^2]
F_b = required clamping force [kN]
A_{nut} = surface of the nut [mm^2]
A_{washer} = surface of the washer [mm^2]

In order to know how much margin is left, the remaining safety of this requirement is calculated. This is done with Equation 5.22. In case γ_{B3} is smaller than 1, this requirement is not met, so there is no remaining safety. In case γ_{B3} is larger than 1, the requirement is met. The larger the value of remaining safety is on top of 1, the more reliable a bolt is.

$$\gamma_{B3} = \frac{p_G}{p} \tag{5.22}$$

With:
γ_{B3} = safety factor of the surface tension [-]
p_G = maximum surface pressure below nut that is allowed [N/mm^2]
p = present surface pressure in nut or washer [N/mm^2]

5.2. Calculation method Omega-seal

Once it is known which requirements the Omega-seal needs to meet, the calculation can be made. In order to do that, some values are needed. In this paragraph, it is explained how the needed values of Paragraph 5.1 can be determined.

5.2.1. Procedure calculations

In this section, it is explained in which sequence the calculations are made. Besides, it is told which calculated values are used in other calculations.

Calculation governing force in the bolt
First, a calculation is made to determine the maximum force that can occur in the bolt. The governing force of the two calculation methods is determined. This force will be used in the calculation on the individual bolt. This is done in two ways:

- Directly after installation of the Omega-seal: Assumed that there is no water pressure against the Omega-seal, it is calculated what the preload in the bolt can be.
- During use of the Omega-seal: Assumed that there is water pressure against the Omega-seal, it is calculated what the force in the bolt will be 40 years and 100 years after installation. This calculation is actually made in the calculation of the watertightness.

Calculation watertightness
From this calculation, it is concluded when the Requirements O1, O2 and O3 are met. It is told with which value of compression of the flange of the Omega-gasket (c_O) is watertight. Important input values are related to the design of the Omega-seal and the movements (Δx, Δy and Δz). Two values from this calculation will be used in another calculation:

- Force in the bolt (F_b) – This value is used to determine the governing force in the bolt (during use of the Omega-seal).
- Compression of the flange of the Omega-gasket (c_O) – This value will be used in the calculation on the multiple bolts.

Calculation individual bolt
Result of this calculation is when the Requirements B1, B2 and B3 are met. In this calculation, it is told with which value of the penetration depth of the corrosion (d_p) the bolt is still able to take the forces. Important input value are related to the design of the Omega-seal and the force in the bolt (F_b). The value of the maximum value of the force in the bolt (F_b) that is allowed, is used in the calculation on multiple bolts.

Calculation multiple bolts
From this calculation, it is concluded what happens when one or more bolts fail. The clamping structure fails when the maximum value of the force in the bolt (F_b) is exceeded or when the minimum required compression of the flange of the Omega-gasket (c_O) is insufficient.

5.2.2. Forces within Omega-seal

There are a few forces in the Omega-seal that determine whether the checks are met. An overview of all forces is shown in Figure 56. In this section, all the different terms are described. Also, it is explained how the values can be determined.

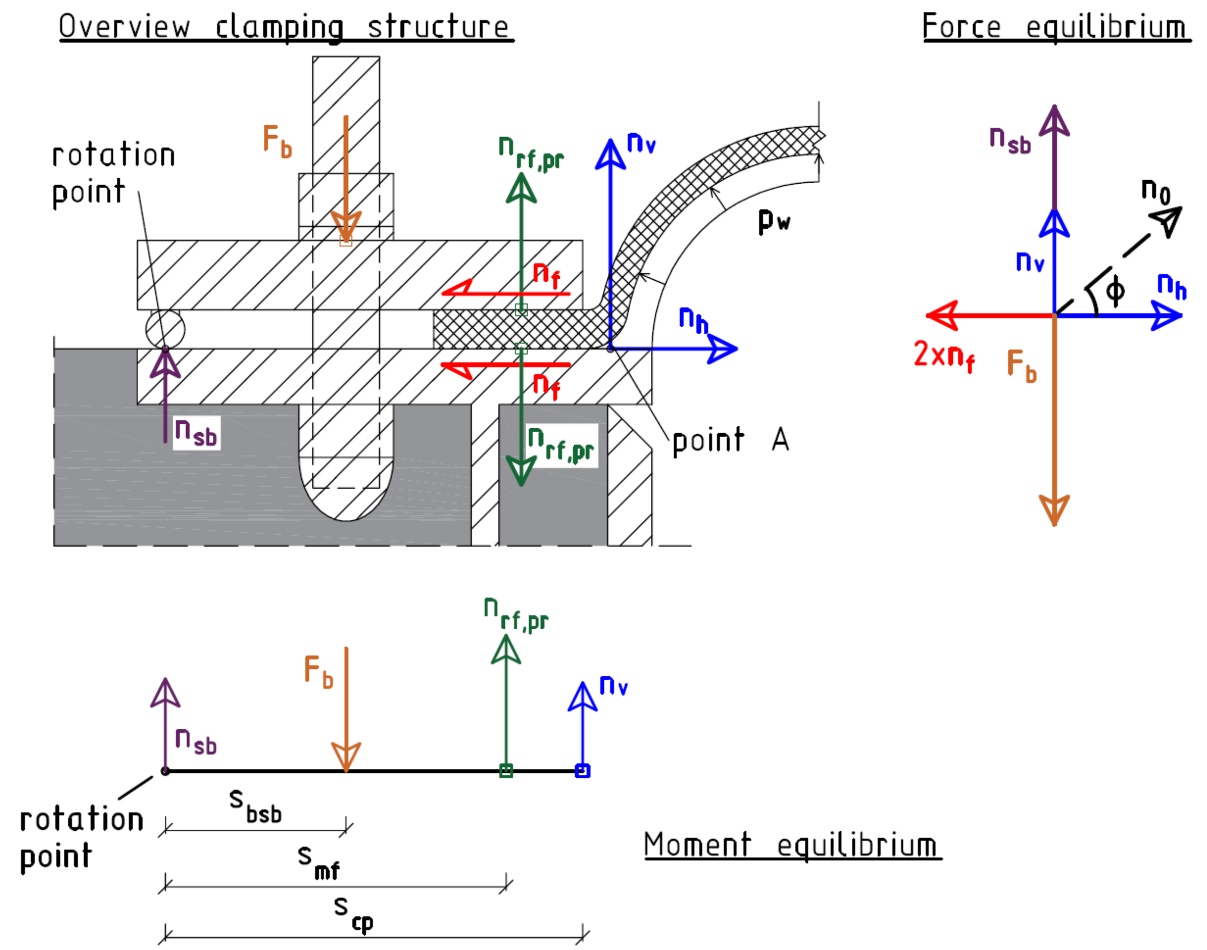

Figure 56: Forces working on the left side of the Omega-seal, the moment equilibrium and the force equilibria in horizontal and vertical direction

Reaction forces flange Omega-gasket and friction ($n_{rf,pr}$)

When the flange of the Omega-gasket is compressed, it will generate some reaction forces. The magnitude of these forces depends on the amount of compression. This is shown in Figure 57. When the compression of the flange of the Omega-gasket is known, the reaction force can be determined with the force-compression curve. The compression is determined with Equation 5.23.

$$c_O = h_{O,fl,in} - h_{O,fl,pr} \tag{5.23}$$

With:

c_O = compression of the flange of the Omega-gasket [mm]

$h_{O,fl,or}$ = original height of the flange of the Omega-gasket [mm]

$h_{O,fl,pr}$ = present height of the flange of the Omega-gasket [mm]

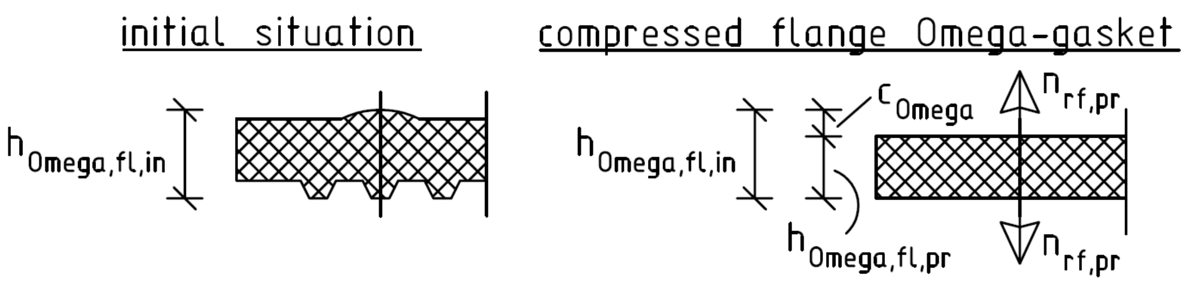

Figure 57: Example of the compression of a flange of an Omega-gasket, showing the forces that occur

An example of a force-compression curve of the Omega-gasket is shown in Figure 58.

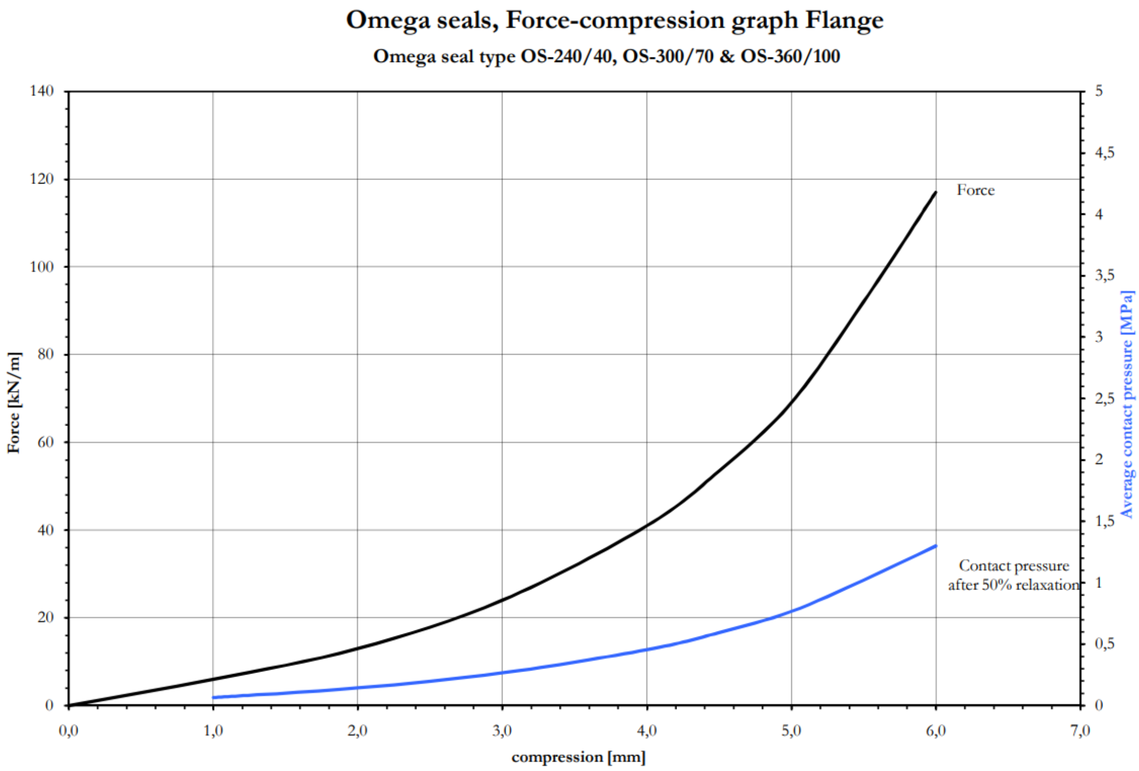

Figure 58: Example of a force-compression curve of the Omega-gasket, with the compression [mm] on the x-axis and the force [kN/m] on the y-axis

Friction force (n_f)
The friction force will be determined as in Equation 5.7.

Forces from curved part Omega-gasket (n_h and n_v)
At the transition of the flange to the curved part of the Omega-gasket, a force acts when there is hydrostatic pressure (p_w). As shown in Figure 59, the vector of n_0 can be split up into the vectors of n_h and n_v. First, vector n_0 needs to be determined. This is done with Formula 5.24, which is based on the formula of stress in a shallow-walled pressure vessel (in Dutch: *ketelformule*).

The value of the water pressure (p_w) is determined by Equation 5.25. This value is constant. However, the value of the present radius (R) changes when the differential settlements occur. The radius needs to be determined by iteration.

$$n_0 = p_w \times R \tag{5.24}$$
$$p_{water} = \rho_w \times s_{wc} \tag{5.25}$$

With:
n_0 = force in the curved part of the Omega-gasket [N/mm']
p_{water} = water pressure working on the Omega-gasket [N/mm^2]
R = present radius of the Omega-gasket [mm]
ρ_w = density of water [kN/m^3]
s_{wc} = height of the water column [m]

The present radius of the Omega-gasket (R) needs to be determined by iteration. In Figure 59, on the left side, the initial situation of the Omega-gasket is shown. The radius is 75 mm. This means that the forces (n_0) are directed upwards. However, when differential movements take place, the magnitude and direction of these forces changes. This is shown in Figure 59, on the right side. There is a differential movement in x-direction (Δx) of 10 mm, and in z-direction (Δz) of 55 mm. By iteration, it is determined that R will be 81.46 mm. When the water pressure is known, the magnitude of the force can be determined.

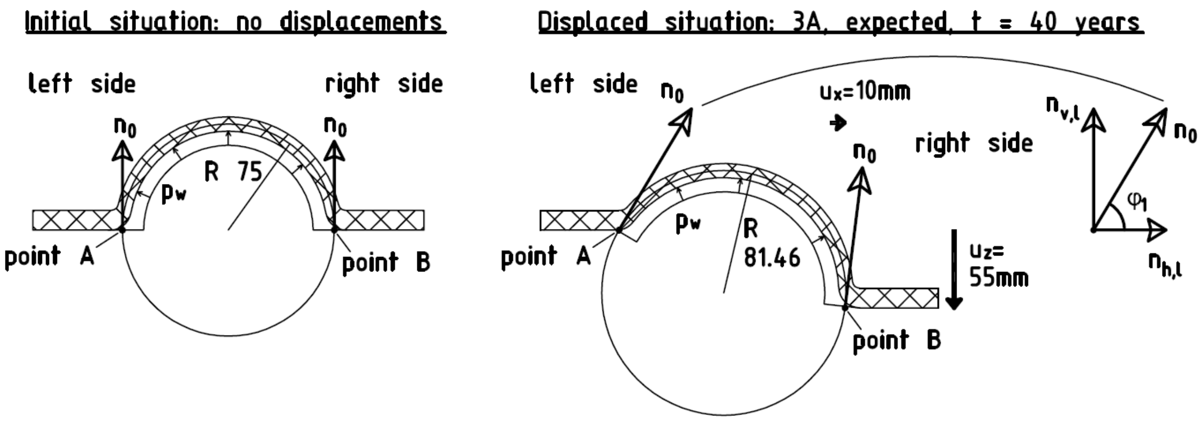

Figure 59: Example of how the forces in the Omega-gasket change when displacements occur (case Kil Tunnel)

When the value of the force in the curved part of the Omega-gasket (n_0) is known, it must be found out in which direction it acts from point A and B. Following the tangent of the radius, the direction of the forces can be determined. This is needed to split the force into a horizontal and a vertical part. Therefore, the value of the angle in point A (φ_1) and in point B (φ_2) needs to be known. With this information, the force n_0 can be split up into a horizontal component (n_h) and a vertical component (n_v) on each side.

$$n_h = \cos(\varphi) \times n_0 \tag{5.26}$$
$$n_v = \sin(\varphi) \times n_0 \tag{5.27}$$

With:

n_h = force in the curved part of the Omega-gasket, working in horizontal direction [N/mm']
n_v = force in the curved part of the Omega-gasket, working in vertical direction [N/mm']
φ = angle of the curved part of the Omega-gasket [radians]
n_0 = force in the curved part of the Omega-gasket [N/mm']

Force in the bolt (F_b)

Since the clamping structure does not move, there should be a horizontal, vertical and moment equilibrium. The rotation point is determined as the steel bar. By taking the rotation point here, the value of n_{sb} can be neglected in this calculation. The moment equilibrium around the steel bar is zero. This equilibrium is used to find the force that is present in the bolt. This is calculated by Equation 5.16.

$$\Sigma M = 0 = F_b \times s_{bsb} - F_{rf,pr} \times s_{mf} - F_v \times s_{cb} \tag{5.28}$$

With:

F_b = clamping force that should be provided by the bolt [kN]
s_{bsb} = distance between bolt and steel bar [mm]
$F_{rf,pr}$ = reaction force present per bolt [kN]
s_{mf} = distance between the middle of the flange of the Omega-gasket and the steel bar [mm]
F_v = vertical force Omega-gasket per bolt [kN]
s_{cb} = distance between the end of the clamping plate and the steel bar [mm]

Since this consideration is made for one bolt, some line-loads need to be transferred into point loads. This is done is Equation 5.29 and 5.30. The centre-to-centre distance of the bolts is therefore important.

$$F_{rf,pr} = n_{rf,pr} \times s_{ctc} \tag{5.29}$$
$$F_v = n_v \times s_{ctc} \tag{5.30}$$

With:

$F_{rf,pr}$ = reaction force present per bolt [in kN]
$n_{rf,pr}$ = reaction force of the flange (accounted for relaxation) [N/mm']
s_{ctc} = centre-to-centre distance bolts [mm]
F_v = vertical force Omega-gasket per bolt [kN]
n_v = force in vertical direction caused by the curved part of the Omega-gasket [N/mm']

Also, some distances need to be determined. This is done with Equation 5.31 and 5.32.

$$s_{mf} = s_{bsb} + 0.5 \times d + s_{bof} + s_{omf} \tag{5.31}$$
$$s_{cb} = s_{bsb} + s_{bop} \tag{5.32}$$

With:
s_{mf} = distance between the middle of the flange of the Omega-gasket and the steel bar [mm]
s_{bsb} = distance between bolt and steel bar [mm]
d = diameter bolt [mm]
s_{bof} = distance between bolt and outside flange Omega-gasket [mm]
s_{omf} = distance between outside and middle flange Omega-gasket [mm]
s_{cb} = distance between the end of the clamping plate and the steel bar [mm]
s_{bsb} = distance between bolt and steel bar [mm]
s_{bop} = distance between bolt and outside plate [mm]

Force steel bar (n_{sb})
When the force in the bolt is known, the force in the steel bar can easily be calculated by taking the moment equation around the bolt. The sum of all terms should be zero. However, this value is not calculated, since it is not so important. It is assumed that the steel bar is able to take the loads, so it will not move or become damaged.

5.3. Mechanisms that influence the functioning over the lifetime

Basically, there are four mechanisms that determine the watertightness of the Omega-gasket over the lifetime. These are described in this section. In Figure 60, the locations where these mechanisms occur are shown.

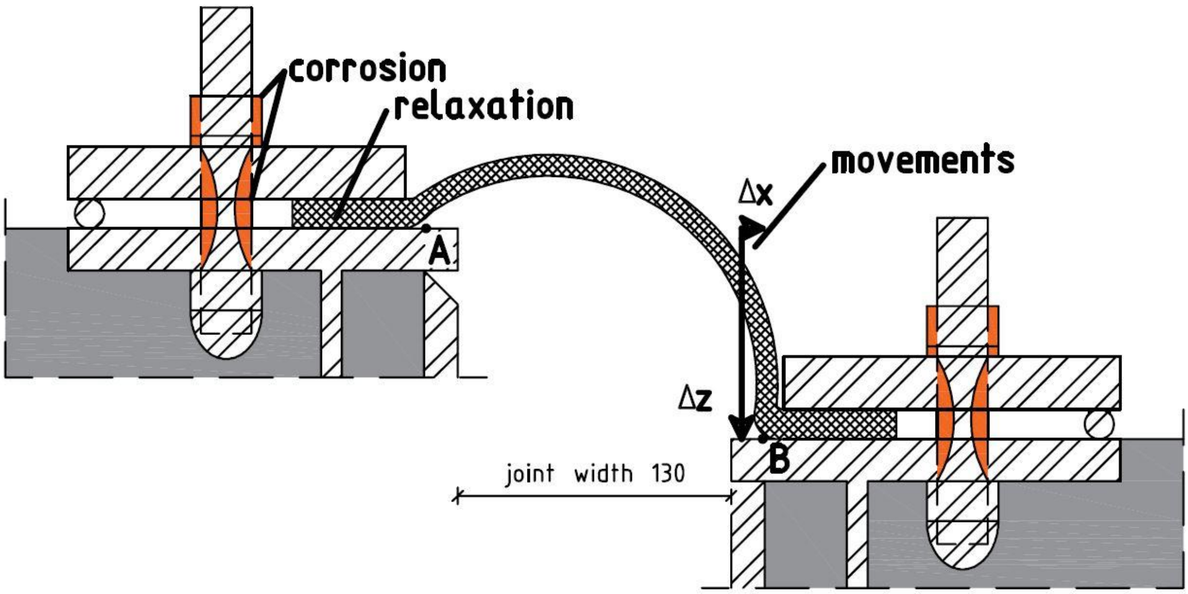

Figure 60: Overview of the mechanisms that determine the watertightness

5.3.1. Corrosion in the clamping structure

Corrosion leads to a decrease of the capacity of the clamping structure over the lifetime. In Section 3.4.2, an explanation of corrosion in the clamping structure is given. Basically, there are a few locations in the clamping structure where corrosion can harm functioning of the clamping structure. The locations where corrosion can lead to problems are shown in Figure 61. Since preload to the nut has occurred, it is assumed that the surface between the stud and the nut is not corroded. Corrosion influences the Requirements B1 and B3.

Also, there are places where corrosion does not influence the functioning of the clamping structure. An overview of these locations is shown in Paragraph D.2.

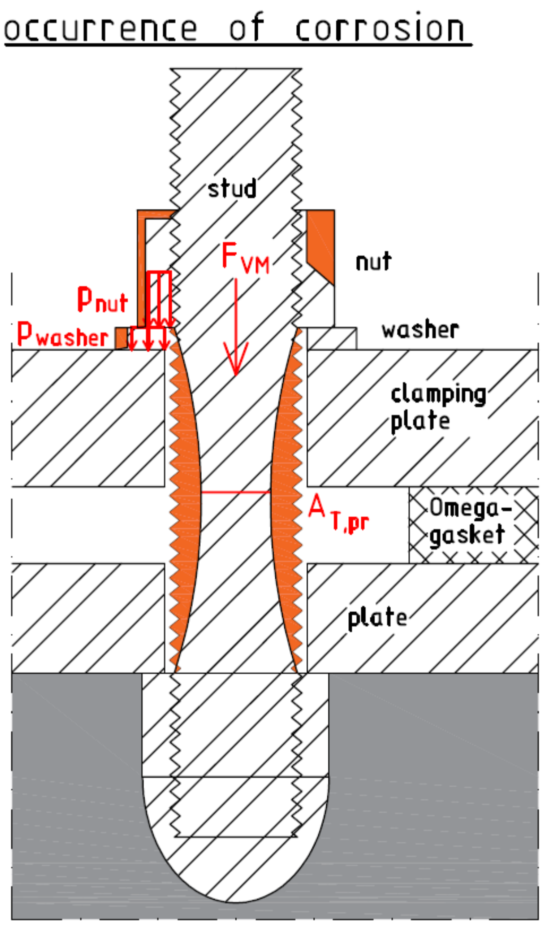

Figure 61: Cross section of the bolt, showing where the structure is deteriorated when corrosion occurs

The following can happen at these locations:

- Stud – When corrosion becomes too large, the stud is not able to transfer the loads. In that case, cracks can occur. The present surface of the bolt ($A_{T,pr}$), after corrosion has occurred, can be calculated with Equation 5.33 in case the corrosion is equal all around the stud. When corrosion is much larger on one side of the stud, the present surface should be calculated by hand.
- Nut – When corrosion becomes too large, two things can happen:
    - The forces (p_{nut}) that the nut transfers to the washer become too large, so the washer is damaged. When the nut is corroded, its surface will decrease and therefore the pressure will increase. The surface of the nut, after corrosion has occurred, can be calculated by Equation 5.34.
    - The corrosion in the nut is so large, that due to the forces through the nut, the nut breaks.
- Washer – When corrosion becomes too large, the washer loses part of its surface. The pressure that acts on the clamping plate (p_{washer}) can become so large, that damage occurs. The surface of the washer, after corrosion has occurred, can be calculated by Equation 5.35.

$$A_{T,pr} = 0.25 \times \pi \times (d_3 - 2 \times d_p)^2 \tag{5.33}$$

$$A_{nut} = 0.25 \times \pi \times (d_{n,max} - 2 \times d_p)^2 - 0.25 \times \pi \times {d_{n,min}}^2 \tag{5.34}$$

$$A_{washer} = 0.25 \times \pi \times (d_{w,max} - 2 \times d_p)^2 - 0.25 \times \pi \times {d_{w,min}}^2 \tag{5.35}$$

With:

$A_{T,pr}$ = surface bolt present [mm^2]
d_3 = core diameter of the bolt [mm]
d_p = penetration depth of the corrosion [mm]
A_{nut} = surface of the nut [mm^2]
$d_{n,max}$ = diameter of the outer side of the nut [mm]
$d_{n,min}$ = diameter of the inner side of the nut [mm]
$d_{w,max}$ = diameter of the outer side of the washer [mm]
$d_{w,min}$ = diameter of the inner side of the washer [mm]

5.3.2. Movements of the immersion joint

Movements of the immersion joint lead to a different radius of the curved part of the Omega-gasket. As a consequence, the forces from the curved part of the Omega-gasket increase and the direction of the force changes. Therefore, this phenomenon must be taken into account. Movements influence Requirement O2 and O3.

The movements in y-direction and in z-direction are mainly important. From calculations, it follows that these have a more significant influence on this phenomenon.

5.3.3. Relaxation

As well as the Gina-gasket, the Omega-gasket relaxes over time. This means that the stress within the Omega-gasket decreases. Over time, the reaction force decreases. This phenomenon is called relaxation. The amount of force that remains can be calculated with Equation 5.29. The amount of force that remains in the Omega-gasket is calculated with Equation 5.30. Relaxation influences Requirement O1 and O2.

$$\frac{\sigma(t)}{\sigma(t=0)} = 1 - 0.01 \times r_{Omega} \times \log(t \times 365 \times 24 \times 60) \tag{5.36}$$

$$n_{rf,pr} = \frac{\sigma(t)}{\sigma(t=0)} \times n_{rf,in} \tag{5.37}$$

With:

$\sigma(t)/\sigma(t=0)$	= part of the initial force that is still left [-]
r_{Omega}	= relaxation per decade of the flange of the Omega-gasket [%]
t	= time after immersion [years]
$n_{rf,pr}$	= reaction force of the flange (accounted for relaxation) [N/mm’]
$n_{rf,in}$	= initial reaction force of the flange [N/mm’]

5.4. Case study Kil Tunnel: calculations

The case study Kil Tunnel is considered. In this paragraph, the first of three calculations is made: the watertightness. As described in Section 5.2.1, this will lead to the value of compression (c_O) of the Omega-gasket to meet Requirements O1, O2 and O3.

5.4.1. Input values

As described in Chapter 3, there are three immersion joints in the Kil Tunnel. Two of them are exactly the same, namely the joints 1A and 2E (type 1A / 2E). The other immersion joint is 3A (type 3A). The input values from these two types are described in Section 3.3.2 and 3.3.4. The other relevant parameters are described in this section.

Location and time

The governing location of the watertightness of the Omega-seal is in the floor. When the Gina-gasket leaks, the water pressure will be largest at that location.

The clamping structure is considered at the three moments in time: at completion of the Kil Tunnel (t = 0.75 years), in the present situation (t = 40 years) and at the design lifetime (t = 100 years). The determined values for the movement of the tunnel are used.

Compression of the flange of the Omega-gasket (c_O)

The amount of compression (c_O) determines the reaction force in the flange of the Omega-gasket. This is an important value in the calculation. According to the design drawings, the intended compression of the flange of the Omega-gasket is 6 mm. When the nuts are tightened well and the quality of the clamping structure is still sufficient, the amount of compression will still be 6 mm.

However, it could be the case that the compression has decreased over the years or that the bolts are not installed according to the design drawings. Therefore, a calculation is made what the effect on the watertightness is, when there is less compression. The values of compression that are calculated are 4, 5 and 6 mm.

Steel quality

Many variables are needed in order to make a calculation of the forces in the bolt. The following values are used:

- Dimensions clamping structures – The dimensions, as described in Chapter 3, are used for the calculation.
- Dimensions and quality of bolts – The bolts consist of M24 nuts, M24 cap nuts and stud with a diameter of 24 mm. The quality is 8.8.
- Quality of steel bar, plate and clamping plate – It is assumed that the used steel is of the quality S235.

Relaxation (r_O)

The amount of relaxation per decade (r_O) depends of the loads during the lifetime and the fabrication. From tests, it is expected that the relaxation of the flange of the Omega-gasket is between 5 and 6 % per decade. Since it is not possible to determine an expected value, a calculation with both values is made. Since 5 % relaxation is not necessarily more favourable for watertightness than 6%, the situations are not divided into 'favourable' and 'unfavourable'.

Other parameters

There are a few calculation parameters that are the same for all calculations. These are presented in Table 14. The friction factor (μ) is a standard design value that are used by Trelleborg. The density of water is assumed too, based on the fact that the water in the Dordtsche Kil is fresh water.

Description	**Symbol**	**Value**	**Unity**
Friction factor	μ	0.3	(-)
Density water	γ_w	10	kN/m^3

Table 14: Calculation parameters that do not change throughout the tunnel and over time

5.4.2. Results calculations governing force in the bolt

The calculations are made. In this section, the main values are presented with an explanation.

Determination of force in the bolt during installation

During installation, the bolts of the Omega-seal are preloaded. The values of the forces in the bolt are calculated. Afterwards, they will be compared with the values of the bolts during use. The largest values are governing in the individual bolt calculation.

First of all, this calculation is executed without the force from the water pressure. This is done, because it is assumed that the Gina-seal is completely watertight during the installation.

Preloading of the bolts of the clamping structure can happen in many ways. The way preloading is executed determines how much preload is present at the moment and in the future. Trelleborg Ridderkerk prescribes that the bolts are tightened two times. The first reason is to compensate for the large amount of relaxation that occurs just after installation. The second reason is to be sure that all bolts are tightened. It is not clear what happened during the construction of the Kil Tunnel. Therefore, a few scenarios are taken into account.

In order to determine this, the force-compression curve is needed, which is explained in Paragraph D.3.

A few preloading scenarios are possible, according to the present-day procedures:

- Procedure A: The nut is tightened only once. This means that it is forced enough to reach a compression of 6 mm. No second tightening has taken place.
- Procedure B: The nut is firstly tightened to 4, 4.5, 5 or 5.5 mm and secondly (after 2 until 7 days) to 6 mm.
- Procedure C: The nut is firstly tightened until 65 kN (corresponding to 6 mm compression) and secondly (after 2 until 7) again until 65 kN, leading to a compression of more than 6 mm.

Since there is a range in the amount of relaxation, between 5 and 6 %, both values are calculated. Also, the amount of days the nut is tightened after the first session ranges, from 2 days until 7 days. Per procedure, a calculation of the present compression of the flange of the Omega-gasket and the clamping force that should be provided per bolt are calculated. The results are shown in Table 15.

Description	**Symbol**	**Value**					**Unity**
		Procedure A	Procedure B		Procedure C		
Tightening session		1	1	2	1	2	(-)
Compression of flange Omega-gasket left	c_O	6	4 - 5,5	6	6	6,33 - 6,48	mm
Preload of the bolt	F_b	65	17,4 - 48,1	49,4 - 53,8	65	65	kN

Table 15: amount of compression and clamping force per tightening procedure

The governing value is 65 kN. This value is is larger than during use, and will therefore be used during the calculations on the bolts. The total calculation is shown in Paragraph D.4.

Determination of the force in the bolt during use

During use, the bolts of the Omega-seal are preloaded. The present values of the forces in the bolt are calculated. Afterwards, they will be compared with the values of the bolts during use. The largest values are governing in the individual bolt calculation.

A calculation of the required amount of preload is made for 3 different values (4, 5, and 6 mm) of compression. Also, the lifetime of the tunnel differs per calculation: 40 and 100 years are calculated. The minimum value ("Min") is always the bolt on the side that is least loaded, with relaxation (r_O) of 6%. The maximum value ("Max") is always the bolt on the side that is most loaded, with relaxation (r_O) of 5%. This is shown in order to show the range of the required preload.

The force of the bolt is calculated at the present lifetime (40 years old) of the Kil Tunnel. The results are shown in Table 16. The governing situation is during extreme settlements, in joint 3A, with a compression of 6 mm. The force that occurs at that moment is 57.1 kN.

Joint	**Description**	**Symbol**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Unity**
			c_O = 4 mm		c_O = 5 mm		c_O = 6 mm		
1A/2E	Force in bolt	F_b	12.5	22.6	22.3	33.7	39.2	52.8	kN
3A	Force in bolt	F_b	14.6	25.4	24.8	37.0	42.4	57.1	kN

Table 16: Minimum and maximum forces in the bolt at the present lifetime of the Kil Tunnel (t = 40 years)

The force of the bolt is calculated at the design lifetime (100 years old) of the Kil Tunnel. The results are shown in Table 17. The governing situation is during extreme settlements, in joint 3A, with a compression of 6 mm. The force that occurs at that moment is 57.4 kN.

Joint	**Description**	**Symbol**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Unity**
			c_O = 4 mm		c_O = 5 mm		c_O = 6 mm		
1A/2E	Force in bolt	F_b	12.0	22.3	21.4	33.0	37.6	51.5	kN
3A	Force in bolt	F_b	14.3	25.7	24.5	37.4	42.0	57.4	kN

Table 17: Minimum and maximum forces in the bolt at the design lifetime of the Kil Tunnel (t = 100 years)

The largest value is 57.4 kN. This value is smaller than the load during preloading and is therefore not governing. An overview of all calculations can be found in Paragraph D.5.

Conclusion

The following can be concluded:

- The force in the bolt during installation is governing. This force is 65 kN.
- The force in the bolt during use is not governing. This force is 57.4 kN.

5.4.3. Results calculations watertightness

The remaining safety of the watertightness is checked in this section. This is done for 5 different values (4, 5 and 6 mm) for compression and for a lifetime of 40 and 100 years. Per bolt, there are actually 5 checks: O1 and O2 on both sides (left and right) and O3. It is assumed that the compression of the flange of the Omega-gasket is the same on both sides.

In Table 18, the result of the checks that are performed is shown. This holds for the present lifetime of 40 years. It follows that the compression determines strongly whether the requirements on watertightness are met. If the compression is 6 mm, all watertightness checks are met. This is the same for compression of 5 mm, although there is a smaller margin present. When the compression is 4 mm, most of checks are not reached.

Joint	Requirement	Description	Side	Value		
				c_O = 4 mm	c_O = 5 mm	c_O = 6 mm
1A/2E	O1	Enough pressure to stop water (γ_{O1})	Left	0.93	1.86	3.47
			Right	0.93	1.86	3.47
	O2	Prevention of pulling out flange Omega-gasket (γ_{O2})	Left	0.66	1.32	2.46
			Right	7.94	>10	>10
	O3	Cracks in the Omega-gasket	(-)	OK	OK	OK
3A	O1	Enough pressure to stop water (γ_{O1})	Left	0.83	1.66	3.09
			Right	0.83	1.66	3.09
	O2	Prevention of pulling out flange Omega-gasket (γ_{O2})	Left	0.50	1.01	1.88
			Right	1.28	2.57	4.76
	O3	Cracks in the Omega-gasket	(-)	OK	OK	OK

Table 18: Remaining safety of the immersion joints at the present lifetime of the Kil Tunnel (t = 40 years)

In Table 19, the remaining safety of the immersion joints is shown for the design lifetime of 100 years. The conclusion is the same as for the lifetime of 40 years.

Joint	Requirement	Description	Side	Value		
				c_O = 4 mm	c_O = 5 mm	c_O = 6 mm
1A/2E	O1	Enough pressure to stop water (γ_{O1})	Left	0.89	1.78	3.32
			Right	0.89	1.78	3.32
	O2	Prevention of pulling out flange Omega-gasket (γ_{O2})	Left	0.63	1.26	2.36
			Right	5.12	>10	>10
	O3	Cracks in the Omega-gasket	(-)	OK	OK	OK
3A	O1	Enough pressure to stop water (γ_{O1})	Left	0.83	1.66	3.09
			Right	0.83	1.66	3.09
	O2	Prevention of pulling out flange Omega-gasket (γ_{O2})	Left	0.50	1.00	1.87
			Right	1.55	3.12	5.81
	O3	Cracks in the Omega-gasket	(-)	OK	OK	OK

Table 19: Remaining safety of the immersion joints at the design lifetime of the Kil Tunnel (t = 100 years)

Conclusions and recommendations

The following can be concluded:

- The compression of the flange of the Omega-gasket (c_O) determines strongly whether the requirements on watertightness are met.
- When the compression of the flange of the Omega-gasket (c_O) is smaller than 5 mm, the requirements are not met. This means that leakages through the immersion joint can occur.

Since the value of the compression is so important, it is recommended to measure this. Since it is hard to measure the compression of the flange, it is advised to measure the distance between the plate and the clamping plate (d_{cpc}). This can be transferred into the present height of the flange of the (compressed) flange of the Omega-gasket ($h_{Omega,fl,pr}$). With Equation 5.23, this can be transferred into the compression of the flange of the Omega-gasket, that is used in the calculations. In Figure 62, it is shown what should be measured.

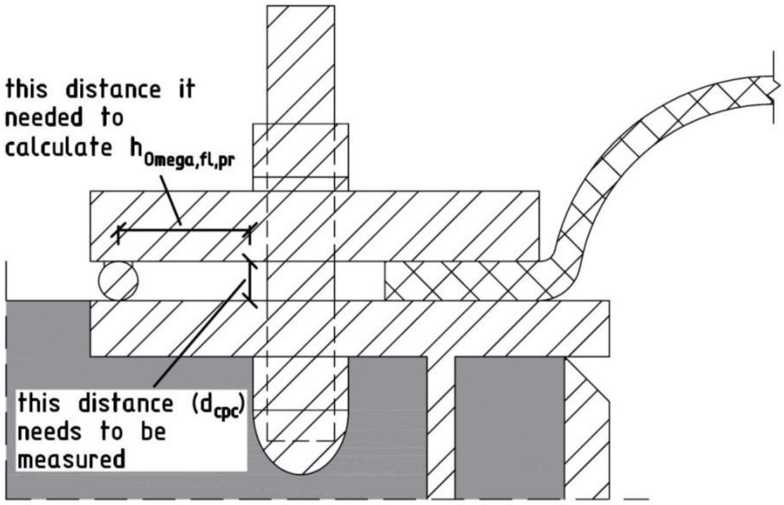

Figure 62: Values that need to be measured around the Omega-seal of the Kil Tunnel

5.4.4. Results calculations individual bolt

During installation, the bolts were preloaded. This was done by tightening of the nut. Earlier in this section, it is calculated how much preload is needed in the calculations. In this section, it is calculated whether the bolts are able to take this preload.

Checks functioning bolts

It is known how large the force is at maximum in the immersion joint: 65 kN. Now, several scenarios of corrosion that penetrates the clamping structure need to be calculated. It is expected that there is a specific amount of penetration depth (d_p), that attacks the nut and the bolt. Different scenarios are calculated, varying from a penetration depth of 0, 1, 2, 3 and 4 mm. An overview of the results is shown in Table 20.

In case the bolt is not equally corroded on all sides, it is also possible to determine the surface of the bolt that is present.

Description	**Symbol**	**Values**					**Unity**
		Clean bolt	Corroded bolt				
Force in bolt	F_b	65	65	65	65	65	kN
Penetration depth of corrosion	d_p	0	1	2	3	4	mm
Surface bolt present	$A_{T,pr}$	324	264	209	161	119	mm^2
Safety factor on the amount of surface in the bolt	γ_{B1}	1.74	1.42	1.13	0.87	0.64	[-]
Safety factor on the clamping capacity	γ_{B2}	2.15	2.15	2.15	2.15	2.15	[-]
Safety factor on the surface tension of the nut	$\gamma_{B3,nut}$	2.26	1.82	1.41	1.02	0.65	[-]
safety factor on the surface tension of the washer	$\gamma_{B3,washer}$	3.96	3.42	2.90	2.41	1.95	[-]

Table 20: Checks for several values of the penetration depth of corrosion

The total calculation is shown in Paragraph D.6.

Conclusions and recommendations

From the calculation, it follows that the maximum allowed penetration depth of the corrosion is 2 mm. If this value is exceeded, the functioning of the bolt is not guaranteed anymore.

The following is recommended:

- A few bolts in the "splash zone" of the Kil Tunnel need to be removed for research. These bolts need to be analysed, in order to see how far the corrosion has penetrated the bolt. This needs to be compared with the values that are calculated. With this analyses, one is able to judge on the state of the bolts.
- It must be checked whether the corrosion of the clamping structure of the Omega-seal is an ongoing process. If the corrosion has reached an equilibrium, and the state is acceptable, action is not urgent. In that case, a check on the state can be performed during the next maintenance period.

5.4.5. Results calculations multiple bolts

In Section 5.4.4 it was calculated what happens in one bolt. However, bolts act together in a clamping plate. Therefore, it is checked how the loads are distributed if one bolt fails. Since this is a rather complex 2D calculation, the computer programme *MatrixFrame 2D Plates* is used. It will be checked whether the 'zipper effect' will occur.

Used model

The governing clamping plate consists of 13 bolts. The centre-to-centre distance between the bolts in the middle of the clamping plate is 200 mm. However, in the outer ends of the clamping plate the centre-to-centre distance is a bit lower (150 mm and 49 / 50 mm). The design of the governing clamping plate is shown in Figure 63.

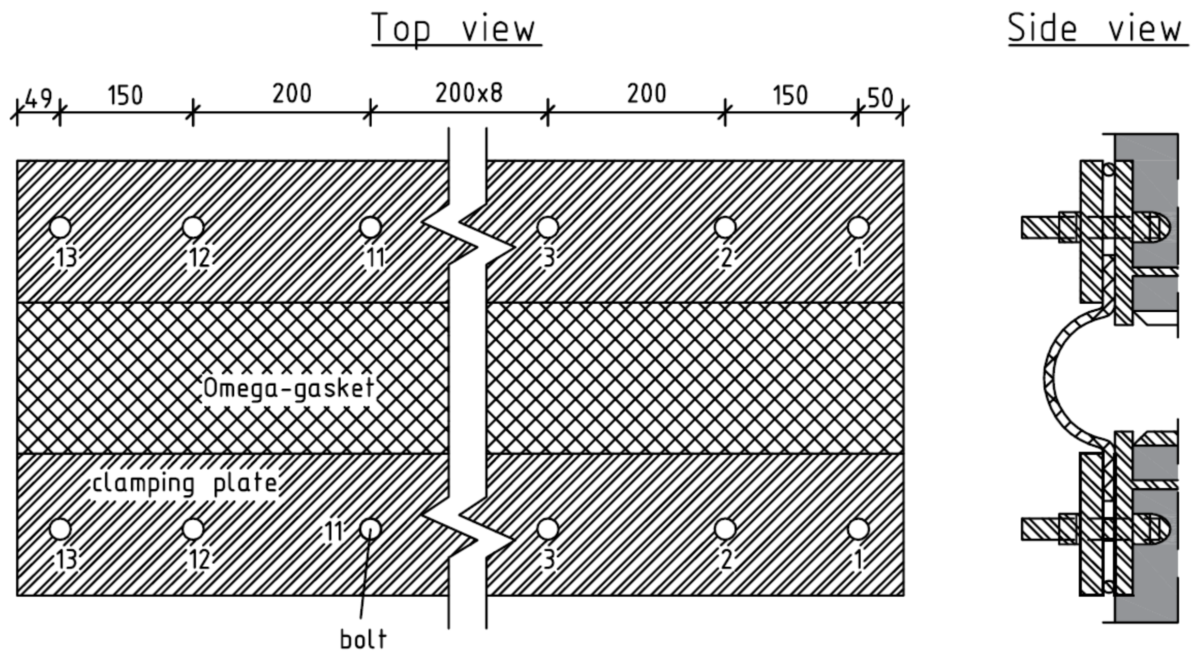

Figure 63: Dimensions of the governing clamping plate

The situation is modelled as a plate. This plate is line-supported on the side where the steel bar is located (n_{sb}). The bolts are modelled as (point) supports (F_b). The reaction force of the flange of the Omega-gasket is modelled as a line load ($n_{rf,pr}$). The vertical force from the curved part of the Omega-gasket is modelled as a line load (n_v). This model is shown in 3D in Figure 64 and in 2D in Figure 65.

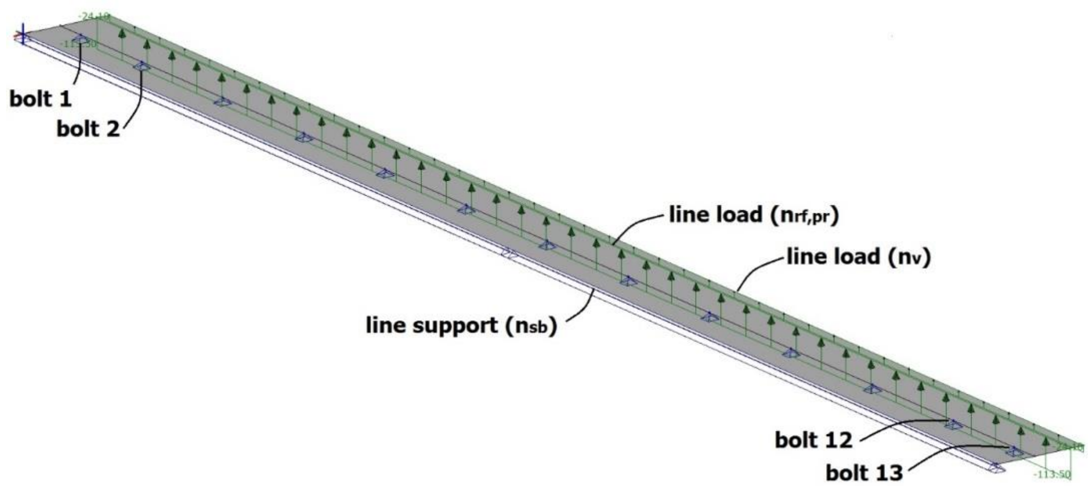

Figure 64: 3D overview of the MatrixFrame model of the clamping plate

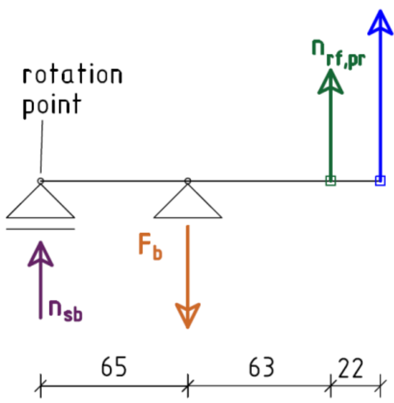

Figure 65: 2D overview of the MatrixFrame model of the clamping plate

The following is calculated:

- Maximum displacement of the clamping plate at the location where the bolt does not function – This will means that the amount of compression of the flange decreases. When the displacement is 1 mm, this means that the compression (c_O) at that location will lower with 1 mm. As a result, the reaction force of the flange ($nr_{f,pr}$) decreases. This leads to smaller forces in the bolt. However, the watertightness will decrease due to the smaller compression. When the compression will lower to more than 1 mm, the seal is not watertight anymore.
- Forces in the bolts adjacent to the location where the bolt fails (F_b) – These bolts will take the loads. The values need to be compared with the calculations of Section 5.4.4. The bolts will certainly be able to take the loads until 65 kN. When the forces become larger, it depends on the condition of the bolt if it is able to take this load.

Immersion joint 3A and 1A/2E have a slightly different design. However, 3A is governing, since the loads are larger. Therefore, all calculations are related to joint 3A. The input values of the forces are shown in Table 21. They come from the calculations that are presented in Paragraph D.5. It is assumed that compression in the flange of the Omega-gasket is 6 mm.

Description	**Value [N/mm']**
Reaction force of the flange of the Omega-gasket ($n_{rf,pr}$)	113.5
Vertical force from the curved part of the Omega-gasket (n_v)	25.4

Table 21: Input values for the MatrixFrame model

<u>Failure of one bolt</u>

First, the calculation is made when one bolt fails. The following situations are calculated:

- Situation A: All bolts function well (reference)
- Situation B: Bolt 7 in the centre failed
- Situation C: Bolt 13 on the outside failed
- Situation D: Bolt 12 on the outside failed

Situations A, B, C and D are calculated. In Table 22, the results of the calculations are shown.

Situation	**Bolt that fails**	**Governing force [kN]**	**Bolt where the governing force occurs**	**Maximum displacement at the bolt that fails [mm]**
A	No bolt	56.5	3	Not applicable
B	7	88.1	6, 8	1
C	13	88.2	12	1
D	12	83.5	11	0

Table 22: Results for the calculations of situations A, B, C and D

In situation D, no displacement of the clamping plate will occur. As a consequence, the adjacent bolt must take the load of 83.5 kN. This force is larger than the governing value of the bolt. It depends therefore on the condition of the bolt if it is able to take the loads.

However, in situation B and C, displacement of the clamping plate occurs. Since the displacement leads to a decrease in compression, the forces on the clamping plate decrease. Another calculation, taking into account the decrease in forces, is performed. The values are shown in Table 23.

Compression of the flange of the Omega-gasket (c_O) [mm]	Reaction force of the flange of the Omega-gasket ($n_{rf,pr}$) [N/mm']
6	113.5
5	60.9

Table 23: Change in reaction force if the compression decreases

The calculation of situation B is made again, but then with the reaction force corresponding to 5 mm instead of 6 mm. This means that the total force working on the clamping plate is lower. This holds only for the location where the displacement of 1 mm has taken place. Bolts 7 and 13 are able to take the loads. Therefore, failure of more bolts will not occur.

Situation	Bolt that fails	Governing force [kN]	Bolt where the governing force occurs	Maximum displacement at the bolt that fails [mm]
B	7	65.6	6, 8	1
C	13	65.7	12	1

Table 24: Re-calculation of a clamping plate where one bolt failed after taking into account the displacement

After failure of one bolt, the load on the adjacent bolts increases. However, due to the decrease in compression, this load is only 16% higher than the loads on the bolt in the situation without any damage in situation B and C.

Therefore, it can be concluded that the clamping plate still functions if one bolt fails. Bolt 12 is however an exception. If this bolt fails, the adjacent bolt will also fail, leading to the 'zipper effect'.

Failure of two bolts

Since the clamping structure still functions when one bolt fails, a check must be made what will happen if two bolts fail. The following situations are calculated:

- Situation A: All bolts function well (reference)
- Situation E: Bolts 7 and 8 failed (in the centre)
- Situation F: Bolts 7 and 9 failed (in the centre)
- Situation G: Bolts 7 and 10 failed (in the centre)
- Situation H: Bolts 12 and 13 failed (on the outside)

Situations A, E, F, G and H are calculated. In Table 25, the results of the calculations are shown.

Situation	Bolt that fails	Governing force [kN]	Bolt where the governing force occurs	Displacement at the bolt that fails [mm]
A	No bolt	56.5	3	Not applicable
E	7, 8	120.7	6, 9	1
F	7, 9	115.2	8	1
G	7, 10	88.9	11	1
H	12, 13	153.2	11	3

Table 25: Results for the calculations of situations A, B, C and D

In case of situation H, the displacements are so large, that the clamping structure has lost its watertightness immediately. Besides, due to the load failure of the bolt will take place.

In case of situation E, F and G, displacement occurs. Since the displacement leads to a decrease in compression, the forces on the clamping plate decrease. The different value is shown in Table 26. Therefore, another calculation is made, in which this effect is taken into account. The results are shown in Table 26.

Situation	Bolt that fails	Governing force [kN]	Bolt where the governing force occurs	Displacement at the bolt that fails [mm]
E	7, 8	86.1	6, 9	2
F	7, 9	72.3	8	1
G	7, 10	65.7	6	1

Table 26: Re-calculation of a clamping plate where two bolts failed after taking into account the displacement

In case of situation E, it follows that 2 mm of displacement will occur. From the checks, it follows that the Omega-seal is not watertight.

In case of situation F and G, it follows that displacement will be 1 mm. Therefore, the Omega-seal will be watertight. In case of situation F, the bolt may not be able to take the loads. In case of situation G, the bolt will be able to take the loads. Therefore, in situation G the Omega-seal will still be watertight.

Conclusions

The following can be concluded:

- When one bolt fails, the clamping plate will deform. As a result the forces on the adjacent bolts will be lower. It depends on the state of the bolt whether this is able to take the loads. This will determine whether the 'zipper effect' will occur.
- When one bolt fails, the clamping structure will still be watertight. One exception is bolt 2 or 12: if this bolt fails, the 'zipper effect' takes place when the adjacent bolt is not able to take the load of 83.5 kN.
- When two bolts next to each other fail, the clamping structure loses its watertightness.
- When two bolts fail with 1 or 2 functioning bolts in between, the structure stays watertight if the adjacent bolts are able to take a load of 86.1 kN.

5.5. Summary

The Omega-seal has to fulfil a few requirements in order to be watertight:

- Requirement O1: Enough pressure to stop water – The flanges of the Omega-gasket should be pressed strongly enough to both tunnel element in order to create a watertight layer.
- Requirement O2: Prevention of pulling out flange Omega-gasket – When differential displacements take place and hydrostatic pressure works on the Omega-gasket, horizontal loads act on the flange of the Omega-gasket. This should be prevented.
- Requirement O3: Cracks in the Omega-gasket – Strain of the curved part of the Omega-gasket, as a result of differential movements, can lead to cracks. This should be prevented.
- Next to the three requirements, there is also the requirement that the Gina-gasket may not be pushed away (Requirement G2), because this could lead to damage to the Omega-seal.

The bolt forms a crucial link within in the clamping structure. Therefore, the bolt needs to have enough surface to transfer the loads (Req. B1), enough clamping capacity (Req. B2) and the surface tension of the nut and washer should stay within a certain limit (Req. B3).

The calculation of the Omega-seal is split up into a few steps. First of all, the maximum force that occurs in the bolt needs to be determined. This is done directly after installation of the bolts and during use of the bolts. Then, for an individual bolt, it is calculated when the Requirements O1, O2 and O3 are met. The input is the design and the movements (Δx, Δy and Δz). Result is for which values of the compression of the flange of the Omega-gasket (c_O) is watertight. Regarding the governing force in the bolt (F_b), it is calculated how much penetration depth due to corrosion (d_p) is allowed to take the forces. Finally, it is calculated what happens when one or more bolts fail.

All forces that work in the clamping structure are calculated. The moment equation around the steel bar is taken, in order to determine the force in the bolt. Furthermore, there is a horizontal and a vertical force equilibrium.

Three mechanisms determine the watertightness of the Omega-gasket over the lifetime:

- Corrosion in the clamping structure – This leads to a decrease of the capacity of the clamping structure.
- Movements of the immersion joint – These lead to larger forces from the curved part of the Omega-gasket.
- Relaxation – This leads to a decrease in stress within the Omega-gasket.

The case Kil Tunnel is considered. The calculation procedure is followed, and leads to a few conclusions and recommendations.

The following is concluded:

- The force in the bolt during installation is governing. This force is 65 kN.
- The compression of the flange of the Omega-gasket (c_O) determines strongly whether the requirements on watertightness are met.
- When the compression of the flange of the Omega-gasket (c_O) is smaller than 5 mm, the requirements are not met. This means that leakages through the immersion joint can occur.
- From the calculation, it follows that the maximum allowed penetration depth of the corrosion is 2 mm of the core of the bolt. If this value is exceeded, the functioning of the bolt is not guaranteed anymore.

- When one bolt fails, the clamping plate will deform. As a result the forces on the adjacent bolts will be lower. It depends on the state of the bolt whether this is able to take the loads. This will determine whether the 'zipper effect' will occur.
- When one bolt fails, the clamping structure will still be watertight. One exception is bolt 2 or 12: if this bolt fails, the 'zipper effect' takes place when the adjacent bolt is not able to take the load of 83.5 kN.
- When two bolts next to each other fail, the clamping structure loses its watertightness.
- When two bolts fail with 1 or 2 functioning bolts in between, the structure stays watertight if the adjacent bolts are able to take a load of 86.1 kN.

The following is recommended:
- Since the value of the compression of the flange of the Omega-gasket is so important, it is recommended to measure this in the Kil Tunnel. Since it is hard to measure the compression of the flange, it is advised to measure the distance between the plate and the clamping plate (d_{pcp}). This can be transferred into the present height of the flange of the (compressed) flange of the Omega-gasket ($h_{Omega,fl,pr}$). With Equation 5.23, this can be transferred into the compression of the flange of the Omega-gasket, that is used in the calculations.
- A few bolts in the "splash zone" of the Kil Tunnel need to be removed for research. These bolts need to be analysed, in order to see how far the corrosion has penetrated the bolt (d_p) or to see how much surface is still left in the bolt ($A_{T,pr}$). This needs to be compared with the values that are calculated. With this analysis, one is able to judge on the state of the bolts.
- It must be checked whether the corrosion of the clamping structure of the Omega-seal is an ongoing process. If the corrosion has reached an equilibrium, and the state is acceptable, action is not urgent. In that case, a check on the state can be performed during the next maintenance period.

6

Chapter 6 – Application of results

In Chapter 6, it is shown how the results of the calculations in Chapter 4 and 5 can be used in practice. First, it is explained if the model can be used in other existing tunnels. Then, some suggestions are prescribed how to improve the model. Then, it is recommended which values need to be measured in the Kil Tunnel. Finally, it is explained how the consideration can be used for the design of new tunnels.

6.1. Application model in existing immersed tunnels

In this report, the Kil Tunnel is analysed. It is attempted to prescribe general requirements for the Gina-seal and the Omega-seal. These requirements can also be used to check other immersed tunnels than the Kil Tunnel. In this paragraph, it is checked whether this analysis can be used for other existing immersed tunnels. Since there is relatively little information available on the details, this analysis will be rather simple.

First Coen Tunnel (1966)

In the First Coen Tunnel, the model can be used. The design looks similar to the Kil Tunnel. A detail is shown in Figure 66. Since this detail is rather unclear, it is hard to judge which mechanisms will be governing in this tunnel. In order to do this, also details of the roof and the floor are needed. Then, it is also known which kind of dowels is used.

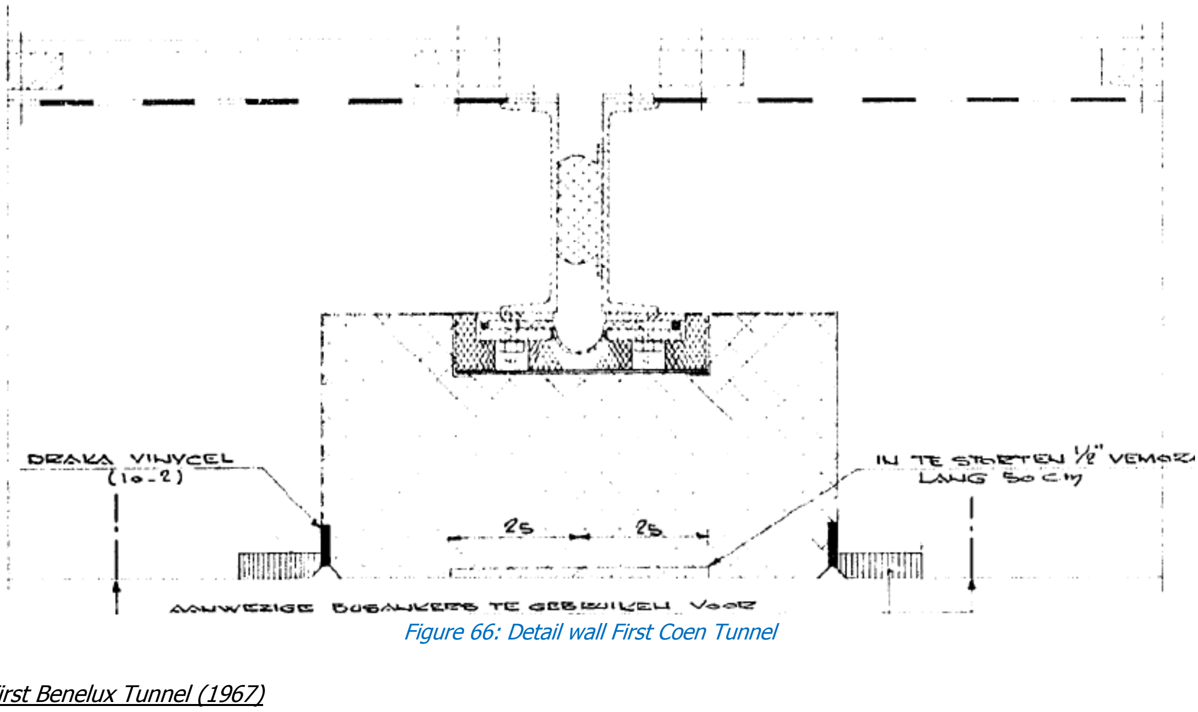

Figure 66: Detail wall First Coen Tunnel

First Benelux Tunnel (1967)

The First Benelux Tunnel does not have an Omega-gasket. The design of the Gina-gasket looks similar to the Kil Tunnel. A detail is shown in Figure 67. Since there is no Omega-gasket, this complete analysis can be left out. As a consequence, the requirements of the Gina-seal should be stricter. When this Gina-seal fails, there is no back-up, so leakage will immediately occur.

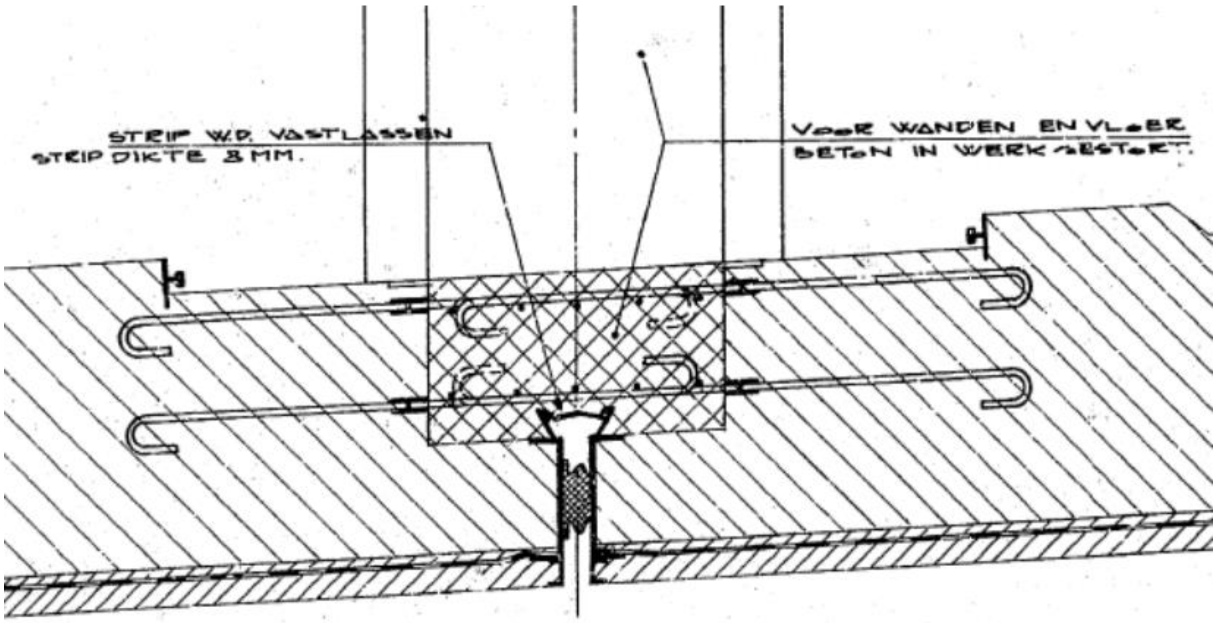

Figure 67: Detail of the floor of the First Benelux Tunnel

Metro Tunnel Rotterdam (1968)

The design of the Gina-seal in the Metro Tunnel Rotterdam looks a bit different from the Kil Tunnel. The clamping structure is different: it has a kind of wing on the inner side of the tunnel. Therefore, the structural calculation will be different. A detail is shown in Figure 68. This immersion joint has an Omega-seal, but this is not in shown in Figure 68. A detail of this Omega-seal is needed to judge whether it is similar to the Kil Tunnel.

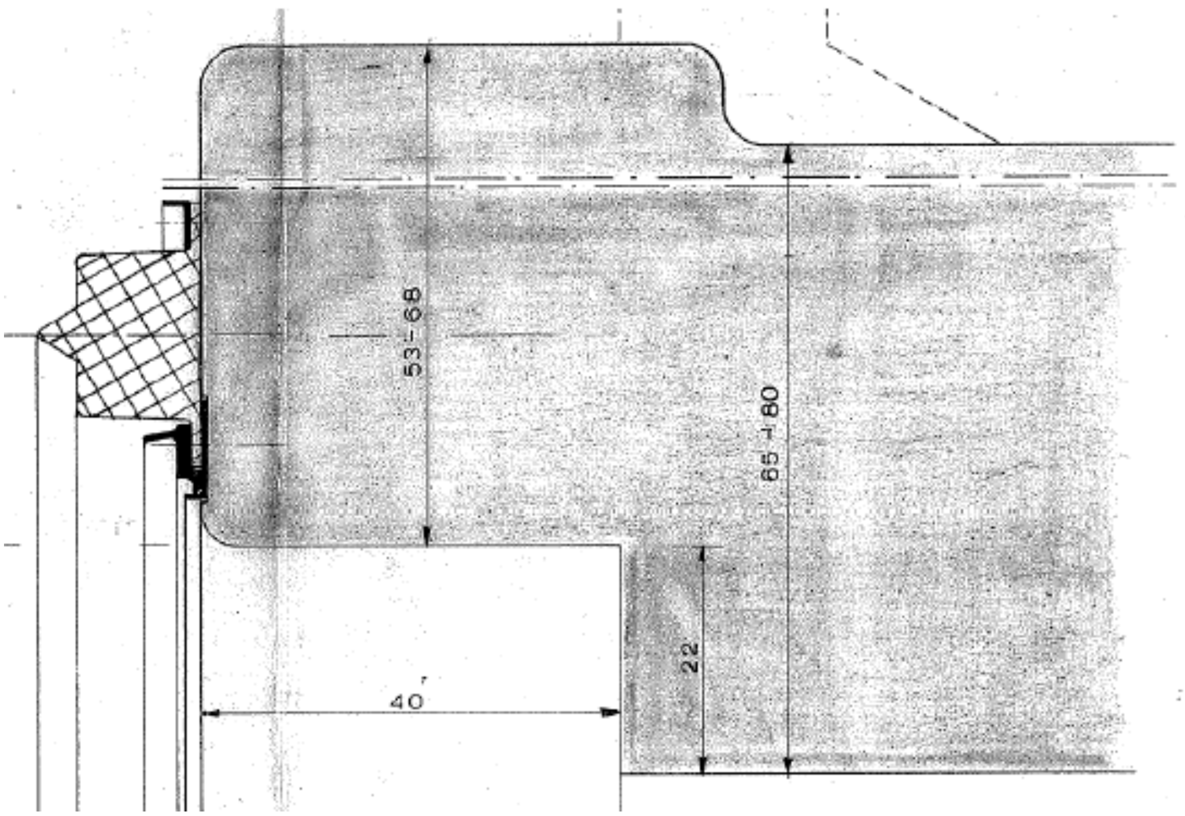

Figure 68: Detail of the wall of the Rotterdam Metro Tunnel

First Heinenoord Tunnel (1969)

The design of the immersion joint of the First Heinenoord Tunnel is rather similar to the one of the Kil Tunnel. However, the position of the Gina-seal is shifted to the outside of the tunnel. This avoids soil from compression in the area in between the two tunnel elements. With the analysis on the Gina-seal, it can be proven that this leads to less compression and limited soil loads on the Gina-seal. A detail is show in Figure 69. Further, the design of the Omega-seal looks similar to the Kil Tunnel.

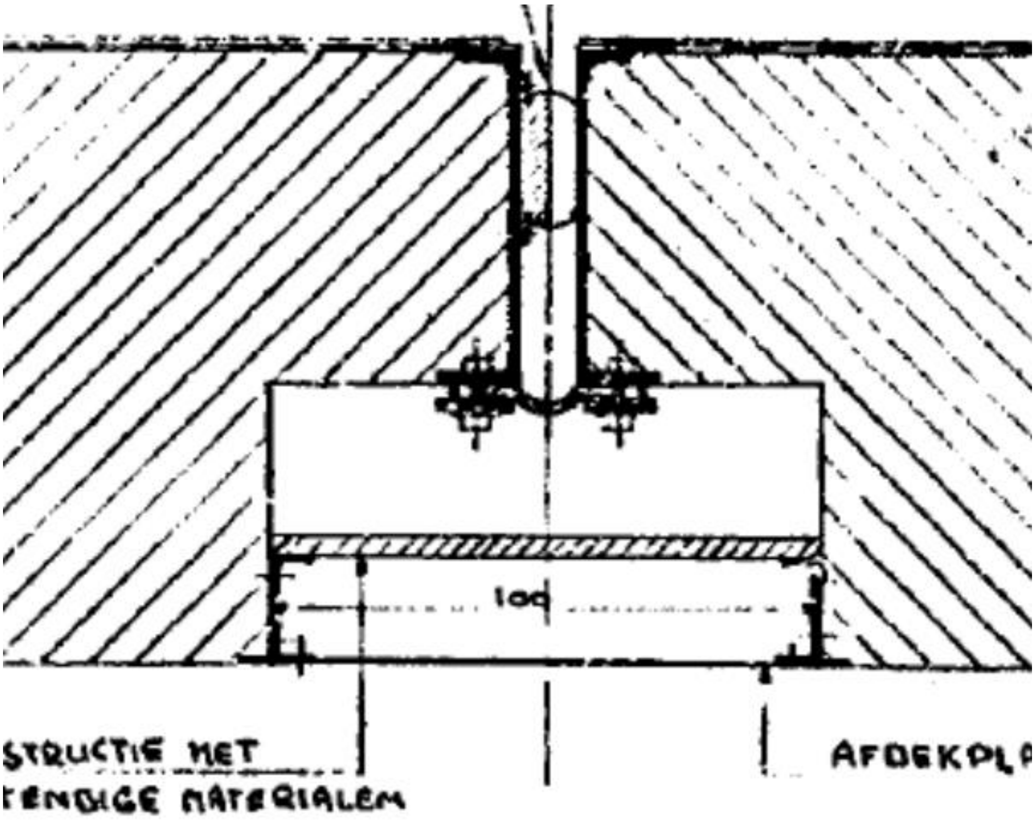

Figure 69: Detail of the roof of the First Heinenoord Tunnel

<u>*Vlake Tunnel (1975)*</u>
This tunnel has a similar design of the Gina-seal and the Omega-seal with respect to the Kil Tunnel. Therefore, the analysis of the Kil Tunnel can be used for the Vlake Tunnel. Increase in soil pressure will probably also occur in this tunnel, since there is a rather large space in the joint where the soil can compress over the years. A detail is shown in Figure 70.

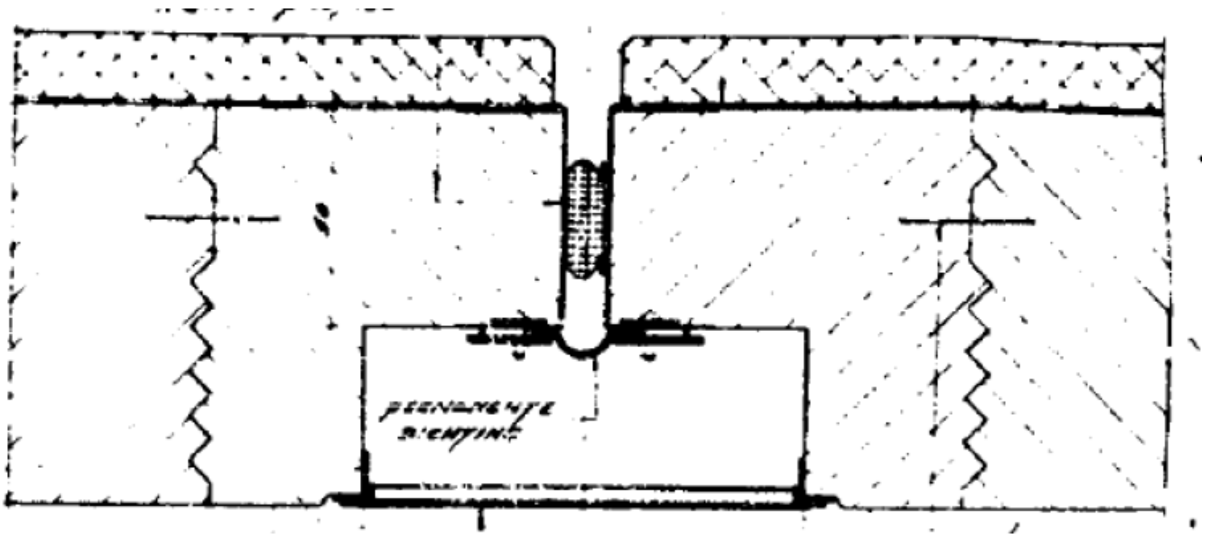

Figure 70: Detail of the roof of the Vlake Tunnel

Botlek Tunnel (1980)
The detail of the immersion joints of the Botlek Tunnel differs from the immersed tunnels made earlier in the Netherlands. As shown in Figure 71, there is some extra concrete that prevents the Gina-gasket from being pushed towards the Omega-gasket. With this detail the analysis on the Gina-seal, as described in this rapport, is only partly applicable to this situation. However, the design of the Omega-seal is similar, so the method from this report can be used for that application, too.

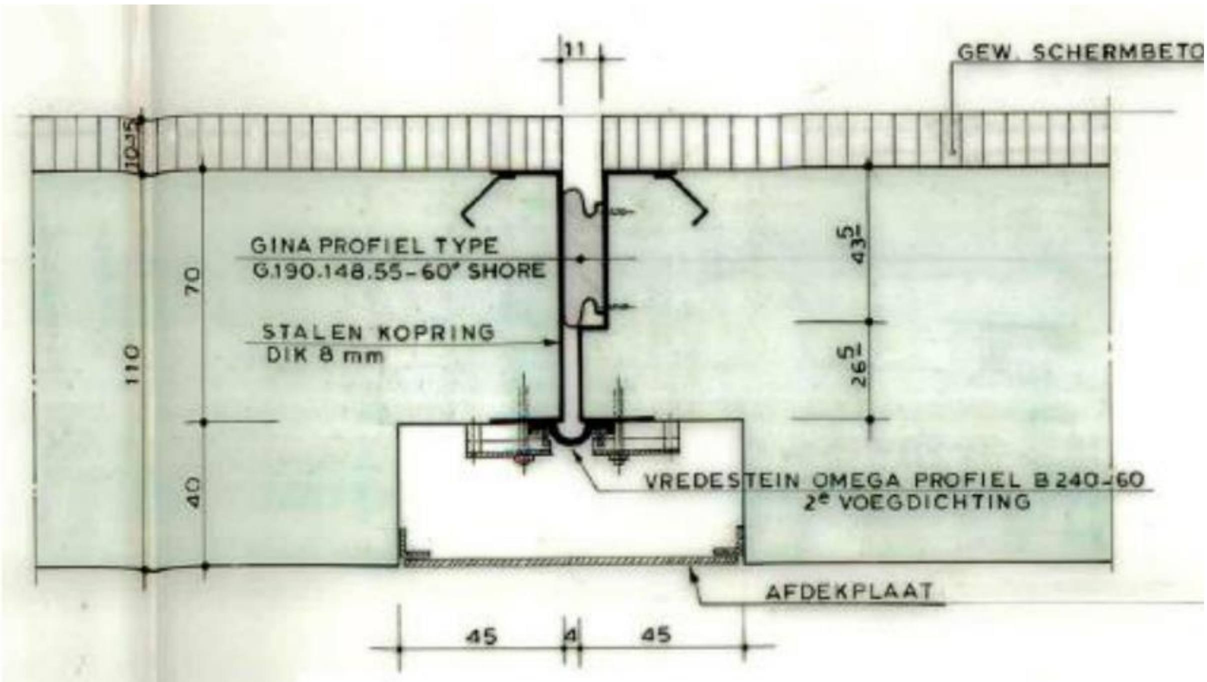

Figure 71: Detail of the roof of the Botlek Tunnel

6.2. Improvement model

Within the model, there are still many uncertainties. Since it is not economical to check everything, a choice should be made which measurements and research should be done. In this paragraph, this will be explained. It is split up into two parts: about the Gina-seal and about the Omega-seal.

6.2.1. Improvement model Gina-seal

In Chapter 4, it is described that the value of maximum difference between winter and summer of the immersion joint in the longitudinal direction (Δx) should be measured. However, there are a few other adaptations or measurements needed to make the model more reliable.

In the model, a few values are used that are assumed:

- Multiplication factor due to the cyclic compression (α) – This value is rather stochastic. In order to do fully understand this problem, more research needs to be done. This will make the model more reliable. However, it will be more economical to first visually check whether this phenomenon has occurred in the Kil Tunnel, before starting a research.
- Differential movement of the immersion joint in y-direction (Δy) – This value is not known. However, from the calculations in the Kil Tunnel, it seems that this is not a very important value.
- Differential movement of the immersion joint in z-direction (Δz) – This value is not known. However, from the calculations in the Kil Tunnel, it is not likely that this movement will lead to leakages. It is small enough not to lead to problems. Besides, it does not increase much since a dowel is placed.

No structural calculations are made on the clamping structure of the Gina-seal. It is assumed that the friction of the Gina-gasket should be able to take all the loads from the water and the soil. However, the clamping structure of the Gina-seal adds some extra capacity. When it follows that the extra capacity is large, this will mean that Requirement G2 (Force equilibrium) will always be met.

Since the value of Δx is rather easy to measure, and it provides much information, it is recommended to measure this value.

6.2.2. Improvement model Omega-seal

In Chapter 5, it is described that the values of c_O (compression of flange Omega-gasket) and d_p (penetration depth of corrosion) or $A_{T,pr}$ (surface bolt present) should be measured. However, there are a few other adaptations or measurements needed to make the model more reliable.

In the model, a few values are used that are assumed:

- Maximum difference between winter and summer of the immersion joint in the longitudinal direction (Δx) – The effect of this value is rather small on the Omega-gasket. Therefore, this does not need to be measured.
- Differential movement of the immersion joint in y-direction (Δy) – This value is not known. However, from the calculations in the Kil Tunnel, it seems that this value will stay within certain limits. Therefore, measurements do not provide much information.
- Differential movement of the immersion joint in z-direction (Δz) – This value is not known. However, from the calculations in the Kil Tunnel, it seems that this value will stay within certain limits. Therefore, measurements do not provide much information.

Further, within the Omega-gasket, there is a transition of the flange to the curved part. Point A and point B are located at this position. In the model, it is assumed that there is a corner at this location. In reality, the transition is more gradual, and does not really form a corner. A better understanding on how the forces in this detail work, would lead to a more reliable model.

6.3. Summary

Other existing immersed tunnels are compared with the Kil Tunnel. The details of the following tunnels look similar to the Kil Tunnel: First Coen Tunnel, First Heinenoord Tunnel and Vlake Tunnel. However, the First Benelux Tunnel, the Metro Tunnel Rotterdam and the Botlek Tunnel have a differend design and therefore need some adaptations in the model.

Furthermore, there are some parameters and methods that need to be improved to make the model more reliable. An important one is the multiplication factor due to the cyclic compression (α).

7

Chapter 7 – Conclusions and recommendations

In this chapter, the conclusions and the recommendations are summed up. In 7.1 the conclusions are presented. In 7.2 the recommendations that follow are described.

7.1. Conclusions

The main goal of this research was to obtain both qualitative and quantitative insight into the remaining capacity of existing Gina-seals and Omega-seals in immersed tunnels. This is successfully done. The conclusions from this study are presented in this paragraph.

Occurrence of leakage
Leakage through immersion joints can only take place when both the Gina-seal and the Omega-seal fail. The main cause of failure of the Gina-seal is pushing out. This is caused by increased soil pressure, as a consequence of cyclic deformation of the joints. The main cause of failure of the Omega-seal is loss of compression of the flange of the Omega-gasket. This is caused by corrosion of the bolt of the clamping structure.

Requirements of the Gina-seal
The Gina-seal has to meet all of the following requirements in order to be watertight:

- Requirement G1 – Enough pressure in the Gina-gasket to stop water: The available pressure of the Gina-gasket should to be larger than the water required pressure to stop the water.
- Requirement G2 – Force equilibrium: The amount of friction force in the Gina-gasket should be larger than the sum of the water force and the soil force, in order to prevent that the Gina-seal is pushed away.
- Requirement G3 – Contact between Gina-gasket and opposite tunnel element: The Gina-gasket must press against the opposite tunnel element.
- Requirement G4 – Cracks in the Gina-gasket: When the Gina-gasket is compressed heavily for a long time, cracks could occur.

Requirements of the Omega-seal
The Omega-seal has to meet all of the following requirements in order to be watertight:

- Requirement O1: Enough pressure to stop water – The flanges of the Omega-gasket should be pressed strongly enough to both tunnel element in order to create a watertight layer.
- Requirement O2: Prevention of pulling out flange Omega-gasket – When differential displacements take place and hydrostatic pressure works on the Omega-gasket, horizontal loads act on the flange of the Omega-gasket. This should be prevented.
- Requirement O3: Cracks in the Omega-gasket – Strain of the curved part of the Omega-gasket, as a result of differential movements, can lead to cracks. This should be prevented.
- Next to the three requirements, there is also the requirement that the Gina-gasket may not be pushed away (Requirement G2), because this could lead to damage to the Omega-seal.
- The bolt forms a crucial link within in the clamping structure. Therefore, the bolt also needs to meet a few requirements.

Case study Kil Tunnel

The Kil Tunnel (case study, finished in 1977, below Dordtsche Kil) has 3 immersion joints (1A, 2E and 3A). Immersion joint 1A and 2E connect the tunnel to both abutments and are exactly the same. Immersion joint 3A connects two tunnel elements to each other. The Gina-seal and the Omega-seal are slightly different for 1A/2E and 3A.

The conclusions of the case study on the Gina-seal in the Kil Tunnel are the following:

- Joint 1A/2E does not meet Requirement G2 roof (Force equilibrium in the roof). This check requires attention. All the other requirements are met with large margins.
- Joint 3A meets all requirements with large margins. It is expected that this Gina-seal fulfils its function over the entire lifetime.

The conclusions of the case study on the Omega-seal in the Kil Tunnel are the following:

- The compression of the flange of the Omega-gasket (c_O) largely determines whether the requirements on watertightness are met. When the compression of the flange of the Omega-gasket (c_O) is smaller than 5 mm, the requirements are not met. This means that leakages through the immersion joint can occur. It is recommended to measure this value.
- The maximum allowed penetration depth of corrosion is 2 mm of the core of the bolt. If this value is exceeded, the functioning of the bolt is not guaranteed anymore. It is recommended to remove a bolt at the "splash zone" in order to see how far the corrosion has penetrated the bolt. Furthermore, it must be checked whether the corrosion is an on-going process.
- When one bolt fails, the clamping plate will deform. As a result, the forces on the adjacent bolts will be lower. It depends on the state of the bolt whether it is able to take the loads. This will determine whether the 'zipper effect' will occur.

The basics of the model (used for the case study) can be used for the consideration of the Gina-seal and the Omega-seal in the First Coen Tunnel, the First Heinenoord Tunnel and the Vlake Tunnel. For the First Benelux Tunnel, the Metro Tunnel Rotterdam and the Botlek Tunnel, some adaptations need to be made.

7.2. Recommendations

The recommendations follow from the conclusions.

Requirements of the Gina-seal

It is recommended to check these requirements in other existing immersed tunnels, too. The First Heinenoord Tunnel is a relevant project, since large-scale maintenance is planned there. It is expected that more experience with the model will lead to better results.

Requirements of the Omega-seal

The same is recommended as for the Gina-seal: check these requirements in other tunnels.

Case study Kil Tunnel

From the analysis on the Gina-seal, the following is recommended:

- It is recommended to do some visual inspections on the functioning of the Gina-seal in the roof of joint 1A/2E. If failure of the Gina-seal occurs, this will be the first location. In order to reach the Gina-seal, (part of) the Omega-seal needs to be removed temporarily. It is recommended to check this every few years.
- Furthermore, it is recommended to measure the difference between the joint width in winter and in summer (Δx). This gives important information on the functioning of the Gina-seal. It is recommended to do this every month, because the width changes with the temperature.

From the analysis of the Omega-seal, the following is recommended:

- Since the value of the compression of the flange of the Omega-gasket is so important, it is recommended to measure this in the Kil Tunnel. Since it is hard to measure the compression of the flange, it is advised to measure the present height of the flange of the (compressed) flange of the Omega-gasket ($h_{Omega,fl,pr}$).
- A few bolts in the "splash zone" of the Kil Tunnel need to be removed for research. These bolts need to be analysed, in order to see how far the corrosion has penetrated the bolt (d_p) or to see how much surface is still left in the bolt ($A_{T,pr}$). This needs to be compared with the values that are calculated.
- It must be checked whether the corrosion of the clamping structure of the Omega-seal is an ongoing process. If the corrosion has reached an equilibrium, and the state is acceptable, action is not urgent. In that case, a check on the condition can be performed during the next maintenance period.

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A

Appendix A – Glossary

Since this report is written for the Dutch engineering practice, many words are translated from Dutch into English. A list with translations is made, so readers can understand the English words that are used in this report.

English term	Dutch translation	description
access road	toerit	the part of the tunnel structure that provides the road between ground level and the immersed tunnel
access shaft	schacht	temporary shafts that allow personnel and equipment to enter the interior of an immersed tunnel while it is floating or submerged
ballast	ballast	material, either solid or liquid, that is placed inside or outside an immersed tunnel to increase the effective weight
backfill	vulgrond	material placed on both sides and on top of the tunnel element, when it is placed in the trench
bulkhead	kopschot	walls at the ends of tunnel elements to keep water out during floating and immersion
clamping plate	klemplaat, klemlijst	plate that is clamped to the Gina-gasket or the Omega-gasket
cap nut	dopmoer	a nut with a rounded end
clamping structure	klemconstructie	part of the Gina-seal and the Omega-seal; it consists of the clamping plate, bolts and the part of the gasket that is clamped to the tunnel element
concrete fill	vulbeton	concrete layer that is placed after immersion, in order to protect the watertight rubber gaskets in immersion joints and final joints
concrete frame	kraagconstructie	concrete part of the immersion joint, to which the Gina-seal and Omega-seal are connected
design lifetime	ontwerplevensduur	the period in which a structure can operate on the required safety level, assuming regular maintenance is performed
dredging	baggeren	excavation of the trench in which the tunnel element will be placed
dry dock	droogdok	area that can be dewatered for the repair of ships, that can also be used for construction of tunnel elements
dowel	deuvel	a steel part cast-in-concrete that transfers shear forces in an immersion joints
(tunnel) element	(tunnel)element	a part of the tunnel that is floated and immersed as a single unit, consisting of several segments that are connected
endoscopic	endoscopisch	with the help of a flexible camera
expansion joint	mootvoeg	a joint between two tunnel segment (each 20 – 25 m)
final joint	sluitvoeg	the joint between two tunnel element (each 100 – 150 m) that is made at last; only one of this type present per tunnel
gasket	profile	a device that acts as a seal between two contacting surfaces
Gina-gasket	Gina-profiel	the rubber gasket that is used as water seal during immersion; one gasket that follows the perimeter of the tunnel
Gina-seal	Gina-afdichting	the rubber Gina-gasket including steel plates and bolts on both sides
immersed tunnel	afzinktunnel	tunnel that is consists of prefabricated elements that are floated to the site, installed and connected under water
immersion	afzinken	the construction phase between floating of the element and laying on its foundation in the trench
immersion joint	zinkvoeg	a joint between two tunnel elements (each 100 – 150 m)

joint	voeg	connection between two concrete parts of a tunnel
middle tunnel channel	middentunnelkanaal	channel in between both tunnel tubes, used as escape route in case of emergency
nut	moer	a sort of ring that can be moved around a bolt in order to give clamping force
Omega-gasket	Omega-profiel	the rubber gasket, shaped like the Greek letter Omega (Ω); one gasket that follows the perimeter of the tunnel
Omega-seal	Omega-afdichting	the seal, consisting of the Omega-gasket and the clamping structure
prestress	voorspanning	force used to lock a flexible joint during transportation and immersion
sand bedding	zandbed	a foundation formed by filling the space between the underside of an element and the excavated trench
sand flow	onderstromen	a method of sand bedding whereby the sand-water mix is transported through a pipe system with fixed outlets in the soffit of the element, creating pancake-shaped mounts
sand jetting	onderspoelen	a method of sand bedding whereby the sand-water mix is transported through a moveable jet pipe in the void between the underside of the tunnel and the trench bottom
screeded foundation	grindbed	a gravel foundation that is prepared by screeding to close tolerances
(tunnel) segment	segment, moot	part of a tunnel element, with a length of 20 – 25 m
shear key	shear key	a concrete element that transfers shear forces in an immersion joint
stud	draadeinde	a blank screw or bolt
trench	afzinksleuf	the area below the waterway bed level that is excavated and in which the tunnel is placed
tube	buis	space of the cross section in which the road or rail is located
tunnel structure	tunnelconstructie	total structure of a tunnel, consisting of the access road and the tunnel
ventilation	ventilatie	a system in which fresh air is supplied at one end of the traffic tunnel and the polluted air is expelled at the other
washer	ring	a ring-shaped element that is placed in between a nut and a plate, in order to divide the load over a larger surface
watertightness	waterdichtheid	a measure of the capability to resist the penetration of water
zipper effect	ritssluitingseffect	the effect of many adjacent parts that fail after each other

B

Appendix B – Additional information Chapter 3

In this appendix, the additional information from Chapter 3 is presented.

B.1. Description Kil Tunnel

In Paragraph 3.2, a very short description of the Kil Tunnel is given. In this paragraph, some details about the traffic and construction are added.

The Kil Tunnel is an immersed tunnel located below the river Dordtsche Kil. It is part of the N217, that connects the island Hoeksche Waard (west) with the island of Dordrecht (east), as shown in Figure 72. Considered closer, the tunnel connects the town of 's-Gravendeel (west) with the city of Dordrecht (east). The road N217 connects the A29 (Barendrecht-Willemstad) and the A16 (Ridderkerk-Breda) and is an important road on the island Hoeksche Waard. In the tunnel, in both directions there are two lanes. Also, there are separate cycling lanes in both directions.

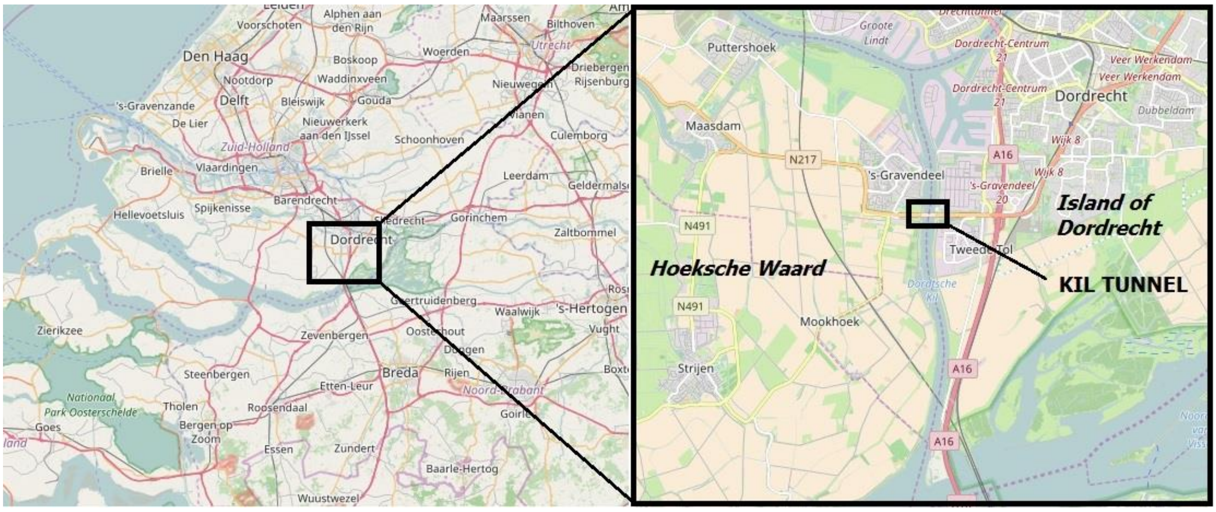

Figure 72: Overview of the location of the Kil Tunnel

As a result of the Delta Works in the Netherlands, the flow velocity in the Dordtsche Kil increased largely. In order to lower the velocity, the river was widened. Due to the increase of ships and the high costs for reconstruction of the quays for the ferries, it was decided to build a fixed connection. It became an immersed tunnel, since in case of a bridge the amount of ships in the Dordtsche Kil would lead to many openings. Since a tunnel was not affordable for the province, the tunnel became a toll road. A foundation that exploited the tunnel was founded, called *Stichting Tunnel Dordtsche Kil*.

The tunnel was designed by *directie Sluizen en Stuwen* ('directory Sluices and Weirs'), part of Rijkswaterstaat. Also, supervision was performed by *Sluizen en Stuwen*. Construction started in September 1974 and the work was finished in August 1977.

B.2. Details immersion joints 1A/2E and 3A Kil Tunnel

As described in Section 3.3.2, the details of the immersion joint differ a bit over the cross section. In this paragraph, the differences are explained. In Figure 73, an overview of the design of the different cross sections is shown. This will be further explained in Section B.2.1 and B.2.2.

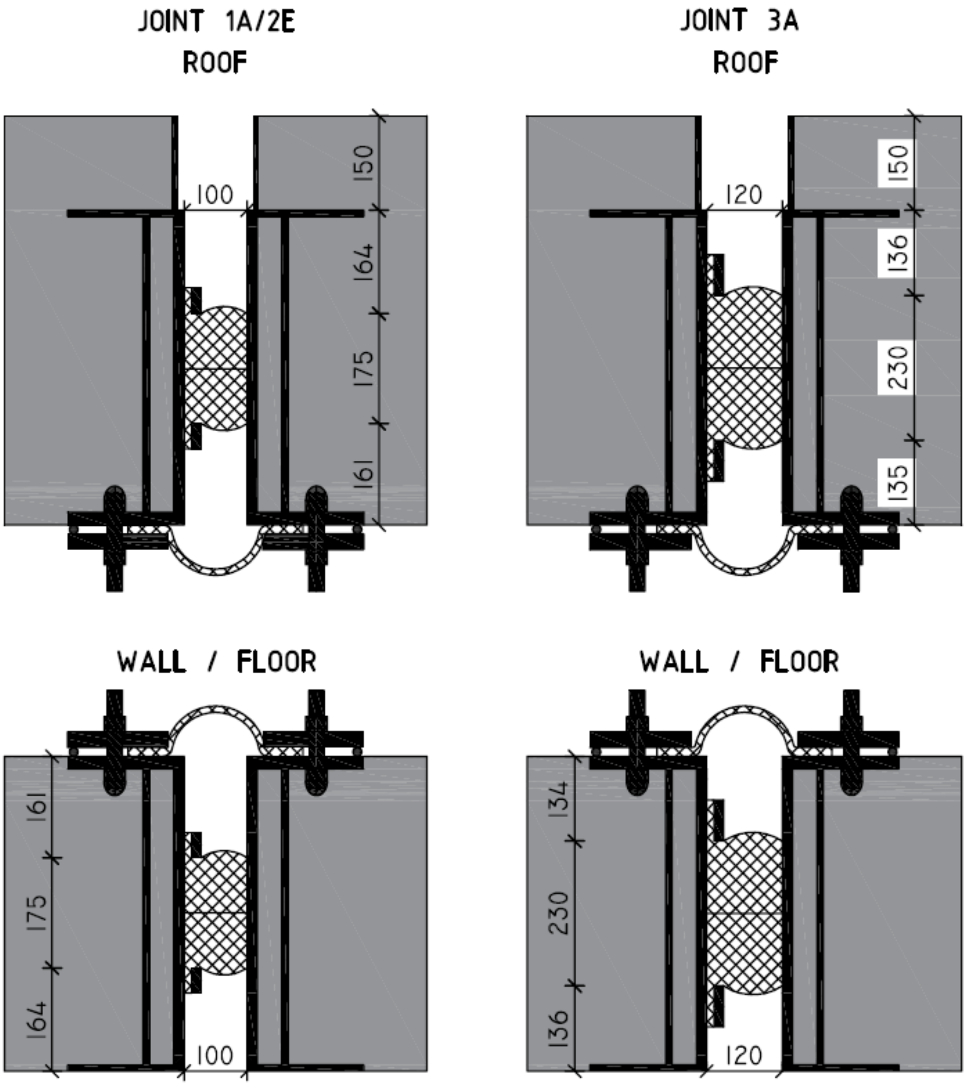

Figure 73: Overview of the different designs of the immersion joint in 1A/2E and 3A

B.2.1. Immersion joint 1A / 2E

This immersion joint is the connection between an abutment and a tunnel element. First, an overview of the cross section is shown (Figure 74). Then, the details of the roof (Figure 75), the wall (Figure 76) and the floor (Figure 77) are presented.

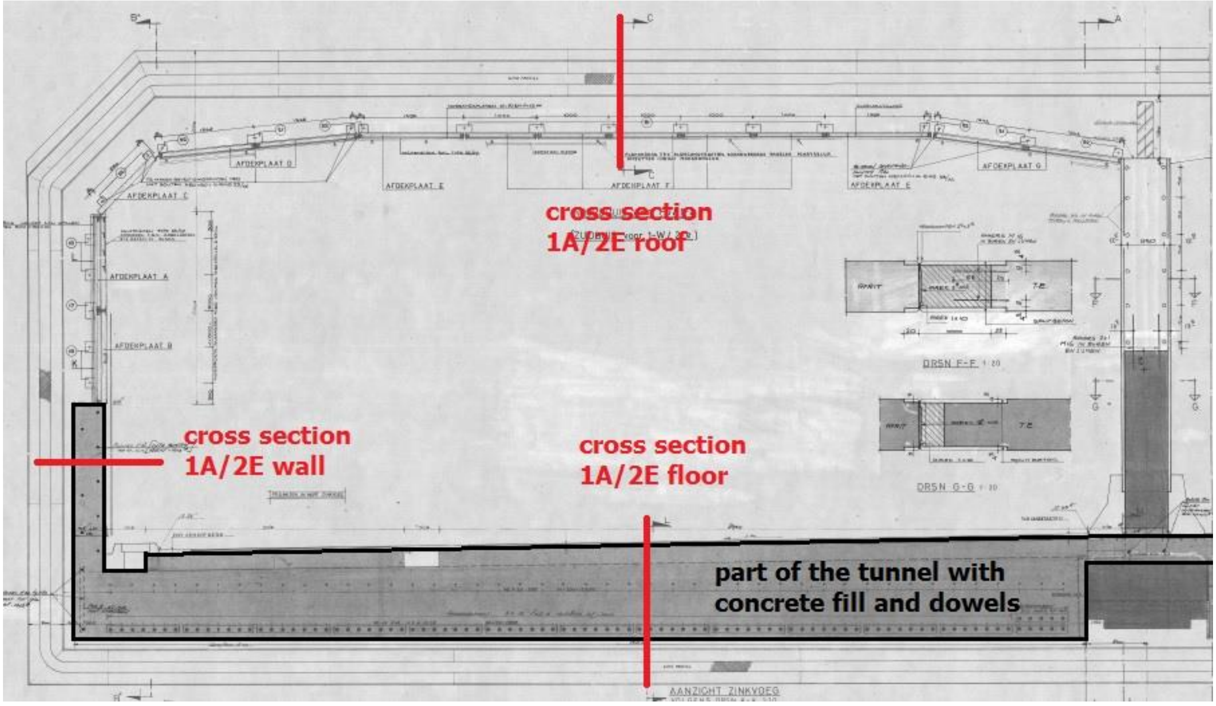

Figure 74: Overview tunnel element (based on (Rijkswaterstaat, 1974))

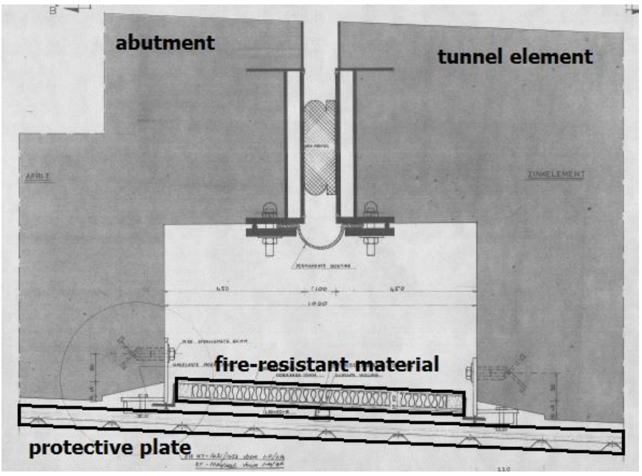

Figure 75: Cross section roof (based on (Rijkswaterstaat, 1974))

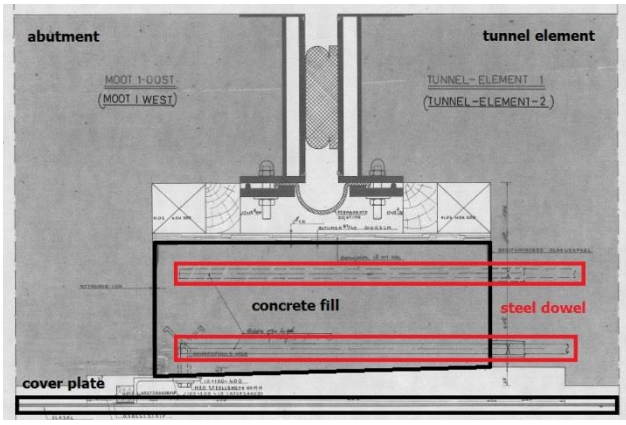

Figure 76: Cross section wall (based on (Rijkswaterstaat, 1974))

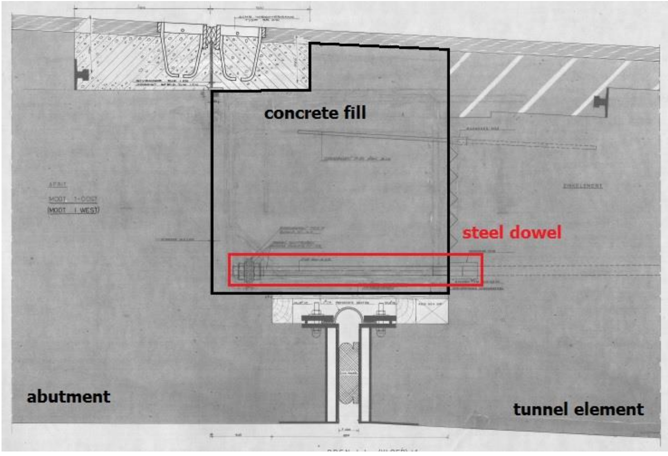

Figure 77: Cross section floor (based on (Rijkswaterstaat, 1974))

B.2.2. Immersion joint 3A

This immersion joint is the connection between two tunnel elements. First, an overview of the cross section is shown (Figure 78). Then, the details of the roof (Figure 79), the wall (Figure 80) and the floor (Figure 81) are presented.

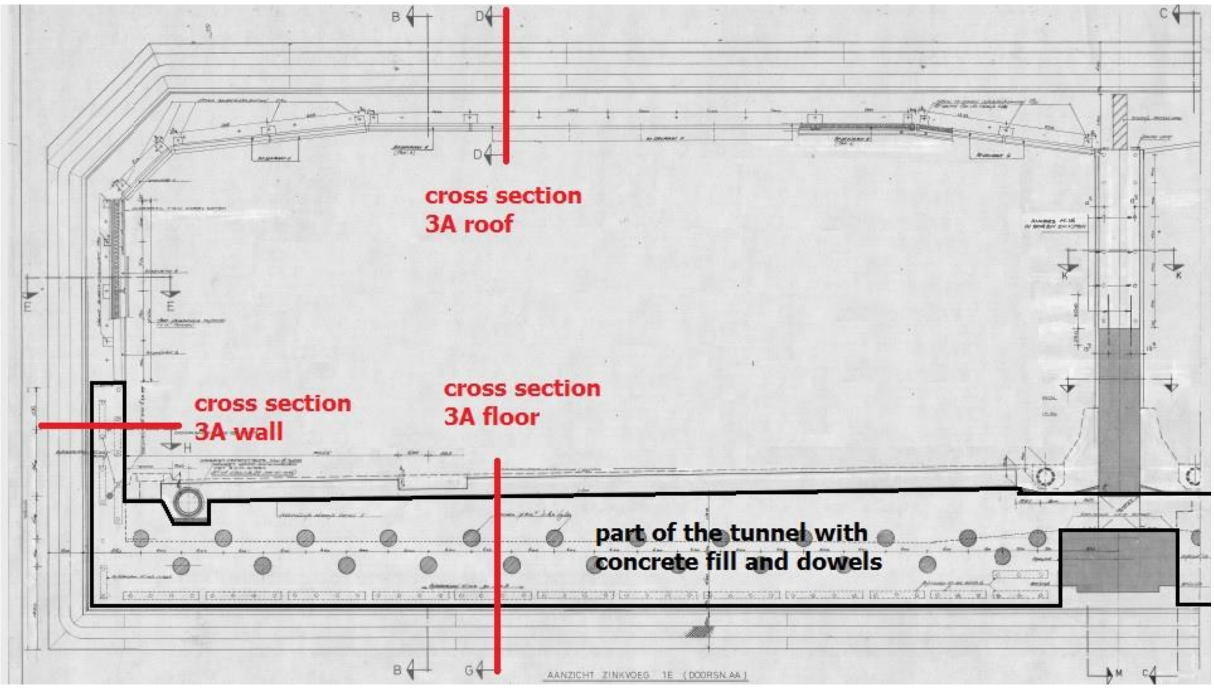

Figure 78: Overview tunnel element (based on (Rijkswaterstaat, 1974))

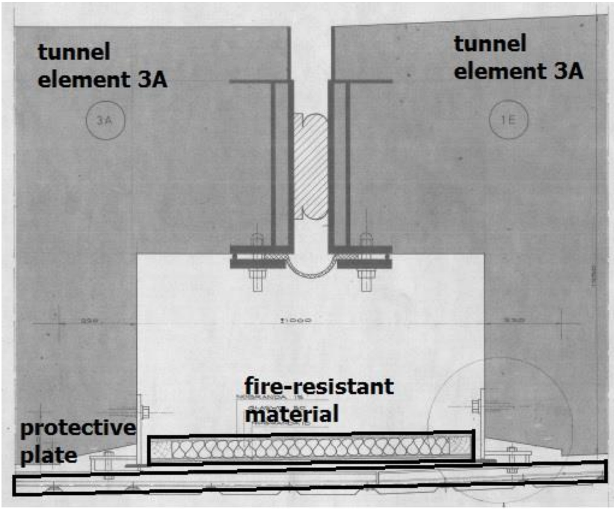

Figure 79: Cross section roof (based on (Rijkswaterstaat, 1974))

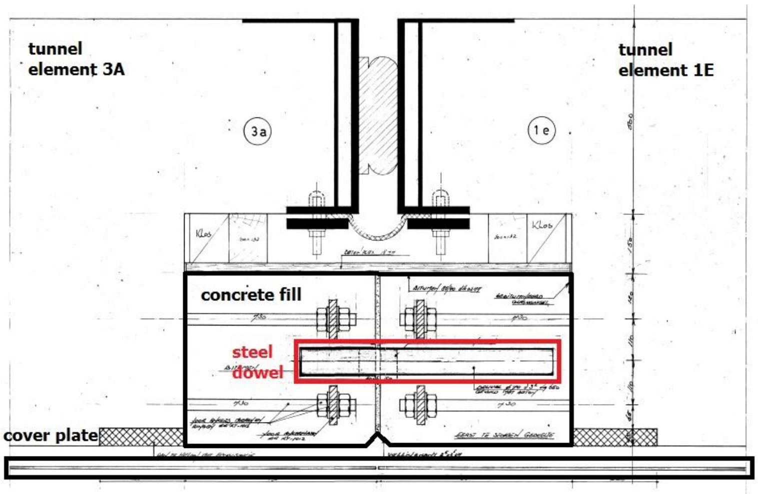

Figure 80: Cross section wall (based on (Rijkswaterstaat, 1974))

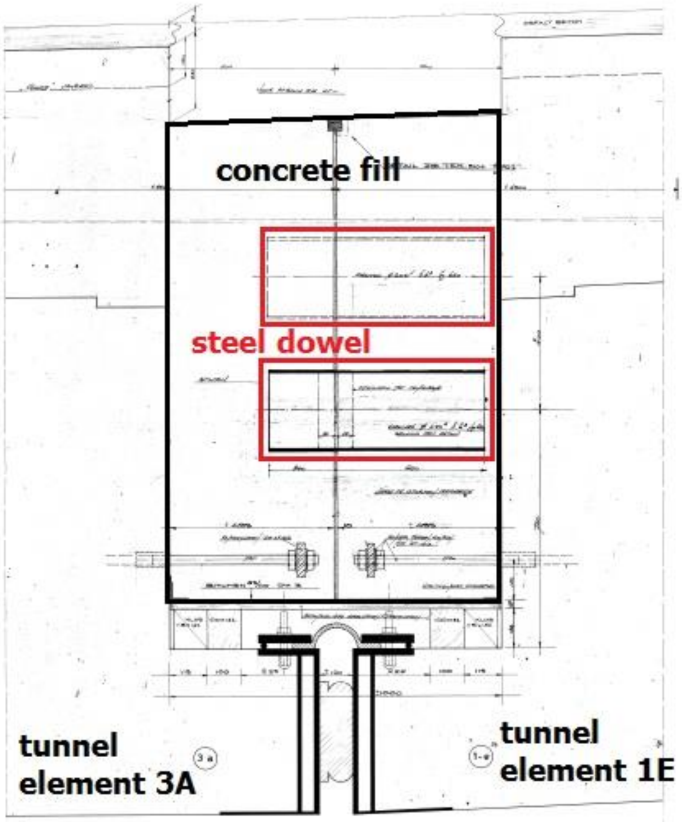

Figure 81: Cross section floor (based on (Rijkswaterstaat, 1974))

B.3. Centre to centre distance bolts Omega-seal

In Section 3.3.4, the design of the Omega-gasket is described. The centre-to-centre distance of the bolts of the clamping structure differs over the cross section. In this section, it is explained which value is governing.

In Figure 82, it is shown where all the clamping plates are located. Also, the length of the clamping plates is shown. In Figure 83, the design of each clamping plate is shown. The governing situation is at the floor (clamping plate G, H and J). The maximum centre-to-centre distance is 200 mm. This value is used in the calculations.

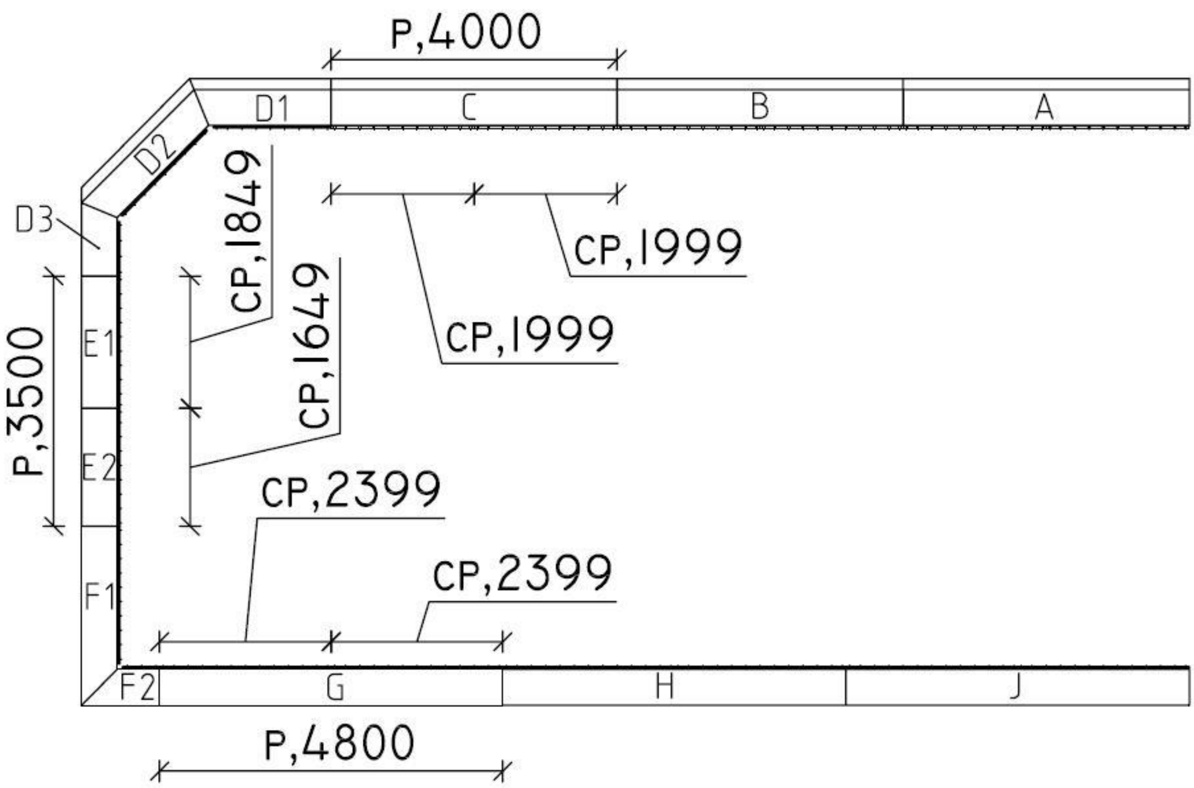

Figure 82: Overview of half of the Kil Tunnel, showing where the clamping plates are located

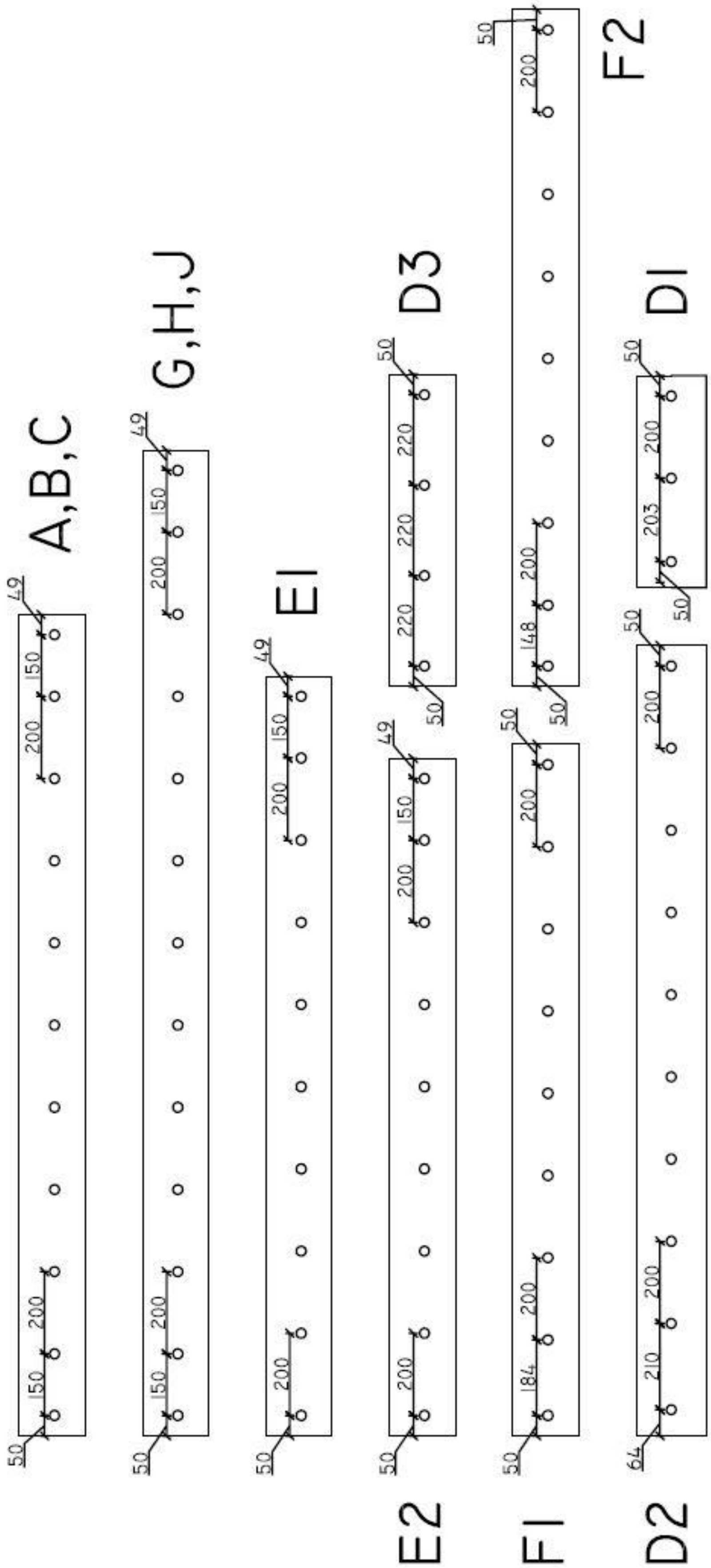

Figure 83: Overview of the centre-to-centre distance of the various clamping plates

C

Appendix C – Additional information Chapter 4

In this appendix, the additional information from Chapter 4 is presented.

C.1. Force-compression curve Gina-gaskets

In this paragraph, the formulas for the force compression curves are calculated. These values are needed for the calculation as described in Section 4.2.1.

In Figure 84, an example of the force-compression curve is shown. From this, the values are written down and inserted in Excel.

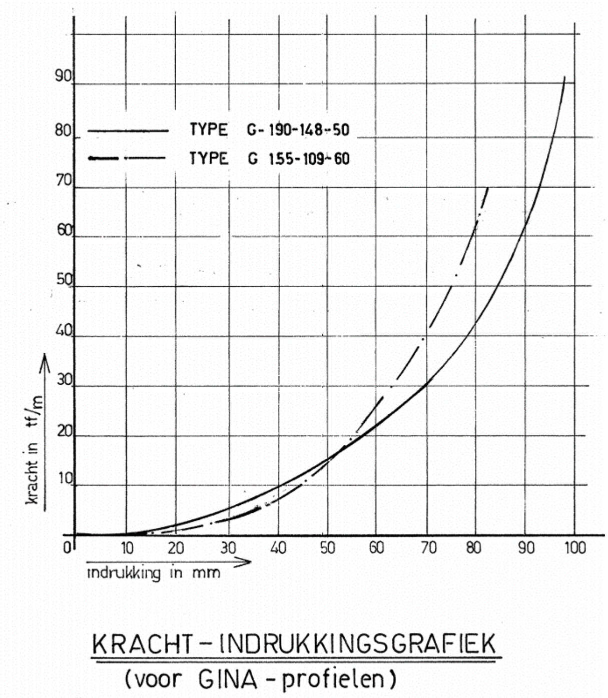

Figure 84: Force-compression curves for the two Gina-gaskets

Then, an Excel function creates a polynomial that resembles the original function. The formula of this line is presented in Figure 85.

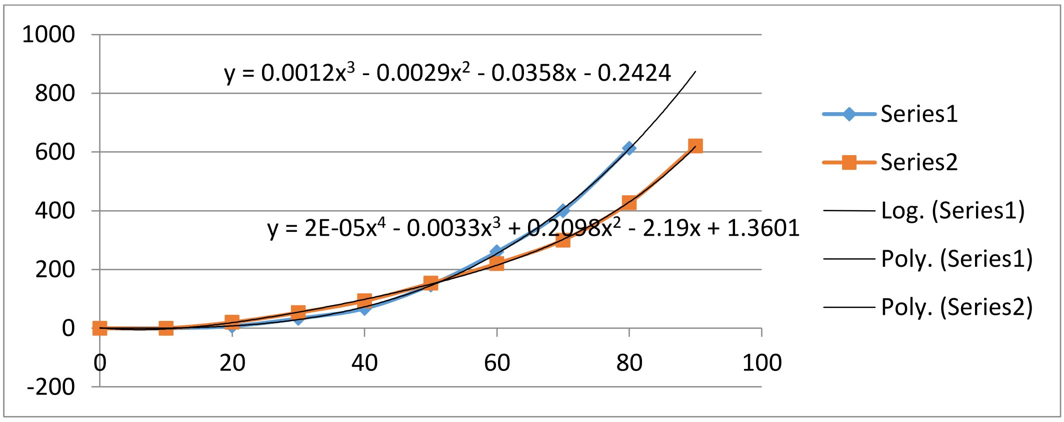

Figure 85: Curves created by Excel

With Excel the equations are determined. These are shown in Table 27.

Gina-gasket	**Equation**
G155-109-60	$n_{G,in}$ = 2*10^-5*c^4 - 0,0033*c^3+ 0,2098*c^2 - 2,19*c + 1,3601
G190-148-50	$n_{G,in}$ = 0,0012*c^3 - 0,0029*c^2 - 0,0358*c - 0,2424

Table 27: Equations determined by Excel

C.2. Complete calculations sheets

As described in Section 4.4.2, the tables with the results are based on the calculation sheets. These are presented in this paragraph. The legend is shown in Table 28.

In Table 29, calculations are made of the Gina-seal of immersion joints 1A and 2E. The Gina-gasket used in this seal is of the type G155-109-60. In Table 30, calculations are made of the Gina-seal of immersion joint 3A. The Gina-gasket used in this seal is of the type G190-148-50. Calculations are made for both expected and extreme displacements. Calculations are also made for the average situation and in case of winter and summer.

Type of box	**Description**
18	value that is filled in
20	calculated value
3.01	value with a safety > 2,5
1.22	value with a safety in between 1 and 2,5
0.98	value with a safety < 1
51.2	calculated value that will be used in calculation on bolts

Table 28: Legend of Table D-1 and D-2

TABLE 29: Gina-seal calculation joint 1A/2E (G155-109-60)

description	symbol	values																		unity	equation / explanation
load situation	t	0,75						40						100						years	In this situation, the Gina-seal at both the lower part of the wall and the floor is calculated. Soil pressure is only present in the wall.
		expected			extreme			expected			extreme			expected			extreme				
		winter	average	summer	winter	average	summer	winter	average	summer	winter	average	summer	winter	average	summer	winter	average	summer		
VALUES PER LOAD SITUATION																					
time after immersion	t	0,75	0,75	0,75	0,75	0,75	0,75	40	40	40	40	40	40	100	100	100	100	100	100	years	explained in Section 3.4.1
maximum difference between winter and summer of the immersion joint in longitudinal direction	Δx	10	10	10	20	20	20	10	10	10	20	20	20	10	10	10	20	20	20	mm	explained in Section 3.4.1
differential movement of the immersion joint in y-direction	Δy	0	0	0	20	20	20	0	0	0	20	20	20	0	0	0	20	20	20	mm	explained in Section 3.4.1
differential movement of the immersion joint in z-direction	Δz	100	100	100	110	110	110	105	105	105	120	120	120	110	110	110	130	130	130	mm	explained in Section 3.4.1
coefficient for seasonal temperature changes	a	1	0	-1	1	0	-1	1	0	-1	1	0	-1	1	0	-1	1	0	-1	(-)	explained in Section 4.4.1
CALCULATION PARAMETERS																					
multiplication factor due to the cyclic compression roof	α_roof	1,5	1,5	1,5	2	2	2	2	2	2	3	3	3	2,5	2,5	2,5	4	4	4	(-)	explained in Section 4.4.1
multiplication factor due to the cyclic compression wall	α_wall	1,2	1,2	1,2	1,4	1,4	1,4	1,4	1,4	1,4	1,8	1,8	1,8	1,6	1,6	1,6	2,2	2,2	2,2	(-)	explained in Section 4.4.1
relaxation per decade	r	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	%	explained in Section 4.4.1
friction factor	μ	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	(-)	explained in Section 4.4.1
wet density sand	γ_s	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	kN/m^3	explained in Section 4.4.1
density water	γ_w	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	kN/m^3	explained in Section 4.4.1
GEOMETRY																					
average joint widt in the joint	s_jwa	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	mm	explained in Section 3.3.2
joint width that is present in the joint	s_jwp	105	100	95	110	100	90	105	100	95	110	100	90	105	100	95	110	100	90	mm	Equation 4.12
original (uncompressed) height of the Gina-gasket	h_G	167	167	167	167	167	167	167	167	167	167	167	167	167	167	167	167	167	167	mm	explained in Section 3.3.3
compression of the Gina-gasket	c_G	62	67	72	57	67	77	62	67	72	57	67	77	62	67	72	57	67	77	mm	Equation 4.11
distance between Gina-gasket and outside tunnel	s_mo1,wall	161	161	161	161	161	161	161	161	161	161	161	161	161	161	161	161	161	161	mm	explained in Section 3.3.2
distance between Gina-gasket and outside tunnel	s_mo1,roof	161	161	161	161	161	161	161	161	161	161	161	161	161	161	161	161	161	161	mm	explained in Section 3.3.2
distance between Gina-gasket and Omega-gasket	s_mo2,wall	164	164	164	164	164	164	164	164	164	164	164	164	164	164	164	164	164	164	mm	explained in Section 3.3.2
distance between Gina-gasket and Omega-gasket	s_mo2,roof	314	314	314	314	314	314	314	314	314	314	314	314	314	314	314	314	314	314	mm	explained in Section 3.3.2
deepest point joint (relative to NAP)	s_dp	-14,12	-14,12	-14,12	-14,12	-14,12	-14,12	-14,12	-14,12	-14,12	-14,12	-14,12	-14,12	-14,12	-14,12	-14,12	-14,12	-14,12	-14,12	m + NAP	explained in Section 3.3.2
height of the tunnel	s_ht	8,75	8,75	8,75	8,75	8,75	8,75	8,75	8,75	8,75	8,75	8,75	8,75	8,75	8,75	8,75	8,75	8,75	8,75	m	explained in Section 3.3.2
height dike (relative to NAP)	s_hd	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	m + NAP	explained in Section 3.3.2
height governing water table below dike	s_gwt	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	m	explained in Section 3.3.2
height of the sand cover of the tunnel	s_sc	10,47	10,47	10,47	10,47	10,47	10,47	10,47	10,47	10,47	10,47	10,47	10,47	10,47	10,47	10,47	10,47	10,47	10,47	m	explained in Section 3.3.2
width of the surface of the Gina-gasket that is pushed against the opposite tunnel element	s_cw	175	175	175	175	175	175	175	175	175	175	175	175	175	175	175	175	175	175	mm	explained in Section 3.3.2
CALCULATIONS																					
amount of force that is present in the Gina-gasket when it is completely new	n_G,in	181	207	237	158	207	273	181	207	237	158	207	273	181	207	237	158	207	273	N/mm'	n_G,in = 2*10^-5*c^4 - 0,0033*c^3+ 0,2098*c^2 - 2,19*c + 1,3601 (determined by Excel)
part of the initial force that is still left	σ(t)/σ(t=0)	0,72	0,72	0,72	0,72	0,72	0,72	0,63	0,63	0,63	0,63	0,63	0,63	0,61	0,61	0,61	0,61	0,61	0,61	(-)	Equation 4.21
amount of force that is present in the Gina-gasket	n_G,pr	130	149	171	114	149	197	115	131	150	100	131	173	111	127	146	97	127	168	N/mm'	Equation 4.22
force of the soil working on the Gina-seal in the roof	n_soil,roof	14,84	14,13	13,43	20,73	18,85	16,96	19,79	18,85	17,90	31,10	28,27	25,44	24,74	23,56	22,38	41,46	37,69	33,92	N/mm'	Equation 4.18
force of the soil working on the Gina-seal in the wall	n_soil,wall	10,90	10,38	9,86	13,32	12,11	10,90	12,71	12,11	11,50	17,13	15,57	14,01	14,53	13,84	13,15	20,93	19,03	17,13	N/mm'	Equation 4.19
height of the water column	s_wc	18,22	18,22	18,22	18,22	18,22	18,22	18,22	18,22	18,22	18,22	18,22	18,22	18,22	18,22	18,22	18,22	18,22	18,22	m	Equation 4.17
force caused by the water column	n_water	19,13	18,22	17,31	20,04	18,22	16,40	19,13	18,22	17,31	20,04	18,22	16,40	19,13	18,22	17,31	20,04	18,22	16,40	N/mm'	Equation 4.16
total force working on the Gina-seal	n_total	30,03	28,60	27,17	33,36	30,33	27,30	31,85	30,33	28,81	37,17	33,79	30,41	33,66	32,06	30,46	40,97	37,25	33,52	N/mm'	Equation 4.6
CHECKS REQUIREMENTS																					
Req. G1: Enough pressure to stop water (floor)																					
calculation value of water pressure	p_ws	0,46	0,46	0,46	0,46	0,46	0,46	0,46	0,46	0,46	0,46	0,46	0,46	0,46	0,46	0,46	0,46	0,46	0,46	N/mm^2	Equation 4.15
resistance pressure of the Gina-gasket against the opposite tunnel element	p_G,pr	0,75	0,85	0,98	0,65	0,85	1,12	0,66	0,75	0,86	0,57	0,75	0,99	0,64	0,73	0,83	0,55	0,73	0,96	N/mm^2	Equation 4.13
safety factor of Requirement G1	γ_G1	1,64	1,87	2,14	1,43	1,87	2,47	1,44	1,65	1,88	1,26	1,65	2,17	1,39	1,59	1,83	1,22	1,59	2,10	(-)	Equation 4.3
Req. G2: Force equilibrium (roof)																					
total force working on the Gina-seal	n_total	33,97	32,35	30,74	40,77	37,07	33,36	38,92	37,07	35,21	51,14	46,49	41,84	43,87	41,78	39,69	61,50	55,91	50,32	N/mm'	Equation 4.6
friction force in the Gina-gasket	n_G,fr	78,26	89,42	102,43	68,34	89,42	118,03	68,87	78,70	90,15	60,15	78,70	103,88	66,71	76,23	87,32	58,26	76,23	100,62	N/mm'	Equation 4.5
safety factor of Requirement G2	γ_G2	2,30	2,76	3,33	1,68	2,41	3,54	1,77	2,12	2,56	1,18	1,69	2,48	1,52	1,82	2,20	0,95	1,36	2,00	(-)	Equation 4.7
Req. G2: Force equilibrium (wall)																					
total force working on the Gina-seal	n_total	30,03	28,60	27,17	33,36	30,33	27,30	31,85	30,33	28,81	37,17	33,79	30,41	33,66	32,06	30,46	40,97	37,25	33,52	N/mm'	Equation 4.6
friction force in the Gina-gasket	n_G,fr	78,26	89,42	102,43	68,34	89,42	118,03	68,87	78,70	90,15	60,15	78,70	103,88	66,71	76,23	87,32	58,26	76,23	100,62	N/mm'	Equation 4.5
safety factor of Requirement G2	γ_G2	2,61	3,13	3,77	2,05	2,95	4,32	2,16	2,59	3,13	1,62	2,33	3,42	1,98	2,38	2,87	1,42	2,05	3,00	(-)	Equation 4.7
Req. G2: Force equilibrium (floor)																					
total force working on the Gina-seal	n_total	19,13	18,22	17,31	20,04	18,22	16,40	19,13	18,22	17,31	20,04	18,22	16,40	19,13	18,22	17,31	20,04	18,22	16,40	N/mm'	Equation 4.6
friction force in the Gina-gasket	n_G,fr	78,26	89,42	102,43	68,34	89,42	118,03	68,87	78,70	90,15	60,15	78,70	103,88	66,71	76,23	87,32	58,26	76,23	100,62	N/mm'	Equation 4.5
safety factor of Requirement G2	γ_G2	4,09	4,91	5,92	3,41	4,91	7,20	3,60	4,32	5,21	3,00	4,32	6,33	3,49	4,18	5,04	2,91	4,18	6,14	(-)	Equation 4.7
Req. G3: Contact between Gina-gasket and opposite tunnel element (wall)																					
differential movement of the immersion joint in y-direction	Δy	0	0	0	20	20	20	0	0	0	20	20	20	0	0	0	20	20	20	mm	explained in Section 3.4.1
distance between Gina-gasket and outside tunnel	s_mo1,wall	161	161	161	161	161	161	161	161	161	161	161	161	161	161	161	161	161	161	mm	explained in Section 3.3.2
check	(-)	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	(-)	Equation 4.8
Req. G3: Contact between Gina-gasket and opposite tunnel element (floor)																					
differential movement of the immersion joint in z-direction	Δz	100	100	100	110	110	110	105	105	105	120	120	120	110	110	110	130	130	130	mm	explained in Section 3.4.1
distance between Gina-gasket and outside tunnel	s_mo1,roof	161	161	161	161	161	161	161	161	161	161	161	161	161	161	161	161	161	161	mm	explained in Section 3.3.2
check	(-)	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	(-)	Equation 4.9
Req. G4: Cracks in the Gina-gasket																					
compression of the Gina-gasket	c_G	62	67	72	57	67	77	62	67	72	57	67	77	62	67	72	57	67	77	mm	Equation 4.11
original (uncompressed) height of the Gina-gasket	h_G	167	167	167	167	167	167	167	167	167	167	167	167	167	167	167	167	167	167	mm	explained in Section 3.3.3
check	(-)	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	(-)	Equation 4.10

TABLE 30: Gina-seal calculation joint 3A (G190-148-50)

description	symbol	values																		unity	equation / explanation
load situation	t	0,75						40						100						years	In this situation, the Gina-seal at both the lower part of the wall and the floor is calculated. Soil pressure is only present in the wall.
		expected			extreme			expected			extreme			expected			extreme				
		winter	average	summer	winter	average	summer	winter	average	summer	winter	average	summer	winter	average	summer	winter	average	summer		
VALUES PER LOAD SITUATION																					
time after immersion	t	0,75	0,75	0,75	0,75	0,75	0,75	40	40	40	40	40	40	100	100	100	100	100	100	years	explained in Section 3.4.1
maximum difference between winter and summer of the immersion joint in longitudinal direction	Δx	10	10	10	20	20	20	10	10	10	20	20	20	10	10	10	20	20	20	mm	explained in Section 3.4.1
differential movement of the immersion joint in y-direction	Δy	0	0	0	20	20	20	0	0	0	20	20	20	0	0	0	20	20	20	mm	explained in Section 3.4.1
differential movement of the immersion joint in z-direction	Δz	50	50	50	70	70	70	55	55	55	80	80	80	60	60	60	90	90	90	mm	explained in Section 3.4.1
coefficient for seasonal temperature changes	a	1	0	-1	1	0	-1	1	0	-1	1	0	-1	1	0	-1	1	0	-1	(-)	explained in Section 4.4.1
CALCULATION PARAMETERS																					
multiplication factor due to the cyclic compression roof	α_roof	1,1	1,1	1,1	1,2	1,2	1,2	1,2	1,2	1,2	1,4	1,4	1,4	1,3	1,3	1,3	1,6	1,6	1,6	(-)	explained in Section 4.4.1
multiplication factor due to the cyclic compression wall	α_wall	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	(-)	explained in Section 4.4.1
relaxation per decade	r	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	%	explained in Section 4.4.1
friction factor	μ	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	(-)	explained in Section 4.4.1
wet density sand	γ_s	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	kN/m^3	explained in Section 4.4.1
density water	γ_w	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	kN/m^3	explained in Section 4.4.1
GEOMETRY																					
average joint widt in the joint	s_jwa	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	mm	explained in Section 3.3.2
joint width that is present in the joint	s_jwp	125	120	115	130	120	110	125	120	115	130	120	110	125	120	115	130	120	110	mm	Equation 4.12
original (uncompressed) height of the Gina-gasket	h_G	205	205	205	205	205	205	205	205	205	205	205	205	205	205	205	205	205	205	mm	explained in Section 3.3.3
compression of the Gina-gasket	c_G	80	85	90	75	85	95	80	85	90	75	85	95	80	85	90	75	85	95	mm	Equation 4.11
distance between Gina-gasket and outside tunnel	s_mo1,wall	134	134	134	134	134	134	134	134	134	134	134	134	134	134	134	134	134	134	mm	explained in Section 3.3.2
distance between Gina-gasket and outside tunnel	s_mo1,roof	135	135	135	135	135	135	135	135	135	135	135	135	135	135	135	135	135	135	mm	explained in Section 3.3.2
distance between Gina-gasket and Omega-gasket	s_mo2,wall	136	136	136	136	136	136	136	136	136	136	136	136	136	136	136	136	136	136	mm	explained in Section 3.3.2
distance between Gina-gasket and Omega-gasket	s_mo2,roof	286	286	286	286	286	286	286	286	286	286	286	286	286	286	286	286	286	286	mm	explained in Section 3.3.2
deepest point joint (relative to NAP)	s_dp	-19,19	-19,19	-19,19	-19,19	-19,19	-19,19	-19,19	-19,19	-19,19	-19,19	-19,19	-19,19	-19,19	-19,19	-19,19	-19,19	-19,19	-19,19	m + NAP	explained in Section 3.3.2
height of the tunnel	s_ht	8,75	8,75	8,75	8,75	8,75	8,75	8,75	8,75	8,75	8,75	8,75	8,75	8,75	8,75	8,75	8,75	8,75	8,75	m	explained in Section 3.3.2
height dike (relative to NAP)	s_hd	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	m + NAP	explained in Section 3.3.2
height governing water table below dike	s_gwt	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	m	explained in Section 3.3.2
height of the sand cover of the tunnel	s_sc	15,54	15,54	15,54	15,54	15,54	15,54	15,54	15,54	15,54	15,54	15,54	15,54	15,54	15,54	15,54	15,54	15,54	15,54	m	explained in Section 3.3.2
width of the surface of the Gina-gasket that is pushed against the opposite tunnel element	s_cw	230	230	230	230	230	230	230	230	230	230	230	230	230	230	230	230	230	230	mm	explained in Section 3.3.2
CALCULATIONS																					
amount of force that is present in the Gina-gasket when it is completely new	n_G,in	593	713	848	487	713	999	593	713	848	487	713	999	593	713	848	487	713	999	N/mm'	n_G,in = 0,0012*c^3 - 0,0029*c^2 - 0,0358*c - 0,2424 (determined by Excel)
part of the initial force that is still left	σ(t)/σ(t=0)	0,72	0,72	0,72	0,72	0,72	0,72	0,63	0,63	0,63	0,63	0,63	0,63	0,61	0,61	0,61	0,61	0,61	0,61	(-)	Equation 4.21
amount of force that is present in the Gina-gasket	n_G,pr	427	513	611	351	513	720	376	452	537	309	452	633	364	438	521	299	438	613	N/mm'	Equation 4.22
force of the soil working on the Gina-seal in the roof	n_soil,roof	19,23	18,46	17,69	21,82	20,14	18,46	20,98	20,14	19,30	25,45	23,50	21,54	22,73	21,82	20,91	29,09	26,85	24,62	N/mm'	Equation 4.18
force of the soil working on the Gina-seal in the wall	n_soil,wall	13,66	13,12	12,57	14,21	13,12	12,02	13,66	13,12	12,57	14,21	13,12	12,02	13,66	13,12	12,57	14,21	13,12	12,02	N/mm'	Equation 4.19
height of the water column	s_wc	23,29	23,29	23,29	23,29	23,29	23,29	23,29	23,29	23,29	23,29	23,29	23,29	23,29	23,29	23,29	23,29	23,29	23,29	m	Equation 4.17
force caused by the water column	n_water	29,11	27,95	26,78	30,28	27,95	25,62	29,11	27,95	26,78	30,28	27,95	25,62	29,11	27,95	26,78	30,28	27,95	25,62	N/mm'	Equation 4.16
total force working on the Gina-seal	n_total	42,78	41,06	39,35	44,49	41,06	37,64	42,78	41,06	39,35	44,49	41,06	37,64	42,78	41,06	39,35	44,49	41,06	37,64	N/mm'	Equation 4.6
CHECKS REQUIREMENTS																					
Req. G1: Enough pressure to stop water (floor)																					
calculation value of water pressure	p_ws	0,58	0,58	0,58	0,58	0,58	0,58	0,58	0,58	0,58	0,58	0,58	0,58	0,58	0,58	0,58	0,58	0,58	0,58	N/mm^2	Equation 4.15
resistance pressure of the Gina-gasket against the opposite tunnel element	p_G,pr	1,86	2,23	2,65	1,53	2,23	3,13	1,63	1,96	2,34	1,34	1,96	2,75	1,58	1,90	2,26	1,30	1,90	2,67	N/mm^2	Equation 4.13
safety factor of Requirement G1	γ_G1	3,19	3,83	4,56	2,62	3,83	5,37	2,81	3,37	4,01	2,31	3,37	4,73	2,72	3,27	3,89	2,23	3,27	4,58	(-)	Equation 4.3
Req. G2: Force equilibrium (roof)																					
total force working on the Gina-seal	n_total	48,34	46,41	44,48	52,10	48,09	44,08	50,09	48,09	46,08	55,73	51,44	47,16	51,84	49,77	47,69	59,37	54,80	50,23	N/mm'	Equation 4.6
friction force in the Gina-gasket	n_G,fr	256,14	307,98	366,38	210,45	307,98	431,71	225,43	271,06	322,45	185,22	271,06	379,95	218,35	262,55	312,33	179,40	262,55	368,02	N/mm'	Equation 4.5
safety factor of Requirement G2	γ_G2	5,30	6,64	8,24	4,04	6,40	9,79	4,50	5,64	7,00	3,32	5,27	8,06	4,21	5,28	6,55	3,02	4,79	7,33	(-)	Equation 4.7
Req. G2: Force equilibrium (wall)																					
total force working on the Gina-seal	n_total	42,78	41,06	39,35	44,49	41,06	37,64	42,78	41,06	39,35	44,49	41,06	37,64	42,78	41,06	39,35	44,49	41,06	37,64	N/mm'	Equation 4.6
friction force in the Gina-gasket	n_G,fr	256,14	307,98	366,38	210,45	307,98	431,71	225,43	271,06	322,45	185,22	271,06	379,95	218,35	262,55	312,33	179,40	262,55	368,02	N/mm'	Equation 4.5
safety factor of Requirement G2	γ_G2	5,99	7,50	9,31	4,73	7,50	11,47	5,27	6,60	8,19	4,16	6,60	10,09	5,10	6,39	7,94	4,03	6,39	9,78	(-)	Equation 4.7
Req. G2: Force equilibrium (floor)																					
total force working on the Gina-seal	n_total	29,11	27,95	26,78	30,28	27,95	25,62	29,11	27,95	26,78	30,28	27,95	25,62	29,11	27,95	26,78	30,28	27,95	25,62	N/mm'	Equation 4.6
friction force in the Gina-gasket	n_G,fr	256,14	307,98	366,38	210,45	307,98	431,71	225,43	271,06	322,45	185,22	271,06	379,95	218,35	262,55	312,33	179,40	262,55	368,02	N/mm'	Equation 4.5
safety factor of Requirement G2	γ_G2	8,80	11,02	13,68	6,95	11,02	16,85	7,74	9,70	12,04	6,12	9,70	14,83	7,50	9,39	11,66	5,93	9,39	14,37	(-)	Equation 4.7
Req. G3: Contact between Gina-gasket and opposite tunnel element (wall)																					
differential movement of the immersion joint in y-direction	Δy	0	0	0	20	20	20	0	0	0	20	20	20	0	0	0	20	20	20	mm	explained in Section 3.4.1
distance between Gina-gasket and outside tunnel	s_mo1,wall	134	134	134	134	134	134	134	134	134	134	134	134	134	134	134	134	134	134	mm	explained in Section 3.3.2
check	(-)	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	(-)	Equation 4.8
Req. G3: Contact between Gina-gasket and opposite tunnel element (floor)																					
differential movement of the immersion joint in z-direction	Δz	50	50	50	70	70	70	55	55	55	80	80	80	60	60	60	90	90	90	mm	explained in Section 3.4.1
distance between Gina-gasket and outside tunnel	s_mo1,roof	135	135	135	135	135	135	135	135	135	135	135	135	135	135	135	135	135	135	mm	explained in Section 3.3.2
check	(-)	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	(-)	Equation 4.9
Req. G4: Cracks in the Gina-gasket																					
compression of the Gina-gasket	c_G	80	85	90	75	85	95	80	85	90	75	85	95	80	85	90	75	85	95	mm	Equation 4.11
original (uncompressed) height of the Gina-gasket	h_G	205	205	205	205	205	205	205	205	205	205	205	205	205	205	205	205	205	205	mm	explained in Section 3.3.3
check	(-)	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	(-)	Equation 4.10

D

Appendix D – Additional information Chapter 5

In this appendix, the additional information from Chapter 5 is presented.

D.1. Extra explanation equations

In this paragraph, further explanation on some terms that are used in the calculations on the Omega-seal is presented.

The central line of the curved part of the Omega-seal is important for the calculations. The initial radius, following the central line, can be calculated with Equation D.1.

$$R_0 = R_{Omega} + 0.5 \times t_{Omega} \tag{D.1}$$

With:
R_0 = initial radius Omega-gasket [mm]
R_{Omega} = initial inner radius Omega-gasket [mm]
t_{Omega} = thickness curved part Omega-gasket [mm]

Then, it is possible to calculate the length of the curved part of the Omega-gasket. This is needed for Requirement O3. This is calculated with Equation D.2.

$$s_{cp} = \pi \times R_0 \tag{D.2}$$

With:
s_{cp} = length curved part Omega-gasket [mm]
R_0 = initial radius Omega-gasket [mm]

The initial distance between point A and B is important for some calculations on the geometry of the Omega-gasket during use. This can be calculated with Equation D.3.

$$l_{c,0} = 2 \times R_0 \tag{D.3}$$

With:
$l_{c,0}$ = initial distance between point A and B [mm]
R_0 = initial radius Omega-gasket [mm]

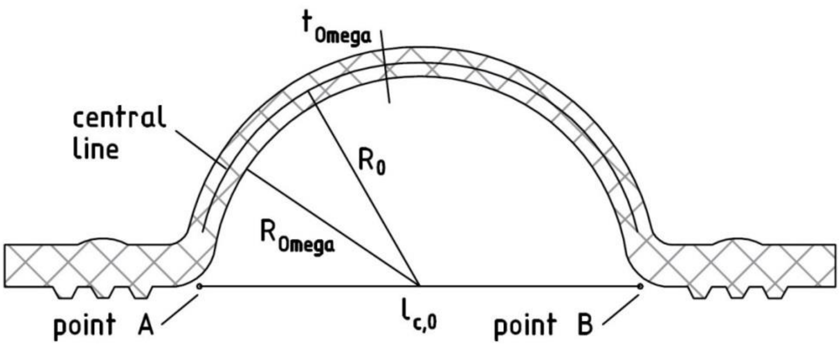

Figure 86: Overview of the dimensions of the Omega-gasket

The value of R (radius in curved part Omega-gasket after displacement) needs to be determined by an iteration. The value of R is filled in in Equation D.4 and D.5, and the result of this calculation should be the same. The check, whether these values are the same, is performed in Equation D.6.

$$l_{c,1} = \sqrt{(l_{c,0} + \Delta x)^2 + (\Delta z)^2} \tag{D.4}$$

$$l_{c,2} = 2 \times R \times \sin\left(\frac{s_{cp}}{2 \times R}\right) \tag{D.5}$$

$$\Delta l_c = l_{c,1} - l_{c,2} \tag{D.6}$$

With:

$l_{c,1}$ = absolute distance between point A and point B (by calculation method 1) [mm]
$l_{c,0}$ = initial distance between point A and B [mm]
Δx = maximum difference between winter and summer of the immersion joint in longitudinal direction [mm]
Δz = differential movement of the immersion joint in z-direction [mm]
$l_{c,2}$ = absolute distance between point A and point B (by calculation method 2) [mm]
R = radius in curved part Omega-gasket after displacement [mm]
s_{cp} = length curved part Omega-gasket [mm]

When the radius and the coordinates of point A and B are known, it is possible to determine the angle under which the force in the curved part of the Omega-gasket works. This is done with Equation D.7 and D.8.

$$\varphi_1 = \arcsin\left(\frac{l_{c,1}}{2 \times R}\right) - \arcsin\left(\frac{\Delta z}{l_{c,1}}\right) \tag{D.7}$$

$$\varphi_2 = \arcsin\left(\frac{l_{c,1}}{2 \times R}\right) + \arcsin\left(\frac{\Delta z}{l_{c,1}}\right) \tag{D.8}$$

φ_1 = angle in point A [radians]
$l_{c,1}$ = absolute distance between point A and point B (by calculation method 1) [mm]
R = radius in curved part Omega-gasket after displacement [mm]
Δz = differential movement of the immersion joint in z-direction [mm]
φ_2 = angle in point B [radians]

In Equation D.9, it is explained which values are used to calculate the required amount of surface in the bolt.

$$A_{T,req} \geq \frac{F_B + F_{Kl}}{\frac{R_{p0,2}}{k \times k_A} - \beta \times E \times \frac{f_z}{l_k}} \tag{D.9}$$

With:

$A_{T,req}$ = surface bolt required [mm^2]
F_B = axial load [kN]
F_{Kl} = required clamping force [kN]
$R_{p0,2}$ = 0,2% strain of the material according to Table 8-4 [-]
E = E-modulus of the material [N/mm^2]
f_z = settlement, mean value: 0.011 mm [mm]
k_A = tightening factor, dependent of tightening method [-]
β = deformability [-]
k = reduction factor, dependent of μ_G and the type of screw [-]

D.2. Potential locations for corrosion

In Section 5.3.1, it is shown where the corrosion may lead to problems in the clamping structure. However, this is said after an analysis of all possible locations. In this paragraph, it is shown where all possible locations are.

An overview of the possible locations is shown in Figure 87. There are a few locations where corrosion will not occur, since water or air is not able to access this location. This is at location 1, 2, 5, 6, 7 and 8. Besides, there are locations where the structure is wide enough, so that will always have enough capacity. This is at location 3 and 9.

The location where corrosion is most dangerous is at location 4. Therefore, this location will be further focussed on in the calculations.

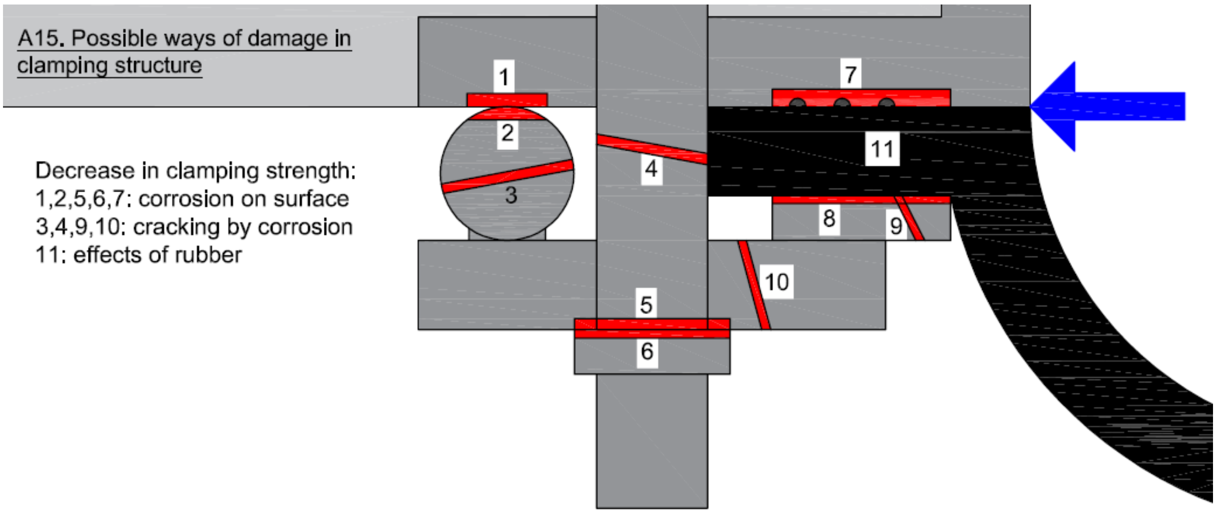

Figure 87: Overview of all potential locations of corrosion in the clamping structure of the Omega-seal

D.3. Force-compression curve Omega-gaskets

In this paragraph, the formulas for the force compression curves are calculated. These values are needed for the calculation as described in Section 5.4.2.

In Figure 88, an example of the force-compression curve is shown. From this, the values are written down and inserted in Excel. It contains an error. The unity of the force is presented in t/m^2. This should be t/m' and stands for ton per running meter. This has to be transferred into the unity N/mm'.

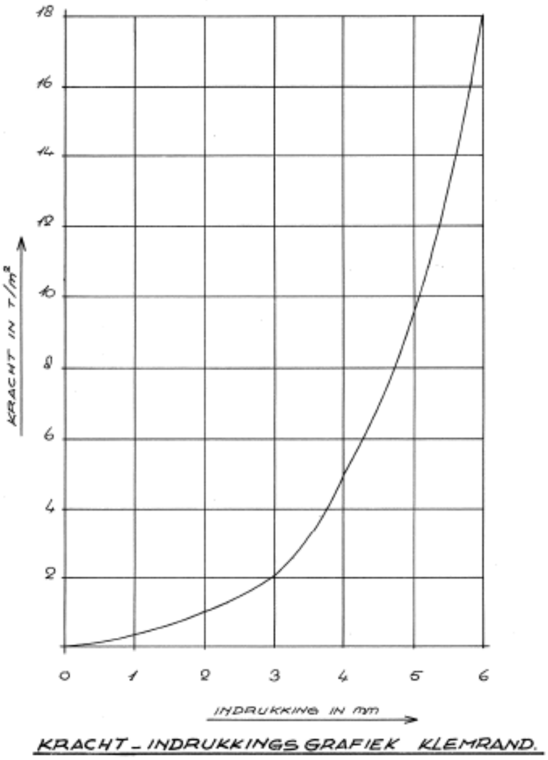

Figure 88: Force-compression curves for the two Gina-gaskets

Then, an Excel function creates a polynomial that resembles the original function. The formula of this line is presented in Figure 89.

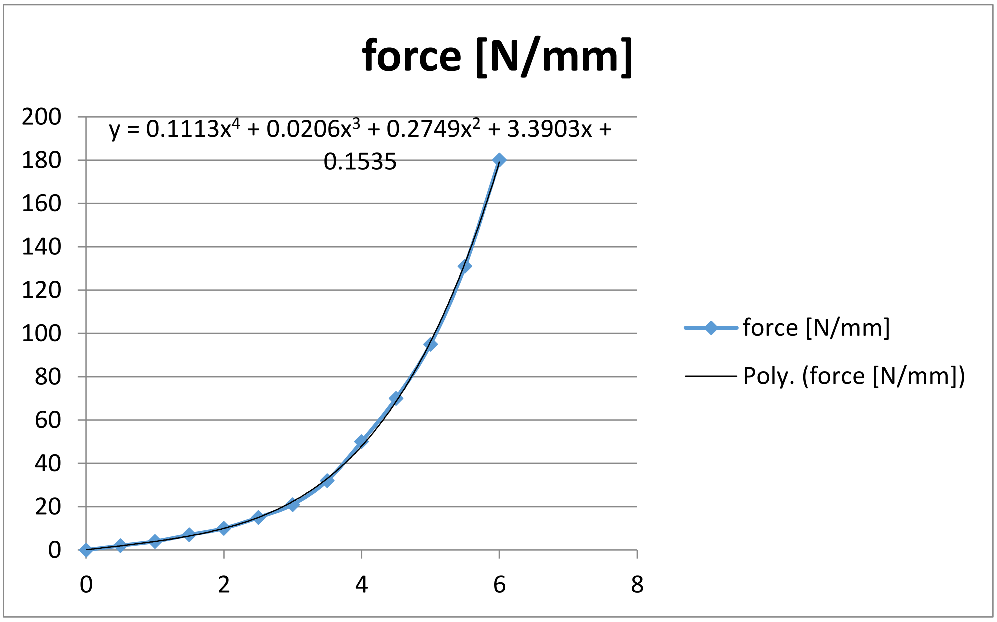

Figure 89: Curves created by Excel

With Excel the equations are determined. These are shown in Equation D.10.

$$n_{rf,in} = 0.1113 \times c_O{}^4 + 0.0206 \times c_O{}^3 + 0.2749 \times c_O{}^2 + 3.3903 \times c_O + 0.1535 \tag{D.10}$$

With:

$n_{rf,in}$ initial reaction force of the flange [N/mm']

c_O compression of flange Omega-gasket [mm]

D.4. Determination of force in the bolt during installation

In Section 5.4.2, a calculation of the bolt during installation is made. In this section, the entire calculation is shown.

Three procedures are calculated:

A. First time tightening – In this procedure, the bolts are tightened only once, until they reach a compression of 6 mm.
B. Second time tightening until c_O = 6 mm – In this procedure, the bolts are first tightened until c_O is smaller than 6 mm. The second time, they are tightened until 6 mm. Four scenarios are calculated: the second time tightening is 2 (minimum) and 7 (maximum) days after the first tightening, and the relaxation of the Omega-gasket is 5% per decade and 6% per decade.
C. Second time tightening until F_b = 65.0 kN – In this procedure, the bolts are first tightened to 6 mm. The second time, they are tightened to F_b = 65.0 kN. Then, the compression becomes larger than 6 mm.

TABLE 31: Determination of force in the bolt during installation

Description	Symbol	procedure A: first time tightening	procedure B: second time tightening until c_O = 6 mm				procedure C: second time tightening until F_b = 65.0 kN				Unity	Explanation
		joint 1A / 2E										
values per load situation												
relaxation per decade	r_Omega	n/a	5	5	6	6	5	5	6	6	%	range between 5 and 6 %
time between first and second tightening	t	0	2	7	2	7	2	7	2	7	days	range between 2 days and 7 days
compression of flange Omega-gasket left	c_O	6	6	6	6	6	6,33	6,39	6,405	6,48	mm	
geometry												
diameter stud	d	24	24	24	24	24	24	24	24	24	mm	
distance between bolt and steel bar	s_bsb	65	65	65	65	65	65	65	65	65	mm	
distance between bolt and outside flange Omega-gasket	s_bof	9,5	9,5	9,5	9,5	9,5	9,5	9,5	9,5	9,5	mm	
distance between outside and middle flange Omega-gasket	s_omf	31,5	31,5	31,5	31,5	31,5	31,5	31,5	31,5	31,5	mm	
centre-to-centre distance bolts	s_ctc	200	200	200	200	200	200	200	200	200	mm	
calculations												
<u>clamping forces flange Omega-gasket</u>												
resting force after time t relative to initial situation	σ(t)/σ(t=0)	100,0	82,7	80,0	79,2	76,0	82,7	80,0	79,2	76,0	%	5.36
clamping force, left (accounted for relaxation)	n_rf,pr	179,1	148,1	143,2	141,9	136,1	179,1	179,1	179,0	178,9	N/mm	from force-compression curve, depends of c_O
<u>forces in bolt</u>												
clamping force present, left, per bolt	F_rf,pr	35,8	29,6	28,6	28,4	27,2	35,8	35,8	35,8	35,8	kN	5.29
clamping force that should be provided by the bolt	F_b	**65,0**	**53,8**	**52,0**	**51,5**	**49,4**	**65,0**	**65,0**	**65,0**	**65,0**	kN	moment equilibrium
		joint 3A										
values per load situation												
relaxation per decade	r_Omega	n/a	5	5	6	6	5	5	6	6	%	range between 5 and 6 %
time between first and second tightening	t	0	2	7	2	7	2	7	2	7	days	range between 2 days and 7 days
compression of flange Omega-gasket left	c_O	6	6,33	6,388	6,395	6,48	6	6	6	6	mm	
geometry												
diameter stud	d	24	24	24	24	24	24	24	24	24	mm	
distance between bolt and steel bar	s_bsb	65	65	65	65	65	65	65	65	65	mm	
distance between bolt and outside flange Omega-gasket	s_bof	19,5	19,5	19,5	19,5	19,5	19,5	19,5	19,5	19,5	mm	
distance between outside and middle flange Omega-gasket	s_omf	31,5	31,5	31,5	31,5	31,5	31,5	31,5	31,5	31,5	mm	
centre-to-centre distance bolts	s_ctc	200	200	200	201	200	200,5	200,6	200,7	200,8	mm	
calculations												
<u>clamping forces flange Omega-gasket</u>												
resting force after time t relative to initial situation	σ(t)/σ(t=0)	100,0	82,7	80,0	79,2	76,0	82,7	80,0	79,2	76,0	%	5.36
clamping force, left (accounted for relaxation)	n_rf,pr	179,1	179,1	178,9	178,0	178,9	148,1	143,2	141,9	136,1	N/mm	from force-compression curve, depends of c_O
<u>forces in bolt</u>												
clamping force present, left, per bolt	F_rf,pr	35,8	35,8	35,8	35,8	35,8	29,7	28,7	28,5	27,3	kN	5.29
clamping force that should be provided by the bolt	F_b	**70,5**	**70,5**	**70,5**	**70,5**	**70,5**	**58,5**	**56,6**	**56,1**	**53,8**	kN	moment equilibrium

D.5. Calculation watertightness

In Section 5.4.2 and 5.4.3, the results of the calculations on the watertightness are presented. These results come from several calculation sheets. In this paragraph, these sheets are presented.

The main results from these calculation sheets are the force in the bolt (F_b) and the remaining safety ($\gamma_{O1,left}$, $\gamma_{O1,right}$, $\gamma_{O2,left}$ and $\gamma_{O2,right}$). Below, in Table 32 a legend is shown.

18	value that is filled in
20	calculated value
3.01	value with a safety > 2,5
1.22	value with a safety in between 1 and 2,5
0.98	value with a safety < 1
51.2	calculated value that will be used in calculation on bolts

Table 32: Legend of Tables 33, 34, 35 and 36

The following is presented:

- Table 33: the results for joint 1A/2E of 40 years old.
- Table 34: the results for joint 1A/2E of 100 years old.
- Table 35: the results for joint 3A of 40 years old.
- Table 36: the results for joint 3A of 100 years old.

TABLE 33: Calculation watertightness (joint 1A/2E, 40 years)

Description	Symbol	Values																Unity	Explanation
Load situation	t	0,75				40													
		expected		extreme		expected						extreme							
	r_Omega	5	6	5	6	5	6	5	6	5	6	5	6	5	6	5	6	%	explained in 5.4.1
VALUES PER LOAD SITUATION																			
age of the tunnel	t	0,75	0,75	0,75	0,75	40	40	40	40	40	40	40	40	40	40	40	40	years	explained in 5.4.1
maximum difference between winter and summer in longitudinal direction	Δx	10	10	20	20	10	10	10	10	10	10	20	20	20	20	20	20	mm	explained in 3.4.1
differential movement of the immersion joint in y-direction	Δy	0	0	0	0	0	0	0	0	0	0	20	20	20	20	20	20	mm	explained in 3.4.1
differential movement of the immersion joint in z-direction	Δz	100	100	110	110	105	105	105	105	105	105	120	120	120	120	120	120	mm	explained in 3.4.1
compression of flange Omega-gasket left	c_O,left	6	6	6	6	4	4	5	5	6	6	4	4	5	5	6	6	mm	explained in 5.4.1
compression of flange Omega-gasket right	c_O,right	6	6	6	6	4	4	5	5	6	6	4	4	5	5	6	6	mm	explained in 5.4.1
CALCULATION PARAMETERS																			
density water	ρ_w	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	kN/m^3	explained in 5.4.1
friction factor	μ	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	(-)	explained in 5.4.1
GEOMETRY																			
immersed tunnel																			
height dike (relative to NAP)	s_hd	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	m + NAP	explained in 3.3.2
height governing water table below dike	s_gwt	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	m	explained in 3.3.2
deepest point joint 1A/2E (relative to NAP)	s_dp	-14,12	-14,12	-14,12	-14,12	-14,12	-14,12	-14,12	-14,12	-14,12	-14,12	-14,12	-14,12	-14,12	-14,12	-14,12	-14,12	m + NAP	explained in 3.3.2
height water column	s_wc	18,22	18,22	18,22	18,22	18,22	18,22	18,22	18,22	18,22	18,22	18,22	18,22	18,22	18,22	18,22	18,22	m	4.17
clamping structure																			
initial inner radius Omega-gasket	R_Omega	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	mm	explained in 3.3.4
thickness curved part Omega-gasket	t_Omega	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	mm	explained in 3.3.4
diameter bolt	d	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	mm	explained in 3.3.4
distance between bolt and steel bar	s_bsb	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	mm	explained in 3.3.4
distance between bolt and outside flange Omega-gasket	s_bof	9,5	9,5	9,5	9,5	9,5	9,5	9,5	9,5	9,5	9,5	9,5	9,5	9,5	9,5	9,5	9,5	mm	explained in 3.3.4
distance between outside and middle flange Omega-gasket	s_omf	31,5	31,5	31,5	31,5	31,5	31,5	31,5	31,5	31,5	31,5	31,5	31,5	31,5	31,5	31,5	31,5	mm	explained in 3.3.4
distance between bolt and outside plate	s_bop	85	85	85	85	85	85	85	85	85	85	85	85	85	85	85	85	mm	explained in 3.3.4
width clamped flange	s_ws	63,5	63,5	63,5	63,5	63,5	63,5	63,5	63,5	63,5	63,5	63,5	63,5	63,5	63,5	63,5	63,5	mm	s_ws = s_bop - s_bof - 0.5 × d
centre-to-centre distance bolts	s_ctc	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	mm	explained in 3.3.4
Omega-gasket																			
initial radius Omega-gasket	R_0	75	75	75	75	75	75	75	75	75	75	75	75	75	75	75	75	mm	D.1
length curved part Omega-gasket	s_cp	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	mm	D.2
initial distance between point A and point B	l_c,0	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150	mm	D.3
radius in curved part Omega-gasket after displacement	R	104,4	104,4	125,5	125,5	107,7	107,7	107,7	107,7	107,7	107,7	138,2	138,2	138,2	138,2	138,2	138,2	mm	iteration
CALCULATIONS																			
reaction forces flange Omega-gasket																			
initial reaction force of the flange, left	n_rf,in,l	179,1	179,1	179,1	179,1	47,9	47,9	96,1	96,1	179,1	179,1	47,9	47,9	96,1	96,1	179,1	179,1	N/mm	from force-compression curve
initial reaction force of the flange, right	n_rf,in,r	179,1	179,1	179,1	179,1	47,9	47,9	96,1	96,1	179,1	179,1	47,9	47,9	96,1	96,1	179,1	179,1	N/mm	from force-compression curve
resting force after time t relative to initial situation	σ(t) / σ(t=0)	0,72	0,66	0,72	0,66	0,63	0,56	0,63	0,56	0,63	0,56	0,63	0,56	0,63	0,56	0,63	0,56	%	5.36
reaction force of the flange, left (accounted for relaxation)	n_rf,pr,l	129,0	119,0	129,0	119,0	30,4	26,9	60,9	53,9	113,5	100,4	30,4	26,9	60,9	53,9	113,5	100,4	N/mm	5.37
reaction force of the flange, right (accounted for relaxation)	n_rf,pr,r	129,0	119,0	129,0	119,0	30,4	26,9	60,9	53,9	113,5	100,4	30,4	26,9	60,9	53,9	113,5	100,4	N/mm	5.37
forces from curved part Omega-gasket																			
absolute distance between point A and point B (by calculation method 1)	l_c,1	188,7	188,7	202,5	202,5	191,4	191,4	191,4	191,4	191,4	191,4	208,1	208,1	208,1	208,1	208,1	208,1	mm	D.4
absolute distance between point A and point B (by calculation method 2)	l_c,2	188,7	188,7	202,5	202,5	191,4	191,4	191,4	191,4	191,4	191,4	208,1	208,1	208,1	208,1	208,1	208,1	mm	D.5
check whether iteration is correct	Δl_c	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	mm	D.6
governing water pressure working on Omega-gasket	p_w	0,182	0,182	0,182	0,182	0,182	0,182	0,182	0,182	0,182	0,182	0,182	0,182	0,182	0,182	0,182	0,182	N/mm^2	5.25
force in curved part Omega-gasket	n_0	19,0	19,0	22,9	22,9	19,6	19,6	19,6	19,6	19,6	19,6	25,2	25,2	25,2	25,2	25,2	25,2	N/mm	5.24
angle in point A	φ_1	0,57	0,57	0,36	0,36	0,51	0,51	0,51	0,51	0,51	0,51	0,24	0,24	0,24	0,24	0,24	0,24	rad	D.7
force in horizontal direction (left)	n_h,l	16,0	16,0	21,4	21,4	17,1	17,1	17,1	17,1	17,1	17,1	24,5	24,5	24,5	24,5	24,5	24,5	N/mm	5.26
force in vertical direction (left)	n_v,l	10,3	10,3	8,2	8,2	9,6	9,6	9,6	9,6	9,6	9,6	5,9	5,9	5,9	5,9	5,9	5,9	N/mm	5.27
angle in point B	φ_2	1,69	1,69	1,51	1,51	1,67	1,67	1,67	1,67	1,67	1,67	1,47	1,47	1,47	1,47	1,47	1,47	rad	D.8
force in horizontal direction (right)	n_h,r	-2,2	-2,2	1,3	1,3	-2,0	-2,0	-2,0	-2,0	-2,0	-2,0	2,6	2,6	2,6	2,6	2,6	2,6	N/mm	5.26
force in vertical direction (right)	n_v,r	18,9	18,9	22,8	22,8	19,5	19,5	19,5	19,5	19,5	19,5	25,0	25,0	25,0	25,0	25,0	25,0	N/mm	5.27
forces in bolt																			
reaction force present, left, per bolt	F_rf,pr,l	25,8	23,8	25,8	23,8	6,1	5,4	12,2	10,8	22,7	20,1	6,1	5,4	12,2	10,8	22,7	20,1	kN	5.29
vertical force Omega-gasket left, per bolt	F_v,l	2,1	2,1	1,6	1,6	1,9	1,9	1,9	1,9	1,9	1,9	1,2	1,2	1,2	1,2	1,2	1,2	kN	5.30
clamping force that should be provided by the bolt	F_b,l	**51,6**	**47,9**	**50,6**	**47,0**	**15,5**	**14,2**	**26,6**	**24,0**	**45,7**	**40,9**	**13,8**	**12,5**	**24,9**	**22,3**	**44,0**	**39,2**	kN	5.28
reaction force present, right, per bolt	F_rf,pr,r	25,8	23,8	25,8	23,8	6,1	5,4	12,2	10,8	22,7	20,1	6,1	5,4	12,2	10,8	22,7	20,1	kN	5.29
vertical force Omega-gasket right, per bolt	F_v,r	3,8	3,8	4,6	4,6	3,9	3,9	3,9	3,9	3,9	3,9	5,0	5,0	5,0	5,0	5,0	5,0	kN	5.30
clamping force that should be provided by the bolt	F_b,r	**55,5**	**51,9**	**57,4**	**53,7**	**20,0**	**18,8**	**31,1**	**28,6**	**50,2**	**45,5**	**22,6**	**21,3**	**33,7**	**31,1**	**52,8**	**48,0**	kN	5.28
REQUIREMENTS																			
O1: Enough pressure to stop water																			
resistance pressure of the Omega-gasket (left)	p_Omega,l	2,03	1,87	2,03	1,87	0,48	0,42	0,96	0,85	1,79	1,58	0,48	0,42	0,96	0,85	1,79	1,58	N/mm^2	5.3
pressure required to stop water (left)	p_ws,l	0,46	0,46	0,46	0,46	0,46	0,46	0,46	0,46	0,46	0,46	0,46	0,46	0,46	0,46	0,46	0,46	N/mm^2	5.2
safety check 1 left side	γ_O1,left	4,46	4,11	4,46	4,11	1,05	0,93	2,11	1,86	3,92	3,47	1,05	0,93	2,11	1,86	3,92	3,47	(-)	5.5
resistance pressure of the Omega-gasket (right)	p_Omega,r	2,03	1,87	2,03	1,87	0,48	0,42	0,96	0,85	1,79	1,58	0,48	0,42	0,96	0,85	1,79	1,58	N/mm^2	5.3
pressure required to stop water (right)	p_ws,r	0,46	0,46	0,46	0,46	0,46	0,46	0,46	0,46	0,46	0,46	0,46	0,46	0,46	0,46	0,46	0,46	N/mm^2	5.2
safety check 1 right side	γ_O1,right	4,46	4,11	4,46	4,11	1,05	0,93	2,11	1,86	3,92	3,47	1,05	0,93	2,11	1,86	3,92	3,47	(-)	5.5
O2: Prevention of pulling out flange Omega-gasket																			
reaction force of the flange, left (accounted for relaxation)	n_f,l	38,7	35,7	38,7	35,7	9,1	8,1	18,3	16,2	34,1	30,1	9,1	8,1	18,3	16,2	34,1	30,1	N/mm'	5.7
required reaction force (left)	n_v,l	16,0	16,0	21,4	21,4	17,1	17,1	17,1	17,1	17,1	17,1	24,5	24,5	24,5	24,5	24,5	24,5	N/mm'	5.27
safety check 2 left side	γ_O2,left	4,83	4,46	3,62	3,34	1,07	0,94	2,14	1,89	3,98	3,52	0,75	0,66	1,49	1,32	2,78	2,46	(-)	5.5
reaction force of the flange, right (accounted for relaxation)	n_f,r	38,7	35,7	38,7	35,7	9,1	8,1	18,3	16,2	34,1	30,1	9,1	8,1	18,3	16,2	34,1	30,1	N/mm'	5.7
required reaction force (right)	n_v,r	-2,2	-2,2	1,3	1,3	-2,0	-2,0	-2,0	-2,0	-2,0	-2,0	2,6	2,6	2,6	2,6	2,6	2,6	N/mm'	5.27
safety check 2 right side	γ_O2,right	>10	>10	>10	>10	8,98	7,94	>10	>10	>10	>10	7,02	6,21	>10	>10	>10	>10	(-)	5.5
O3: Crack in the Omega-gasket																			
length curved part Omega-gasket	s_cp	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	mm	D.3
distance between point A and B	l_c	100,5	100,5	111,8	111,8	105,5	105,5	105,5	105,5	105,5	105,5	123,3	123,3	123,3	123,3	123,3	123,3	mm	5.10
check Requirement O3	(-)	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	(-)	5.9

TABLE 34: Calculation watertightness (joint 1A/2E, 100 years)

Description	Symbol	Values																Unity	Explanation
Load situation	t	0,75				40													
		expected		extreme		expected						extreme							
	r_Omega	5	6	5	6	5	6	5	6	5	6	5	6	5	6	5	6	%	explained in 5.4.1
VALUES PER LOAD SITUATION																			
age of the tunnel	t	0,75	0,75	0,75	0,75	100	100	100	100	100	100	100	100	100	100	100	100	years	explained in 5.4.1
maximum difference between winter and summer in longitudinal direction	Δx	10	10	20	20	10	10	10	10	10	10	20	20	20	20	20	20	mm	explained in 3.4.1
differential movement of the immersion joint in y-direction	Δy	0	0	0	0	0	0	0	0	0	0	20	20	20	20	20	20	mm	explained in 3.4.1
differential movement of the immersion joint in z-direction	Δz	100	100	110	110	110	110	110	110	110	110	130	130	130	130	130	130	mm	explained in 3.4.1
compression of flange Omega-gasket left	c_O,left	6	6	6	6	4	4	5	5	6	6	4	4	5	5	6	6	mm	explained in 5.4.1
compression of flange Omega-gasket right	c_O,right	6	6	6	6	4	4	5	5	6	6	4	4	5	5	6	6	mm	explained in 5.4.1
CALCULATION PARAMETERS																			
density water	ρ_w	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	kN/m^3	explained in 5.4.1
friction factor	μ	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	(-)	explained in 5.4.1
GEOMETRY																			
immersed tunnel																			
height dike (relative to NAP)	s_hd	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	m + NAP	explained in 3.3.2
height governing water table below dike	s_gwt	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	m	explained in 3.3.2
deepest point joint 1A/2E (relative to NAP)	s_dp	-14,12	-14,12	-14,12	-14,12	-14,12	-14,12	-14,12	-14,12	-14,12	-14,12	-14,12	-14,12	-14,12	-14,12	-14,12	-14,12	m + NAP	explained in 3.3.2
height water column	s_wc	18,22	18,22	18,22	18,22	18,22	18,22	18,22	18,22	18,22	18,22	18,22	18,22	18,22	18,22	18,22	18,22	m	4.17
clamping structure																			
initial inner radius Omega-gasket	R_Omega	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	mm	explained in 3.3.4
thickness curved part Omega-gasket	t_Omega	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	mm	explained in 3.3.4
diameter bolt	d	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	mm	explained in 3.3.4
distance between bolt and steel bar	s_bsb	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	mm	explained in 3.3.4
distance between bolt and outside flange Omega-gasket	s_bof	9,5	9,5	9,5	9,5	9,5	9,5	9,5	9,5	9,5	9,5	9,5	9,5	9,5	9,5	9,5	9,5	mm	explained in 3.3.4
distance between outside and middle flange Omega-gasket	s_omf	31,5	31,5	31,5	31,5	31,5	31,5	31,5	31,5	31,5	31,5	31,5	31,5	31,5	31,5	31,5	31,5	mm	explained in 3.3.4
distance between bolt and outside plate	s_bop	85	85	85	85	85	85	85	85	85	85	85	85	85	85	85	85	mm	explained in 3.3.4
width clamped flange	s_ws	63,5	63,5	63,5	63,5	63,5	63,5	63,5	63,5	63,5	63,5	63,5	63,5	63,5	63,5	63,5	63,5	mm	s_ws = s_bop - s_bof - 0.5 × d
centre-to-centre distance bolts	s_ctc	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	mm	explained in 3.3.4
Omega-gasket																			
initial radius Omega-gasket	R_0	75	75	75	75	75	75	75	75	75	75	75	75	75	75	75	75	mm	D.1
length curved part Omega-gasket	s_cp	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	mm	D.2
initial distance between point A and point B	l_c,0	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150	mm	D.3
radius in curved part Omega-gasket after displacement	R	104,4	104,4	125,5	125,5	111,5	111,5	111,5	111,5	111,5	111,5	156,6	156,6	156,6	156,6	156,6	156,6	mm	iteration
CALCULATIONS																			
reaction forces flange Omega-gasket																			
initial reaction force of the flange, left	n_rf,in,l	179,1	179,1	179,1	179,1	47,9	47,9	96,1	96,1	179,1	179,1	47,9	47,9	96,1	96,1	179,1	179,1	N/mm	from force-compression curve
initial reaction force of the flange, right	n_rf,in,r	179,1	179,1	179,1	179,1	47,9	47,9	96,1	96,1	179,1	179,1	47,9	47,9	96,1	96,1	179,1	179,1	N/mm	from force-compression curve
resting force after time t relative to initial situation	σ(t) / σ(t=0)	0,72	0,66	0,72	0,66	0,61	0,54	0,61	0,54	0,61	0,54	0,61	0,54	0,61	0,54	0,61	0,54	%	5.36
reaction force of the flange, left (accounted for relaxation)	n_rf,pr,l	129,0	119,0	129,0	119,0	29,4	25,7	59,0	51,6	110,0	96,1	29,4	25,7	59,0	51,6	110,0	96,1	N/mm	5.37
reaction force of the flange, right (accounted for relaxation)	n_rf,pr,r	129,0	119,0	129,0	119,0	29,4	25,7	59,0	51,6	110,0	96,1	29,4	25,7	59,0	51,6	110,0	96,1	N/mm	5.37
forces from curved part Omega-gasket																			
absolute distance between point A and point B (by calculation method 1)	l_c,1	188,7	188,7	202,5	202,5	194,2	194,2	194,2	194,2	194,2	194,2	214,0	214,0	214,0	214,0	214,0	214,0	mm	D.4
absolute distance between point A and point B (by calculation method 2)	l_c,2	188,7	188,7	202,5	202,5	194,2	194,2	194,2	194,2	194,2	194,2	214,0	214,0	214,0	214,0	214,0	214,0	mm	D.5
check whether iteration is correct	Δl_c	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	mm	D.6
governing water pressure working on Omega-gasket	p_w	0,182	0,182	0,182	0,182	0,182	0,182	0,182	0,182	0,182	0,182	0,182	0,182	0,182	0,182	0,182	0,182	N/mm^2	5.25
force in curved part Omega-gasket	n_0	19,0	19,0	22,9	22,9	20,3	20,3	20,3	20,3	20,3	20,3	28,5	28,5	28,5	28,5	28,5	28,5	N/mm	5.24
angle in point A	φ_1	0,57	0,57	0,36	0,36	0,45	0,45	0,45	0,45	0,45	0,45	0,10	0,10	0,10	0,10	0,10	0,10	rad	D.7
force in horizontal direction (left)	n_h,l	16,0	16,0	21,4	21,4	18,3	18,3	18,3	18,3	18,3	18,3	28,4	28,4	28,4	28,4	28,4	28,4	N/mm	5.26
force in vertical direction (left)	n_v,l	10,3	10,3	8,2	8,2	8,9	8,9	8,9	8,9	8,9	8,9	2,8	2,8	2,8	2,8	2,8	2,8	N/mm	5.27
angle in point B	φ_2	1,69	1,69	1,51	1,51	1,66	1,66	1,66	1,66	1,66	1,66	1,41	1,41	1,41	1,41	1,41	1,41	rad	D.8
force in horizontal direction (right)	n_h,r	-2,2	-2,2	1,3	1,3	-1,8	-1,8	-1,8	-1,8	-1,8	-1,8	4,7	4,7	4,7	4,7	4,7	4,7	N/mm	5.26
force in vertical direction (right)	n_v,r	18,9	18,9	22,8	22,8	20,2	20,2	20,2	20,2	20,2	20,2	28,1	28,1	28,1	28,1	28,1	28,1	N/mm	5.27
forces in bolt																			
reaction force present, left, per bolt	F_rf,pr,l	25,8	23,8	25,8	23,8	5,9	5,1	11,8	10,3	22,0	19,2	5,9	5,1	11,8	10,3	22,0	19,2	kN	5.29
vertical force Omega-gasket left, per bolt	F_v,l	2,1	2,1	1,6	1,6	1,8	1,8	1,8	1,8	1,8	1,8	0,6	0,6	0,6	0,6	0,6	0,6	kN	5.30
clamping force that should be provided by the bolt	F_b,l	**51,6**	**47,9**	**50,6**	**47,0**	**14,8**	**13,5**	**25,5**	**22,8**	**44,0**	**39,0**	**12,0**	**10,6**	**22,7**	**20,0**	**41,2**	**36,2**	kN	5.28
reaction force present, right, per bolt	F_rf,pr,r	25,8	23,8	25,8	23,8	5,9	5,1	11,8	10,3	22,0	19,2	5,9	5,1	11,8	10,3	22,0	19,2	kN	5.29
vertical force Omega-gasket right, per bolt	F_v,r	3,8	3,8	4,6	4,6	4,0	4,0	4,0	4,0	4,0	4,0	5,6	5,6	5,6	5,6	5,6	5,6	kN	5.30
clamping force that should be provided by the bolt	F_b,r	**55,5**	**51,9**	**57,4**	**53,7**	**20,0**	**18,7**	**30,8**	**28,1**	**49,3**	**44,2**	**23,7**	**22,3**	**34,4**	**31,7**	**52,9**	**47,9**	kN	5.28
REQUIREMENTS																			
O1: Enough pressure to stop water																			
resistance pressure of the Omega-gasket (left)	p_Omega,l	2,03	1,87	2,03	1,87	0,46	0,41	0,93	0,81	1,73	1,51	0,46	0,41	0,93	0,81	1,73	1,51	N/mm^2	5.3
pressure required to stop water (left)	p_ws,l	0,46	0,46	0,46	0,46	0,46	0,46	0,46	0,46	0,46	0,46	0,46	0,46	0,46	0,46	0,46	0,46	N/mm^2	5.2
safety check 1 left side	γ_O1,left	4,46	4,11	4,46	4,11	1,02	0,89	2,04	1,78	3,80	3,32	1,02	0,89	2,04	1,78	3,80	3,32	(-)	5.5
resistance pressure of the Omega-gasket (right)	p_Omega,r	2,03	1,87	2,03	1,87	0,46	0,41	0,93	0,81	1,73	1,51	0,46	0,41	0,93	0,81	1,73	1,51	N/mm^2	5.3
pressure required to stop water (right)	p_ws,r	0,46	0,46	0,46	0,46	0,46	0,46	0,46	0,46	0,46	0,46	0,46	0,46	0,46	0,46	0,46	0,46	N/mm^2	5.2
safety check 1 right side	γ_O1,right	4,46	4,11	4,46	4,11	1,02	0,89	2,04	1,78	3,80	3,32	1,02	0,89	2,04	1,78	3,80	3,32	(-)	5.5
O2: Prevention of pulling out flange Omega-gasket																			
reaction force of the flange, left (accounted for relaxation)	n_f,l	38,7	35,7	38,7	35,7	8,8	7,7	17,7	15,5	33,0	28,8	8,8	7,7	17,7	15,5	33,0	28,8	N/mm'	5.7
required reaction force (left)	n_v,l	16,0	16,0	21,4	21,4	18,3	18,3	18,3	18,3	18,3	18,3	28,4	28,4	28,4	28,4	28,4	28,4	N/mm'	5.27
safety check 2 left side	γ_O2,left	4,83	4,46	3,62	3,34	0,97	0,85	1,94	1,70	3,61	3,16	0,62	0,54	1,25	1,09	2,32	2,03	(-)	5.5
reaction force of the flange, right (accounted for relaxation)	n_f,r	38,7	35,7	38,7	35,7	8,8	7,7	17,7	15,5	33,0	28,8	8,8	7,7	17,7	15,5	33,0	28,8	N/mm'	5.7
required reaction force (right)	n_v,r	-2,2	-2,2	1,3	1,3	-1,8	-1,8	-1,8	-1,8	-1,8	-1,8	4,7	4,7	4,7	4,7	4,7	4,7	N/mm'	5.27
safety check 2 right side	γ_O2,right	>10	>10	>10	>10	9,88	8,63	>10	>10	>10	>10	3,76	3,28	7,53	6,59	14,04	12,27	(-)	5.5
O3: Crack in the Omega-gasket																			
length curved part Omega-gasket	s_cp	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	mm	D.3
distance between point A and B	l_c	100,5	100,5	111,8	111,8	110,5	110,5	110,5	110,5	110,5	110,5	133	133	133	133	133	133	mm	5.10
check Requirement O3	(-)	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	(-)	5.9

TABLE 35: Calculation watertightness (joint 3A, 40 years)

Description	Symbol	Values																Unity	Explanation
Load situation	t	0,75				40													
		expected		extreme		expected						extreme							
	r_Omega	5	6	5	6	5	6	5	6	5	6	5	6	5	6	5	6	%	explained in 5.4.1
VALUES PER LOAD SITUATION																			
age of the tunnel	t	0,75	0,75	0,75	0,75	40	40	40	40	40	40	40	40	40	40	40	40	years	explained in 5.4.1
maximum difference between winter and summer in longitudinal direction	Δx	10	10	20	20	10	10	10	10	10	10	20	20	20	20	20	20	mm	explained in 3.4.1
differential movement of the immersion joint in y-direction	Δy	0	0	0	0	0	0	0	0	0	0	20	20	20	20	20	20	mm	explained in 3.4.1
differential movement of the immersion joint in z-direction	Δz	50	50	70	70	55	55	55	55	55	55	80	80	80	80	80	80	mm	explained in 3.4.1
compression of flange Omega-gasket left	c_O,left	6	6	6	6	4	4	5	5	6	6	4	4	5	5	6	6	mm	explained in 5.4.1
compression of flange Omega-gasket right	c_O,right	6	6	6	6	4	4	5	5	6	6	4	4	5	5	6	6	mm	explained in 5.4.1
CALCULATION PARAMETERS																			
density water	ρ_w	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	kN/m^3	explained in 5.4.1
friction factor	μ	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	(-)	explained in 5.4.1
GEOMETRY																			
immersed tunnel																			
height dike (relative to NAP)	s_hd	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	m + NAP	explained in 3.3.2
height governing water table below dike	s_gwt	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	m	explained in 3.3.2
deepest point joint 1A/2E (relative to NAP)	s_dp	-19,2	-19,19	-19,19	-19,19	-19,19	-19,19	-19,19	-19,19	-19,19	-19,19	-19,19	-19,19	-19,19	-19,19	-19,19	-19,19	m + NAP	explained in 3.3.2
height water column	s_wc	23,29	23,29	23,29	23,29	23,29	23,29	23,29	23,29	23,29	23,29	23,29	23,29	23,29	23,29	23,29	23,29	m	4.17
clamping structure																			
initial inner radius Omega-gasket	R_Omega	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	mm	explained in 3.3.4
thickness curved part Omega-gasket	t_Omega	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	mm	explained in 3.3.4
diameter bolt	d	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	mm	explained in 3.3.4
distance between bolt and steel bar	s_bsb	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	mm	explained in 3.3.4
distance between bolt and outside flange Omega-gasket	s_bof	19,5	19,5	19,5	19,5	19,5	19,5	19,5	19,5	19,5	19,5	19,5	19,5	19,5	19,5	19,5	19,5	mm	explained in 3.3.4
distance between outside and middle flange Omega-gasket	s_omf	31,5	31,5	31,5	31,5	31,5	31,5	31,5	31,5	31,5	31,5	31,5	31,5	31,5	31,5	31,5	31,5	mm	explained in 3.3.4
distance between bolt and outside plate	s_bop	85	85	85	85	85	85	85	85	85	85	85	85	85	85	85	85	mm	explained in 3.3.4
width clamped flange	s_ws	53,5	53,5	53,5	53,5	53,5	53,5	53,5	53,5	53,5	53,5	53,5	53,5	53,5	53,5	53,5	53,5	mm	s_ws = s_bop - s_bof - 0.5 × d
centre-to-centre distance bolts	s_ctc	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	mm	explained in 3.3.4
Omega-gasket																			
initial radius Omega-gasket	R_0	75	75	75	75	75	75	75	75	75	75	75	75	75	75	75	75	mm	D.1
length curved part Omega-gasket	s_cp	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	mm	D.2
initial distance between point A and point B	l_c,0	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150	mm	D.3
radius in curved part Omega-gasket after displacement	R	85,36	85,36	99,03	99,03	86,46	86,46	86,46	86,46	86,46	86,46	103,4	103,4	103,4	103,4	103,4	103,4	mm	iteration
CALCULATIONS																			
reaction forces flange Omega-gasket																			
initial reaction force of the flange, left	n_rf,in,l	179,1	179,1	179,1	179,1	47,9	47,9	96,1	96,1	179,1	179,1	47,9	47,9	96,1	96,1	179,1	179,1	N/mm	from force-compression curve
initial reaction force of the flange, right	n_rf,in,r	179,1	179,1	179,1	179,1	47,9	47,9	96,1	96,1	179,1	179,1	47,9	47,9	96,1	96,1	179,1	179,1	N/mm	from force-compression curve
resting force after time t relative to initial situation	σ(t) / σ(t=0)	0,72	0,66	0,72	0,66	0,63	0,56	0,63	0,56	0,63	0,56	0,63	0,56	0,63	0,56	0,63	0,56	%	5.36
reaction force of the flange, left (accounted for relaxation)	n_rf,pr,l	129,0	119,0	129,0	119,0	30,4	26,9	60,9	53,9	113,5	100,4	30,4	26,9	60,9	53,9	113,5	100,4	N/mm	5.37
reaction force of the flange, right (accounted for relaxation)	n_rf,pr,r	129,0	119,0	129,0	119,0	30,4	26,9	60,9	53,9	113,5	100,4	30,4	26,9	60,9	53,9	113,5	100,4	N/mm	5.37
forces from curved part Omega-gasket																			
absolute distance between point A and point B (by calculation method 1)	l_c,1	167,6	167,6	183,8	183,8	169,2	169,2	169,2	169,2	169,2	169,2	187,9	187,9	187,9	187,9	187,9	187,9	mm	D.4
absolute distance between point A and point B (by calculation method 2)	l_c,2	167,6	167,6	183,8	183,8	169,2	169,2	169,2	169,2	169,2	169,2	187,9	187,9	187,9	187,9	187,9	187,9	mm	D.5
check whether iteration is correct	Δl_c	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	mm	D.6
governing water pressure working on Omega-gasket	p_w	0,233	0,233	0,233	0,233	0,233	0,233	0,233	0,233	0,233	0,233	0,233	0,233	0,233	0,233	0,233	0,233	N/mm^2	5.25
force in curved part Omega-gasket	n_0	19,9	19,9	23,1	23,1	20,1	20,1	20,1	20,1	20,1	20,1	24,1	24,1	24,1	24,1	24,1	24,1	N/mm	5.24
angle in point A	φ_1	1,08	1,08	0,80	0,80	1,03	1,03	1,03	1,03	1,03	1,03	0,70	0,70	0,70	0,70	0,70	0,70	rad	D.7
force in horizontal direction (left)	n_h,l	9,4	9,4	16,1	16,1	10,3	10,3	10,3	10,3	10,3	10,3	18,4	18,4	18,4	18,4	18,4	18,4	N/mm	5.26
force in vertical direction (left)	n_v,l	17,5	17,5	16,5	16,5	17,3	17,3	17,3	17,3	17,3	17,3	15,5	15,5	15,5	15,5	15,5	15,5	N/mm	5.27
angle in point B	φ_2	1,68	1,68	1,58	1,58	1,69	1,69	1,69	1,69	1,69	1,69	1,58	1,58	1,58	1,58	1,58	1,58	rad	D.8
force in horizontal direction (right)	n_h,r	-2,2	-2,2	-0,2	-0,2	-2,5	-2,5	-2,5	-2,5	-2,5	-2,5	-0,2	-0,2	-0,2	-0,2	-0,2	-0,2	N/mm	5.26
force in vertical direction (right)	n_v,r	19,8	19,8	23,1	23,1	20,0	20,0	20,0	20,0	20,0	20,0	24,1	24,1	24,1	24,1	24,1	24,1	N/mm	5.27
forces in bolt																			
reaction force present, left, per bolt	F_rf,pr,l	25,8	23,8	25,8	23,8	6,1	5,4	12,2	10,8	22,7	20,1	6,1	5,4	12,2	10,8	22,7	20,1	kN	5.29
vertical force Omega-gasket left, per bolt	F_v,l	3,5	3,5	3,3	3,3	3,5	3,5	3,5	3,5	3,5	3,5	3,1	3,1	3,1	3,1	3,1	3,1	kN	5.30
clamping force that should be provided by the bolt	F_b,l	**58,9**	**54,9**	**58,4**	**54,5**	**19,9**	**18,6**	**32,0**	**29,2**	**52,7**	**47,5**	**19,1**	**17,7**	**31,1**	**28,4**	**51,9**	**46,7**	kN	5.28
reaction force present, right, per bolt	F_rf,pr,r	25,8	23,8	25,8	23,8	6,1	5,4	12,2	10,8	22,7	20,1	6,1	5,4	12,2	10,8	22,7	20,1	kN	5.29
vertical force Omega-gasket right, per bolt	F_v,r	4,0	4,0	4,6	4,6	4,0	4,0	4,0	4,0	4,0	4,0	4,8	4,8	4,8	4,8	4,8	4,8	kN	5.30
clamping force that should be provided by the bolt	F_b,r	**59,9**	**56,0**	**61,4**	**57,5**	**21,2**	**19,8**	**33,2**	**30,4**	**53,9**	**48,8**	**23,1**	**21,7**	**35,1**	**32,3**	**55,8**	**50,7**	kN	5.28
REQUIREMENTS																			
O1: Enough pressure to stop water																			
resistance pressure of the Omega-gasket (left)	p_Omega,l	2,41	2,22	2,41	2,22	0,57	0,50	1,14	1,01	2,12	1,88	0,57	0,50	1,14	1,01	2,12	1,88	N/mm^2	5.3
pressure required to stop water (left)	p_ws,l	0,58	0,58	0,58	0,58	0,58	0,58	0,58	0,58	0,58	0,58	0,58	0,58	0,58	0,58	0,58	0,58	N/mm^2	5.2
safety check 1 left side	γ_O1,left	4,14	3,82	4,14	3,82	0,98	0,86	1,96	1,73	3,64	3,22	0,98	0,86	1,96	1,73	3,64	3,22	(-)	5.5
resistance pressure of the Omega-gasket (right)	p_Omega,r	2,41	2,22	2,41	2,22	0,57	0,50	1,14	1,01	2,12	1,88	0,57	0,50	1,14	1,01	2,12	1,88	N/mm^2	5.3
pressure required to stop water (right)	p_ws,r	0,58	0,58	0,58	0,58	0,58	0,58	0,58	0,58	0,58	0,58	0,58	0,58	0,58	0,58	0,58	0,58	N/mm^2	5.2
safety check 1 right side	γ_O1,right	4,14	3,82	4,14	3,82	0,98	0,86	1,96	1,73	3,64	3,22	0,98	0,86	1,96	1,73	3,64	3,22	(-)	5.5
O2: Prevention of pulling out flange Omega-gasket																			
reaction force of the flange, left (accounted for relaxation)	n_f,l	38,7	35,7	38,7	35,7	9,1	8,1	18,3	16,2	34,1	30,1	9,1	8,1	18,3	16,2	34,1	30,1	N/mm'	5.7
required reaction force (left)	n_v,l	9,4	9,4	16,1	16,1	10,3	10,3	10,3	10,3	10,3	10,3	18,4	18,4	18,4	18,4	18,4	18,4	N/mm'	5.27
safety check 2 left side	γ_O2,left	8,22	7,58	4,81	4,44	1,76	1,56	3,54	3,13	6,59	5,83	0,99	0,87	1,98	1,75	3,69	3,27	(-)	5.5
reaction force of the flange, right (accounted for relaxation)	n_f,r	38,7	35,7	38,7	35,7	9,1	8,1	18,3	16,2	34,1	30,1	9,1	8,1	18,3	16,2	34,1	30,1	N/mm'	5.7
required reaction force (right)	n_v,r	-2,2	-2,2	-0,2	-0,2	-2,5	-2,5	-2,5	-2,5	-2,5	-2,5	-0,2	-0,2	-0,2	-0,2	-0,2	-0,2	N/mm'	5.27
safety check 2 right side	γ_O2,right	>10	>10	>10	>10	7,38	6,53	>10	>10	>10	>10	>10	>10	>10	>10	>10	>10	(-)	5.5
O3: Crack in the Omega-gasket																			
length curved part Omega-gasket	s_cp	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	mm	D.3
distance between point A and point B	l_c	50,99	50,99	72,8	72,8	55,9	55,9	55,9	55,9	55,9	55,9	84,85	84,85	84,85	84,85	84,85	84,85	mm	5.10
check Requirement O3	(-)	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	(-)	5.9

TABLE 36: Calculation watertightness (joint 3A, 100 years)

Description	Symbol	Values																Unity	Explanation
Load situation	t	0,75				40													
		expected		extreme		expected						extreme							
	r_Omega	5	6	5	6	5	6	5	6	5	6	5	6	5	6	5	6	%	explained in 5.4.1
VALUES PER LOAD SITUATION																			
age of the tunnel	t	0,75	0,75	0,75	0,75	100	100	100	100	100	100	100	100	100	100	100	100	years	explained in 5.4.1
maximum difference between winter and summer in longitudinal direction	Δx	10	10	20	20	10	10	10	10	10	10	20	20	20	20	20	20	mm	explained in 3.4.1
differential movement of the immersion joint in y-direction	Δy	0	0	0	0	0	0	0	0	0	0	20	20	20	20	20	20	mm	explained in 3.4.1
differential movement of the immersion joint in z-direction	Δz	50	50	70	70	60	60	60	60	60	60	90	90	90	90	90	90	mm	explained in 3.4.1
compression of flange Omega-gasket left	c_O,left	6	6	6	6	4	4	5	5	6	6	4	4	5	5	6	6	mm	explained in 5.4.1
compression of flange Omega-gasket right	c_O,right	6	6	6	6	4	4	5	5	6	6	4	4	5	5	6	6	mm	explained in 5.4.1
CALCULATION PARAMETERS																			
density water	ρ_w	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	kN/m^3	explained in 5.4.1
friction factor	μ	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	(-)	explained in 5.4.1
GEOMETRY																			
immersed tunnel																			
height dike (relative to NAP)	s_hd	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	m + NAP	explained in 3.3.2
height governing water table below dike	s_gwt	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	m	explained in 3.3.2
deepest point joint 1A/2E (relative to NAP)	s_dp	-19,2	-19,19	-19,19	-19,19	-19,19	-19,19	-19,19	-19,19	-19,19	-19,19	-19,19	-19,19	-19,19	-19,19	-19,19	-19,19	m + NAP	explained in 3.3.2
height water column	s_wc	23,29	23,29	23,29	23,29	23,29	23,29	23,29	23,29	23,29	23,29	23,29	23,29	23,29	23,29	23,29	23,29	m	4.17
clamping structure																			
initial inner radius Omega-gasket	R_Omega	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	mm	explained in 3.3.4
thickness curved part Omega-gasket	t_Omega	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	mm	explained in 3.3.4
diameter bolt	d	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	mm	explained in 3.3.4
distance between bolt and steel bar	s_bsb	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	mm	explained in 3.3.4
distance between bolt and outside flange Omega-gasket	s_bof	19,5	19,5	19,5	19,5	19,5	19,5	19,5	19,5	19,5	19,5	19,5	19,5	19,5	19,5	19,5	19,5	mm	explained in 3.3.4
distance between outside and middle flange Omega-gasket	s_omf	31,5	31,5	31,5	31,5	31,5	31,5	31,5	31,5	31,5	31,5	31,5	31,5	31,5	31,5	31,5	31,5	mm	explained in 3.3.4
distance between bolt and outside plate	s_bop	85	85	85	85	85	85	85	85	85	85	85	85	85	85	85	85	mm	explained in 3.3.4
width clamped flange	s_ws	53,5	53,5	53,5	53,5	53,5	53,5	53,5	53,5	53,5	53,5	53,5	53,5	53,5	53,5	53,5	53,5	mm	s_ws = s_bop - s_bof - 0.5 × d
centre-to-centre distance bolts	s_ctc	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	mm	explained in 3.3.4
Omega-gasket																			
initial radius Omega-gasket	R_0	75	75	75	75	75	75	75	75	75	75	75	75	75	75	75	75	mm	D.1
length curved part Omega-gasket	s_cp	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	mm	D.2
initial distance between point A and point B	l_c,0	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150	mm	D.3
radius in curved part Omega-gasket after displacement	R	85,36	85,36	99,03	99,03	87,7	87,7	87,7	87,7	87,7	87,7	109	109	109	109	109	109	mm	iteration
CALCULATIONS																			
reaction forces flange Omega-gasket																			
initial reaction force of the flange, left	n_rf,in,l	179,1	179,1	179,1	179,1	47,9	47,9	96,1	96,1	179,1	179,1	47,9	47,9	96,1	96,1	179,1	179,1	N/mm	from force-compression curve
initial reaction force of the flange, right	n_rf,in,r	179,1	179,1	179,1	179,1	47,9	47,9	96,1	96,1	179,1	179,1	47,9	47,9	96,1	96,1	179,1	179,1	N/mm	from force-compression curve
resting force after time t relative to initial situation	σ(t) / σ(t=0)	0,72	0,66	0,72	0,66	0,61	0,54	0,61	0,54	0,61	0,54	0,61	0,54	0,61	0,54	0,61	0,54	%	5.36
reaction force of the flange, left (accounted for relaxation)	n_rf,pr,l	129,0	119,0	129,0	119,0	29,4	25,7	59,0	51,6	110,0	96,1	29,4	25,7	59,0	51,6	110,0	96,1	N/mm	5.37
reaction force of the flange, right (accounted for relaxation)	n_rf,pr,r	129,0	119,0	129,0	119,0	29,4	25,7	59,0	51,6	110,0	96,1	29,4	25,7	59,0	51,6	110,0	96,1	N/mm	5.37
forces from curved part Omega-gasket																			
absolute distance between point A and point B (by calculation method 1)	l_c,1	167,6	167,6	183,8	183,8	170,9	170,9	170,9	170,9	170,9	170,9	192,4	192,4	192,4	192,4	192,4	192,4	mm	D.4
absolute distance between point A and point B (by calculation method 2)	l_c,2	167,6	167,6	183,8	183,8	170,9	170,9	170,9	170,9	170,9	170,9	192,4	192,4	192,4	192,4	192,4	192,4	mm	D.5
check whether iteration is correct	Δl_c	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	mm	D.6
governing water pressure working on Omega-gasket	p_w	0,233	0,233	0,233	0,233	0,233	0,233	0,233	0,233	0,233	0,233	0,233	0,233	0,233	0,233	0,233	0,233	N/mm^2	5.25
force in curved part Omega-gasket	n_0	19,9	19,9	23,1	23,1	20,4	20,4	20,4	20,4	20,4	20,4	25,4	25,4	25,4	25,4	25,4	25,4	N/mm	5.24
angle in point A	φ_1	1,08	1,08	0,80	0,80	0,98	0,98	0,98	0,98	0,98	0,98	0,59	0,59	0,59	0,59	0,59	0,59	rad	D.7
force in horizontal direction (left)	n_h,l	9,4	9,4	16,1	16,1	11,3	11,3	11,3	11,3	11,3	11,3	21,0	21,0	21,0	21,0	21,0	21,0	N/mm	5.26
force in vertical direction (left)	n_v,l	17,5	17,5	16,5	16,5	17,0	17,0	17,0	17,0	17,0	17,0	14,2	14,2	14,2	14,2	14,2	14,2	N/mm	5.27
angle in point B	φ_2	1,68	1,68	1,58	1,58	1,70	1,70	1,70	1,70	1,70	1,70	1,57	1,57	1,57	1,57	1,57	1,57	rad	D.8
force in horizontal direction (right)	n_h,r	-2,2	-2,2	-0,2	-0,2	-2,7	-2,7	-2,7	-2,7	-2,7	-2,7	0,1	0,1	0,1	0,1	0,1	0,1	N/mm	5.26
force in vertical direction (right)	n_v,r	19,8	19,8	23,1	23,1	20,2	20,2	20,2	20,2	20,2	20,2	25,4	25,4	25,4	25,4	25,4	25,4	N/mm	5.27
forces in bolt																			
reaction force present, left, per bolt	F_rf,pr,l	25,8	23,8	25,8	23,8	5,9	5,1	11,8	10,3	22,0	19,2	5,9	5,1	11,8	10,3	22,0	19,2	kN	5.29
vertical force Omega-gasket left, per bolt	F_v,l	3,5	3,5	3,3	3,3	3,4	3,4	3,4	3,4	3,4	3,4	2,8	2,8	2,8	2,8	2,8	2,8	kN	5.30
clamping force that should be provided by the bolt	F_b,l	**58,9**	**54,9**	**58,4**	**54,5**	**19,4**	**18,0**	**31,1**	**28,2**	**51,2**	**45,7**	**18,1**	**16,7**	**29,8**	**26,9**	**49,9**	**44,4**	kN	5.28
reaction force present, right, per bolt	F_rf,pr,r	25,8	23,8	25,8	23,8	5,9	5,1	11,8	10,3	22,0	19,2	5,9	5,1	11,8	10,3	22,0	19,2	kN	5.29
vertical force Omega-gasket right, per bolt	F_v,r	4,0	4,0	4,6	4,6	4,0	4,0	4,0	4,0	4,0	4,0	5,1	5,1	5,1	5,1	5,1	5,1	kN	5.30
clamping force that should be provided by the bolt	F_b,r	**59,9**	**56,0**	**61,4**	**57,5**	**20,9**	**19,5**	**32,6**	**29,7**	**52,7**	**47,2**	**23,3**	**21,8**	**35,0**	**32,0**	**55,0**	**49,6**	kN	5.28
REQUIREMENTS																			
O1: Enough pressure to stop water																			
resistance pressure of the Omega-gasket (left)	p_Omega,l	2,41	2,22	2,41	2,22	0,55	0,48	1,10	0,96	2,06	1,80	0,55	0,48	1,10	0,96	2,06	1,80	N/mm^2	5.3
pressure required to stop water (left)	p_ws,l	0,58	0,58	0,58	0,58	0,58	0,58	0,58	0,58	0,58	0,58	0,58	0,58	0,58	0,58	0,58	0,58	N/mm^2	5.2
safety check 1 left side	γ_O1,left	4,14	3,82	4,14	3,82	0,94	0,83	1,89	1,66	3,53	3,09	0,94	0,83	1,89	1,66	3,53	3,09	(-)	5.5
resistance pressure of the Omega-gasket (right)	p_Omega,r	2,41	2,22	2,41	2,22	0,55	0,48	1,10	0,96	2,06	1,80	0,55	0,48	1,10	0,96	2,06	1,80	N/mm^2	5.3
pressure required to stop water (right)	p_ws,r	0,58	0,58	0,58	0,58	0,58	0,58	0,58	0,58	0,58	0,58	0,58	0,58	0,58	0,58	0,58	0,58	N/mm^2	5.2
safety check 1 right side	γ_O1,right	4,14	3,82	4,14	3,82	0,94	0,83	1,89	1,66	3,53	3,09	0,94	0,83	1,89	1,66	3,53	3,09	(-)	5.5
O2: Prevention of pulling out flange Omega-gasket																			
reaction force of the flange, left (accounted for relaxation)	n_f,l	38,7	35,7	38,7	35,7	8,8	7,7	17,7	15,5	33,0	28,8	8,8	7,7	17,7	15,5	33,0	28,8	N/mm'	5.7
required reaction force (left)	n_v,l	9,4	9,4	16,1	16,1	11,3	11,3	11,3	11,3	11,3	11,3	21,0	21,0	21,0	21,0	21,0	21,0	N/mm'	5.27
safety check 2 left side	γ_O2,left	8,22	7,58	4,81	4,44	1,56	1,37	3,13	2,74	5,84	5,10	0,84	0,73	1,68	1,47	3,14	2,74	(-)	5.5
reaction force of the flange, right (accounted for relaxation)	n_f,r	38,7	35,7	38,7	35,7	8,8	7,7	17,7	15,5	33,0	28,8	8,8	7,7	17,7	15,5	33,0	28,8	N/mm'	5.7
required reaction force (right)	n_v,r	-2,2	-2,2	-0,2	-0,2	-2,7	-2,7	-2,7	-2,7	-2,7	-2,7	0,1	0,1	0,1	0,1	0,1	0,1	N/mm'	5.27
safety check 2 right side	γ_O2,right	>10	>10	>10	>10	6,60	5,77	>10	>10	>10	>10	>10	>10	>10	>10	>10	>10	(-)	5.5
O3: Crack in the Omega-gasket																			
length curved part Omega-gasket	s_cp	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	235,6	mm	D.3
distance between point A and B	l_c	50,99	50,99	72,8	72,8	60,83	60,83	60,83	60,83	60,83	60,83	94,34	94,34	94,34	94,34	94,34	94,34	mm	5.10
check Requirement O3	(-)	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	(-)	5.9

D.6. Calculation individual bolt

In Section 5.5.3, a summary of the calculation of the bolts is presented. The calculations on the bolts are performed in an Excel sheet. The complete sheet is presented in Table 37.

Five situations are calculated:

- Penetration depth of corrosion of 0 mm
- Penetration depth of corrosion of 1 mm
- Penetration depth of corrosion of 2 mm
- Penetration depth of corrosion of 3 mm
- Penetration depth of corrosion of 4 mm

It is assumed that the penetration depth of the bolt is the same as for the nut.

TABLE 37: Results calculation individual bolt

Description	Symbol	Clean bolt	Corroded bolt				Unity	Explanation
		0	1	2	3	4	mm	
VALUES PER LOAD SITUATION								
force in bolt	F_b	65	65	65	65	65	kN	calculated in Section D.5
penetration depth of corrosion	d_p	0	1	2	3	4	mm	this value needs to be assumed, because no data is available
tightening factor	k_A	1,2	1,2	1,2	1,2	1,2	(-)	dependent of method of spinning, according to Table 8-4
reduction factor	κ	1,4	1,4	1,4	1,4	1,4	(-)	dependent of μ_G and the type of screw
deformability of the stud	β	0,8	0,8	0,8	0,8	0,8	(-)	about 1.1 for attenuated studs; about 0.8 for full screws; about 0.6 for 'verjongde' screws
clamping capacity	F_sp	168	168	168	168	168	kN	dependent of μ,tot, from Roloff Matek Table 8-14
GEOMETRY								
strength class		8.8	8.8	8.8	8.8	8.8	(-)	from design drawing KT-227
major diameter	d	24	24	24	24	24	mm	from Roloff Matek Table 8-1
core diameter	d_3	20,319	20,319	20,319	20,319	20,319	mm	from Roloff Matek Table 8-1
clamping length	l_k	59	59	59	59	59	mm	20 mm (plate) + 14 mm (flange Omega-gasket) + 25 mm (clamping plate) = 59 mm
maximum diameter nut	d_n,max	36	36	36	36	36	mm	from design drawing KT-227
minimum diameter nut	d_n,min	24	24	24	24	24	mm	from design drawing KT-227
maximum diameter washer	d_w,max	44	44	44	44	44	mm	from design drawing KT-227
minimum diameter washer	d_w,min	26	26	26	26	26	mm	from design drawing KT-227
REQUIREMENTS								
B1. Amount of surface in the bolt								
E-modulus	E	210.000	210.000	210.000	210.000	210.000	N/mm^2	standard value for steel
0.2% yield stress of the stud	R_p0.2	640	640	640	640	640	N/mm^2	from Roloff Matek Table 8-4: class 8.8 and >M16
settlement	f_Z	0,011	0,011	0,011	0,011	0,011	mm	mean value: 0.011 mm, more significant according to Roloff Matek Table 8-10a
surface bolt required	A_T,req	186	186	186	186	186	mm^2	5.13
surface bolt present	A_T,pr	324	264	209	161	119	mm^2	5.33
safety factor of the surface in the bolt	γ_B1	1,74	1,42	1,13	0,87	0,64	(-)	5.14
B2. Clamping capacity								
prestressing force	F_VM	78	78	78	78	78	kN	5.16
clamping capacity	F_sp	168	168	168	168	168	kN	dependent of μ,tot, from Roloff Matek Table 8-14
safety factor of the clamping capacity	γ_B2	2,15	2,15	2,15	2,15	2,15	(-)	5.17
B3. Surface tension								
the surface of the nut	A_nut	565	456	352	254	163	mm^2	5.34
present surface pressure below nut	p_nut	115	143	185	255	398	N/mm^2	5.20
the surface of the washer	A_washer	990	855	726	603	487	mm^2	5.35
present surface pressure below washer	p_washer	66	76	90	108	133	N/mm^2	5.21
maximum surface pressure below nut that is al	p_G	260	260	260	260	260	N/mm^2	from Roloff Matek Table 8-10: S235
safety factor of the surface tension nut	γ_B3,nut	2,26	1,82	1,41	1,02	0,65	(-)	5.22
safety factor of the surface tension washer	γ_B3,washer	3,96	3,42	2,90	2,41	1,95	(-)	5.22