REPORT

Immersed tunnels subjected to a sunken ship load

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1 Summary

A sunken ship load needs more and more to be taken into account in the design of an immersed tunnel. Such a load is often governing the design. The designer gets often a prescribed value (in kN/m^2) from the client for a sunken ship load. The range in prescribed values show however a big scatter. There are also a lot of tunnels over which a lot of ships are passing, without having a sunken ship load taken into account in the design. This gives the need to get more insight in the behaviour of a sunken ship to predict a representative sunken ship load. Another important question is, if a ship sinks on an immersed tunnel, whether the tunnel collapses or not. If the tunnel collapses, the users are not safe anymore.

The insight in the behaviour of a sunken ship is gained through a literature study. From this literature study it resulted that a sunken ship load depends on a lot of parameters. It depends on the mass density of the carried cargo, the size of the ship, the depth of the waterway, and the way how a ship sinks. To determine a sunken ship load, all events in which a ship hits the tunnel are set out in a fault tree. All those events are evaluated with respect to the probability of occurrence an the magnitude of load. The magnitude of load is determined with the aid of a developed model. In that model the different parameters on which a sunken ship load depends are taken into account. The event in which a ship sinks with its bow on the tunnel deck appears to be the most important one. Sunken ship loads ranging from 50 – 300kN/m^2 are found then.

The response of an immersed tunnel depends on the type of tunnel. Concrete tunnels appear to be the most important type of tunnel. Concrete tunnels on a typical Dutch subsoil are evaluated with respect to a large sunken ship load of 300kN/m^2. For the cross sectional analysis, an globally increase in U.C. of 1.3 for shear and a decrease in U.C. of 0.7 for bending moment was found. For the longitudinal analysis, monolithic tunnels obtain shear forces in the joints which are three times bigger than the strength. The bending moments cause through cracking of the tunnel structure. The deformation of the water seals remain below the requirements. The shear forces in the joints for a segmented tunnel lie in the same order of magnitude as the strength. The bending moments remain small and cause no through cracking of the tunnel structure. The deformations of the water seals can become twice as high as allowed.

The Wijkertunnel is used as a case study to evaluate the response of a specific tunnel when subjected to a sunken ship load. The Wijkertunnel is a segmented tunnel with an immersed part of 575m consisting out of 6 elements. Each element contains four segments. The sunken ship loads applied on the tunnel are derived from the shipping characteristics of the ships passing that tunnel. The tunnel is evaluated for a small ship (a general cargo carrier) and a big ship (an iron ore bulk carrier). For the general cargo carrier only the event of the (bow of the) ship sinking on the tunnel deck is evaluated. For the iron ore bulk carrier the same event is evaluated, and also the event if the ship sinks just next to the tunnel. If the tunnel sinks just next to the tunnel, a load is induced on the tunnel wall. From the cross sectional analysis it resulted that one tunnel tube fails under the load from the general cargo carrier and the load from the iron ore bulk carrier when sinking on the deck. Shear failure is the governing failure mechanism. From the longitudinal analysis it followed that the shear kay fails in the wall if the tunnel is loaded from aside.

Failure of one tube of the cross section implies that the structure is no longer structural safe. The users of the tunnel are in great danger then. Failure of the shear key in the wall causes only big leakage problems. The tunnel remains structural safe then. Users of the tunnel are still able to leave the tunnel safely. The risk of a sunken ship load leading to failure of the Wijkertunnel is lower than the risk of a BLEVE. The risk of a BLEVE is often accepted and not covered in the design of immersed tunnels. It is therefore concluded that the risk of a sunken ship load also can be accepted.

2 Preface

Tunnels have always had my personal interest. After having spoken to Cees Blom, I would like to find a graduation project about tunnels. Preferably at a company. At the *Civiele bedrijven dagen* I came in contact with Royal Haskoning DHV. They made me aware of the existence of TEC (Tunnel Engineering Consultants). TEC is a specialist on immersed tunnels.

TEC gave me the opportunity to be an intern graduate at their office in Amersfoort. During the first weeks I read some general papers about immersed tunnels. With the aid of those papers and meetings with my supervisors of TEC, we came to the following interesting research topic: immersed tunnels subjected to a sunken ship load.

Doing research to the behaviour of a sunken ship was quite new for me. Because I've been educated to become a structural engineer. The behaviour of a sinking ship is something different. I'd like to thank Ms. Stroo-Moredo a lot for their support which she gave me about this topic.

Doing my master thesis research, does not only mean that I learned a lot about immersed tunnels and sunken ships. No, also the strategy about how to do research in general appeared to be very important. It is very important to have a clear defined research question. Formulating a good defined research question costs a little bit more time and effort in the beginning, but saves a lot at the end.

Finally, I would like to thank the colleagues from TEC who helped me during my research and gave me a nice working environment.

Amersfoort, 17 May 2016
Geurt van Lagen

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3 Introduction

This introduction gives insight to the level of importance of this research. The problem description and the research setup are specified in more detail.

Immersed tunnels lie often in rivers, harbours or areas with a lot of passing ships. Over time, the amount of immersed tunnels as well as the amount of ships passing an immersed tunnel increases. This leads to an increasing probability of a ship sinking on an immersed tunnel. Therefore, in case of a lot of passing ships, often the load of a sunken ship needs to be taken into account as an accidental load case in the design.

Then the question arises, what the magnitude of a sunken ship load is. If engineers should take a sunken ship load into account in the design, they get a prescribed value from the client. There is however a big range in values (in kN/m^2) which they get. Also the values which are given in literature show a big scatter. This large variation in loads is partly caused by the fact that each tunnel lies at a different location. Secondly this is caused by how such a load is determined. Therefore the need arises to get more insight in the behaviour of a sinking ship. Based on that insight it is possible to show if the prescribed values in literature are realistic or not. The insight in the behaviour of a sinking ship will be gained through a literature study. Based on this study it can be said what types of ships are most relevant and what the corresponding loads are.

On the other hand, it is important to know what the consequences are of such big loads. Because the tunnel has to fulfil certain design criteria. Therefore the design criteria need to be evaluated. Based on the design criteria it can be said which aspects are important for the design, and what the influences of these are on the design. Through this insight it is possible to say which aspects of an immersed tunnel are critical when subjected to a sunken ship load. This is important, because there are a lot of tunnels with many ships passing that tunnel, but whereby the load from a sunken ship is not taken into account in the design. It is then well possible that if a ship sinks on such a tunnel, the design criteria are no longer met. In the worst case the tunnel structure might collapse. The users of the tunnel become in danger of their life then.

To be able to say something about the consequences, it is important to know how an immersed tunnel behaves under such representative sunken ship loads. For this reason the structural response needs to be examined. It is important to get insight in the basic behaviour of the tunnel under the loads, with the aid of simple calculations. In this way it is possible to see what types of tunnels are critical with respect to sunken ship loads and what critical locations are with respect to such loads.

An already built immersed tunnel will be used to evaluate the sunken ship loads. Based on the gained insight, as described in the previous paragraph, a choice can be made for a tunnel which is critical under sunken ship loads. From this tunnel a model can be made to evaluate the structural behaviour of that tunnel with the aid of a linear analysis. The model can be validated with the aid of the available design calculations.

Through a linear analysis on that tunnel, the behaviour of the tunnel can be evaluated both for normal conditions as well as when subjected to a sunken ship load. In that way the influence of a sunken ship load becomes clear. When comparing the structural behaviour of the tunnel (in case of a sunken ship) with the design criteria, the critical locations in the tunnel appear. Based on this it is possible to say something about the consequences. The consequences reveal if the tunnel structure remain structural safe. If the tunnel remains structural safe, the users of the tunnel are still safe.

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3.1 Research question

3.1.1 Main question

Based on the previous description the following research question results:

What are representative loads from a sunken ship on an immersed tunnel and how does an immersed tunnel behave under such loads? Does an existing tunnel still met the design criteria and if not, is the tunnel still structural safe?

3.1.2 Sub questions

The main question can be divided in the following sub questions:

1. What are the design criteria for an immersed tunnel in relation to a sunken ship load?
2. What are representative loads from a sunken ship on an immersed tunnel?
3. What is the structural behaviour of an immersed tunnel when subjected to a sunken ship load?
4. What is the structural behaviour of an existing tunnel when subjected to a sunken ship load?
    - What is the structural behaviour?
    - What are the consequences of the sunken ship loads for that immersed tunnel?
5. How should a sunken ship load be taken into account in the design of an immersed tunnel?

3.2 Research setup

In this paragraph an explanation is given about the research setup. In Table 1 an overview is given of all topics which will be treated. These topics are worked out more detailed in the paragraph thereafter.

3.2.1 Overview research setup

Table 1 - Overview research setup

Main topic		Sub topics
Design criteria		Determining relevant design criteria
Representative sunken ship loads		Mapping all possible events of a ship hitting the tunnel
		Determining probability of occurrence and load for each event
		Determining most important event
Structural behaviour immersed tunnels		Describing type of immersed tunnels
		Investigation to (the structural behaviour of) most relevant types of immersed tunnels
		Determining critical locations
Case	Choice for tunnel	Making choice for an existing tunnel to evaluate the sunken ship loads
	Sunken ship	Determining representative sunken ship loads for tunnel

	loads	
	Structural analysis	Making model from chosen tunnel + validation
		Investigation to structural behaviour of the tunnel
		Verification of tunnel under sunken ship loads
	Consequences	In this part the consequences for the tunnel are evaluated based on the design criteria
	Statistical consideration	Doing a small statistical consideration
Guideline		Making a guideline about how to take a sunken ship load in the design
Conclusion and recommendations		

3.2.2 Working out of research setup

In this paragraph the research setup is worked out more detailed, and is hence a good outline of the report.

3.2.2.1 Design criteria (Chapter 4)

To be able to say something about the consequences of the sunken ship loads on the immersed tunnel, it is important what design criteria should be fulfilled. The situation of a sunken ship load is an accidental load case. This load case is evaluated in the ultimate limit state. The design criteria which are related to that are worked out.

3.2.2.2 Determining representative sunken ship loads (Chapter 5)

There are different events how a ship can sink. All failure events in which the ship can hit the tunnel are set out in a failure tree. This failure tree is worked out, and each event is evaluated with respect to the probability of occurrence the magnitude of load. In this way the most important loading event is determined.

To be able to predict the load of a sunken ship for each event, certain models will be made. Those models should be validated with results in literature. After those models are validated, it can be used to predict the representative sunken ship loads.

3.2.2.3 Structural behaviour (Chapter 6)

The different types of immersed tunnels are evaluated at first. Based on that elaboration the most relevant types of tunnel are determined. These tunnels are only evaluated in that chapter.

These most relevant type of tunnels are evaluated in more detail through a linear analysis. In this analysis both the cross sectional as well as the longitudinal behaviour will be evaluated. At first an indication is given of the behaviour of the tunnel in normal load conditions. After that the behaviour is shown of the tunnel when subjected to a sunken ship load.

Based on this first investigation, the critical elements in an immersed tunnel appear.

3.2.2.4 Case (Chapter 7)

3.2.2.4.1 **Choice for tunnel**

A framework is used for selecting a critical tunnel. This framework should consist out of certain criteria which the tunnel should fulfil anyway. Due to this framework not every immersed tunnel present in the world needs to be examined. From this framework a certain amount of critical tunnels results.

From these critical tunnels a choice is made through a Multi Criteria Analysis (MCA). In this MCA the critical tunnels are weighted against certain criteria which are relevant for the research.

3.2.2.4.2 **Sunken ship loads**

The sunken ship loads for the tunnel are determined based on the shipping characteristics which are passing that tunnel.

3.2.2.4.3 **Structural analysis**

The chosen tunnel structure is modelled in Scia Engineer. From the tunnel structure two models are made. One for the cross section and one for the longitudinal direction. These models are validated with the aid of the existing design calculations which were carried out for the design.

When these models are validated, the structural behaviour of the tunnel is examined. The tunnel is evaluated for normal conditions and when subjected to sunken ship loads. The tunnel is verified for those loads for the cross sectional and longitudinal direction.

3.2.2.4.4 **Consequences**

The consequences of the tunnel reveal if the tunnel is still structural safe. If the tunnel remains structural safe, the users are still safe.

3.2.2.4.5 **Statistical consideration**

A small statistical consideration is added to see the results in a broader perspective.

3.2.2.5 Guideline (Chapter 8)

In this chapter a simple road map is given about how to take a sunken ship load into account of the design of an immersed tunnel.

3.2.2.6 Conclusion and recommendations

The conclusion contains the answer to the research question. First the answers to the sub-questions are formulated. These answers to the sub-questions are the basis for the answer to the research question.

This chapter ends with some recommendations for further research.

4 Design criteria

4.1 Introduction

The design criteria determine which requirements an immersed tunnel has to fulfil to maintain its functions. There are different types of criteria. Not all of them are of importance with respect to a sunken ship load on an immersed tunnel. What criteria are of importance is outlined under the heading *Limit states*. These criteria are worked out in the paragraphs hereafter. This concerns strength, deformations, durability and water tightness.

The design criteria which are considered relate only to concrete tunnels. Steel-concrete tunnels are not within the scope of this research. See for the reason §6.2*Types of immersed tunnels*.

4.2 Limit states

There are different types of design criteria. There are for example requirements with respect to the clearance in a tunnel. Those requirements are however not of any importance in case of a sunken ship. In case of a sunken ship the limit states are of importance. Limit states are divided in ultimate state (ULS) and serviceability limit state (SLS) (NEN, 2011). A sunken ship load is an accidental load case. The serviceability state is then not of any importance. Therefore only the ultimate limit state is evaluated.

4.2.1 **Ultimate limit state**

The ultimate limit state has to do with (NEN-EN 1990+A1+A1/C2 (nl), §3.3):

- “The safety of people, and/or
- The safety of the structure”

Based on these criteria, the structure should be checked for the following items in ULS (NEN-EN 1990):

- Stability of the structure, the structure may not lose its stability
- Safety of the structure, the structure may not collapse
- The structure may not collapse due to fatigue, or other time depending actions

Not all of these items are of importance in case of a sunken ship. To guarantee the safety of people and/or the safety of the structure, the following criteria are checked:

- Strength
- Deformations
- Water tightness

These criteria are worked out more detailed in several paragraphs later on in this chapter.

4.2.1.1 Design values

To achieve the requirements as given for ULS, use is made from design values. There are design values both for the loads as well as for the materials used.

4.2.1.1.1 **Loads**

The loads which are acting on a structure can be divided into three categories:

- Permanent loads (G)
- Variable loads (Q)
- Accidental loads (A)

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This division is based on the duration of time that the load is acting on the structure.

To obtain the design values for the loads, use is made of partial load factors. They are indicated as γ_G, γ_P and γ_Q – factors. These factors are given in Appendix 1 (§A1.1 *Partial load factors,* Table 34). When multiplying the characteristic load value with the corresponding partial load factor, the design load is obtained.

4.2.1.1.2 **Materials**

The design values for the material are obtained in the same manner as for the loads. Also here use is made from partial factors, now named as the partial factor for the material. This material factor is mostly indicated with the symbol γ_m. In this case however, the characteristic value should not be multiplied with, but divided by the material factor.

4.2.1.2 Load combinations

The limit states are related to three design situations:

- Permanent
- Temporary
- Accidental/seismic

To obtain the load which should be taken into account for each design situation, use is made from load combinations. In these load combinations, the loads are combined through combination factors (ψ-factors). Those ψ-factors are given in Appendix 1 (A1*Design Criteria*, Table 33).

The load from a sunken ship falls in the accidental design situation. The load combination for this design combination is given by equation (1):

$$E_d = \Sigma\gamma_{G;j}G_{k,j} + \gamma_P P + A_d + \gamma_{Q,1}Q_{k,1} + \Sigma\gamma_{Q,i}\psi_{0,i}Q_{k,i} \tag{1}$$

In this equation do the symbols stand for:

- G: Permanent loads
- P: Prestressing loads
- A: Accidental loads
- Q: Variable loads

The partial load factors (γ_G, γ_P, γ_Q) are given in Appendix 1. Here it can be seen that for the load combinations in case of an accidental situation, all partial load factors are one. This means that the load combination reduces from equation (1) to equation (2):

$$E_d = \Sigma G_{k,j} + P + A_d + Q_{k,1} + \Sigma\psi_{0,i}Q_{k,i} \tag{2}$$

4.3 Strength

The tunnel should be strong enough to resist all loads which can occur during lifetime, without collapse of the structure (Figure 1). The strength of a concrete structure, in this case an immersed tunnel, is achieved by the concrete together with the reinforcement.

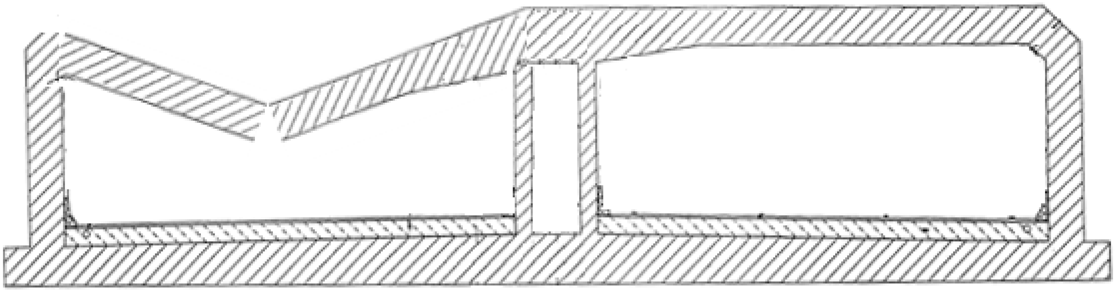

Figure 1 - Collapsed tunnel

The structure should be designed according to the then prevailing standard. With the aid of that standard the strength of the structure can be verified. In such a way it should be verified that the strength of the structure is more than the maximum possible loads.

4.4 Deformations

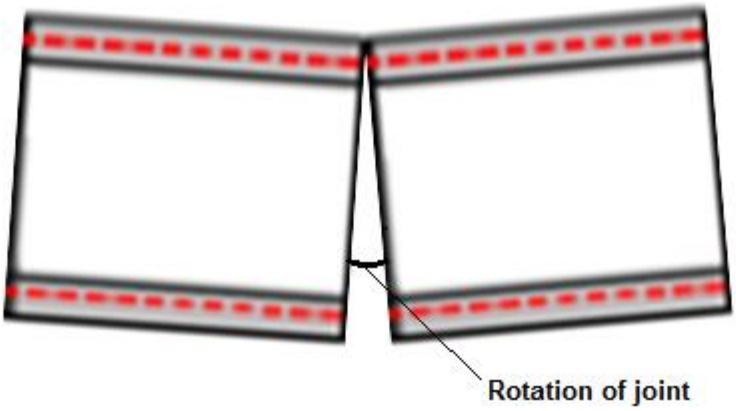

Figure 2 – Rotation in a joint

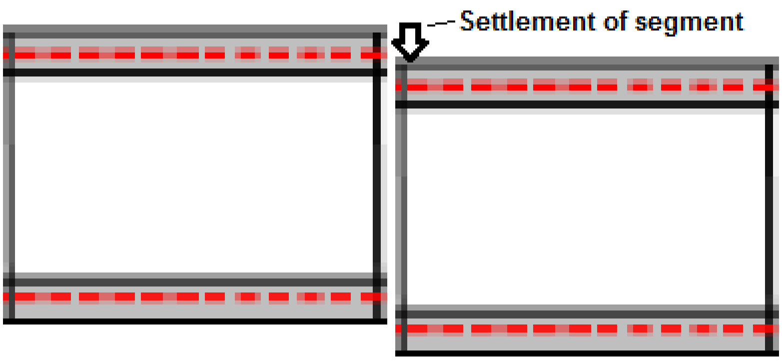

Figure 3 - Translation of a segment

Deformations can be a rotation (Figure 2) or a translation (Figure 3).

If a joint rotates, this is accompanied with deformations of the structure. Depending on how the joint rotates, the deck or the floor needs to elongate. For small rotations that's no problem. But for bigger rotations it is well possible that (if the floor needs to elongate for example) cracks occur in the asphalt layer. As an indication for the maximum rotation, a value of 1m/100m (Marieholm documentation) is reasonable.

Not only the asphalt layer deforms under such rotations, but also the water seals. This water seals are needed for water tightness. More about this is treated in §4.5 *Water tightness*.

Settlements between elements can occur free[1] in the construction phase, before the shear connection is established, although there are restrictions to that. After casting of the shear keys, in principle no translations between segments can occur. The shear keys which form the connection between the segments should prevent this.

4.5 Water tightness

The water tightness of the tunnel structure is primary established by the concrete. For monolithic[2] tunnels, sometimes an additional steel membrane is applied for water tightness. The water tightness of the joints is achieved by water seals.

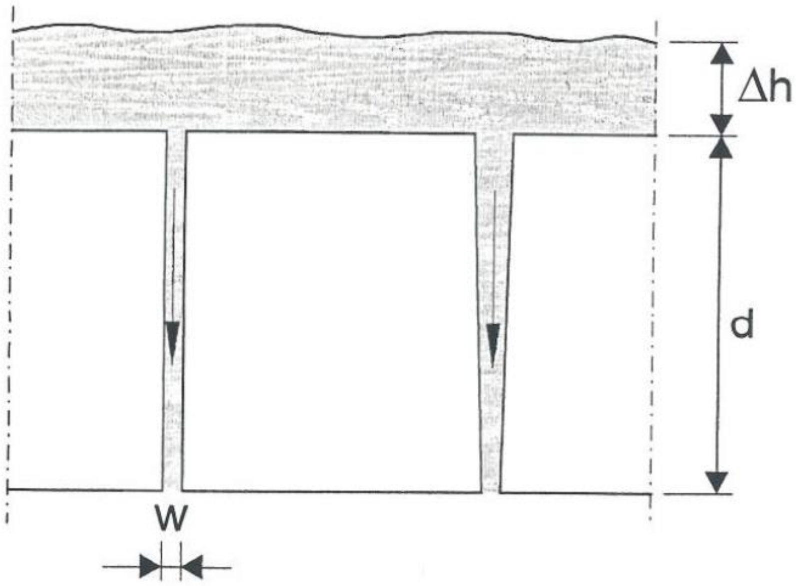

Figure 4 - Water penetrating through cracks in the concrete

Concrete is a porous material. Therefore a concrete wall is always not fully watertight. But the amount of water penetrating through intact concrete will be very small. This becomes different if cracks appear (Figure 4). The amount of leakage will be still small, but considerably higher. A third item which can cause leakage, are the immersion joints between the elements or the segment joints between the segments. If those joints are not working properly, due to any damage for example, the leakage becomes even higher. Braam gives a ratio of $1:10^4:10^{10}$ for normal concrete : cracked concrete : improper working joints (Foundation Postacademic education, 2001). This implies that a joint is a very important detail with respect to leakage. Because if a tunnel cracks under certain unforeseen loads (settlements for example)

[1] *This holds only for the immersion joints, not for the segment joints. The segments joints are already present at the moment the tunnel is placed.*
[2] *For the difference between a segmented and a monolithic tunnel see §6.2.1.1 Concrete tunnels.*

the flow rate of water through the concrete will be still far lower compared to the situation of an improper working joint.

If a steel membrane is applied, they must be able to function during the lifetime of the structure. This steel membrane is typically 6 – 10mm thick (Lunniss & Baber, 2013). This membrane is attached to the concrete by steel dowels. The membrane should be able to fulfil its function during the lifetime of the structure. Therefore the steel can be coated with epoxy paint for example. Because of the fact that a steel membrane (or other types of secondary water sealing elements) is not that often[3] applied if it comes to concrete immersed tunnels, this will not be treated further.

4.5.1 **Concrete**

The requirement with respect to the water tightness of concrete yields: “Free of all visible leakage, seepage, and damp patches” (Lunniss & Baber, 2013). This results in a requirement with respect to the crack width of the concrete (Figure 5).

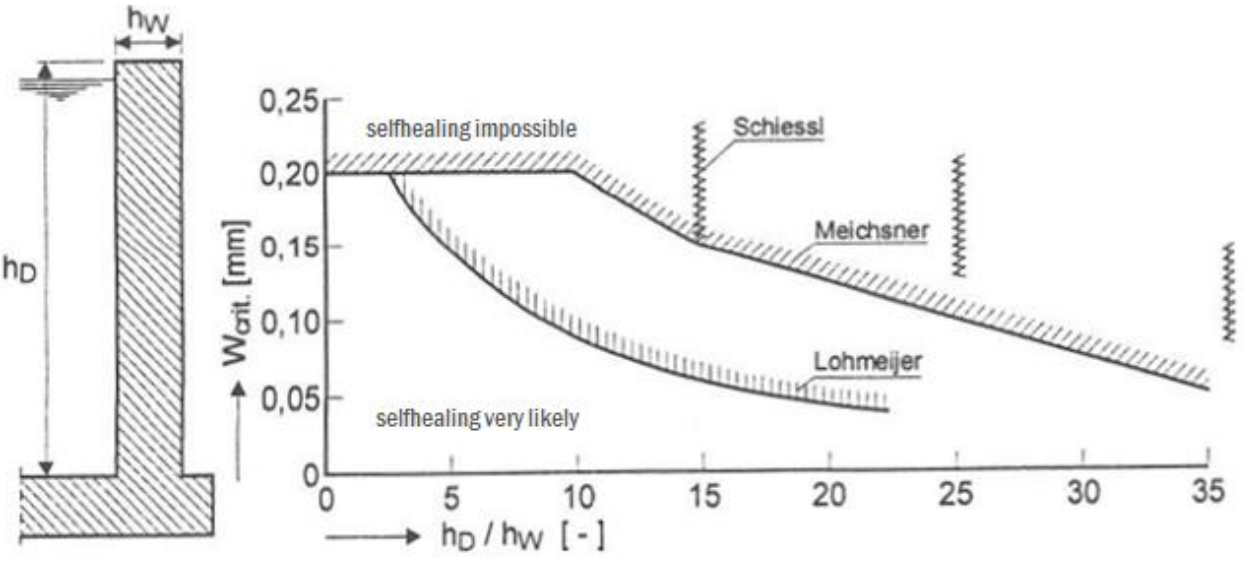

Figure 5 – Water tightness (Foundation Postacademic education, 2001)

In Figure 5 different graphs are given. The graph of Meichsner is based on laboratory tests, while the graph from Lohmeijer is based on practical observations.

From the figure it can be seen that the minimum water tightness criterion is 0.2mm. Most of the time however the criterion will be more stringent. Take for example a tunnel at a depth of 20m and a wall thickness of 1m. That results in a ratio of h_D / h_w = 20. A ratio of 20 gives a maximum allowable crack width of 0.05mm (when using Lohmeijers curve).

4.5.2 **Joints**

The water tightness in the joints is guaranteed by water seals. The type of water seals used, differ between the segment joints and the immersion joints[4]. Therefore they are treated separately.

[3] A steel membrane is only sometimes applied for a monolithic concrete tunnel. However, most concrete tunnels are segmented.
[4] A segment joint is only present in a segmented tunnel. Immersion joints are present in both segmented and monolithic tunnels.

4.5.2.1 Immersion joint

The water tightness in the immersion joint is achieved by the omega seal (permanent water sealing) and the Gina gasket (temporary water sealing)[5], see Figure 6.

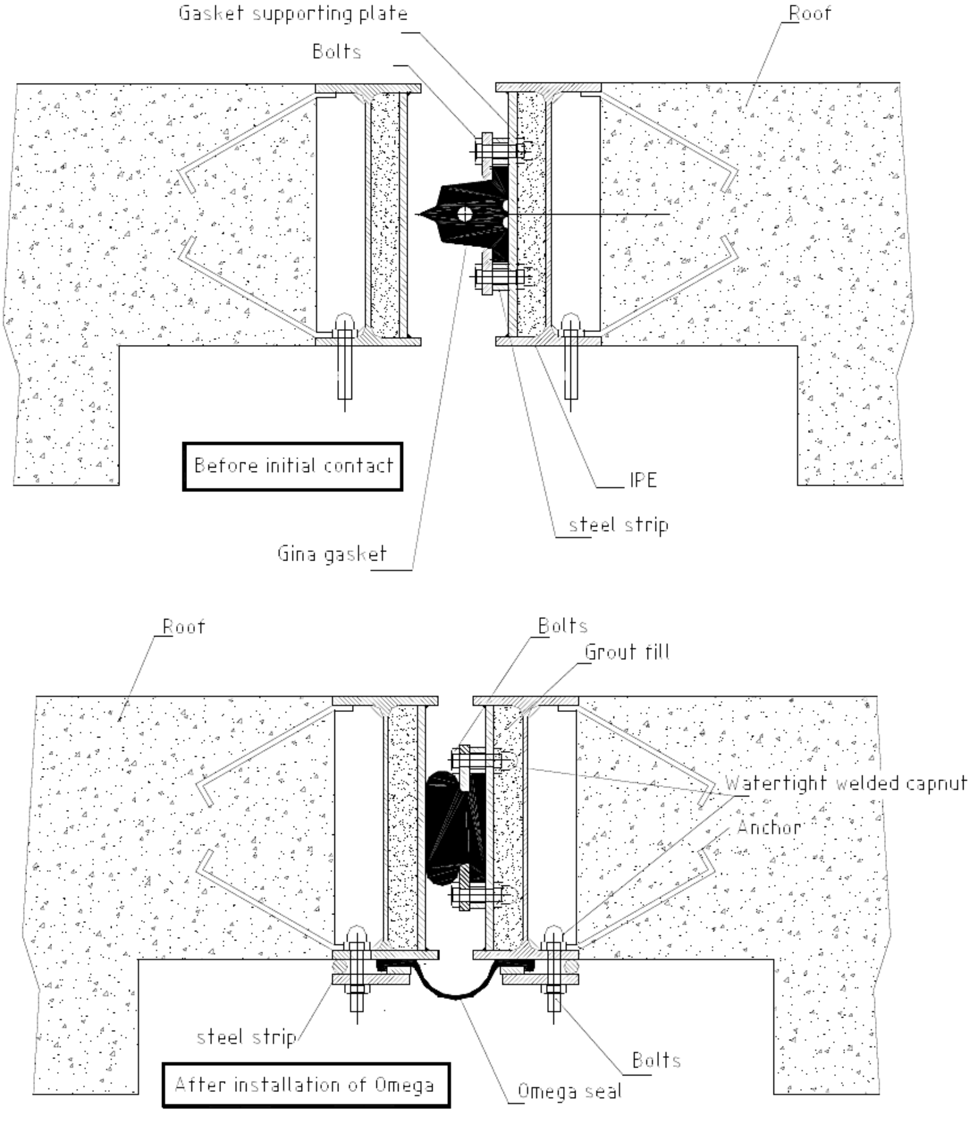

Figure 6 - Omega seal and Gina gasket (Trelleborg)

4.5.2.1.1 **Omega profile**

The Omega is the permanent water sealing. Therefore that profile is treated first.

The following conditions must be fulfilled for an Omega seal to guarantee the water tightness (Trelleborg):

1. "The Omega seal construction will withstand the water pressure, including the accommodation of the expected gap movements in three directions"
2. "The steel clamping construction is capable to keep the Omega flange in position and sealing against the water pressure whilst at the same time allowing for all gap movements"

[5] The Gina has a temporal water sealing functions at the construction phase of the tunnel. But besides the water sealing function, a Gina gasket has also several other functions during lifetime. As: transfer of hydrostatic loads, allowing shortening and elongation of the tunnel structure due to temperature effects and allowing settlements of the tunnel elements (Trelleborg).

3. “The clamping and sealing function of the clamping construction should incorporate the relaxation effect of the rubber flange over the expected tunnel lifetime period”

As can be derived from the above conditions, an omega profile should be able to allow all gap movements. Important to know is how big such gap movements can be before the Omega profile fails.

In Appendix 1 (§A1.2.1.1 *Omega profile*) a detailed overview from a typical Omega profile is shown (OS 360-100). From the requirements with respect to that profile it is expected that a maximum elongation of 90mm is allowed. With a little hand calculation, it is made clear that the maximum elongation which the omega can handle is about 110mm. A complete overview for different standard types of omega profiles is given in Table 2

Table 2 - Maximum elongations for different standard types of omega profiles

Standard Omega profile	Maximum elongation allowed in ULS (mm)	Elongation at break (mm)
OS 240-40	60	85
OS 300-70	65	80
OS 360-100 & OS 400-100	90	110

4.5.2.1.2 **Gina gasket**

To provide water tightness of the structure, the Gina profile should be compressed for a certain amount. There are lower bound and upper bound values for the amount of compression. The lower bound is fixed by the minimal amount of contact pressure which should be present. This minimal contact pressure should always be higher than 2.5 times the water pressure. In addition to this, often a minimal compression of 30mm is required. The upper bound is fixed by the force which the clamping construction can handle or by the force which will cause internal damage to the Gina-profile (COB, 2014).

4.5.2.2 Segment joint

For a segment joint the water tightness is guaranteed by a waterstop (Figure 7).

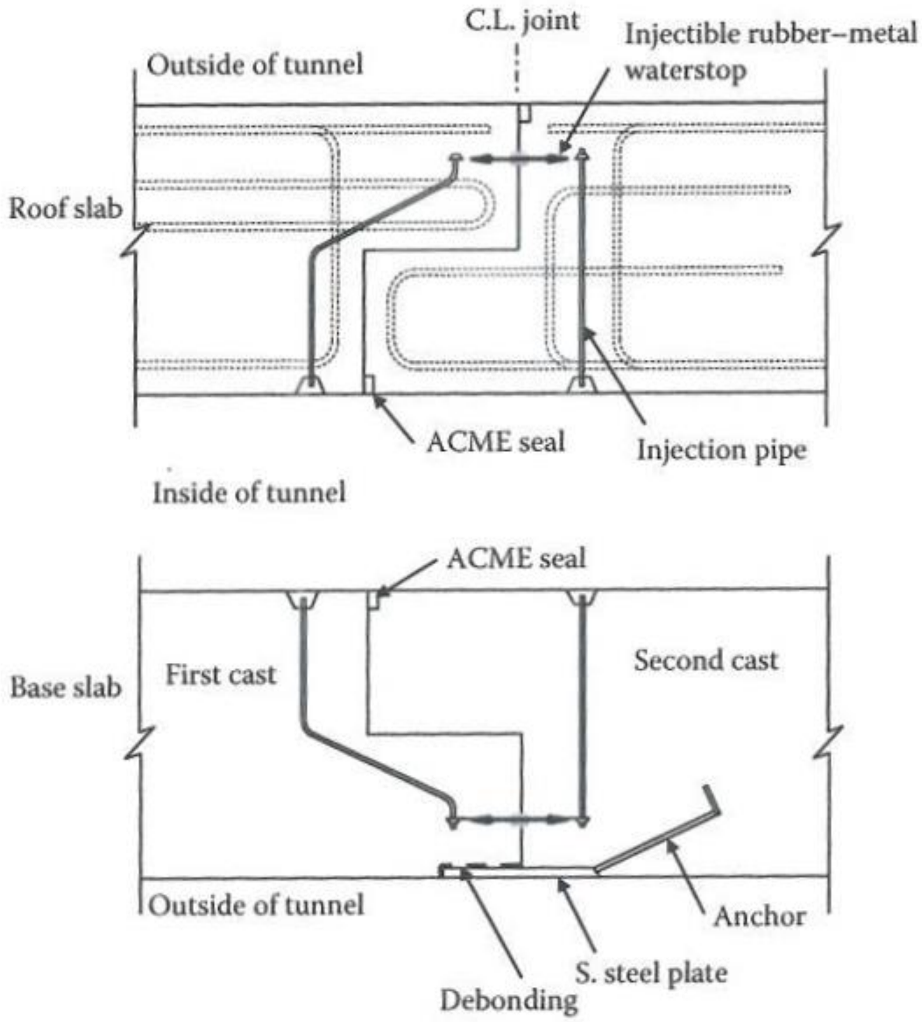

Figure 7 – Waterstop in segment joint (Lunniss & Baber, 2013)

Just as an omega profile, a waterstop has to guarantee the water tightness of the joint, with at the same time allowing for all gap movements. As long as the segments joint remains intact, the water stops are only able to elongate in the direction of the waterstop. This happens if the joint rotate. If the joint fails, translations/settlements in transverse direction become possible. It is assumed that the water stop is not able to follow those movements. Assumed is that the water stop fails then.

The requirements for two typical waterstops are given in Appendix 1 (§ A1.2.2 *Segment joint*). Based on those requirements, it can be seen that a maximum elongation of 37mm is allowed (SLS). For ULS conditions the maximum elongation becomes about 46mm. An example calculation shows that for such a particular waterstop a gap movement of 130mm is possible before failure. A complete overview for different standard types of water stops is given in Table 3.

Table 3 - Maximum elongations for different standard types of water stops

Standard water stop type	Elongation allowed[6] in ULS (mm)	Elongation at break (mm)
W10U	38	75

[6] Only the maximum elongation in ULS conditions for a W10U profile is given by Trelleborg. The other values are calculated by assuming the same ratio between ULS and SLS as for the W10U profile.

W9U & W9U-I	46	130
W9CU & W9CU-I	74	260

4.6 Conclusion

The most important design criteria for an immersed tunnel are related to the limit states. A sunken ship load is an accidental load case. An accidental load case needs only to be evaluated for the ultimate limit state. For that situation all load factors are one (or zero).

The criteria which are of importance for the situation of a sunken ship in the ULS are strength, deformations, durability and water tightness.

For strength the structure should be designed in such a way that all checks are fulfilled according to the prevailing standard. For the deformations the rotations in the joints are the most important item.

The water tightness of the structure is mainly achieved by the concrete. This results in a requirement for the maximum crack width. The crack width criterion for the water tightness is more severe than for durability, so if the crack width criterion is fulfilled for water tightness, also the crack width criterion for durability is fulfilled. The water tightness in the joints is guaranteed by water seals. There are different types of water seals for the immersion joints versus segment joints. Each of them has its own requirements.

5 Sunken ship loads

5.1 Introduction

In normal circumstances a ship can physically not hit a tunnel. A ship hits the tunnel after failure of the ship. A ship can fail in different manners. Each type of failure causes a different behaviour of the ship. The behaviour of the ship determines mainly the type of loading.

The magnitude of loading however depends mainly on the type of ship. An oil tanker for example will cause almost no load on the tunnel. That is because oil has a lower density than water. First a lot of oil needs to be leaked into the water before the ship will sink. Contrary to an oil tanker, ships carrying bulk with a high density cause severe loads on the tunnel. Therefore the most relevant types of ships are treated first.

After that an overview is given of all possible events how a ship hits the tunnel. These failure events are set out in a fault tree. These scenarios are worked out further so that it becomes clear which events are more probable to happen. Thereupon for each event an indication is given for the load which it will induce on the tunnel. These predicted loads are based on a model which is developed for that purpose.

Based on the probability of occurrence for the failure event and the corresponding indication for the load, the conclusion is drawn which event is most relevant.

To give an indication about what magnitudes of load to expect, a range of values which are used in daily practice are presented in Table 4. If a '–´ is stated, that information was not available. It can be seen that there is a lot of variety in the loads which are used. This variation is also caused by the variety in types of ships which are passing that tunnel. Therefore also an indication of the type of ship is given. The same reasoning holds for the width of the ship. The width of the ship (which is presented too) gives an indication of the size of the ship. Because the size of the ship has an influence on the magnitude of load.

Table 4 - Loads which are taken into account by the design for different tunnels and norms

Tunnel	Load (kN/m^2)	Width of ship (m)	Type of shipping traffic
Piet Heintunnel	45	20	Barges
River Lee tunnel	75	20	Seagoing vessels
Medway tunnel	45	14	Barges
Oresund tunnel	50	30	Biggest ships possible
Western harbour crossing	50	-	Barges (seagoing ships possible)
HSL tunnels Dordsche kil and Oude Maas	70	-	Barges
Maliakos Crossing (1)[7]	100	30	Small vessels
Maliakos Crossing (2)[8]	150	30	Small vessels
Oosterweel tunnel (1)[9]	320 ([10])	28	Large Barges
Oosterweel tunnel (2)[11]	340	28	Large Barges

[7] *Taking the full tunnel width as supporting area*
[8] *Taking half of the tunnel width as supporting area*
[9] *Horizontal sinking, tunnel above riverbed*
[10] *The values here presented for the Oosterweel tunnel are based on a study which is carried out for that tunnel. These values are the governing one. However, it is uncertain whether these values are used.*
[11] *Sinking under an angle*

Norms			
ROK (1)[12]	50	-	Barges
ROK (2)[13]	150	-	Seagoing vessels
ITA (1)[14]	100	32	Large Bulk Carrier
ITA (2)[15]	200	32	Large Bulk Carrier

5.2 Relevant types of ships

For the load of a ship one should realize that a ship has a different weight under water than in open air. The weight of a ship under water is determined by the density of the materials of the ship minus the density of the water. Therefore ships which carry bulk with a high density cause the biggest load and are the most relevant for the research. Bulk with a high density is iron ore. Therefore ships which carry iron ore are used as reference ship for the research.

A special case is the tugboat. Due to its configuration, a tugboat causes a big line load on the tunnel. When a tugboat sinks, it rests on its protective plates for the propellers and the skeg. This together with the positon of the centre of gravity causes a line load of 880kN/m^2 (Gent University, 13 november 2003). This load is more or less a line load and will probably be reduced by the gravel layer on top of the tunnel. Due to the fact that this is a special case it is not worked out further in the research.

5.3 Relevant events

In this paragraph the different events for which a ship a load exerts on the tunnel are evaluated. For each event an indication is given about the probability of occurrence.

5.3.1 Mapping relevant events

The events that a ship hits the tunnel are sinking and grounding. Sinking of a ship on a tunnel is always possible at the position of the tunnel just under the main waterway. Grounding of a ship on a tunnel is physically only possible if the tunnel near the bank of the river lies high enough to be able to be touched by a ship.

Based on the argumentation before, the events of grounding and sinking are evaluated. An overview of the possible relevant events is set out in a fault tree (Figure 8).

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[12] *Load should be used in case of barges*
[13] *Load should be used in case of seagoing vessels*
[14] *Horizontal sinking*
[15] *Sinking under an angle*

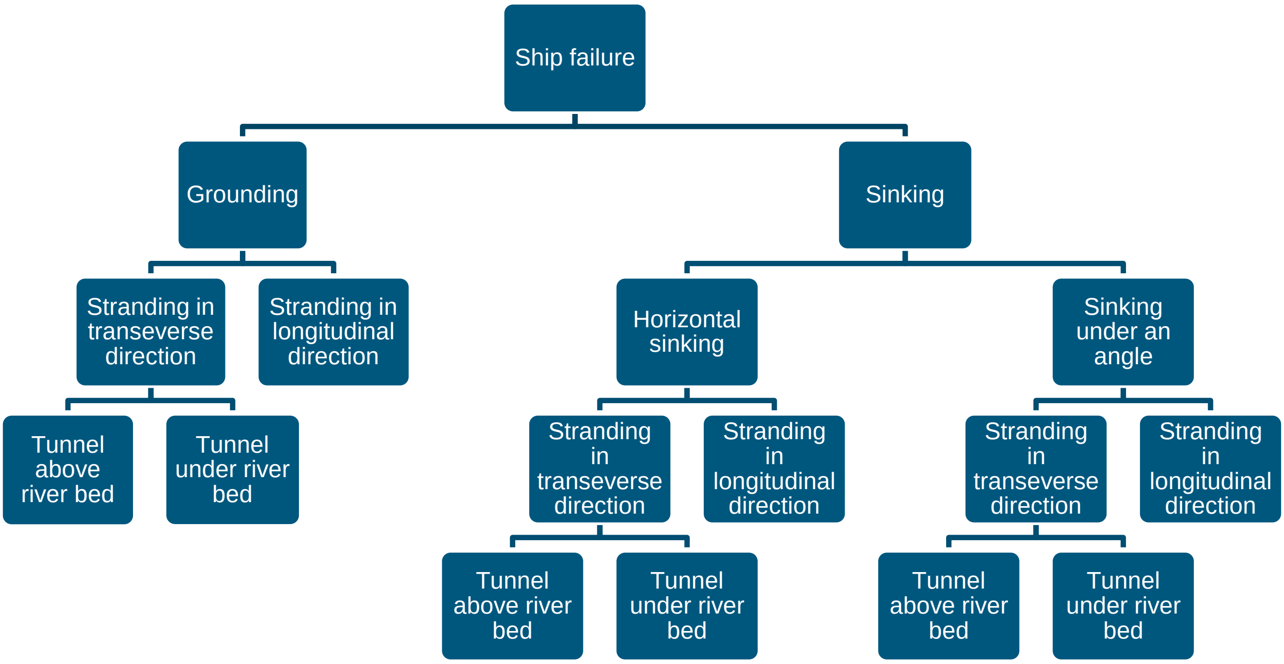

Figure 8 - Fault tree ship failure

In the next paragraphs each event is explained and evaluated with respect to the probability of occurrence.

5.3.2 Grounding

With grounding the event is meant that a ship hits the tunnel with his bottom. The ship can hit the tunnel in longitudinal direction, as well as in transverse direction.

5.3.2.1 Transverse direction

In transverse direction, a ship can ground on the tunnel if the tunnel lies above the river bed (Figure 9) or under the river bed (Figure 10).

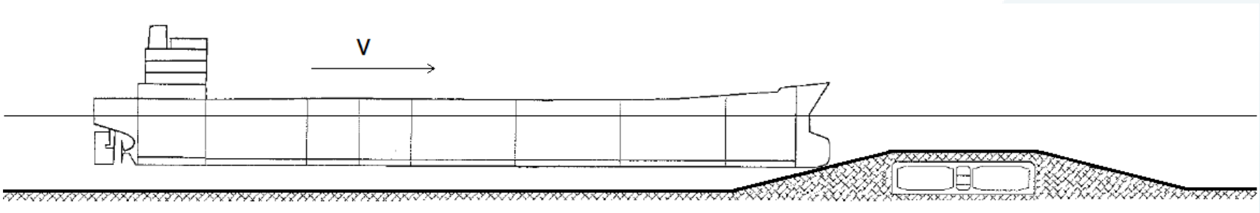

Figure 9- Stranding in transverse direction (tunnel above river bed)

The situation that the ship hits the tunnel from aside is only possible if the tunnel lies above the river or seabed. This situation is rather uncommon. Therefore the probability of this event is quite small.

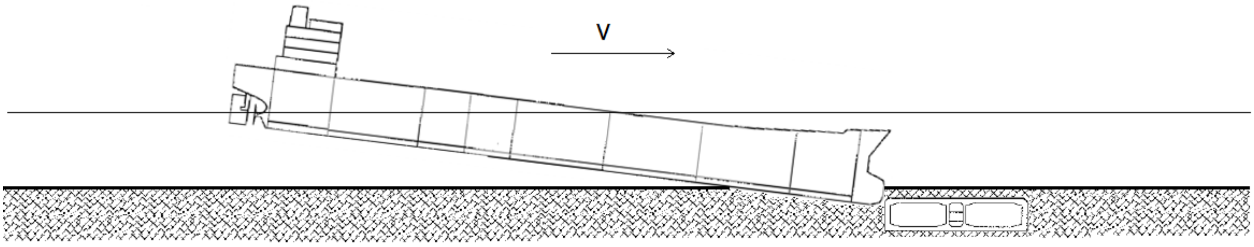

Figure 10 - Stranding in transverse direction (tunnel under river bed)

The situation as sketched in Figure 10 represents a ship grounding just next to the tunnel and hitting the tunnel from aside. The situation of a tunnel lying under the river bed is more common. But the probability of a ship hitting the tunnel just in this manner is very, very low.

5.3.2.2 Longitudinal direction

The ship hitting the tunnel in longitudinal direction is schematised in Figure 11. In this event, the bow of the ship can induce an impact load at the cover layer of the tunnel, just before the tunnel comes above ground level.

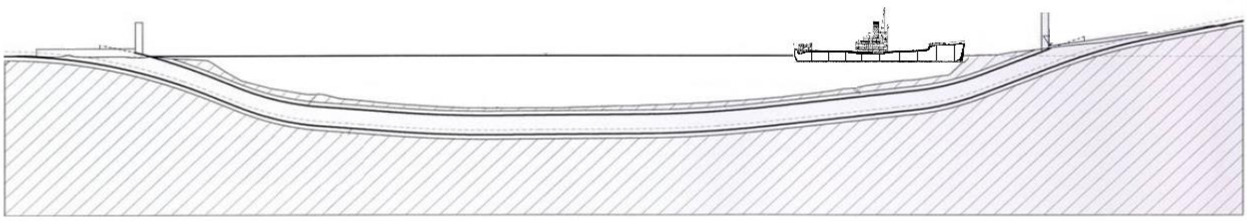

Figure 11 - Stranding in longitudinal direction

The possible locations where a ship can ground on the tunnel in longitudinal direction of the tunnel are indicated in Figure 12.

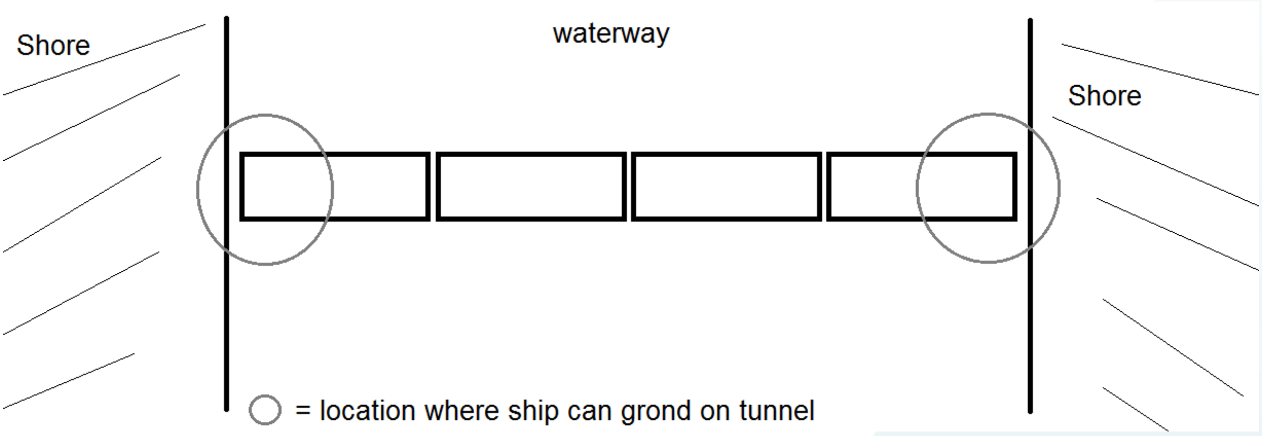

Figure 12 - Indication of locations where a ship can ground on a tunnel (in longitudinal direction)

The probability of occurrence for this event is rather low. Such a situation can occur of the ship makes very strange movements after failure. One can think of failure of the steering system for example. Or a ship which pushes the ship next to the main waterway during a collision.

5.3.3 Sinking

Sinking of a ship is a difficult subject. Therefore it is tried to treat this subject in a straightforward manner, as far as relevant for this research.

How a ship sinks depends mainly on the location where the ship is damaged and the size of the leak. The location of the leak defines the stability of the ship in longitudinal and transverse direction. It makes difference if a ship sinks horizontally, inclined in horizontal direction or under an angle in transverse direction. And this defines the load from a sunken ship on a tunnel.

The size of the leak has an influence on the magnitude of the load from a sunken ship. In case of usual rivers a big ship (as a big iron ore bulk carrier) often touches the tunnel before being totally submerged. Due to this there is still some buoyancy from the intact compartments. The size of the leak determines mainly the amount of compartments flooded and on his turn the magnitude of load.

First the topic of transverse stability is treated. Rotating of the ship in transverse direction is indicated as heeling. After that the stability in longitudinal direction of the ship is treated. That is indicated as pitching.

Transverse stability

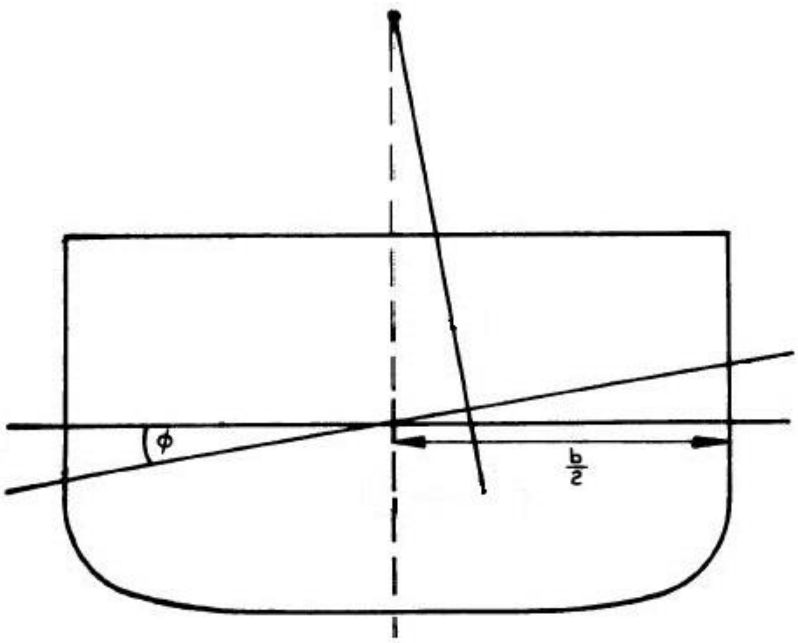

Figure 13 – Heeling of a ship[16]

The amount of heeling (Figure 13) of a ship determines if a ship capsizes or not. If the ship gets leak at the bottom, it’s likely that the ship remains stable in transverse direction. If the ship gets leak at the side, it is likely that the ship will come to lie askew in a certain amount. Assumed is that the ship (an iron ore bulk carrier) will gets leak through colliding with another ship (see Appendix A2.4). This implies that the ship gets leak at the side.

At the moment a ship gets leak, a certain amount of compartments becomes flooded and the iron ore becomes wet. Be aware that if the iron ore gets wet, the behaviour of the iron ore becomes different. It is

[16] *Picture after http://www.boatdesign.net/forums/stability/primary-stability-considerations-kayaks-42050.html*

no longer dry bulk which stays in place, but it will become more or less a muddy substance. Then the resistance to plastic deformation of the material becomes lower, causing earlier running of the bulk. Due to an initial inclination of the ship and the viscous behaviour of the iron ore, the iron ore will not stay in place, but start to slide to the side. This aggravates the inclination of the ship, so the ship will heel over more and more (Ms. Stroo-Moredo, Appendix A2.2). This is one of the reasons why a ship lies almost never horizontally in transverse direction when it sinks.

As said, immersed tunnels lie most of the time not very deep. So when a ship sinks, it strands on the tunnel before the ship is able to capsize completely. “At the location of an immersed tunnel, a heeling or sinking ship would soon touch the ground and be stabilized by the ground” (Saveur, 1997). For more deep rivers (or smaller ships) the ship is able to heel more. It is then possible that the ship sinks on its side. In an uttermost scenario, although very uncommon, a ship sinks upside down on a tunnel.

The size of the leak can aggravate the effects. More flooded compartments can cause more heeling or earlier capsizing of the ship.

Longitudinal stability

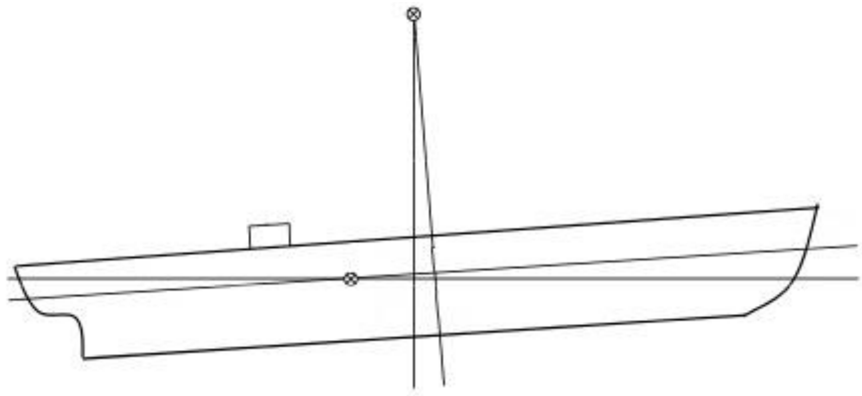

Figure 14 – Pitching of a ship[17]

For the longitudinal stability (Figure 14), the location of the leak in longitudinal direction is important. The size of the leak has also an influence on this (besides that it influences the magnitude of load). About the location and size of the leak, something is published by Gent University. The results are presented in Figure 15 and Figure 16.

[17] *Picture after http://www.slideshare.net/muhammmadadlijaaffar/small-angle-stabilitylongicompatibilitymode*

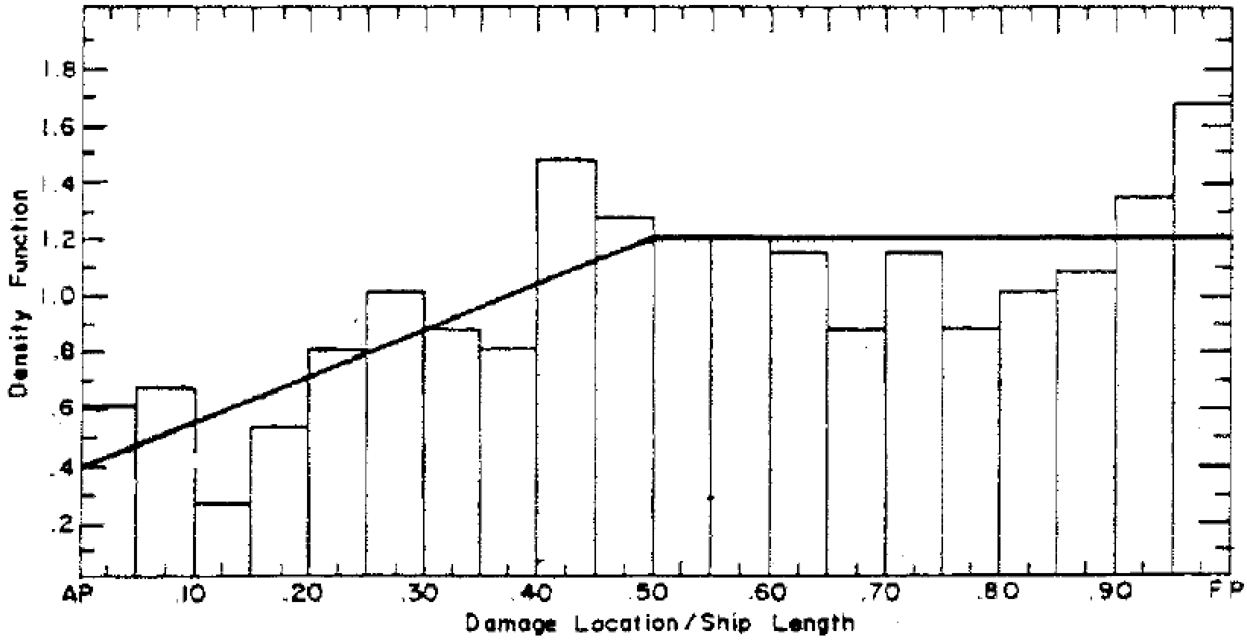

Figure 15 - Density function of damage over ship length (Gent University, 13 november 2003)

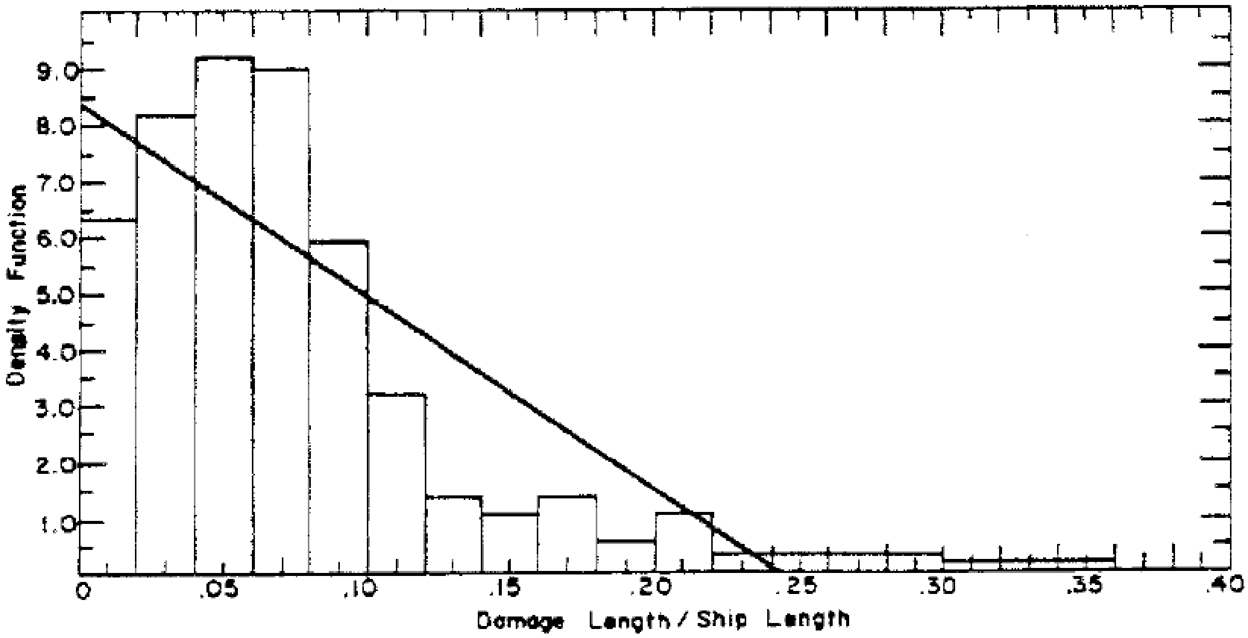

Figure 16 - Density function of damage length (Gent University, 13 november 2003)

From Figure 15 it can be concluded that the ship most of the time gets leak in the front half of the ship. If the leak is near the middle of the ship (between ≈ 0.4 – 0.6 *L) it is assumed that the ship sinks more or less horizontally. For the other locations it is assumed that the ship sinks under an angle. Based on this it can be said that the cumulative chance that a ship sinks under an angle is about three times higher than that a ship sinks in a horizontal position.

At the other hand, the probability of hitting the tunnel when sinking under an angle is lower compared to horizontal sinking. Because the loaded area is significantly lower for sinking under an angle compared to horizontal sinking. The loaded area is assumed to be a factor three[18] lower. This results in an almost equal chance for both failure mechanisms to hit the tunnel.

For the situation that a ship sinks under an angle it is assumed that the bow of the ship rests on the tunnel while the other side of the ship is still floating. It is also possible that the back side of the ship rests on the bottom and that the bow is still floating. But the probability of that event is less compared to the situation of the bow resting on the tunnel. And it is also basically the same type of loading.

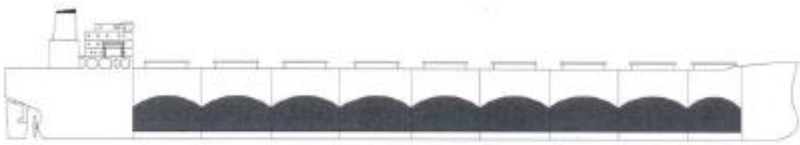

Figure 17 - Ship divided in compartments (Rijeka, 2015)

Figure 16 shows that the size of the leak is most of the time not more than 10% of the ship length. The length of one compartment is assumed to be about 10% of the total length[19] (Figure 17). That means that most of the time only one or two compartments are flooded. But in practice, it often occurs that the shutters which are present in the compartment walls are not closed (Ms. Stroo-Moredo, Appendix A2.2). This causes that more compartments become filled with water than assumed beforehand.

In the marine world, there are two and three compartment ships. That indicates the amount of compartments which can be filled with water without sinking of the ship. The ship should be able to reach a harbour with such damage (Ms. Stroo-Moredo, Appendix A2.2). Based on this argument it is assumed that an iron ore bulk carrier sinks if (at least) three compartments are flooded. This is a conservative approach. Although the total force increases if more compartments become flooded, also the supporting area increases, leading to an overall lower pressure.

5.3.3.1 Horizontal sinking

If the ship sinks horizontally, the ship strands in transverse (Figure 18) or longitudinal direction (Figure 19) of the tunnel. Also here it is most likely that the ship strands transverse on the tunnel, due to the fact that a tunnel lies most of the time perpendicular to the direction of the main waterway.

Important to notice, with respect to the drawings, is that a ship always contains a black box. That black box represents the part of the ship which is flooded with water. The leak of the ship is therefore present in that part of the ship.

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[18] Let's call the length over which a ship can hit the tunnel the influence length. Then the influence length for horizontal sinking varies between 200-450m. For sinking under an angle is that 90 – 140 m. That gives a ratio of (200+450)/(90 + 140) =2.8 ≈ 3.
[19] This is a very rough estimation. For each ship it should be checked whether this assumption is correct or not.

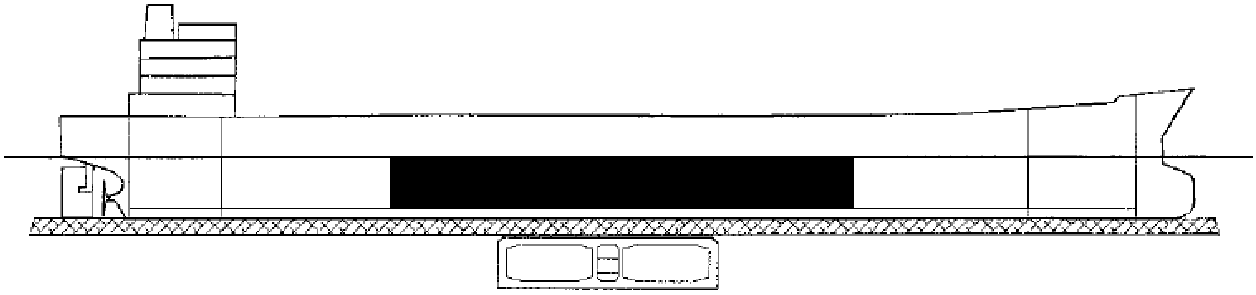


Figure 18 – Ship stranding in transverse direction

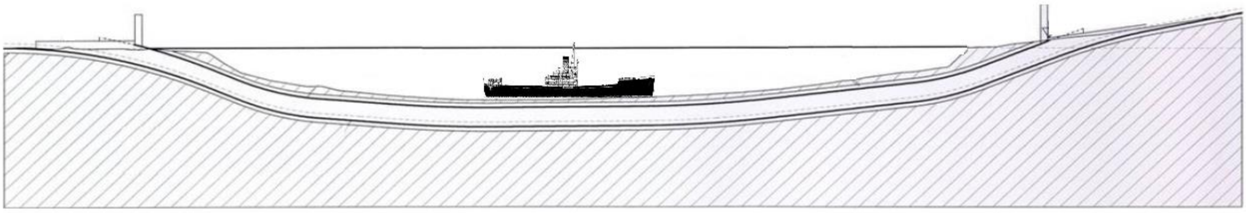


Figure 19 - Ship stranding in longitudinal direction

In case of transverse stranding, the magnitude of load on the tunnel (which is treated later on) depends on whether the tunnel lies under (Figure 18) or above (Figure 20) the river bed. Tunnels which lie above the river bed are exceptions, most of the tunnels lie under the river bed.

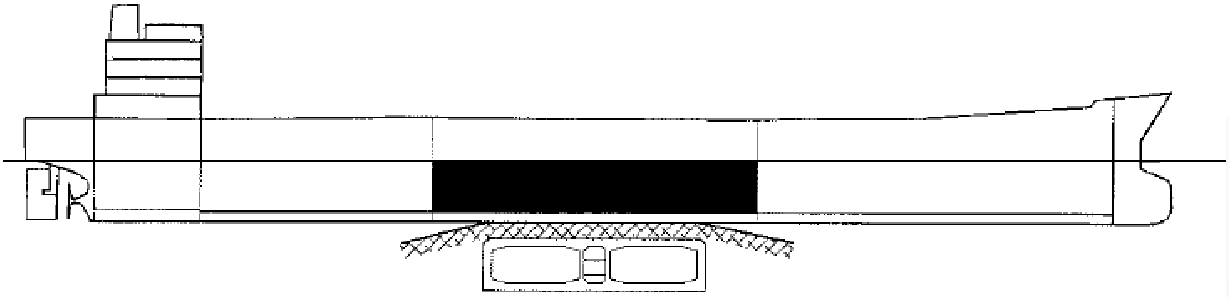


Figure 20 - Ship stranding in transverse direction, tunnel above river bed.

5.3.3.2 Sinking under an angle

In case of sinking under an angle the front of the ship rests on the tunnel while the other part of the ship is still floating. Also here a distinction is made between the situations that the ship sinks in transverse (Figure 21) or in longitudinal direction (Figure 22) of the tunnel.

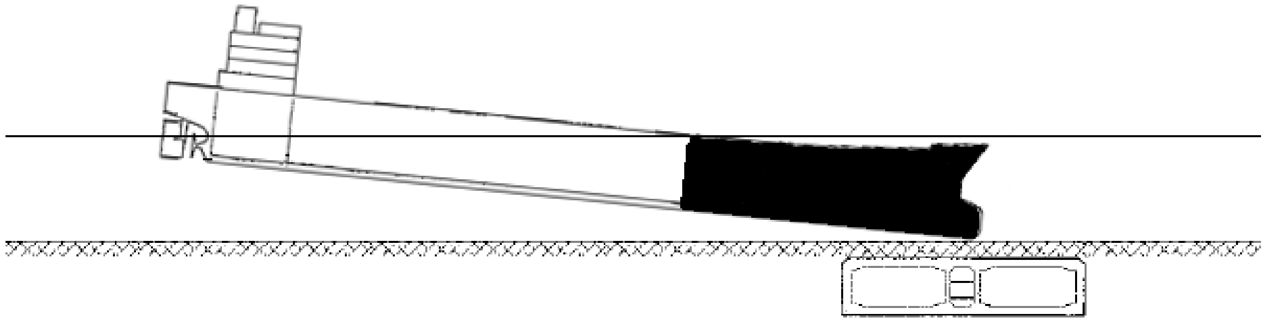


Figure 21 – Ship stranding in transverse direction

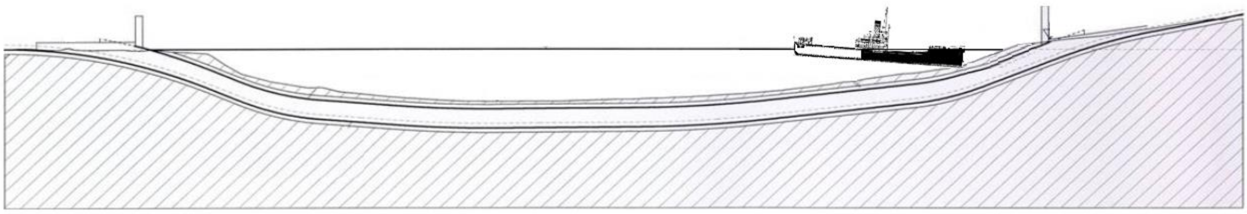


Figure 22 - Ship stranding in longitudinal direction

Important to notice is that the ship can oscillate only a few times up and down with the tide. After that the bow of the ship fails totally due to fatigue. Because the oscillations of the back side of the ship will be accompanied with deformations of the bow. It is therefore assumed that this load configuration only maintains a few days. After failure of the bow the ship sinks totally to the bottom. Then the (almost) same loading scenario is obtained as for horizontal sinking with the tunnel lying under the seabed.

Also here, in case of transverse stranding, the magnitude of load on the tunnel depends on whether the tunnel lies under (Figure 21) or above (Figure 23) the river bed. The last situation occurs only if the tide becomes that low that a large part of the bow extends above the waterline. Such situations are quite exceptional.

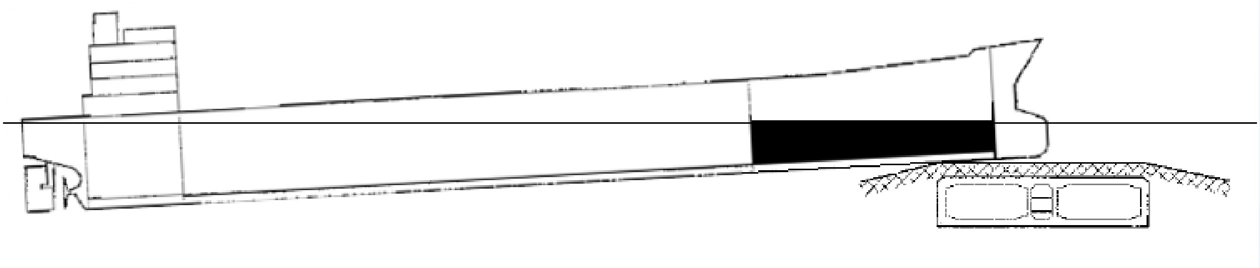


Figure 23 - Ship stranding in transverse direction, tunnel above river bed.

5.4 Loads on tunnel

In this paragraph the events which are treated before are evaluated again, but now to give an indication of the magnitude of load.

The loads which are presented in this paragraph are based on a ship which has the following characteristics: a carrying capacity of 40,000DWT, a length of 200m, a width of 28m and a draught of 11.5m. The total mass of the ship is 54,100 DWT. The tunnel width is 40m.

5.4.1 Grounding

5.4.1.1 Grounding in transverse direction

5.4.1.1.1 Tunnel above river bed

The event of grounding in transverse direction of the tunnel is schematized in Figure 24.

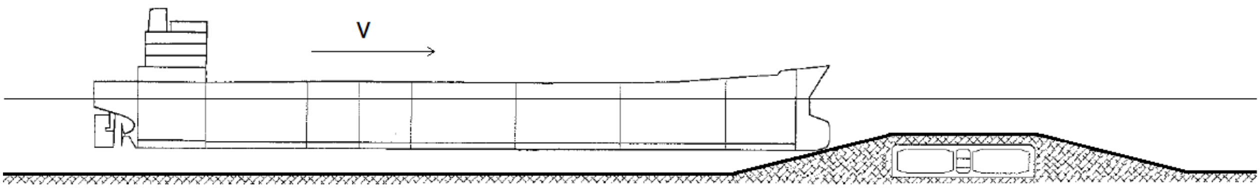


Figure 24 – Grounding in transverse direction of tunnel (tunnel above river bed)

The load on the tunnel depends on how the ship and the tunnel interact during the collision. There are basically three possible scenarios. These scenarios are schematized in Figure 26, Figure 28 and Figure 29. For each of those scenarios an indication of the magnitude of load is given. For those calculations the parameters as presented in Figure 25 are used.

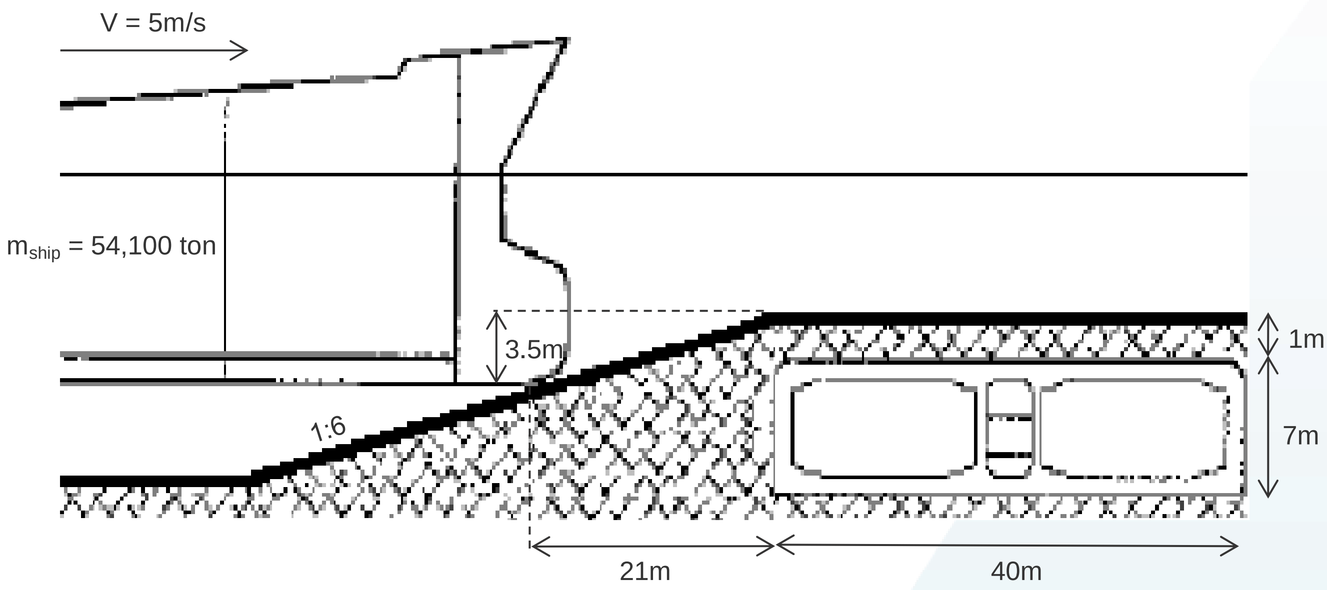


Figure 25 - Overview used parameters

Possible failure modes

<u>Option 1: Ship penetrating into the soil</u>

The first option is that the ship penetrates into the soil. This is schematized in Figure 26.

Royal HaskoningDHV

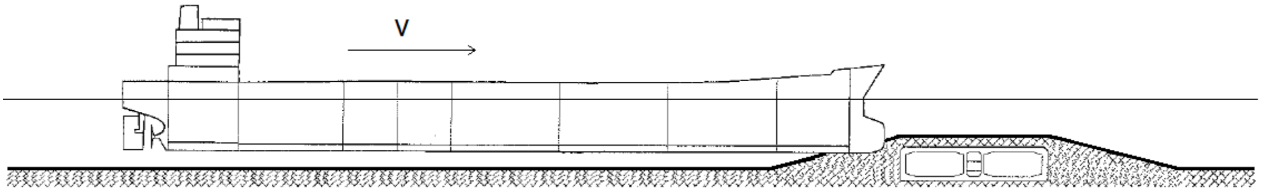


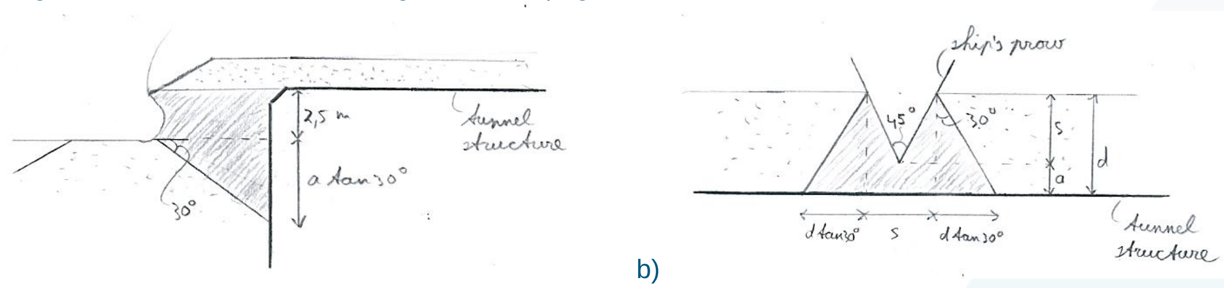
Figure 26 – Option 1: Ship penetrating into the soil

The distance between the bow of the ship and the tunnel is about 3.5*6=21m. Assume that the ship penetrates over 15m into the soil. The load which is acting on the tunnel is caused by the amount of energy absorbed by the soil per unit of time. The resulting load for this situation is calculated in Table 5. Be aware that the presented load is only present at the moment that the ship stops. The reason why the biggest load is found at that position, is explained hereafter.

Table 5 - Load from ship, penetrating into the soil

Parameter	Amount	Unit	Formula	Description
v_{ship}	5	m/s	Assumption	Speed ship
E_{ship}	680	MNm	$0.5m_{ship}v^2_{ship}$	Total amount of energy
d	21	m		Initial distance between ship and tunnel
s	15	m	Assumption	Penetration distance ship
F	45	MN	E_{ship}/s	Force
a	6	m	15-s	Distance from tunnel when ship stops
φ	0.52	rad	=30°	Angle of internal friction for sand
A	230	m^2	(s+2d*tan(φ))*(a*tan(φ)+2.5))	Supporting area tunnelwall
$q_{tunnelwall}$	190	kN/m^2	F/A	Pressure on tunnel wall when ship stops

An explanation of how the supporting area of the wall is determined, is given in Figure 27. For the configuration of the bow see also Figure 160 on page 161.



a) b)

Figure 27 - Explanation spreading of load. a) In vertical direction, b) In horizontal direction

By calculating the force through dividing *F* by *s*, implicitly the assumption is made that the energy is equally dissipated over the whole 10m. In reality most of the energy is dissipated in the last few meters and less in the first few meters.

The energy which is dissipated is caused by the friction between the ship's hull structure and the soil. The contact surface of the ship's hull structure is about a factor two at the moment that the ship stops compared to the mean contact surface. This means that the real load will be about twice as high as the presented value.

Based on the argumentation before, it can be said that the contact surface (between soil and ship) is a measure of the exerted force on the tunnel. This contact surface can be expressed as a function of the penetration distance (s) of the ship[20]. When now dividing this contact surface by the supporting area of the tunnel wall (as explained in Figure 27) a measure for the pressure on the tunnel wall is found. This ratio increases when increasing the penetration distance *s*. That means that the pressure exerted on the tunnel increases with increasing penetration distance. This explains why the pressure on the tunnel wall is the biggest at the moment that the ship stops.

As a last remark it should be said that this load is only present during the time of collision. After the ship stops there is mainly a vertical force from the ship acting on the subsoil. There will be still a horizontal force (due to this vertical force) but less[21].

<u>Option 2: Tunnel sliding over subsoil</u>

The second option, assuming that the tunnel slides over the subsoil, is schematized in Figure 28.

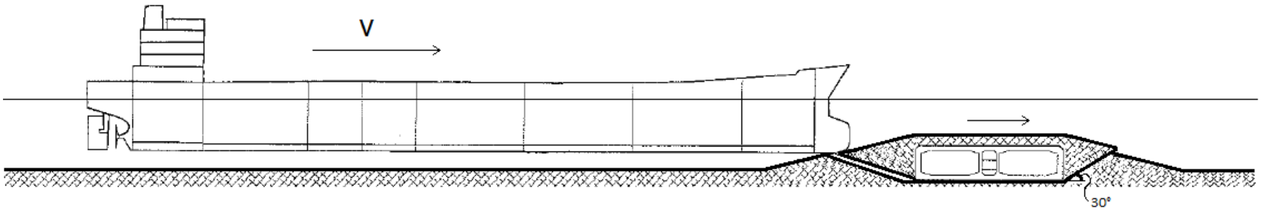


Figure 28 – Option 2: Tunnel sliding over subsoil

In this schematization the ship does not penetrate into the subsoil. In reality the ship will penetrate into the subsoil for a certain amount before the tunnel starts to slide. The total force which can be taken by the soil in case of this failure mode is given in Table 6. For this calculation the assumption is made that two segments of 20m (thus 40m in total) starts to slide.

Table 6 – Load from ship, Tunnel sliding over subsoil

Parameter	Amount	Unit	Formula	Description
V	3,500	m^3	Two segments of 20m length are displaced	Volume of soil displaced
$\rho_{soil,\ eff}$	8	kN/m^3	Assumption	Mass density of soil under water
m	31	MN	$\rho_{soil,\ eff}V$	Total mass soil
F	18	MN	m*tan(φ)	Maximum force which can be taken by the soil

From Table 6 it can be seen that the maximum force is only 18MN. This is much lower compared to the load of 68MN found for the previous option.

Based on the calculations in the previous section, it can be said that a force of 18MN corresponds with a penetration depth of about 3m. This gives a load of 50kN/m^2 on the tunnel wall (based on spreading of the load as shown in Figure 27).

<u>Option 3: Ship sliding over tunnel</u>

The third option is that a ship slides over the tunnel. Such a situation is schematized in Figure 29.

[20] $2s\sqrt{2} * 3.5\frac{s}{d} + \frac{1}{2}s^2$

[21] *Probably not larger than 50kN/m^2*

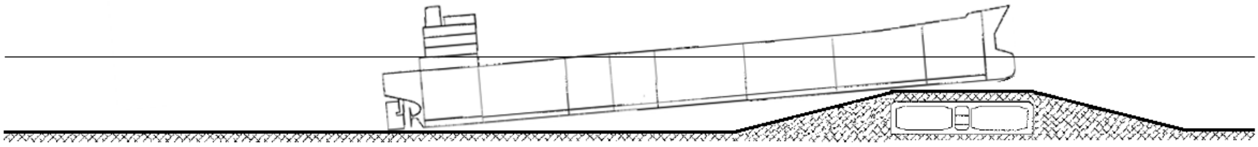


Figure 29 - Option 3: Ship sliding over tunnel

This failure mode is explained more detailed in literature. This failure mode is (in literature) assumed to be the most realistic one for small ships. Pedersen gives an indication of the development of the force in such a situation (Figure 30).

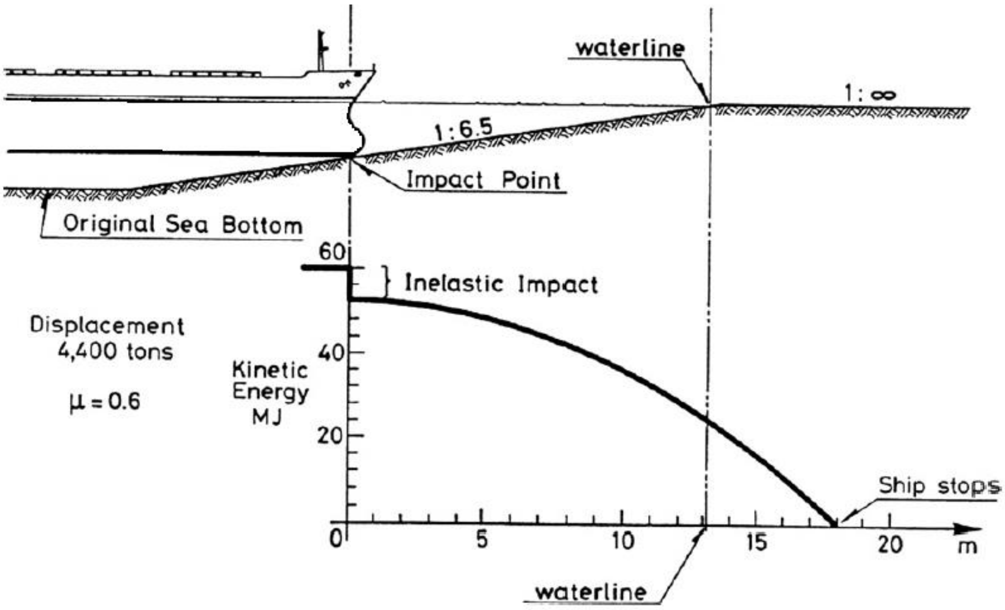


Figure 30 - Energy dissipation during powered grounding on a flat sand or rock bottom (Pedersen, 2010)

From this figure it can be seen that those results are obtained for a ship of only 4,400 tons (DWT). This is much less compared to the here evaluated 54,100DWT ship.

This force distribution starts with an inelastic impact. Pedersen states: “In the case of grounding on flat hard bottoms or sandy beaches the initial kinetic energy of the vessel will be spent on an initial inelastic impact phase, on lifting the ship and on friction between the ship and the sea bottom” (Pedersen, 2010).

The inelastic impact force reduces the total amount of energy for about 8/60=13%. This gives an inelastic impact force for a 54,100DWT ship of 90MJ (0.13*676MNm). When assuming the compression during this collision to be 0.5m, the force exerted on the soil is 90/0.5=180MN. When dividing this by a supporting area of 200m^2 (based on the spreading of load as shown in Figure 27 and *s* = 0), this gives a load on the tunnel wall of 500kN/m^2, which is quite high.

The amount of energy absorbed through friction between ship and the soil is on average 52MNm/18m=2.9MN. For a 54,100DWT ship this will be 2.9*54,100/4,400 = 36MN. This 36MN is larger than the calculated amount of 18MN as calculated in the previous option.

After the ship has loosed all its energy, it lies in the position as showed in Figure 29. This means that the ship is supported half by the tunnel and half by the soil. The ship weighs under water (assumed that the ship is almost fully flooded) only 37,000DWT. Assuming that half of that load is taken by the tunnel, the load will be 185,000kN. If the bow of the ship is assumed to be supported by an area of about 400m^2 (0.5*28^2 = the full bow area) the load becomes 460kN/m^2.

Conclusion

The results of all three options are brought together in Table 7. Be aware that the calculations are based on a lot of assumptions, but the values give an indication.

Table 7 - Forces from different failure modes

	Maximum force possible (MN)	Load on tunnel wall (kN/m²)	Load on tunneldeck (kN/m²)
Ship penetrating into the soil	68	460	0
Tunnel sliding over soil	18	50	0
Ship sliding over tunnel	180	500	460

Based on these results it can be said that highest probably the failure mode of *tunnel sliding over soil* will be the governing one. This means that the tunnel will translate under such a load from a grounding ship. However after a small displacement, the tunnel will be obstructed by the other tunnel elements. The interaction between soil, tunnel and ship becomes quite complex then. It goes too far to search this out, because the intention here is only to give an indication of the load. Therefore that will not be done here.

5.4.1.1.2 **Tunnel under river bed**

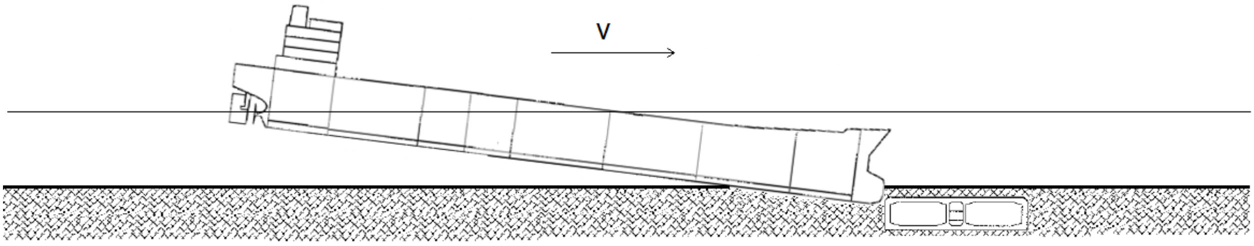


Figure 31 - Grounding in transverse direction of tunnel (tunnel under river bed)

For this event it is assumed that the load of the ship will be taken up mainly through normal forces in the deck. This assumption means that the cross section does not fail under this load. At the other hand is it most likely that the shear key of the tunnel wall fails under such a load. An example of this scenario is worked out in §7.5.2 *Longitudinal direction*, p.108.

Due to the very low probability of occurrence and the uncertainty about the magnitude of loads, this situation will not be treated further.

5.4.1.2 Grounding in longitudinal direction

The situation of grounding in longitudinal direction compares the best with the third option as explained in the previous paragraph. The main difference is the angle under which the ship touches the soil. The slope in longitudinal direction (say about 1: 50)[22] is quite small in comparison with the slope in transverse direction, as shown in Figure 25 (1:6). Therefore it is assumed that there is almost no impact force.

After the ship touches the tunnel, it starts to slide over the tunnel until it loses all its energy. This will cause mainly normal forces in the tunnel deck. But those forces remain small (about 1N/mm² if the force is fully taken by the tunnel deck). After the ship stops the ship is assumed to be fully supported by the tunnel. This is the same situation as for horizontal sinking in longitudinal direction of the tunnel. That situation is

[22] *This is a very rough estimation, but it gives an indication.*

treated in §5.4.2.1.2 *Stranding in longitudinal direction* on page 38. Loads up to 100kN/m^2 are obtained then.

5.4.2 Sinking

In case of sinking, the ship can sink on its bottom, on its side or even upside down. Although it is more likely that the ship will sink on its bottom, it is worked out which type of sinking leads to the highest loads.

First an indication of the strength for each part is given. The bottom structure of a ship is normally double walled. The side of the hull however, consist out of a single skin, with smaller stiffeners. Also the thickness of the skin at the side is less compared to the bottom. The thickness of the skin decreases from bottom to top (Ms. Stroo-Moredo, Appendix A2.2). This means that the strength of the side of the hull has a lower strength compared to the bottom. Therefore it can be assumed that if the strength of the hull structure is the governing parameter, the load from the ship when resting on his bottom is governing over the situation of a ship resting on its side.

In other situations, if the hull structure is fully supported by the bottom of the river for example, the strength of the hull structure has less influence. But it is however questionable if that leads to higher forces. The supporting area is in that situation less, so with respect to this, it can lead to higher forces. At the other hand is it well possible that the hatches go open (if they are present at all) during sinking of the ship, so that the bulk flows out of the ship. This reduces the load.

For a ship that sinks upside down on a tunnel it is assumed that the upper part of the ship will deform plastically. Because the part which is above the deck is not designed for such huge loads. Plastic deformation of the structure leads to a more equal spreading of the load. Although (from this perspective) the loads are locally still higher compared to resting of the ship on its bottom, the ultimate loads are probably less. In this situation it is quite reasonable to assume that the bulk flows out of the ship. This means that also a part of the bulk shall end up next to the tunnel. That reduces the load on the tunnel structure. Therefore it is assumed that this event will not be governing over the other two events when the ship rests on his bottom or side.

From this reasoning (together with the fact that the chance is far more that the ship sinks on its bottom than on its side or upside down) it is assumed that the loads from a ship sinking on its bottom leads to the highest loads. Therefore only that situation is evaluated.

To give an indication of the loads for each event from sinking, certain values are given in this paragraph. These values are based on a model which is presented in Appendix 2 (§A2.1 *Determining ship load on tunnel*).

5.4.2.1 Horizontal sinking

If the ship sinks horizontally, the forces exerted on the tunnel depends on whether the ship strands in transverse or longitudinal direction of the tunnel. If the ship sinks in transverse direction of the tunnel, the tunnel takes only a part of the load (if the tunnel lies under the riverbed, which is most of the time the case). If the ship sinks in longitudinal direction of the tunnel, the tunnel takes the full load of the ship.

5.4.2.1.1 Stranding in transverse direction

If the ship sinks in transverse direction on the tunnel, it makes a big difference whether the tunnel lies above the seabed, or underneath. If the tunnel lies under the riverbed, the load of the ship will be distributed over the total bottom area of the ship. A part of the load will be taken by the tunnel and also a major part by the river bed. But if the tunnel lies above the riverbed, the tunnel should take a much bigger part of the weight of the ship, depending on the strength characteristics of the ship and the amount of damage.

Tunnel above riverbed

For the situation of a tunnel which lies above the riverbed, it is assumed that the ship sinks with its middle on the tunnel (Figure 20). The chance that the ship exactly sinks with its middle on the tunnel is small, but will be treated as a worst case scenario. This is the worst case, because if the ship sinks with its bow on the tunnel, the back side of the ship will be supported by the soil next to the tunnel. The tunnel takes then only half of the load compared to the sketched situation below.

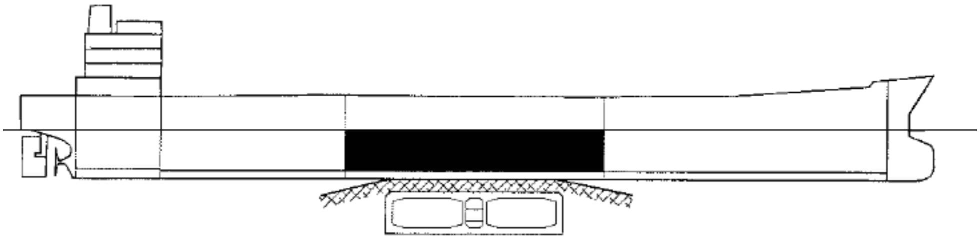


Figure 32 - Ship stranding in transverse direction

The black block represents the leaky compartments which are flooded up to the water level. In the sketched situation the bottom of the ship has reached the top of the tunnel before being totally submerged. However, during high tide, the ship can become totally submerged. It is then possible for the water to flow in the ship from above. But during low tide, the water in the intact compartments will not flow out again, but stays in the ship. This induces an additional load.

The schematisation as given in Figure 32 holds as long as the bending (or shear) capacity of the ship is not exceeded. In this situation it is most likely that the moment capacity will be decisive over the shear capacity. After exceedance of the moment capacity, the ship will break or plastically deform until new support is achieved (Figure 33). This results in a smaller load on the tunnel.

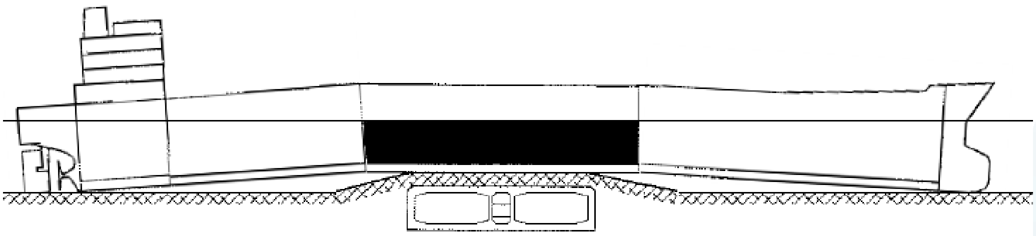


Figure 33 - Failure of bending moment capacity

For the situation before failure of the bending moment capacity of the ship, loads up to 150 kN/m^2 are obtained. This is fairly high.

Tunnel under riverbed

The situation of a tunnel under the riverbed is sketched in Figure 34.

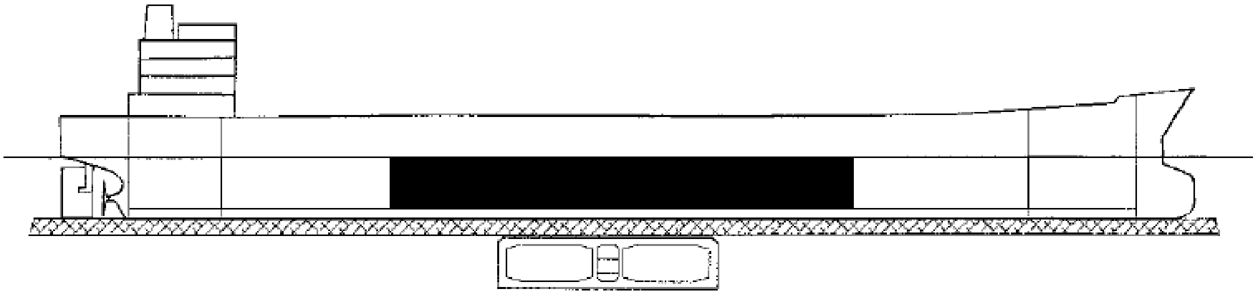


Figure 34 - Tunnel under riverbed

Situations in which a tunnel lies under the riverbed are most common. The vertical pressures are in the order of $80kN/m^2$. This load is based on the weight of the ship (partly under water, partly above) divided by the bottom area of the ship. But in reality the load exerted on the tunnel will be higher. Because the tunnel has a higher stiffness compared to the surrounding soil. It is assumed that the deformations of the supporting soil will be equal over the full length of the ship (the part of the tunnel included). A higher stiffness at the positon of the tunnel causes then a bigger load compared to the weaker surrounding soil[23].

A schematisation of this situation is given in Appendix A2.1.5.3. For that situation an increase of 60% is found[24]. That's quite substantial. This gives loads of $120kN/m^2$ instead of $80kN/m^2$.

5.4.2.1.2 **Stranding in longitudinal direction**

If the ship strands in longitudinal direction of the tunnel, the ship causes a long line load over the tunnel. The magnitudes of loads to be taken into account go up to $80kN/m^2$. This load is not that high for a cross sectional analysis. But for the longitudinal direction, the forces need more careful attention, because of the long length of the load. A ship can have a length of 200m, or even higher.

5.4.2.2 Sinking under an angle

As said, in this case the front of the ship rests on the tunnel, while the other part of the ship is still floating. Also here a distinction is made between the situations that the ship sinks in transverse or longitudinal direction of the tunnel.

5.4.2.2.1 **Stranding in transverse direction**

Tunnel under river bed

A schematisation of this situation is given in Figure 35. The weight of the ship in this situation is taken partly by the buoyancy of the ship and partly by the tunnel. The part taken by the tunnel is induced by the bow of the ship.

[23] *Since F = ku, u is equal over the full length of the ship and k is higher at the positon of the tunnel.*
[24] *For a segmented tunnel. For a monolithic tunnel an increase of 80% is found. This report focusses mainly on concrete tunnels (See §6.2 Types of immersed tunnels). Most of them are segmented. Therefore that value is used.*

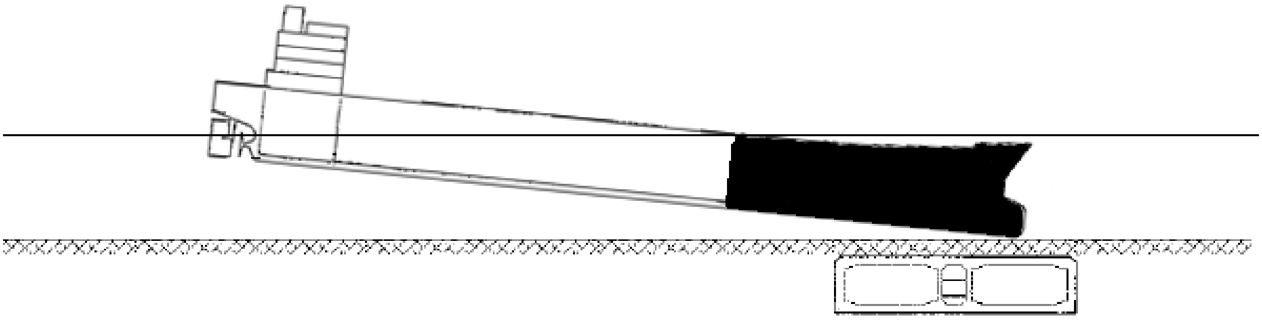


Figure 35 - Ship sunken with front part on tunnel

The bow of the ship is a strong part of the ship. It is however not that strong that it can resist the full load from the ship. When schematising the load from the ship on the tunnel to be in one point, at the far end of the ship, both the bending moment as well as the shear capacity of the ship is exceeded. It is also questionable whether the bow can resist such pressures locally. That means that the bow of the ship will fail, or that the bow punches through the tunnel deck. Those options are presented in Figure 36 and Figure 37.

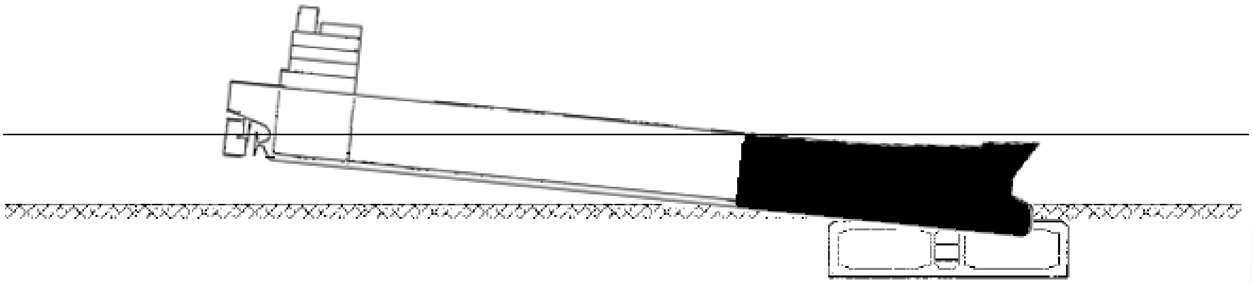


Figure 36 – Option 1: ship punching through tunnel deck

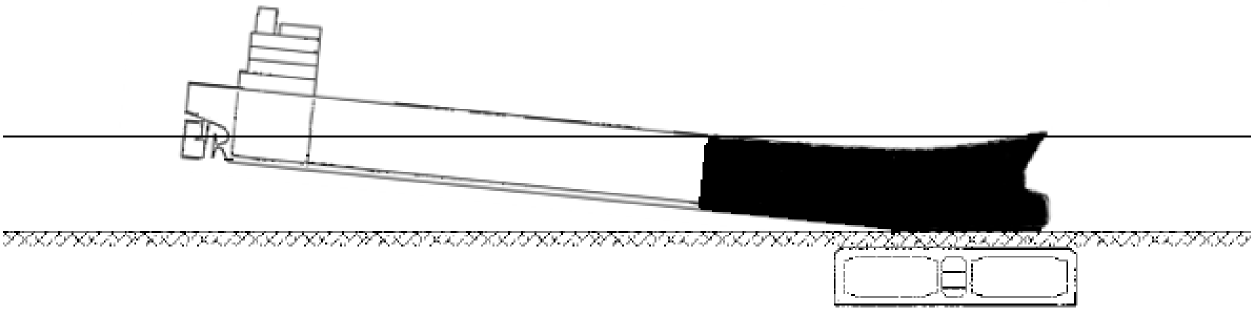


Figure 37 – Option 2: prow deforming plastically

In Appendix 2 (§A2.6 *Punching bow through tunnel deck*, p.191) is calculated what mechanism will be governing. Based on those calculations it was concluded that highest probably the second option will be the governing failure mechanism.

Through the plastic deformations of the bow of the ship, an area support is achieved. It is well possible that a part of this area is above the tunnel, and also a part above the soil. The biggest load on the tunnel is achieved if the ship is (almost[25]) fully supported by the tunnel. For this situation loads up to 190kN/m^2 are possible[26]. These are quite high loads.

Tunnel above river bed

For the situation when the tunnel lies above the riverbed the loading scheme is the same, with the only difference that the back side of the ship can sink deeper (Figure 38).

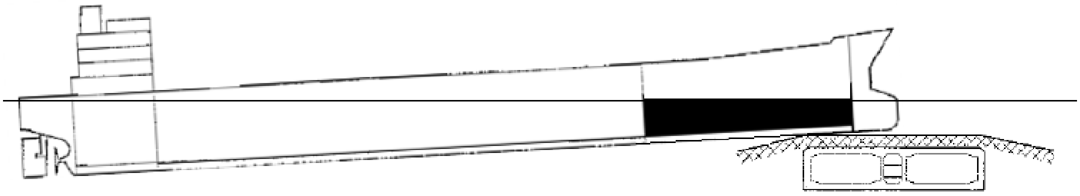


Figure 38 - Tunnel above river bed

Now the total buoyancy of the ship is less. Therefore the loads exerted on the tunnel become a little bit higher. For this situation loads up to 200kN/m^2 are possible. Here it is assumed that the ship is supported over the full length of the bow which is above the tunnel. Which assumption is reasonable, because the inclination of the ship will be small (about 1/100 rad). That means that only little deformations of the soil will give full support to the bow.

5.4.2.2.2 **Stranding in longitudinal direction**

In this situation, the ship lies in longitudinal direction of the tunnel when it fails. Important to notice is that now the back side of the ship cannot go deeper than the tunnel deck. So this is almost the same situation as sketched in Figure 35. The only difference is that now the bow of the ship is always fully supported by the tunnel. After total submerging of the ship, the same situation as for 'horizontal sinking in longitudinal direction' is obtained. So also here loads up to 190kN/m^2 are possible.

5.4.3 **Comparison governing loads with literature**

In this paragraph the values found with the aid of the model, are compared with the values found in literature. In Table 4 a lot of values were given which were used for the design of a certain tunnel. It is however difficult to try to calculate back those results. Because it was found that the load of a ship depends on many parameters. And for those values, only the width of the ship, together with an indication of the size is given. That's too little information to calculate back those results. From a few loads however more detailed information was given. That's the case for the Oosterweel tunnel (Report of Gent University) and the ITA. There is also a paragraph spend on the ROK. That paragraph evaluates whether the ROK prescribes a safe value or not.

5.4.3.1 Report of Gent University

A detailed comparison of the here presented model with the report of Gent University is made in Appendix 2 (in §A2.1.4.2 *Validation of the model* for horizontal sinking and in §A2.1.4.3 *Validation of the model* for sinking under an angle). It can be seen that the results from Gent University correspond quite well with results found in the model. The main difference which is found is the bottom pressure for a ship sinking

[25] Depending on the amount of deformations of the bow. Because due to the deformations of the bow, the supporting area might become larger than the tunnel width. It is then not possible that the ship is fully supported by the tunnel.
[26] In case of the bow being supported by the full tunnel width (which is 40m). If the bow is only supported over a length of 20m, loads even up to 450kN/m^2 are possible. That's a big difference.

under an angle. For clarification see Appendix 2 (§Validation of the modelA2.1.4.3 *Validation of the model*). It was also found that Gent University tend to predict a higher load compared to the model.

5.4.3.2 International Tunnelling Association

The International Tunnelling Association (Saveur, 1997) gives some estimates for the loads from a sunken ship, by doing simple calculations. The characteristics of the Large Bulk Carrier which is presented in the report from the ITA are given in Table 8.

Table 8 - Characteristics of ship from ITA

Parameter	Amount	Unit	Formula	Description
L	215	m		Length
L_{load}	215	m		Loaded length
B	32.2	m		Width
H	19	m		Moulded depth
T	13	m		Draught
DWT	70,000	ton	Dead weight ton	Maximum carrying capacity of ship
Δ	81,500	ton		Volume displacement
W_{ship}	11,500	ton	Δ-DWT	Mass of ship
$W_{iron\ ore}$	66,500	ton	0.9DWT	Mass of iron ore
$W_{supplies}$	3,500	ton	0.1DWT	Mass of supplies
$\rho_{iron\ ore}$	30	kg/m^3	Assumption	Density iron ore
ρ_{water}	10	kg/m^3	Assumption	Density water
ρ_{ship}	70	kg/m^3		Density material ship (steel)

For explanation of the different parameters, see Appendix A2.1.2.2.1. The results from the ITA and from the model are given in Table 9.

Table 9 - Results

	Parameter	Amount	Unit	Formula	Description
ITA					
Horizontal sinking					
	$q_{sunken\ ship\ load}$	103	kN/m^2		Load on bottom when fully submerged
Sinking under an angle					
	$R_{support\ at\ end}$	146,280	kN		Support reaction on tunnel as line load at upper end of ship
	$R_{support\ at\ 10m\ from\ end}$	126,890	kN		Support reaction on tunnel as area load of 20m length
Model					
Horizontal sinking					
	$q_{sunken\ ship\ load}$	87	kN/m^2	$(V_{ship}/L+V_{iron\ ore}/L_{Load})/(B-2)$	Load on bottom when fully submerged

$q_{\text{sunken ship load, with side effects}}$	110	kN/m^2	$q_{\text{sunken ship load}}$*1.27	Idem, with factor for higher stiffness tunnel
Sinking under an angle				
$R_{\text{without check for shear capacity}}$	209,647	kN		Support reaction on tunnel as area load of 20m length
$R_{\text{with check for shear capacity}}$	106,000	kN		Support reaction on tunnel as area load of 20m length

The result under *horizontal sinking* (ITA) is the bottom pressure of the ship on the tunnel. For the model also the value is given when the side effects are taken into account. It can be seen that the model gives a lower value for the bottom pressure when no aggravating factors are taken into account (which was not done by the ITA). When however the factors are taken into account, the estimated pressures are higher as given by the ITA.

The results from the ITA for sinking under an angle are given when assuming the support of the bow as a line load at the end of the ship, and when assuming it as an area of 20m length (times the width of the ship). The centre of this end support lies then at 10m from the end of the ship.

The result from the model for *sinking under an angle* (indicated with *R*) gives the estimated reaction force for a support length on the tunnel of 20m. What can be seen is that the model predicts a much higher load than the ITA paper assumes. That's because the calculations from the ITA are only simple calculations, while the model is much more sophisticated.

By the ITA it is also stated that for this situation the bending moment capacity is just before its breaking strength. But from the model it can be seen that not the bending moment, but the shear capacity of the ship is critical. The model predicts a reaction force (R) of 106,000kN just before shear failure of the ships' hull. This is even lower than the predicted value of 126,890kN of the ITA.

From this example it can be concluded that the value given by the ITA give a good estimation for the load in case of horizontal sinking. But for the event of sinking under an angle, there is a major difference. This situation needs to be worked out more carefully, to give a good estimation.

5.4.3.3 ROK (Richtlijnen Ontwerpen Kunstwerken)[27]

The ROK prescribes a load of 50kN/m^2 for barges, and 150kN/m^2 for sea going ships. Such a load is normally taken into account as a uniform distributed line load for the cross sectional and longitudinal analysis. In this report the load from a sunken ship[28] is taken into account as a line load for the longitudinal analysis, but not for the cross sectional analysis. In Chapter 7 (§7.2.2 *Load from representative ship*, p.77) of this report a load for a barge (the general cargo carrier) and a sea going ship (the iron ore bulk carrier) is given. The following loads are given for the longitudinal analysis: the barge gives a line load of 1050kN/m which equals to a load of 35kN/m^2. The sea going ship gives a line load of 4464 kN/m, which equals to 149kN/m^2. From these two examples, it can be seen that the ROK is on the safe side.

The load for the cross sectional analysis is not taken into account as a line load. Instead of a line load, two different valued line loads are used (called as 'block loads'). When using the same examples from Chapter 7, the barge has two block loads of 101 and 34kN/m^2 for block one and two respectively. The sea going ships has two block loads of 257 and 86kN/m^2.

[27] This is a Dutch guide line, which can be translated as: Guidelines Design civil engineering Structures
[28] In this paragraph there is antedated on the conclusion of the next paragraph that sinking under an angle is the governing failure mechanism.

Now the block loads of the model are compared with the line loads of the ROK (50kN/m^2 for the barge and 150kN/m^2 for the seagoing ship). This is done through comparing the differences in the bending moments halfway the deck from the Wijkertunnel. When taking now the moments from the ROK as 100%, the model predicts a moment which is a factor 2.2 higher for the barge. For the sea going ship the bending moment increases with a factor 1.9. This illustrates that the ROK is not safe for the cross sectional analysis.

Based on these results it can be said that the design values of the ROK can be used for the longitudinal analysis, but not for the cross sectional analysis.

5.5 Conclusion

From this chapter it can be concluded that iron ore bulk carriers are the most important type of ship. Because they cause the biggest load on an immersed tunnel in case of a sunken ship.

It appears also that the load from a ship on a tunnel depends mainly on the way how a ship hits the tunnel. Therefore all possible events of a ship hitting the tunnel are determined. Each of these events is thereafter evaluated with respect to the probability of occurrence. Also an indication of the load is given. The results of these evaluations are summarized in Table 10.

Table 10 - Probability of occurrence and load for each event

<table>
<tr><th colspan="4">Events</th><th>Probability of occurrence</th><th>Load on tunnel deck (kN/m^2)</th></tr>
<tr><td rowspan="2">Grounding</td><td colspan="3">Stranding in transverse direction</td><td>Very low</td><td>50 ([29])</td></tr>
<tr><td colspan="3">Stranding in longitudinal direction</td><td>Low</td><td>100</td></tr>
<tr><td rowspan="6">Sinking</td><td rowspan="3">Horizontal sinking</td><td rowspan="2">Stranding in transverse direction</td><td>Tunnel above river bed</td><td>low</td><td>150</td></tr>
<tr><td>Tunnel under river bed</td><td>High</td><td>120</td></tr>
<tr><td colspan="2">Stranding in longitudinal direction</td><td>Medium</td><td>80</td></tr>
<tr><td rowspan="3">Sinking under an angle</td><td rowspan="2">Stranding in transverse direction</td><td>Tunnel above river bed</td><td>Low</td><td>200</td></tr>
<tr><td>Tunnel under river bed</td><td>High</td><td>190</td></tr>
<tr><td colspan="2">Stranding in longitudinal direction</td><td>Medium</td><td>190</td></tr>
</table>

The results which are given in Table 10 are set out in a graph (Figure 39). In this graph circles are added, to give an indication of the importance for each event.

[29] *Load on tunnel wall and not on tunnel deck! The load on the tunnel deck is zero.*

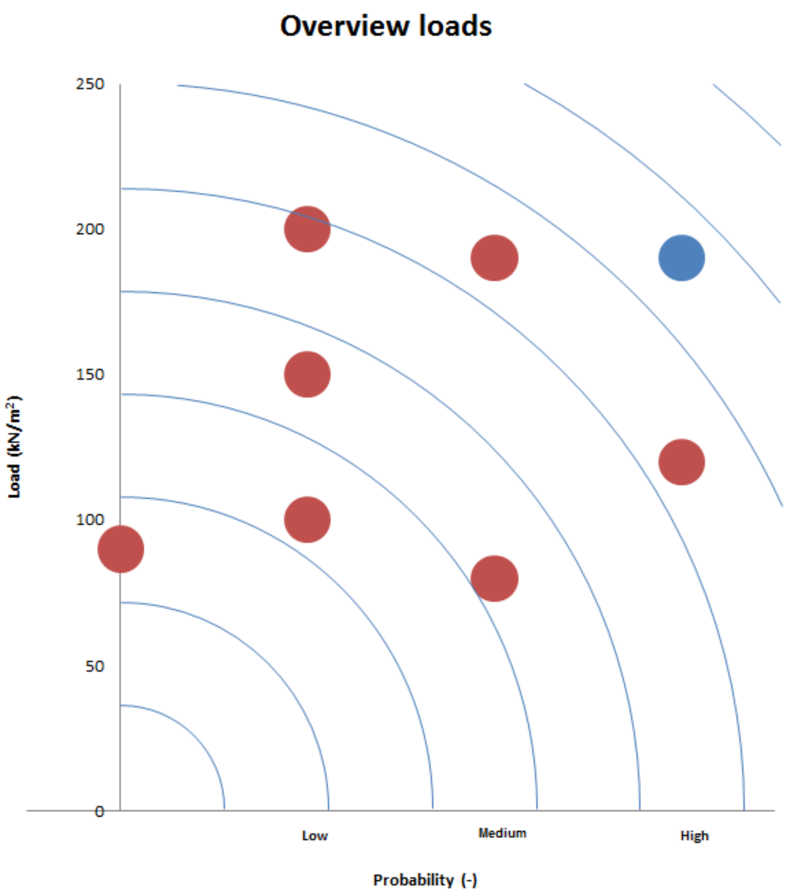


Figure 39 - Load vs probability with circles of importance

From Figure 39 it becomes clear what event has the highest importance (the blue one). That's the event of sinking → sinking under an angle → stranding in transverse direction → tunnel under riverbed.

This result does not necessarily mean that this event always leads to the worst situation for the tunnel. Because the load of this event is only present over a small area. While if the ship sinks horizontally, in longitudinal direction of the tunnel, the full load of the ship rests on the tunnel. This can have more severe consequences[30] compared to sinking under and angle, although the local pressure on the tunnel deck is less.

Due to the many dependences it is difficult to calculate back a sunken ship load. The results from the Report of Gent University are reliable, but tend to be fairly high. The results from the ITA are less reliable, especially for sinking under an angle. The values prescribed by the ROK are safe for the longitudinal analysis, but not for the cross sectional analysis.

[30] *It is meant here that higher forces in the shear keys can be obtained for that situation. But a little investigation showed that this most of the time not will happen.*

6 Structural behaviour

6.1 Introduction

In this chapter the structural behaviour of an immersed tunnel is examined. Before doing this, a short overview is given about the type of immersed tunnels which are most common used. Based on this it is showed which types of tunnels are most relevant for the research.

The structural behaviour of these tunnels is evaluated when subjected to loads in normal conditions and separately when subjected to a sunken ship load. This is done both for the cross section as well as for the longitudinal direction. Based on that evaluations it becomes clear which locations in an immersed tunnel can become critical when subjected to a sunken ship load.

6.2 Types of immersed tunnels

6.2.1.1 Concrete tunnels

A typical example of a concrete tunnel cross section is given in Figure 40. Concrete tunnels usually have a squared cross section. With respect to the longitudinal direction, concrete tunnels can be monolithic or segmented (Figure 41). A concrete tunnel is strengthened by reinforcement to take up the bending moments and shear forces. Monolithic concrete tunnels can also be strengthened by pre-stressing instead of reinforcement.

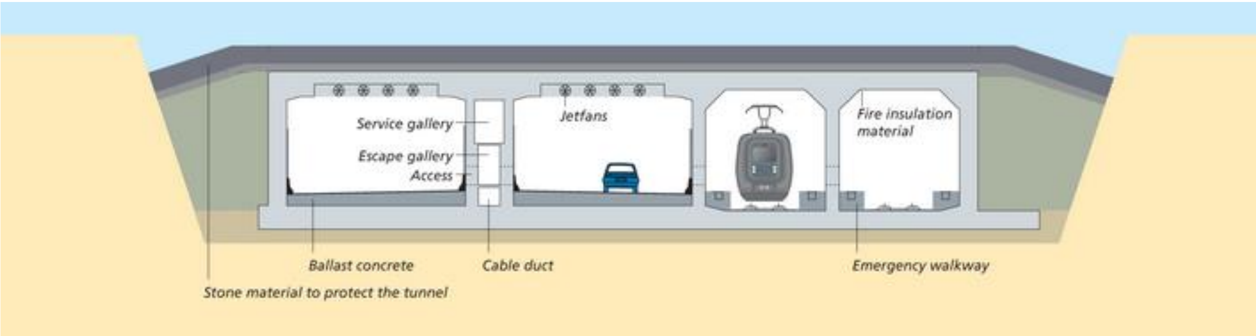


Figure 40 - Concrete tunnel[31]

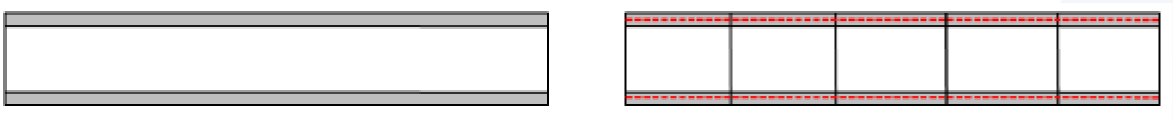


Figure 41 - Monolithic concrete element (left) and segmented conrete element (right)

A monolithic concrete element is casted in different pours. Although this limits the amount of shrinking during hardening of the concrete, the fresh concrete is still restrained by the already hardened concrete from the previous cast. This causes a higher risk of cracking of the concrete during construction. Therefore often a steel membrane is applied as an additional waterproofing. This membrane has however often no structural function. "*Only a number of studs are used, so no composite structural action occurs between the steel and the concrete, and the steelwork acts solely as a waterproofing membrane*" (Lunniss & Baber, 2013).

[31] *Taken from http://www.femern.com/home/construction-phase/the-history-of-oresundsbron/the-oresund-tunnel.*

For a segmented tunnel, the length of a segment is determined such, that no shrinkage cracks develop during hardening of the elements (Lunniss & Baber, 2013). So therefore for segmented tunnels, no steel membrane is needed.

6.2.1.2 Steel concrete tunnels

The most common forms of steel concrete tunnels are single steel shell (Figure 42) and double steel shell tunnels (Figure 43). They have always a more or less circular cross section. There are also tunnels with a fully composite steel concrete sandwich section (Figure 44). They can have (as is showed in the picture) a squared cross section. This type of tunnel however is not commonly applied. Until now only two tunnels of this sandwich construction are applied in Japan and one of them in Turkey. With respect to the longitudinal direction it is here noted that all steel concrete tunnels are monolithic.

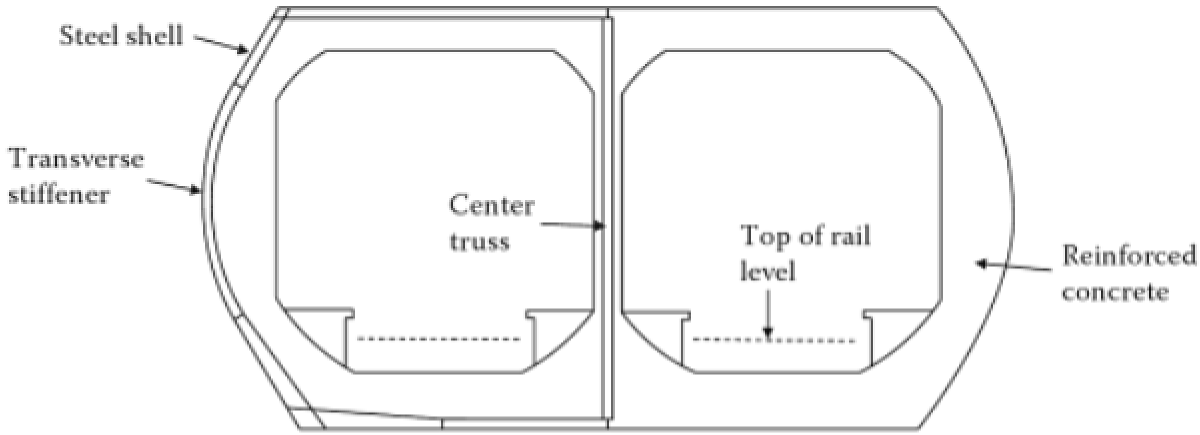


Figure 42 - Single steel shell tunnel (Lunniss & Baber, 2013)

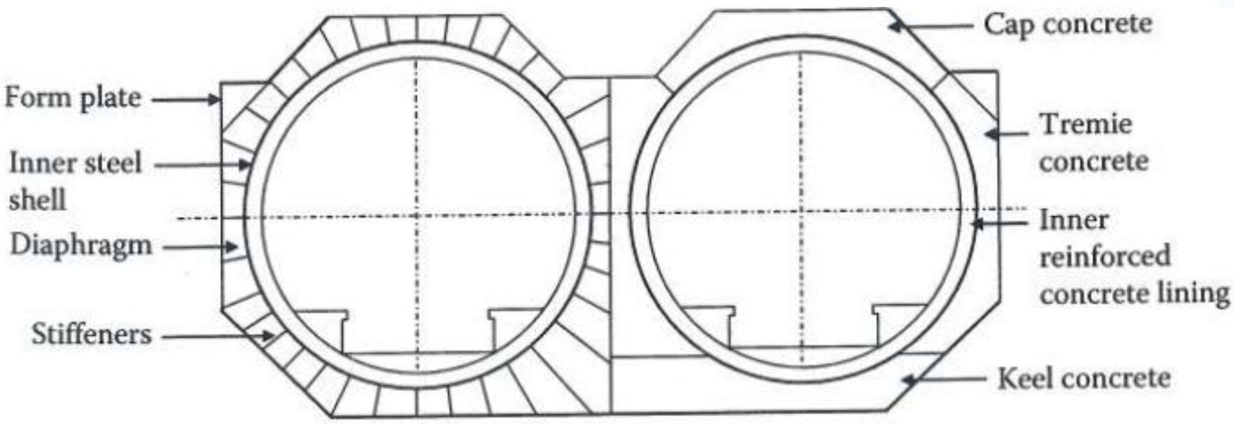


Figure 43 - Double steel shell tunnel (Lunniss & Baber, 2013)

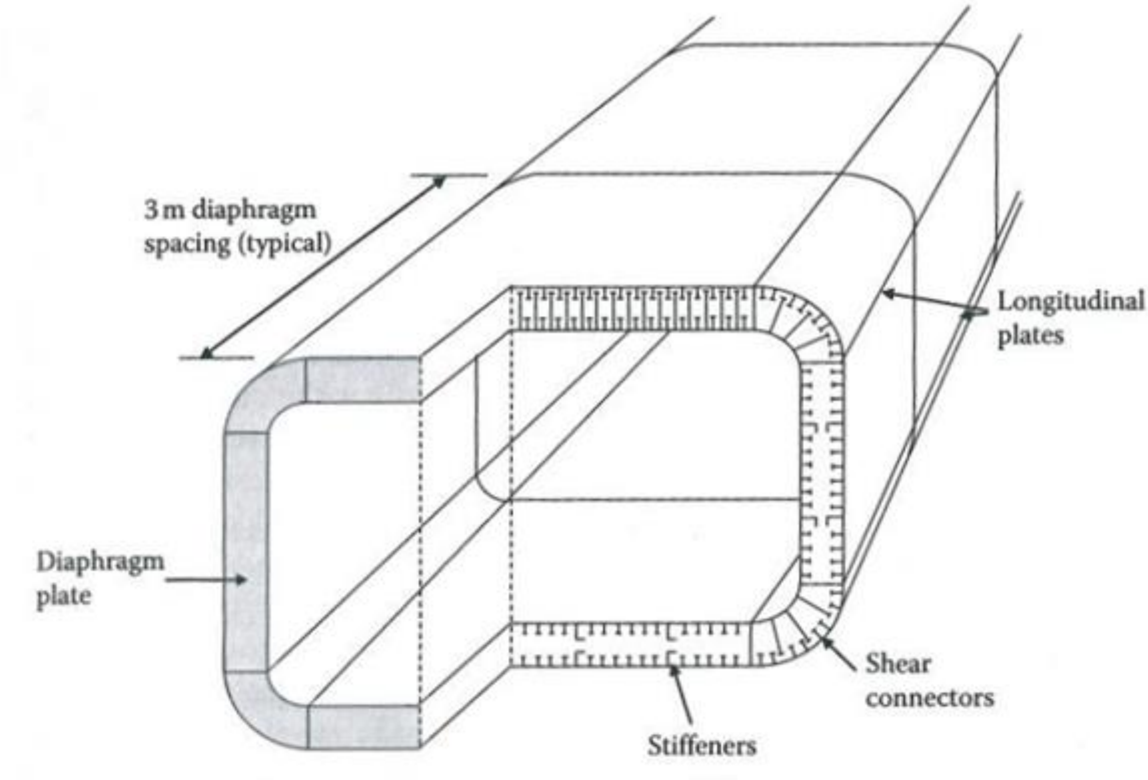


Figure 44 - Sandwich construction (Lunniss & Baber, 2013)

The steel shell from the single steel shell tunnels acts compositely with the concrete. So for this type of tunnel, the steel has both a waterproofing as well as a structural function.

For the double steel shell structure, it is a little bit different. The outer steel shell has only a waterproofing function and the concrete between the inner and outer shell has only a ballast function, so no structural function. The strength of the structure is gained by the inner steel shell together with the inner reinforced concrete lining.

6.2.1.3 Relevant type of tunnel for research

Steel tunnels are commonly applied in the west regions of the world, the US for example. This type of tunnel is however never applied in the Netherlands. Steel concrete tunnels can have a circular or a rectangular cross section. Concrete tunnels however have always a rectangular cross section. There is nowadays a tendency to build mainly immersed tunnels with a rectangular shaped cross section. This makes concrete tunnels more interesting.

For the longitudinal direction, it was explained that steel tunnel are always monolithic. Concrete tunnels can be monolithic as well as segmented. So also with respect to the longitudinal direction it can be concluded that the concrete tunnels are more relevant.

From the reasoning above it is concluded that concrete tunnels are more relevant than steel concrete tunnels. Therefore the focus of the report will be on that type of immersed tunnels.

6.3 Structural behaviour of concrete immersed tunnels

In this part the structural behaviour of concrete immersed tunnels is evaluated. To be able to see the relative importance of a sunken ship load, first the loads in normal conditions are determined. A representative value for the load of a sunken ship can be derived from the previous chapter.

After that the structural response (in terms of normal forces, shear forces and bending moments) of the tunnel is evaluated for both the loads in normal conditions as well as for the case of a sunken ship. This is done for the cross section and the longitudinal direction.

6.3.1 Loads

Loads in normal conditions of a tunnel can be distinguished in permanent, variable and accidental loads. All loads which are mentioned in this paragraph are without load factors. The corresponding load factors are given in each corresponding paragraph when evaluating the forces in the structure.

6.3.1.1 Permanent loads

The most important permanent loads are:

- Self-weight of the tunnel structure
- Ballast Concrete
- Water pressure
- (rock) Protection layer

The self-weight of the tunnel structure is determined by the reinforced concrete tunnel structure. A monolithic element needs more reinforcement compared to a segmented tunnel, therefore the density of a monolithic concrete element is more than for a segmented tunnel. A first estimation gives a load of about 75kN/m^2 for the Wijkertunnel[32], whereby a density of 25kN/m^3 for the reinforced concrete is used. The presented value is calculated by dividing the total mass of the structure by the bottom area of the tunnel.

The ballast concrete is the amount of concrete placed on the bottom of the tunnel. That's needed to prevent uplifting of the tunnel structure. Assuming a thickness of 0.5m, and a density of 23kN/m^3, this gives a load of approximately 10kN/m^2.

The water pressure is defined by the water column above the deck of the tunnel structure. Depending on the depth of the tunnel, the load from water can vary from 50kN/m^2 for a tunnel at 5m depth to 300kN/m^2 for a tunnel at 30m depth. Depending on the height of the tunnel structure, the water load which is acting at the bottom of the tunnel is most of the time about 80kN/m^2 higher (acting in upward direction).

On top of the tunnel almost always a (rock) protection layer is present. The thickness of that layer lies in the order of magnitude of 1m. Assumed is that the gravel density is 15kN/m^3. Then the weight under water becomes 15 - 10 = 5kN/m^3. This results in a load of 5kN/m^2 on top of the tunnel deck.

Table 11 - Indication magnitude of load for permanent loads

	Load (kN/m^2)

[32] The Wijkertunnel is used as reference tunnel to evaluate the loads in this chapter. It was not known yet that this tunnel later on would be used for the case. Therefore sometimes some values are not fully correct. But that doesn't matter, because this chapter is only written to given a first indication of the structural behaviour.

Self-Weight (total load which is acting on foundation)	80
Ballast Concrete	10
Water pressure (deck)	50-300
Water pressure (bottom)	100-400
Protection layer	5

6.3.1.2 Variable loads

The most important variable loads are:

- Traffic through tunnel
- Water level variation

The traffic can be normal vehicles or railway traffic. Loads from vehicles lie in the order of magnitude of 10kN/m^2 for the main traffic lane[33]. For the other lanes a load of about 3kN/m^2 should be used. For railway traffic, the load lies in the order of 100kN/m^2. This load for a train is based on load model SW/2, and a rail bar distance of 1.5m.

Traffic loads are most of the time not significant. Only in very special cases the loads can be of importance in case of railway traffic, supported by suspended slabs (Lunniss & Baber, 2013).

The water level variation differs from place to place. As an example: the water level variation is about 3m during tidal fluctuations in Vlissingen[34]. This gives a variation in load of +15kN/m^2 (during high tide) or -15kN/m^2 (during low tide).

Table 12 - Indication magnitude of load for variable loads

	Load (kN/m^2)
Normal traffic (load on road)	10 (2.5)[35]
Railway traffic (load on track area)	100
Water level variation (load on deck)	+/-15

6.3.1.3 Accidental loads

The most important accidental loads are:

- Extreme high water
- Explosion
- Sunken ship

The height of an extreme high water level differs from place to place. As an example: in Borgharen-dorp the extreme water height was about 46m +NAP, while a more normal water height is 40m +NAP. This is a difference of 6m water column. In other words: a difference of 60kN/m^2.

[33] The presented values here are for bridges (EC1, part 2). The intention is here only to give an indication. It is therefore assumed that the order of magnitude will be the same for bridges as for normal roads.
[34] http://www.watersportalmanak.nl/getijdentabellen-2016/vlissingen
[35] This value should be used for traffic lane two and three. The value of 10kN/m2 needs only to be used for traffic lane 1.

For an explosion event, a load of 100kN/m^2 is prescribed (Foundation Postacademic education, 2001). This load needs only to be present in one tunnel tube.

The sunken ship is explained in more detail in the previous chapter. Based on an example calculation what is carried out in Chapter 8 it can be concluded that 300kN/m^2 a representative load is for a sunken ship. This load is applied over a triangular shaped area (Figure 160). That results in two block loads for the cross sectional analysis as explained in Appendix 2 (§A2.1.3.2.8 *Load on tunnel*, p.164). Block 1 is 280kN/m and block 2 is 93kN/m. Due to the triangular shaped area, the load in longitudinal direction is 0.5*300kN/m^2*width of the tunnel. This equals to 0.5*300*30 = 4500kN/m.

An overview of the loads is given in Table 13.

Table 13 - Indication magnitude of load for accidental loads

	Load (kN/m^2)
Extreme high water (deck)	60
Explosion	100
Sunken ship	300 ([36])

6.3.2 Cross sectional behaviour

Having determined the loads, now the behaviour of the structure can be evaluated with respect to these loads. In this part the cross sectional behaviour is evaluated. That is first done for loads under normal conditions. After that for sunken ship loads.

6.3.2.1 Behaviour under normal load conditions

To give an indication of the forces, they are applied to a road tunnel (Wijkertunnel). A schematisation of this tunnel is given in Figure 45. The dimensions which are used are the centre lines of the structural members. All loads which are applied are for a tunnel at a depth of 30m.

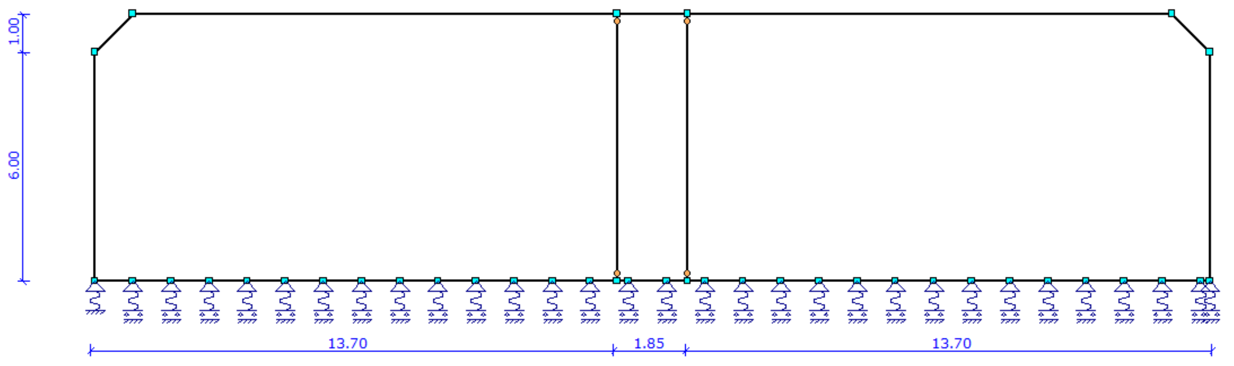


Figure 45 - Schematisation of the road tunnel (Wijkertunnel) which is used for evaluation of the loads (assuming the deck to be at a depth of 30m)

As can be seen in Figure 45, the tunnel is supported by springs. These springs represent the soil. In reality this schematisation is not totally correct. The load from the deck is transferred through the walls to the bottom. This induces high concentrated loads at the bottom of those walls on the ground. As a

[36] *For how this load is taken into account, see the explanatory text above, or the corresponding paragraphs.*

reaction to this, the soil behaves more stiff under the walls compared to the surrounding soil. This information needs to be kept in mind by interpreting the results.

6.3.2.1.1 **Permanent loads**

The permanent loads are indicated in Figure 46.

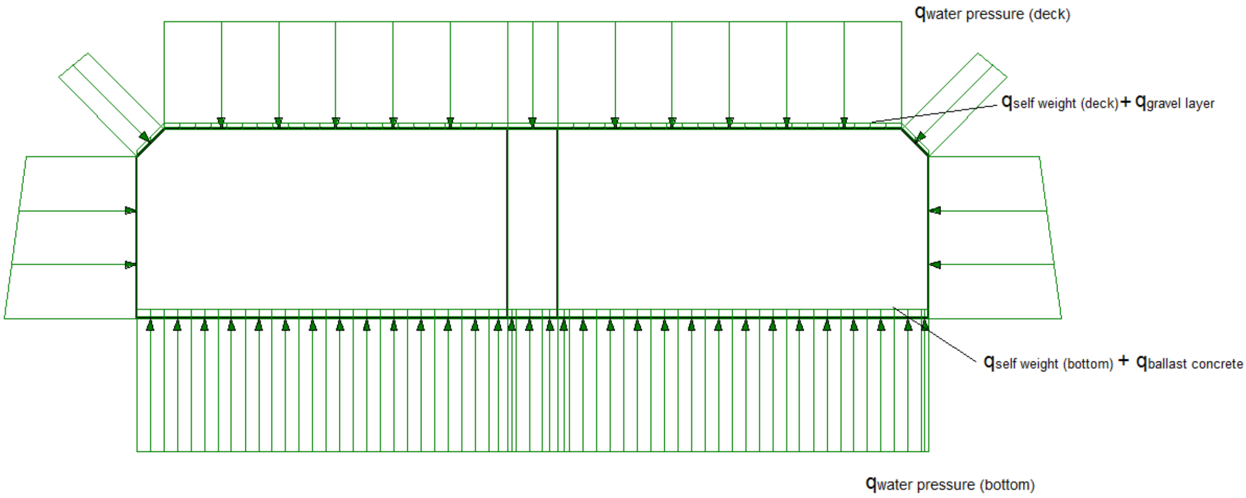


Figure 46 - Permanent loads on tunnel

The results are given in Figure 47 till Figure 49. For these results use is made from the (second) permanent load combination and taking into account only the permanent loads:

$$E_d = \Sigma\gamma_{G;j}G_{k,j} \qquad (3)$$

The corresponding load factors are given in Table 14.

Table 14 - Load factors for permanent load combination

	Load factor
Self-Weight (total load which is acting on foundation)	1.35
Ballast Concrete	1.35
Water pressure	1.35
Protection layer	1.4

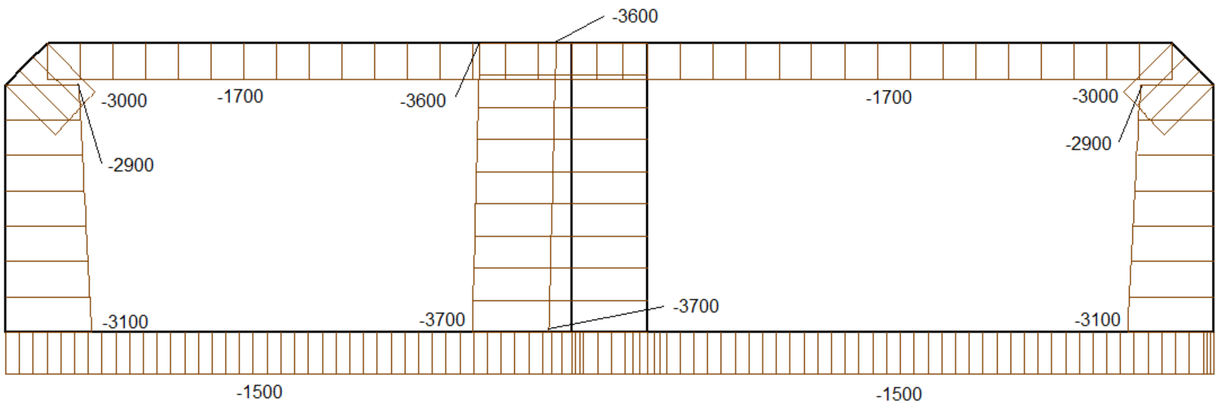


Figure 47 - Normal forces permanent load combination

Important to notice with respect to the normal force, is that the cross section is full under compression. This implies that the structure is fully water tight.

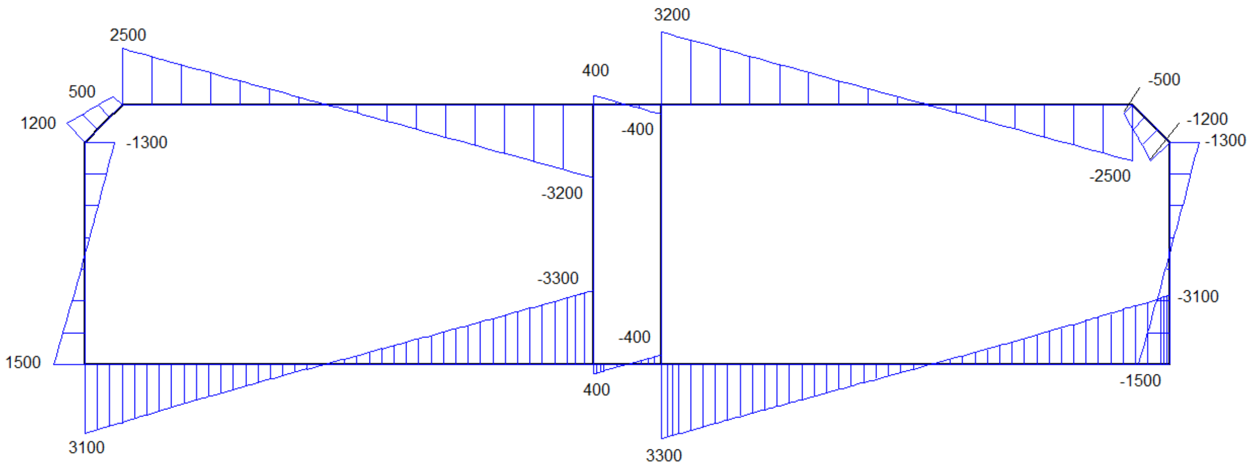


Figure 48 - Shear forces permanent load combination

For the shear forces, the biggest force occurs near the inner wall, at the position of the chamfer. Here also the biggest cross section is available. So a more detailed analysis is needed to see if that shear force is the most critical one.

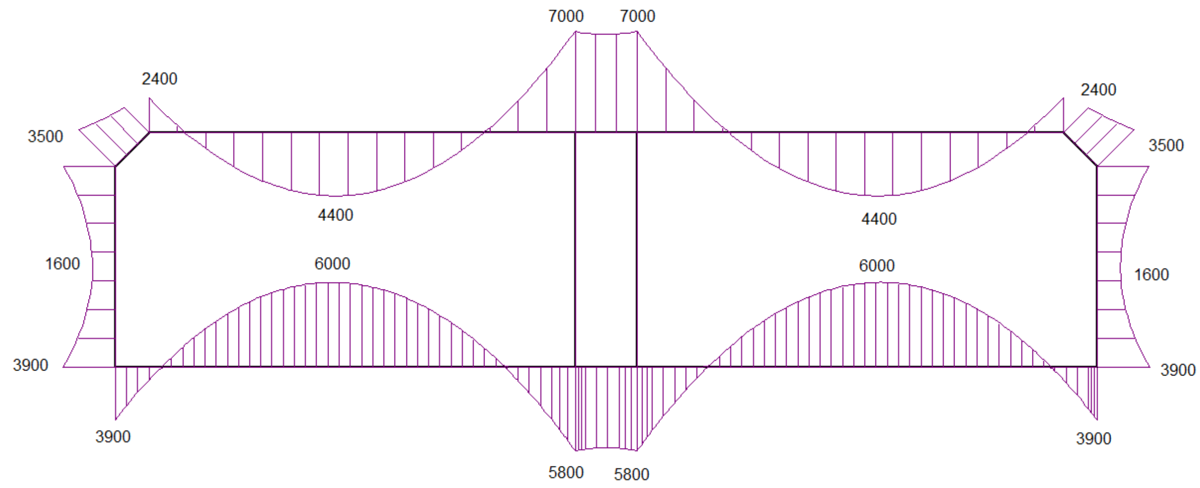


Figure 49 - Bending moments permanent load combination

Also the biggest bending moments occur near the wall. Also here the same reasoning holds as for the shear forces. A more detailed analysis must show what location is most critical with respect to the bending moments.

Loading for a tunnel at 5m depth

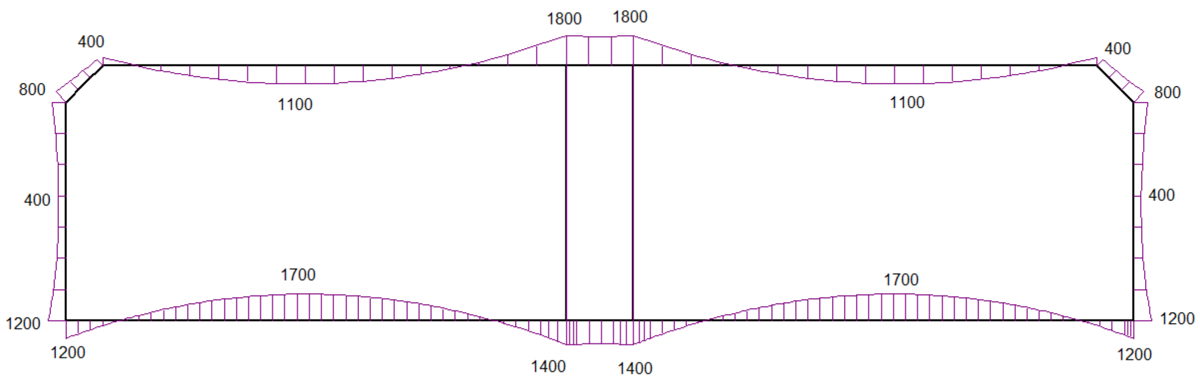


Figure 50 - Bending moments for a tunnel at 5m depth for the permanent load combination

When comparing Figure 50 to Figure 49 it can be seen that the bending moments for a tunnel at 5m depth are much lower than for a tunnel at a depth of 30m.

Loading for a metro tunnel

A railway tunnel has a different configuration. To see the effects of this, the loads are also applied on a railway tunnel (Marmaray tunnel, Istanbul). A schematisation of this tunnel is given in Figure 51.

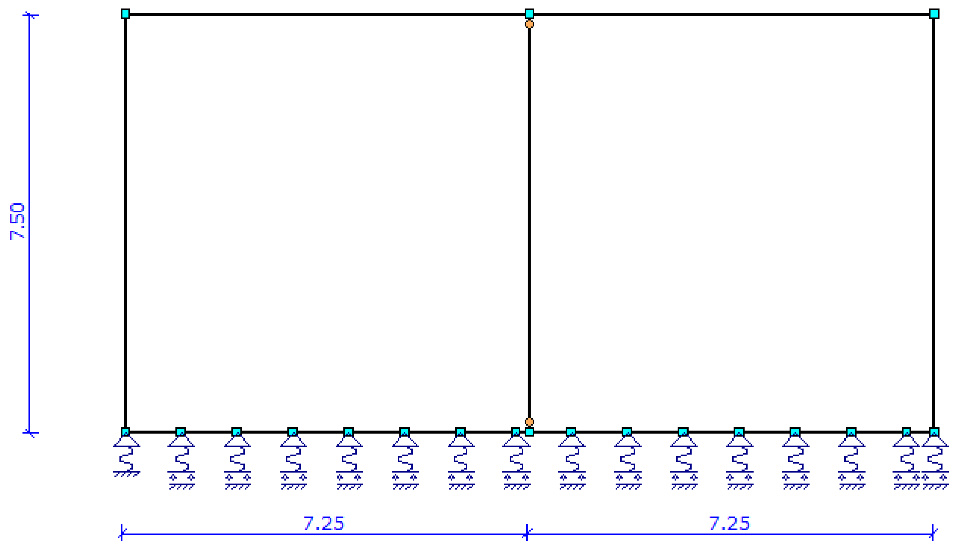


Figure 51 – Schematisation of a railway tunnel (Marmaray tunnel)

The bending moments are given in Figure 52.

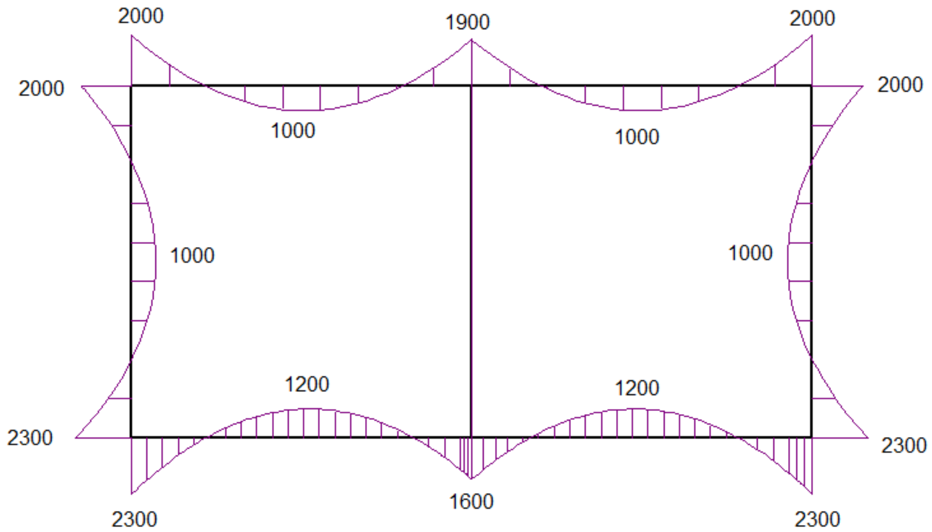


Figure 52 - Bending moments permanent load combination

When comparing Figure 52 with Figure 49 it can be seen that the bending moments in a railway tunnel are much lower compared to a roadway tunnel when subjected to the same loading conditions.

6.3.2.1.2 **Variable loads**

The variable loads are indicated in Figure 53.

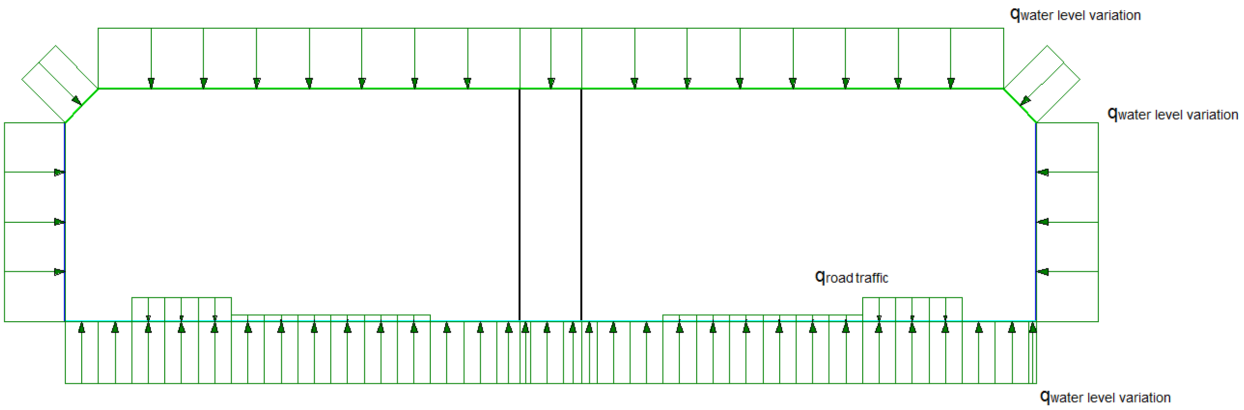


Figure 53 - Water level variation + traffic loads

The resulting bending moments are presented in Figure 54. For this result use is made from the combination:

$E_d = \gamma_{Q,1}Q_{k,1} + \Sigma\gamma_{Q,i}\psi_{0,i}Q_{k,i}$ *(4)*

The load from the water level variation is here assumed to be the dominating load, with the traffic load being the second one. The corresponding load factors (and combination factor) are given in Table 15.

Table 15 - Load factors (and combination factor) for variable loads

	Load factor	Combination factor	Total
Water level variation (load on deck)	1.2	-	1.2
Normal traffic (load on road)	1.5	0.6	0.9

In this way the additional loads due to the variable loads are visualized.

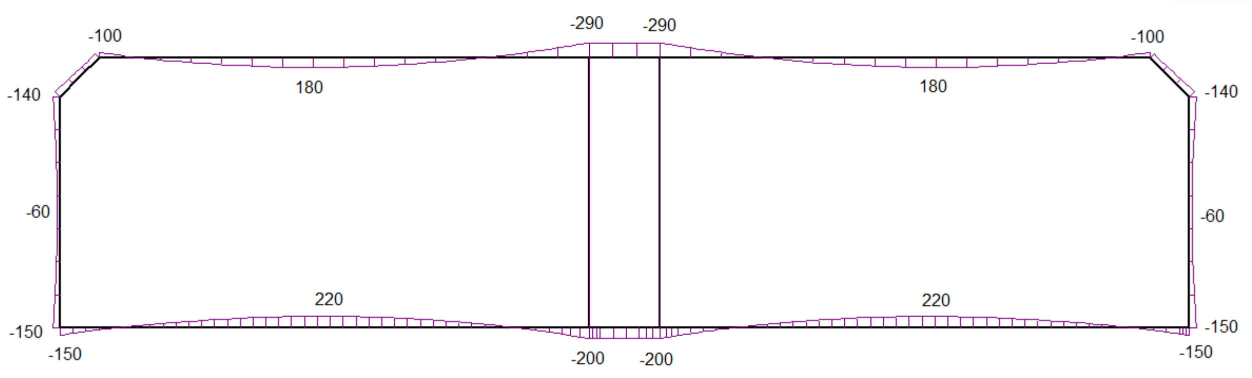


Figure 54 - Bending moments variable loads

From Figure 54 it can be seen that the variable loads has only little influence on the forces in the structure.

When adding those loads to the permanent loads, the bending moments as presented in Figure 55 are obtained. For this result use is made from the combination:

$E_d = \Sigma\gamma_{G;j}G_{k,j} + \gamma_{Q,1}Q_{k,1} + \Sigma\gamma_{Q,i}\psi_{0,i}Q_{k,i}$ *(5)*

For this bending moment diagram use is made from the load factors as presented in Table 16.

Table 16 - Load factors permanent load combination with variable loads included

	Load factor	Combination factor	Total
Self-Weight (total load which is acting on foundation)	1.25	-	1.25
Ballast Concrete	1.25	-	1.25
Water pressure	1.25	-	1.25
Protection layer	1.25	-	1.25
Water level variation (load on deck)	1.2	-	1.2
Normal traffic (load on road)	1.5	0.6	0.9

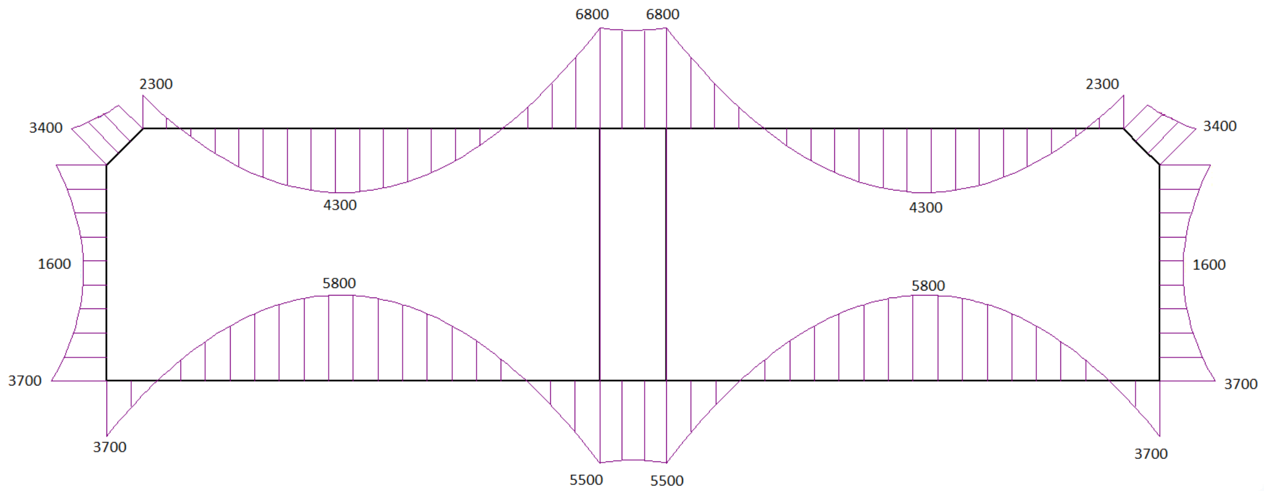


Figure 55 – Permanent load combination with variable loads included

It can be seen that this load combination leads to lower forces compared to the permanent load combination (without variable loads). This can be seen when comparing Figure 55 with Figure 49. That means that this load combination is not the governing one.

6.3.2.1.3 **Accidental loads**

The accidental loads are presented in different figures. Because accidental loads are never taken into account in a combination with other accidental loads. The loads from an extreme high water level and an explosion are given in Figure 56 and Figure 57 respectively. The accidental load case from a sunken ship is treated separately in the next paragraph, because that part needs more detailed evaluation.

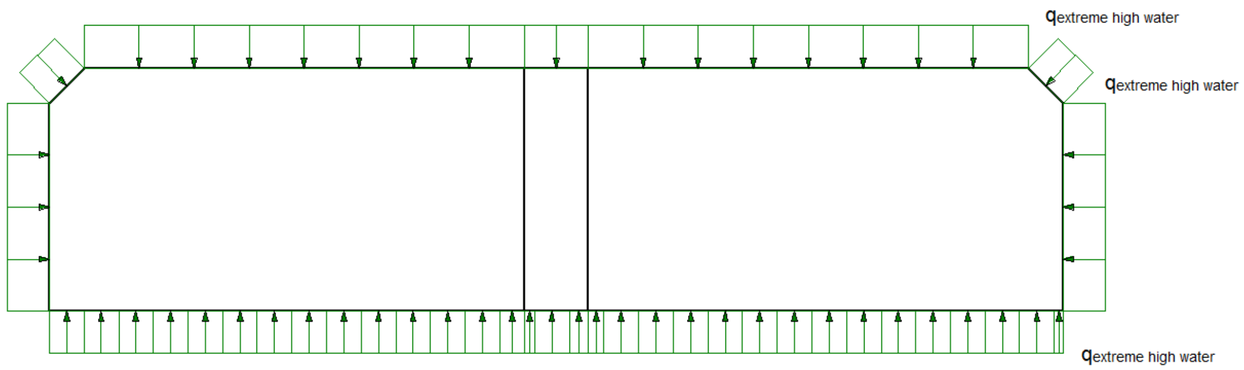


Figure 56 – Extreme high water load

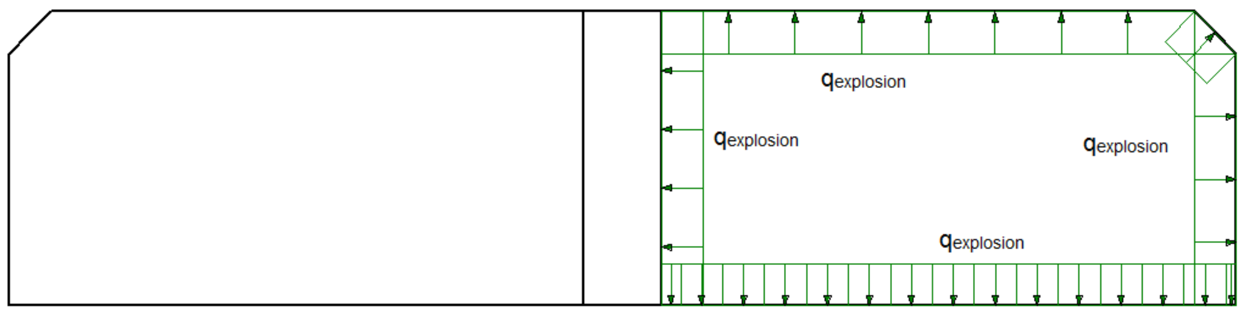


Figure 57 - Explosion load

Due to the separate treatment of each accidental load, the following holds for calculation of the loads:

$E_d = A_d$ *(6)*

For the accidental load combination, no load factors need to be taken into account, because they are all one (Table 17).

Table 17 - Load factors for accidental loads

	Load factor
Extreme high water	1.0
Explosion	1.0
Sunken ship	1.0

The influence of an extreme high water level on the forces in the cross section is given in Figure 58.

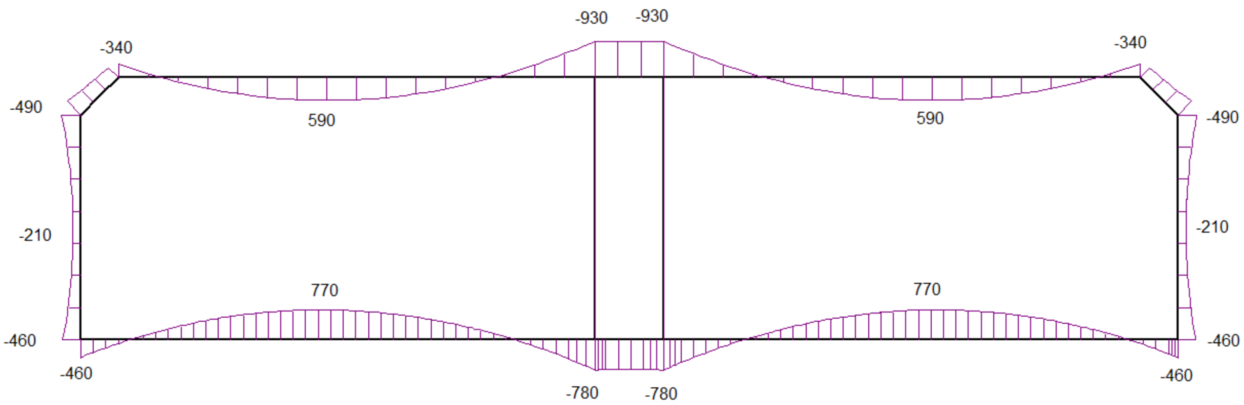


Figure 58 - Bending moments from extreme high water level

From Figure 58 it can be seen that an extreme high water level can have a significant influence on the forces in the cross section. The forces are however still a factor lower compared to the permanent forces.

The total accidental load combination (with an extreme high water as accidental load) is given in Figure 59. For this result use is made from the combination:

$$E_d = \Sigma\gamma_{G;j}G_{k,j} + \gamma_{Q,1}Q_{k,1} + \Sigma\gamma_{Q,i}\psi_{0,i}Q_{k,I} + A_d \qquad (7)$$

For this bending moment diagram use is made from the load factors as presented in Table 18.

Table 18 – Load factors accidental load combination (extreme high water)

	Load factor	Combination factor	Total
Self-Weight (total load which is acting on foundation)	1.0	-	1.0
Ballast Concrete	1.0	-	1.0
Water pressure	1.0	-	1.0
Protection layer	1.0	-	1.0
Water level variation (load on deck)	1.0	-	1.0
Normal traffic (load on road)	1.0	0.6	0.6
Extreme high water	1.0	-	1.0

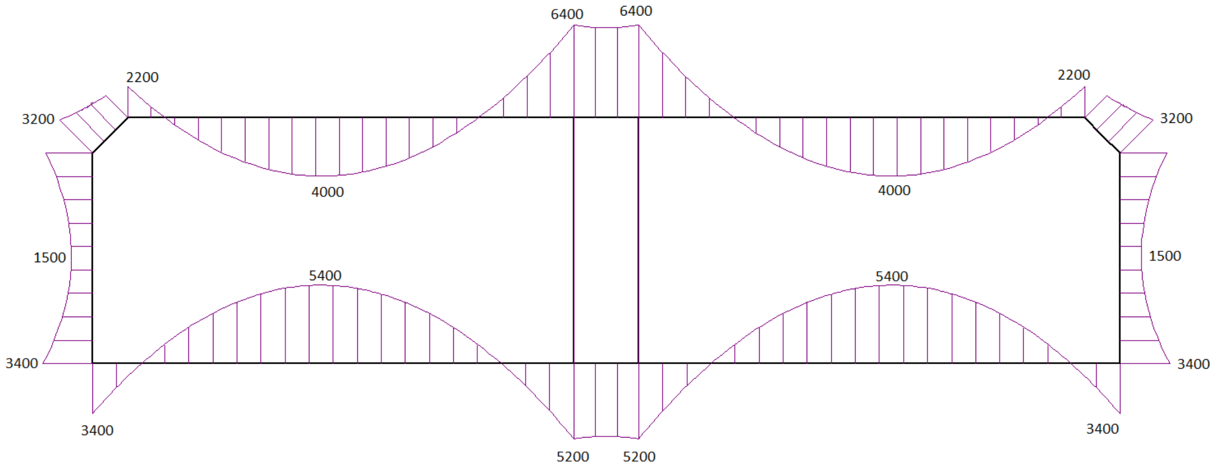


Figure 59 - Accidental load combination (extreme high water as accidental load)

Also now the forces remain lower compared to the permanent load situation. That means that also this load combination is not the governing one.

The influence of an explosion load is given in Figure 60.

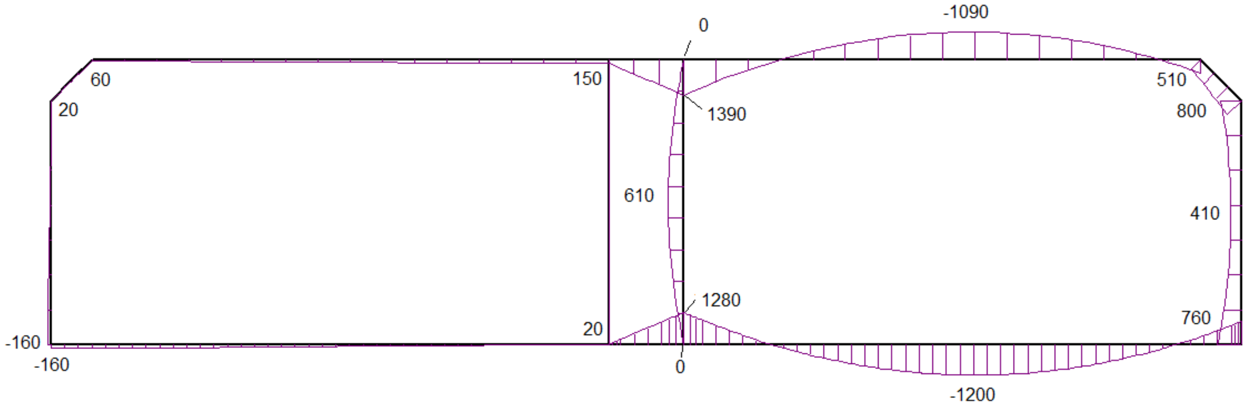


Figure 60 - Bending moments from explosion

From the figure it can be seen that the load from an explosion has a significant impact on the structure. Important however is to notice, that the forces are mainly acting in the opposite direction compared to the forces in the permanent situation. So it can be stated that an explosion load rather leads to a decrease than an increase in forces.

This is however not true for the inner wall. Because all loads so far did not lead to any bending moment in the inner wall[37]. But the load from an explosion leads to a considerable moment in that wall.

The total accidental load combination (with an extreme high water as accidental load) is given in Figure 61. For this result use is made from the combination:

$$E_d = \Sigma\gamma_{G;j}G_{k,j} + \gamma_{Q,1}Q_{k,1} + \Sigma\gamma_{Q,i}\psi_{0,i}Q_{k,I} + A_d \qquad (8)$$

For this load combination use is made from the load factors as presented in Table 19.

[37] *That's due to the schematisation of the inner wall as being connected to the outer walls by a hinge. In reality there will be a certain amount of rotational stiffness, inducing small bending moments.*

Table 19 - Load factors accidental load combination (explosion)

	Load factor	Combination factor	Total
Self-Weight (total load which is acting on foundation)	1.0	-	1.0
Ballast Concrete	1.0	-	1.0
Water pressure	1.0	-	1.0
Protection layer	1.0	-	1.0
Water level variation (load on deck)	1.0	-	1.0
Normal traffic (load on road)	1.0	0.6	0.6
Explosion	1.0	-	1.0

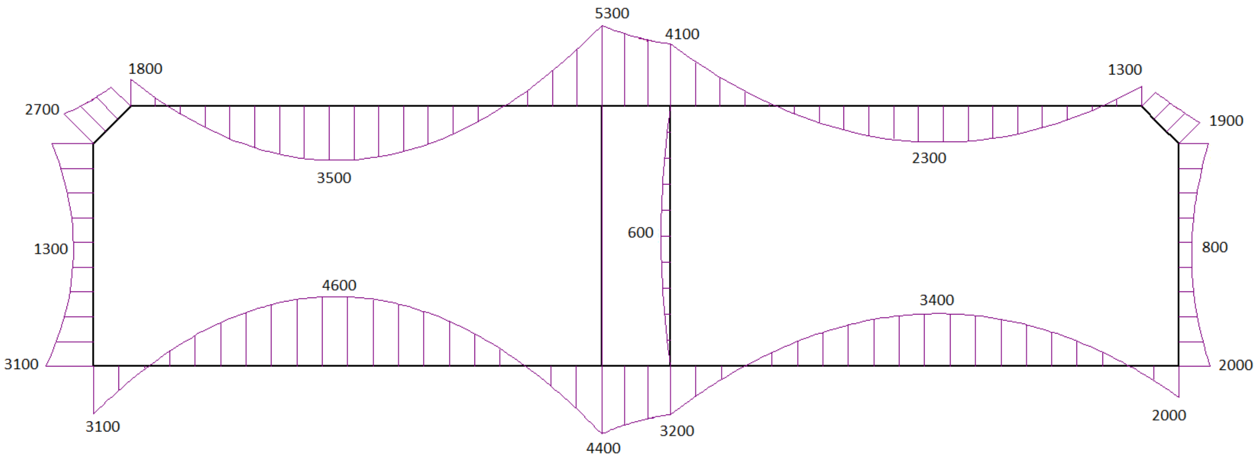


Figure 61 - Accidental load combination (explosion as accidental load)

From Figure 61 it can be concluded that an explosion load decreases the forces significantly. Excepted for the inner wall. That means that this accidental load combination will not be the governing one.

6.3.2.2 Behaviour under sunken ship load

In Figure 62 the situation is given of a sunken ship load applied on (the cross section) of a tunnel.

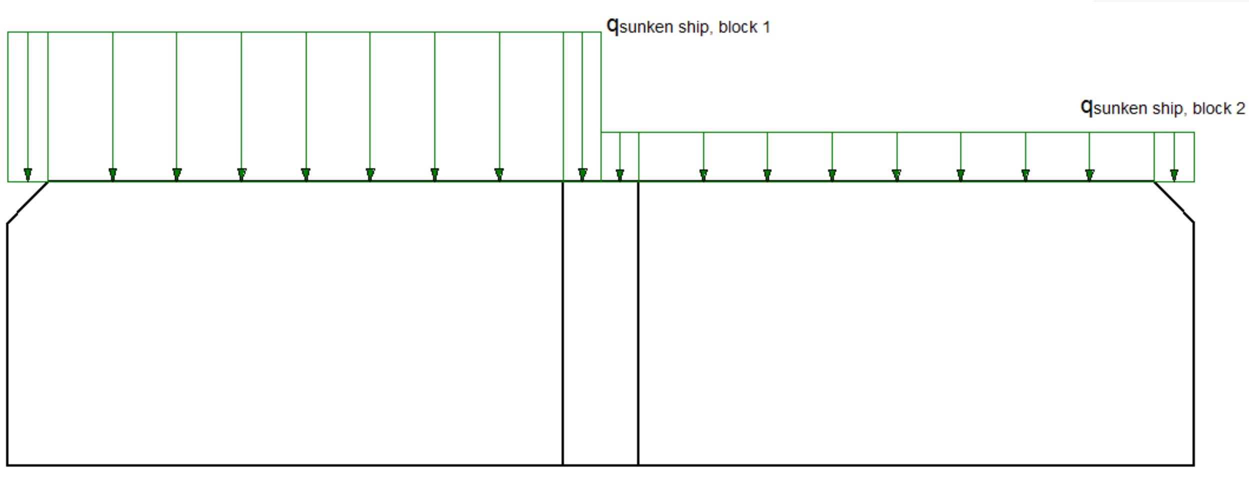


Figure 62 - Load from a sunken ship on tunnel

As already mentioned before, the sunken ship load is taken into account as two ‘block loads’. That due to the triangular shaped bottom area of the bow of the ship. An explanation of how this block loads are determined is given in Appendix 2 (§A2.1.3.2.8 *Load on tunnel*, p.164). The values are 280kN/m (block 1) and 93kN/m (block 2) respectively.

The resulting forces in the structure are given in Figure 63 till Figure 65.

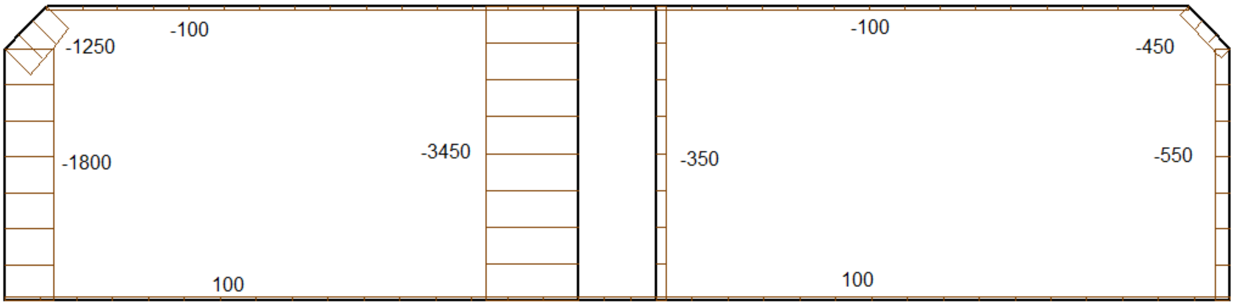


Figure 63 - Normal forces

From Figure 63 it can be seen that there are now tension forces occurring in the bottom of the tunnel. This tension force is however far lower than the force as presented in Figure 47. Therefore it is assumed that a sunken ship load will not lead to tension forces in the bottom. This is of importance, because if tension forces can occur in the bottom, the water tightness is not guaranteed.

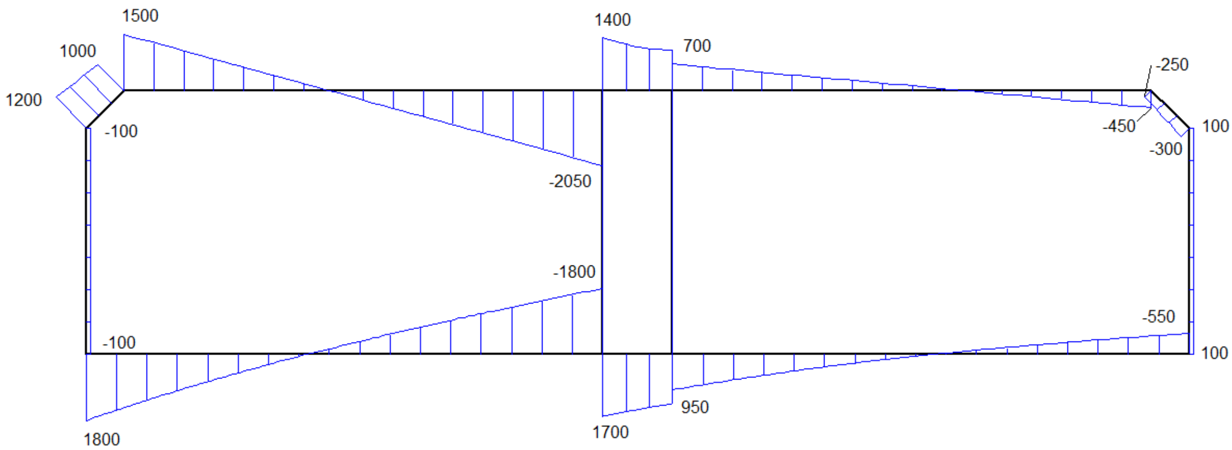


Figure 64 - Shear forces

The biggest shear force lies in the same order of magnitude as the shear force for normal load conditions. This means that this can be an issue[38].

[38] *The shear capacity near the inner wall is a well-known issue. D.A.W. Joosten has written his master thesis on this topic (Joosten, 2011). And there are more reports written about the shear capacity. It is well known that the Eurocode is very conservative with respect to this. This topic will be treated in more detail in chapter 7.*

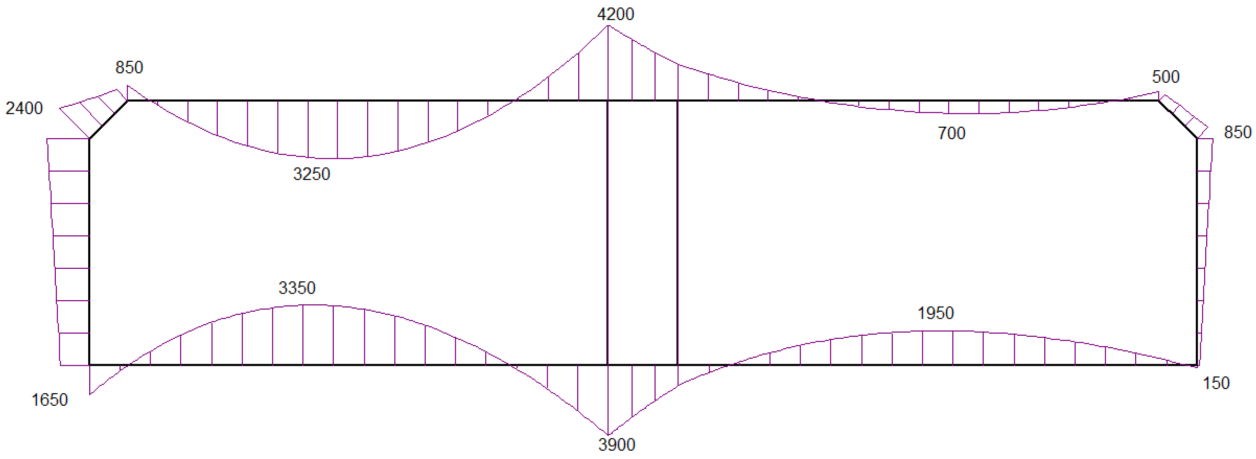


Figure 65 - Bending moments

The bending moments lie in the same order of magnitude as for the permanent loadings. It should be noticed that the bending moments in the bottom are now only generated by the reaction forces. As explained before, the soil under the walls react probably more stiff compared to the soil under the floor (between the walls). Therefore it is assumed that the bending moments in the bottom as presented in the figure are higher than in reality will occur.

6.3.2.2.1 **Comparison with governing load combination from normal conditions**

From §6.3.2.1 *Behaviour under normal load conditions* (p.50 and further) it can be concluded that the permanent load combination is the governing one. In this paragraph it is explained if the capacity of the tunnel is enough to resist a sunken ship load. This will be done through looking to spare capacity on the loading and capacity side. The spare capacity is different for the shear forces and bending moments. Therefore those items are treated separately.

Shear forces

The shear force diagram of the accidental load combination is given in Figure 66.

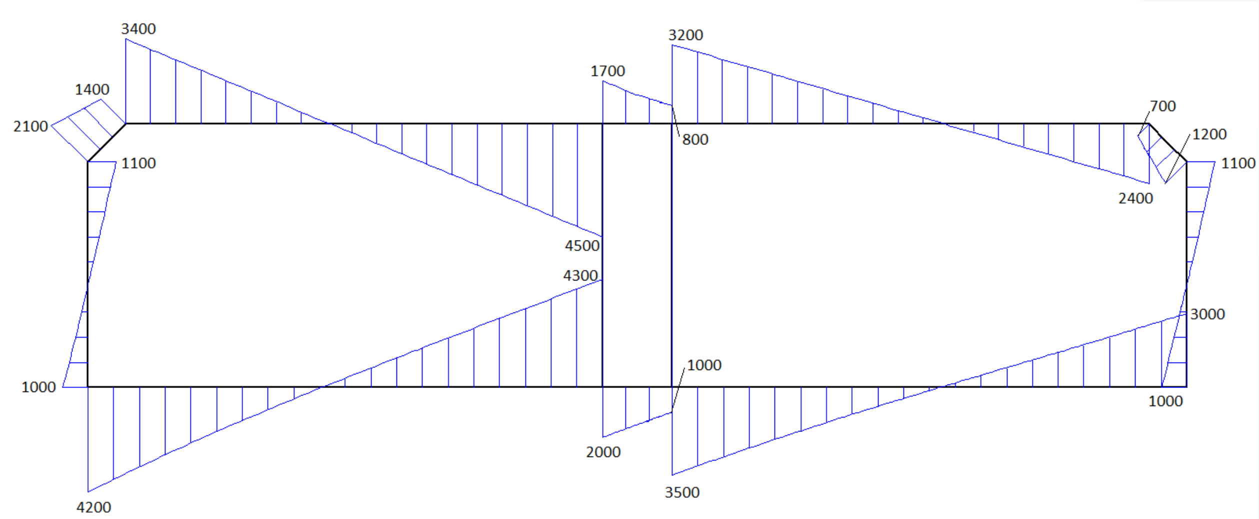


Figure 66 - Shear force diagram accidental load combination (sunken ship as accidental load)

When comparing Figure 66 with Figure 48 it can be derived that the shear forces are approximately a factor 1.4 higher. That's from the loading side.

From the capacity side, it can be said that the concrete material factor reduces from 1.5 to 1.2. For steel the material factor reduces from 1.15 to 1.0. That means that 15% spare capacity is present for the reinforced parts. This does not hold for the parts without reinforcement. Because the shear capacity in the non-reinforced part depends also on the normal force. When neglecting the change in normal force, the reduction in material factors gives an additional capacity of $(1.5/1.2)^{1/3} = 1.08$. Based on these considerations, a spare capacity on the resistance side of 10% is assumed.

When combining the loading and resistance parts, the U.C. becomes globally $1.4/1.1 \approx 1.3$.

Bending moments

The bending diagram of the accidental load combination is given in Figure 67.

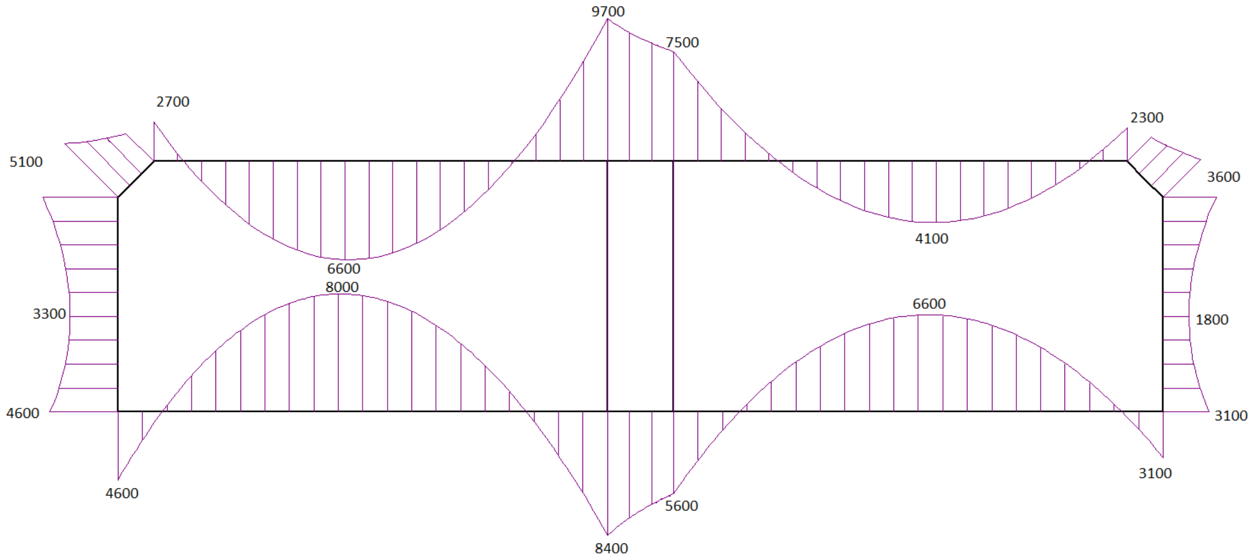


Figure 67 – Bending moment diagram accidental load combination (sunken ship as accidental load)

When comparing Figure 67 with Figure 49, globally an increase of 1.4 is found. This is from the loading side.

From the capacity side, this is a different story than for the shear capacity. Due to the crack width criterion for water tightness of the structure, most of the time more reinforcement is applied than needed for strength. To give an indication about the amount of reinforcement which is applied, little calculations are carried out, see Appendix A3.1.2 *Calculations*. The results are presented in Table 20. The reinforcement percentage which is presented in this table represents the amount of reinforcement needed to fulfil the crack width criterion of 0.2mm. Based on this reinforcement percentage an estimation is given for the bending moment strength (M_{Rd}). The actual bending moments are taken from Figure 50 (tunnel at 5m depth) and Figure 49 (tunnel at 30m depth) at the position halfway the deck.

Table 20 – Reinforcement ratio needed to fulfil the crack width criterion

Depth tunnel	Reinforcement percentage	M_{Rd} (kNm)	M_{Ed} (kNm)	M_{Ed}/M_{Rd} (-)
5m	1.19%	3770	1100	0.29

30m	2.88%	9120	4400	0.48

Form this table it can be seen that (especially for tunnels which lie relatively superficially) the amount of applied reinforcement is much more than needed for strength. Based on these calculations, it is assumed that there is twice as much reinforcement present as needed for strength.

When combining the loading and resistance parts, the U.C. globally becomes 1.4 / 2 ≈ 0.7 for the bending moment. This is lower than one. That means that no problems are expected for the cross sectional analysis with respect to the bending moments.

6.3.2.3 Validation of model

The cross sectional model is validated by checking only the bending moments in the (left half) of the deck (Figure 68).

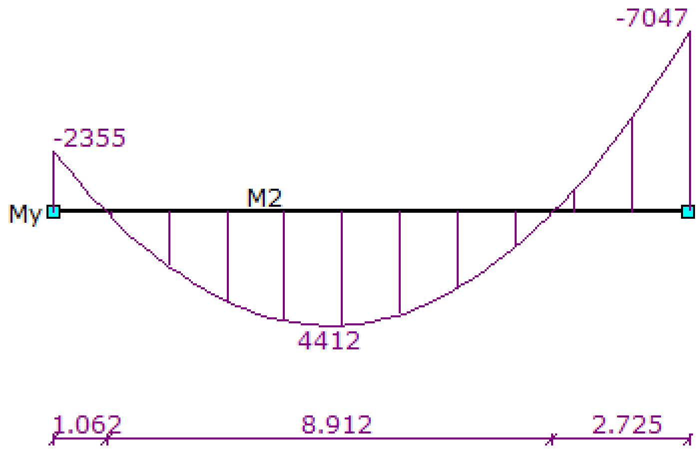


Figure 68 - Bending moments in deck (left side) of tunnel structure (see also Figure 49)

When calculating the maximum bending moment in the field, a value of $\frac{1}{8}ql^2 = \frac{1}{8} * 444 * 8.912^2 = 4408kNm$ is obtained. This is almost equal to the value of 4412 as shown in the picture. This validates the results as obtained for this model.

6.3.3 Longitudinal behaviour

For the longitudinal structural behaviour of an immersed tunnel, the most important aspect is if a tunnel is monolithic or segmented (Figure 69).

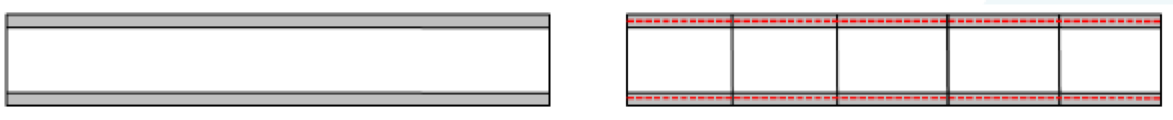


Figure 69 - Monolithic element (left) and segmented element (right) (picture after (Oorsouw, 2010))

Research is done to the behaviour of these different types of tunnels. For the cross section a rectangular shape is assumed, with characteristics as given in Table 21.

Table 21 - Characteristics of tunnel

Parameter	Amount	Unit	Formula	Description
w	30	m		Width tunnel

h	8	m		Height tunnel
d	3	m		Total width walls
I	580	m^4	Calculated by MatrixFrame	Moment of Inertia
E	36,000,000	kN/m^2	from C45/55[39]	E-modulus
k	2,000	kN/m^3	Assumption[40]	Bedding stiffness soil
$1/\lambda$	80	m	$1/((k/(4EI))^{0.25})$	Spreading length

The value $1/\lambda$ is the characteristic length (Simone, 2011). This value is a measure of the length of the tunnel which is influenced under a certain load. In which λ is a measure of the relative strength of the tunnel compared to the soil.

As characteristics for the tunnel in longitudinal direction, a tunnel of 300m is used, with three elements of 100m for the monolithic tunnel (Figure 70) and 15 elements of 20m for the segmented tunnel (Figure 71).

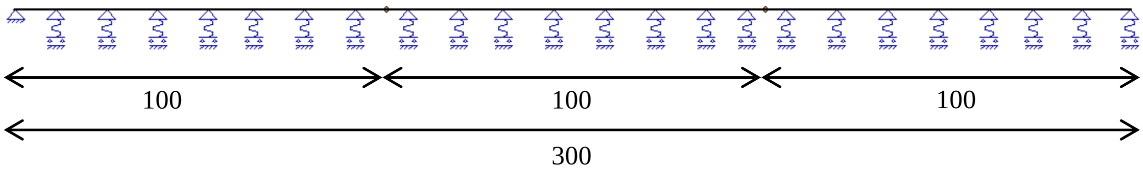


Figure 70 - Schematisation monolithic tunnel

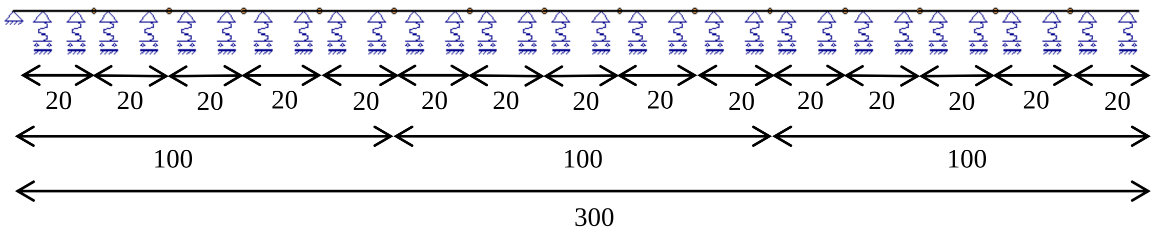


Figure 71 - Schematisation segmented tunnel

By immersed tunnels, the neighbouring elements do have an influence on the force distribution in the loaded element. Therefore, to take this effect into account, use is made from more than one element. In this way these tunnels should represent the behaviour of an immersed tunnel of several elements. This reasoning holds only for loads which are not present over the full length of the tunnel.

Because of the foregoing reason, for evaluation of concentrated loads (loads which are not present over the full length of the tunnel) the behaviour of only the middle element is used. In this way the reaction of the neighbouring elements is taken into account. The influence of the elements further away is hereby neglected. This will have an influence on the results[41], but the trend will be clear.

The hard point at the beginning represents the part of the tunnel which is founded on piles.

[39] Typical strength of immersed tunnel ((Lunniss & Baber, 2013), p.292)
[40] Assumed stiffness for a typical stiffness of Dutch soil
[41] An investigation showed that the results differ on average about 5% when using four monolithic elements instead of three.

Another item is that the behaviour of the connection between the segments / elements is assumed to behave as a hinge. A hinge does not represent the reality completely. In reality there are reaction forces from the neighbouring elements, as visualized in Figure 72.

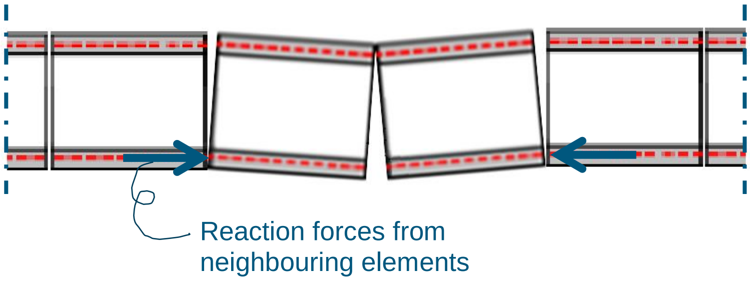


Figure 72 - Interaction elements under deformations

Those reaction forces are caused by the compression of the GINA profile which is present there. The GINA profile behaves very weak for the first amount of compression (≈ 30mm, depending on the initial amount of compression which is assumed to be 70mm). See also the design curves in Appendix A1 (§A1.2.1.2 *Gina gasket*, p.140). Therefore also the reaction forces of the GINA remain small. Only in case of large deformations the reaction forces can become of any importance. It is therefore assumed that a hinged connection will be a rather good estimation of the real behaviour of the tunnel[42]. The larger reaction forces under large deformations will be neglected.

6.3.3.1 Behaviour under normal load conditions

To give an impression of the behaviour of the tunnel in longitudinal direction under normal load conditions, this is first evaluated.

6.3.3.1.1 **Permanent loads**

The permanent loads are given in Figure 73.

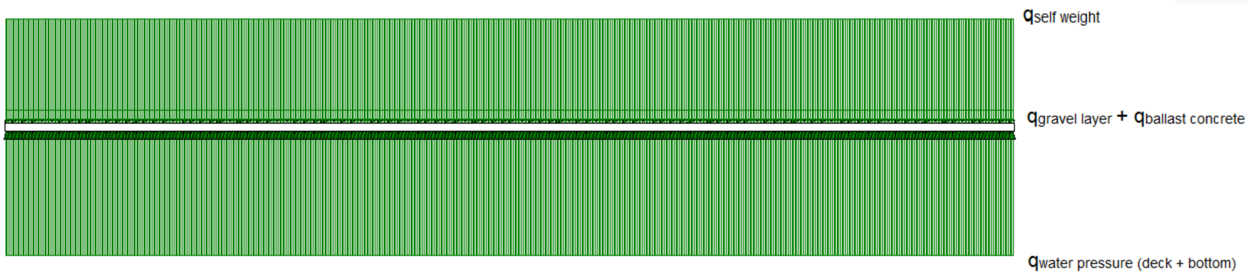


Figure 73 - Permanent loads on monolithic tunnel

The resulting forces are given in Figure 74 till Figure 76.

Normal forces

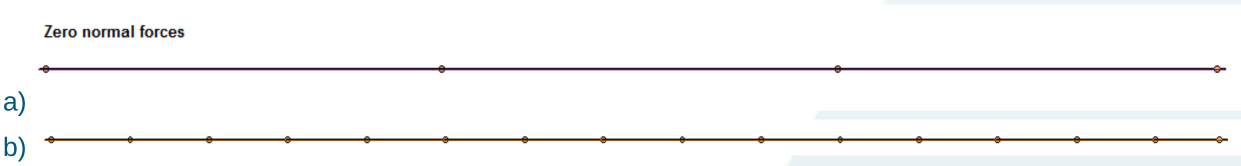


Figure 74 - Normal forces (are zero) [a) for monolithic tunnel b) for segmented tunnel]

[42] *This approach of schematising the connection as a hinge is also common practice by TEC.*

From Figure 74 it can be seen that there are no normal forces due to the used loads. In reality there will be normal forces in longitudinal direction. A major item which contributes to the normal force, is the normal force induced by the water pressure during placing of the elements. This normal force is maintained after placing of all elements. Another factor which causes changes in the normal force is caused by temperature differences. There is also always a minimum amount of compression needed. Because the GINA profile must be subjected to a minimal amount of compression to be water tight.

Shear forces

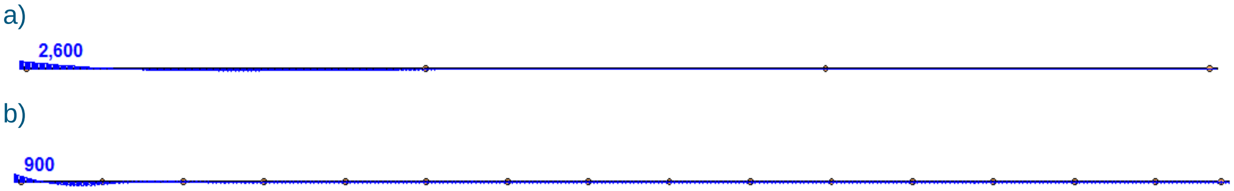


Figure 75 - Shear forces in kN [a) for monolithic tunnel b) for segmented tunnel]

The shear forces are (in this figure) only caused by the hard point at the beginning of the tunnel structure. In reality the forces will be somewhat higher, due to variations in the bedding stiffness and the load being not equally distributed. But the message is that the forces induced by the permanent loads are small.

Bending moments

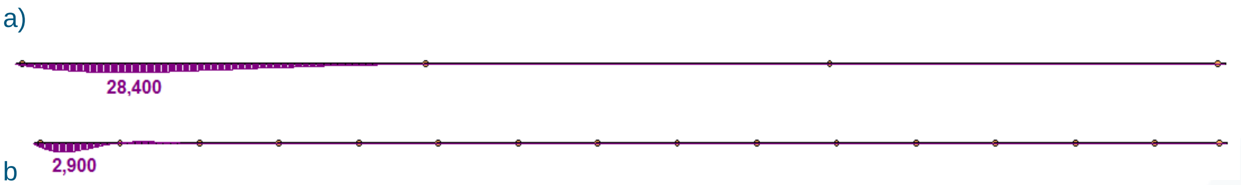


Figure 76 - Bending moments in kNm [a) for monolithic tunnel b) for segmented tunnel]

The same reasoning as given for the shear forces holds also for the bending moments.

6.3.3.1.2 **Variable loads**

The only variable load which cause shear forces and bending moments of any importance is the traffic load. The load from road traffic is very small compared to the load from railway traffic. Therefore only the forces from railway traffic are evaluated (Figure 77).

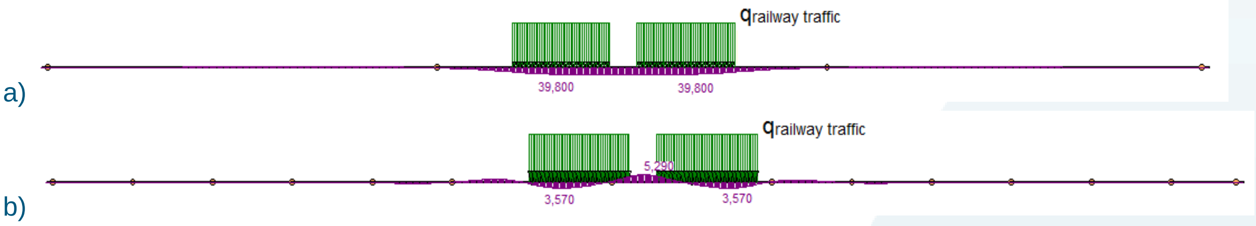


Figure 77 - Bending moments due to railway traffic [a) for monolithic tunnel b) for segmented tunnel]

From Figure 77 it can be seen that the induced bending moments due to traffic loads are small.

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6.3.3.1.3 **Accidental loads**

The load from an extreme high water level is also an equally distributed force which is present over the full length of the tunnel. Therefore this load induces no forces in the structure.

An explosion load causes also no forces in the structure, which has any influence in longitudinal direction. Because the explosion load acting downwards is just as large as the load acting upwards.

6.3.3.2 Behaviour under sunken ship load

In this paragraph the behaviour of immersed tunnels is evaluated when subjected to a sunken ship load. For the longitudinal direction, not only the forces, but also the deformations of the structure are of importance. Because there are limitations to the rotations of the joints.

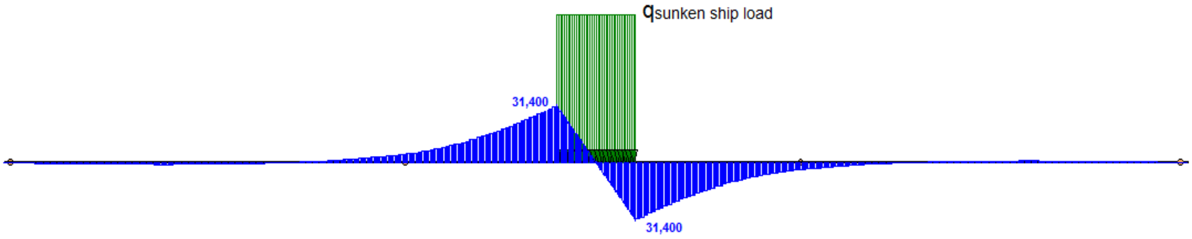
In Figure 78 until Figure 83 some general impressions are given how the tunnel reacts under a sunken ship load. The load is only applied on the middle element of the tunnel. The length of the line load is always 20m. Remember that the load equals 4500kN/m.

6.3.3.2.1 **Forces**

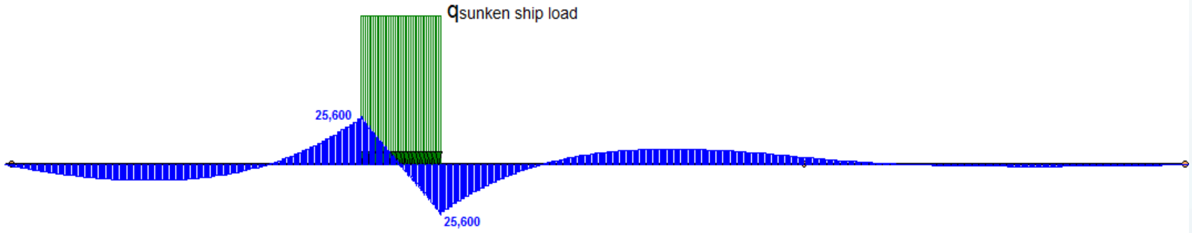
Normal forces

A sunken ship load causes no elongation or shortening of the concrete structure. Therefore the normal forces will not change in an immersed tunnel when subjected to a sunken ship load[43]. So the normal forces are not further evaluated.

Shear forces



a)



b)

Figure 78 - Shear forces in kN, monolithic [a) Load halfway element b) Load over joint]

[43] *Apart from the normal forces induced due to the mechanism as shown in Figure 72.*

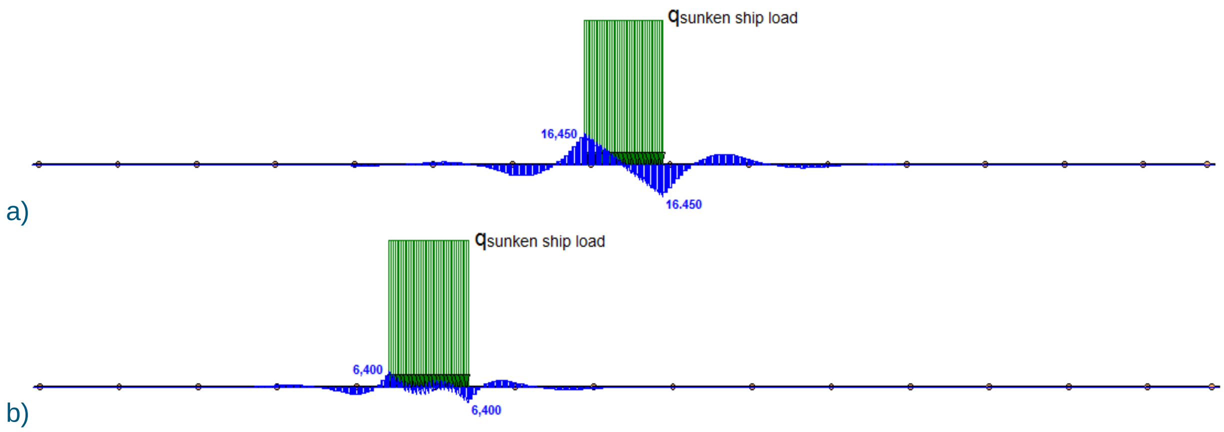


Figure 79 - Shear forces in kN, segmented   [a) Load halfway element b) Load over joint]

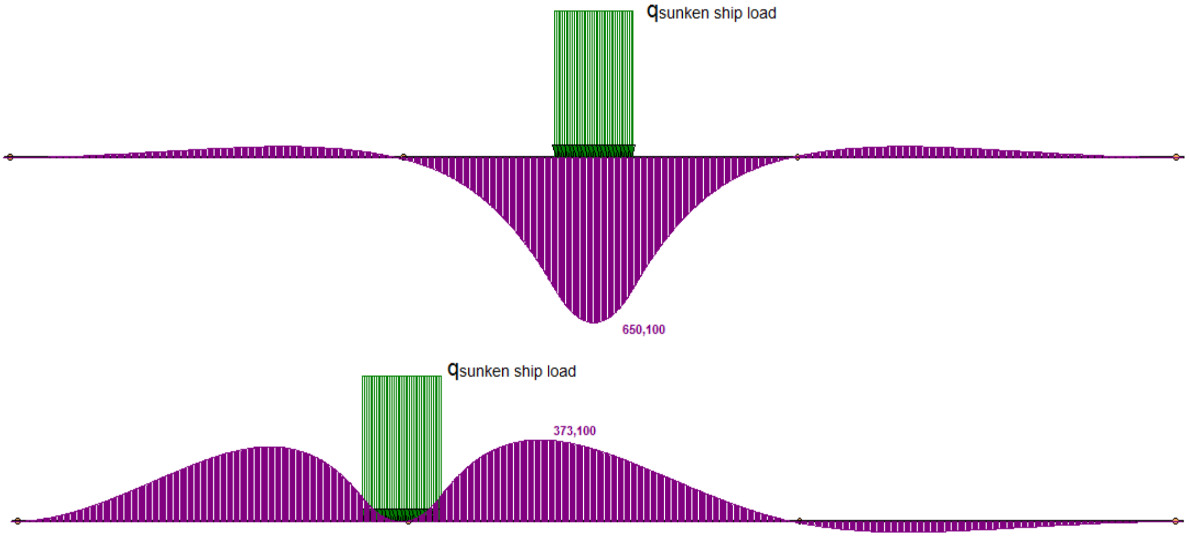
The shear forces are given for the load positioned halfway an element and over a joint. The load halfway an element causes the biggest shear force in the structure, while the load applied on the joint causes the smallest shear force. From the figures it can be seen that the shear forces in a monolithic tunnel are higher than for a segmented tunnel. The shear force should be taken up in the tunnel structure by a strut and tie model. This strut and tie model is build up by the concrete (the struts) and the shear reinforcement (the ties). At the position of the joints is the cross section the smallest to take up the shear forces. There the shear forces are transferred from the one element to the other with the aid of shear keys. These shear keys mean a smaller cross section. Therefore those position of often critical with respect to the shear forces in the structure.

In Appendix 3 (§A3.2 *Shear force in joints under a sunken ship load*) the shear force in the joint (shear key) is determined for different positions of the load. In this appendix the effect of different soil conditions and the effect of a different length of load are taken into account. From these calculations the conclusion can be drawn that in most cases a higher shear force is occurring in the shear key for a monolithic tunnel compared to a segmented tunnel.

When comparing the capacity of the joint (Appendix A3.2.3 *Capacity of a joint*) to the occurring shear force, it can be seen that the strength of the shear key really can be an issue.

The strength of the shear keys is an important item. Because if the shear key fails, the omega in the joint fails (highest probably) also. This omega seal should guarantee the water tightness. Failure of the omega seal causes therefore a lot of leakage. The same reasoning holds for the water stops. With respect to this, the water stops are even more critical than an omega seal. Because an omega seal do have space to deform in vertical direction, while a water stop hasn't.

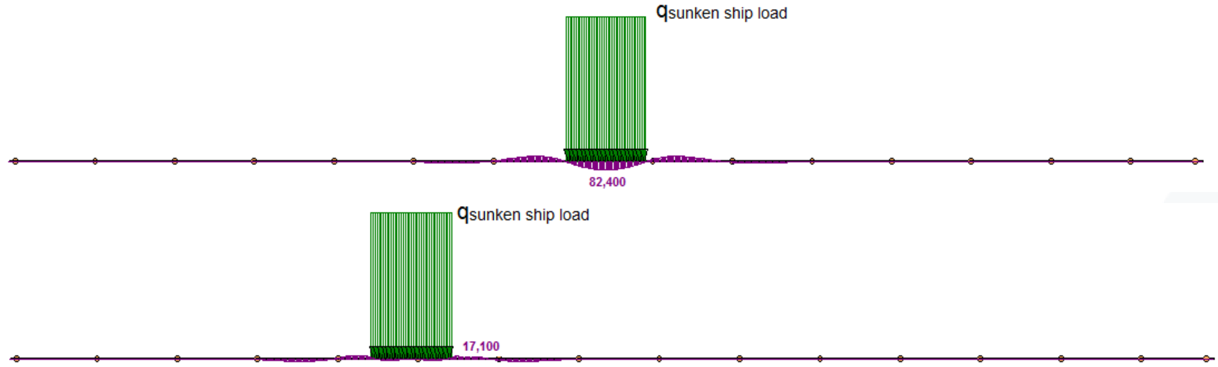
Bending moments



a)

b)

Figure 80 - Bending moments in kNm, monolithic [a) Load halfway element b) Load over joint]



a)

b)

Figure 81 - Bending moments in kNm, segmented   [a) Load halfway element b) Load over joint]

Also here the maximum bending moment is obtained when positioning the load halfway an element. And the minimum bending moment is found when positioning the load over a joint.

When comparing the bending moments from a monolithic tunnel with a segmented tunnel, it can clearly be seen that the bending moments in a monolithic tunnel are far more compared to a segmented tunnel.

Important to know is if the bending moments exceed the cracking moment. Because exceeding of the cracking moment implies that the bottom is full under tension, which means that through cracks can occur. This topic is treated in Appendix 3 (§0

Cracking of concrete due to bending moments, p.203). From these calculations the conclusion can be drawn that the bending moments in longitudinal direction are smaller than the cracking moment.

Even if the tunnel fails (which is possible for tunnels on a very soft bedding), the consequences are not severe. See Appendix 3 (§A3.5 *Flow rates through leaking joints and cracked concrete*, p.207) for an example calculation.

6.3.3.2.2 **Deformations**

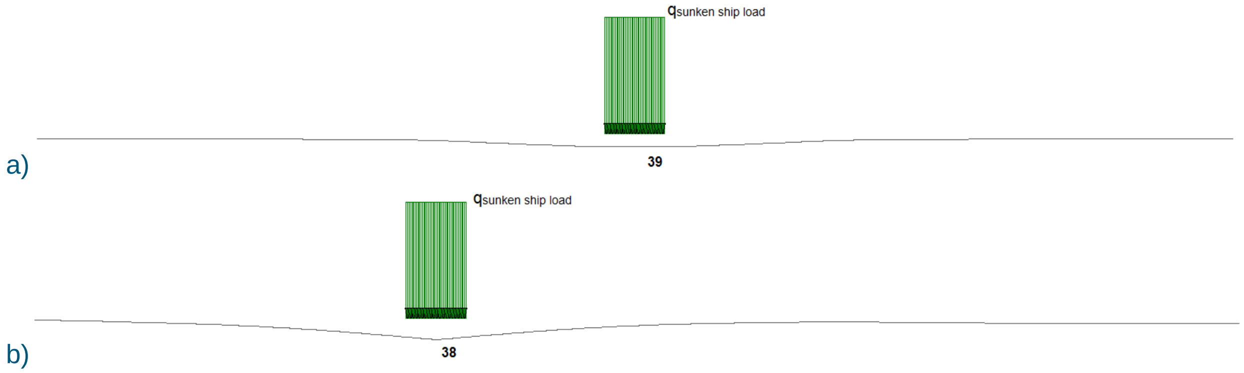


Figure 82 – Deformations in mm, monolithic [a) Load halfway element b) Load over joint]

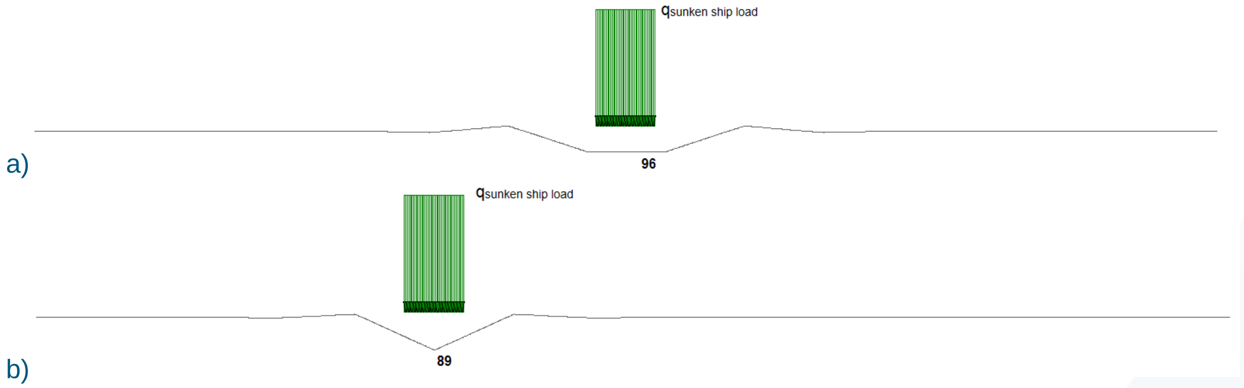


Figure 83 – Deformations in mm, segmented [a) Load halfway element b) Load over joint]

For the deformations, it is the other way around. Now the biggest deformations are found when positioning the load over a joint and the smallest deformations are found when positioning the load halfway an element. The deformations are now more for the segmented tunnel compared to the monolithic tunnel. These results are not that strange. Because, in general, the more rigid a structure is, the more forces it will attract. Less stiff structures on the other hand, deform more, but attract less forces.

From the figures can be seen that the displacements are about a factor three higher for the segmented tunnel compared to the monolithic tunnel. The rotations in the joints however show a lot more difference. The rotations in the joint for the monolithic tunnel remain small. The rotations in the segmented tunnel on the other hand become relatively big. Big rotations have the consequence that the water seals (omega and water stops) needs to elongate a lot. To check if the rotations lead to failure of the water seals, this topic is worked out more detailed in Appendix 3 (§A3.5 *Flow rates through leaking joints and cracked concrete* p.207). Based on those calculations it is concluded that the deformations of the water seals can go beyond the ULS criteria (a factor 1.2), but do not lead to failure.

Even if the water seal fails, the consequences remain relatively low. There will be a lot of water flooding into the tunnel, but not lead to casualties. See Appendix 3 (§A3.5 *Flow rates through leaking joints and cracked concrete*, p.207) for an example calculation.

6.3.3.3 Validation of model

For validation of the longitudinal model, the load configuration as shown in Figure 84 is used.

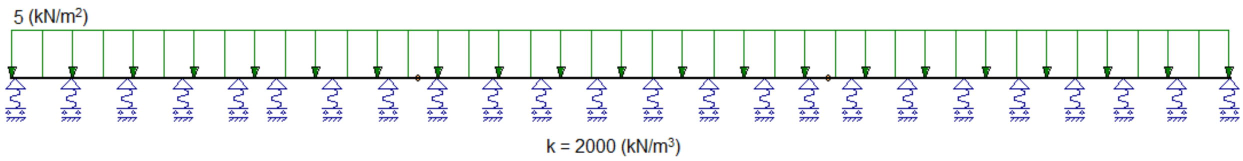


Figure 84 - Load configuration used for validation

That gives the deformation as shown in Figure 85.

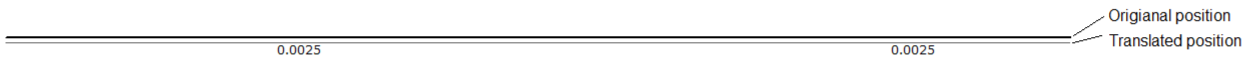


Figure 85 - Deformed structure

As can be seen from the picture above, the overall displacement is 0.0025m (=2.5mm). This corresponds with a displacement of $u = \frac{q}{k} = \frac{5}{2000} = 0.0025m = 2.5mm$. This validates this model.

6.4 Critical locations in concrete immersed tunnels

Based on the considerations before, it is possible to say what locations can become critical in an immersed tunnel when subjected to a sunken ship load. This is treated in this paragraph.

6.4.1 Cross section

From the previous paragraphs it can be seen that due to a sunken ship load the structure will crack, but that the structure probably will not fail. That because of the fact that much more reinforcement is needed to fulfil the crack width criterion, than the amount which is needed for strength.

6.4.2 Longitudinal

From the longitudinal analysis it follows that the joints are an important aspect of the tunnel.

For the monolithic tunnel, the strength of the shear key can become an issue. The forces in the shear key can easily become larger than the strength. The bending moments are probably no issue, only for tunnels on a very weak subsoil

For the segmented tunnels, both the strength of the shear keys as well as the deformations of the water seals can become a problem. In case of failure of the water seal, the consequences not severe.

Based on the considerations above, it cannot be said at forehand which type of tunnel (segmented or monolithic) is most critical with respect to a sunken ship load.

6.5 Conclusion

The main types of immersed tunnels are steel-concrete and solely concrete tunnels. It was concluded that concrete tunnels are more relevant compared to steel-concrete tunnels. Therefore only that type of tunnels was analysed further.

For the cross sectional analysis, a distinction is made between the governing load combination for normal conditions and a sunken ship load. It appeared that globally a U.C. of 1.3 is found for the shear capacity and a U.C. of 0.7 for the bending moment capacity.

For the longitudinal direction there is a distinction made between monolithic and segmented tunnels. For a monolithic tunnel the strength of the shear key can become three times bigger than the strength. The bending moments do not exceed the cracking moment capacity of the tunnel. For a segmented tunnel the strength of the shear key lies in the same order of magnitude as the strength. For this type of tunnels the deformations of the water seals can become a factor 1.2 higher than allowed. The water seals do however not fail.

It cannot be said beforehand which type of tunnel (segmented or monolithic) is most critical with respect to a sunken ship load. That depends largely on the characteristics of each tunnel.

7 Case

In this chapter a real tunnel is evaluated for a sunken ship load. Through doing such an analysis the more general evaluations from the previous chapter are carried out in more detail. This gives more support to (final) conclusions.

7.1 Introduction

First a choice is made for the tunnel which is evaluated. That is done through a Multi Criteria Analysis (MCA). That MCA is carried out in Appendix 4 (§A4.1*Making choice for critical tunnel)*. From this analysis the Wijkertunnel results. An overview of that tunnel is given in Figure 86.

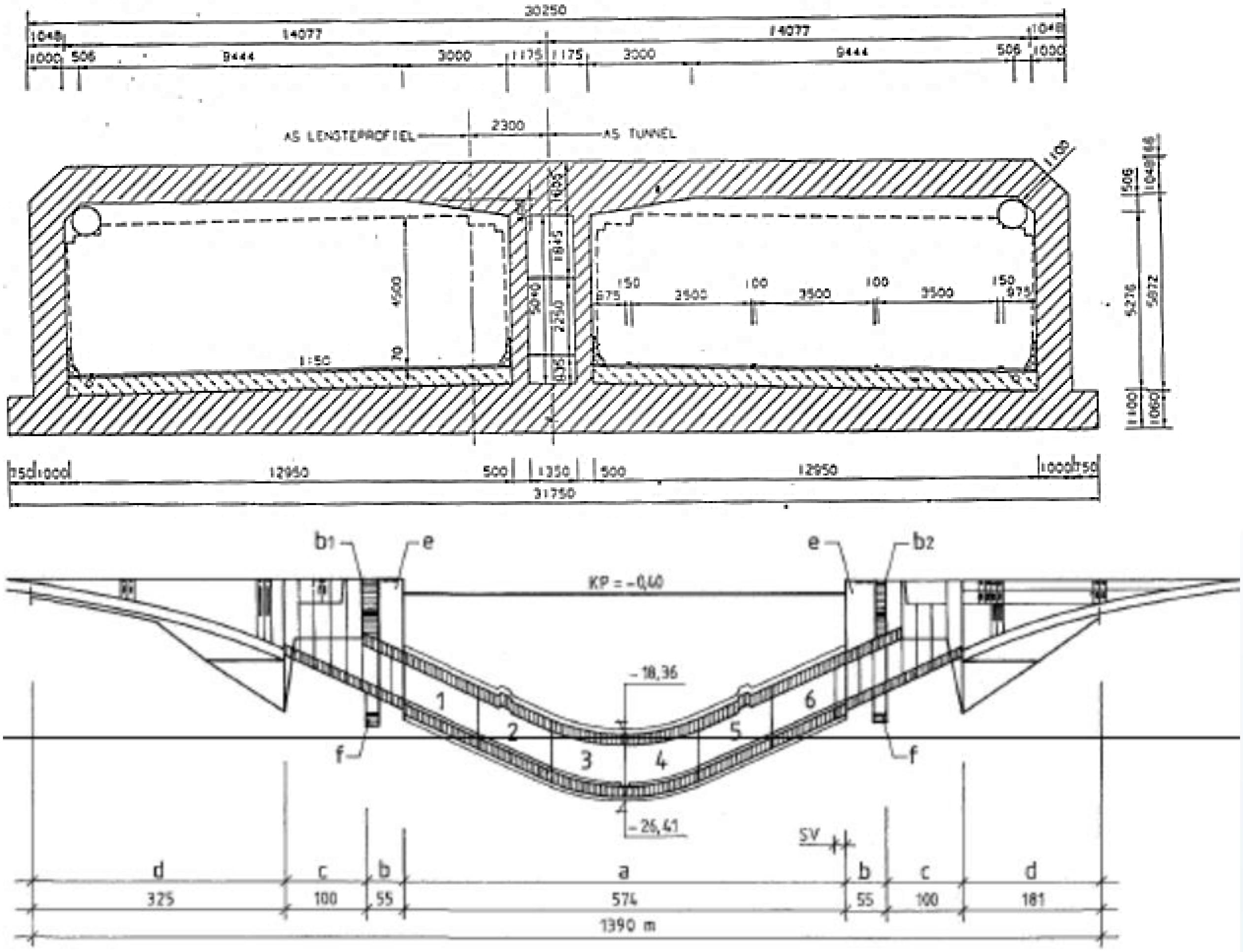


Figure 86 - Overview Wijkertunnel

A more detailed overview of the dimensions is given in Figure 87.

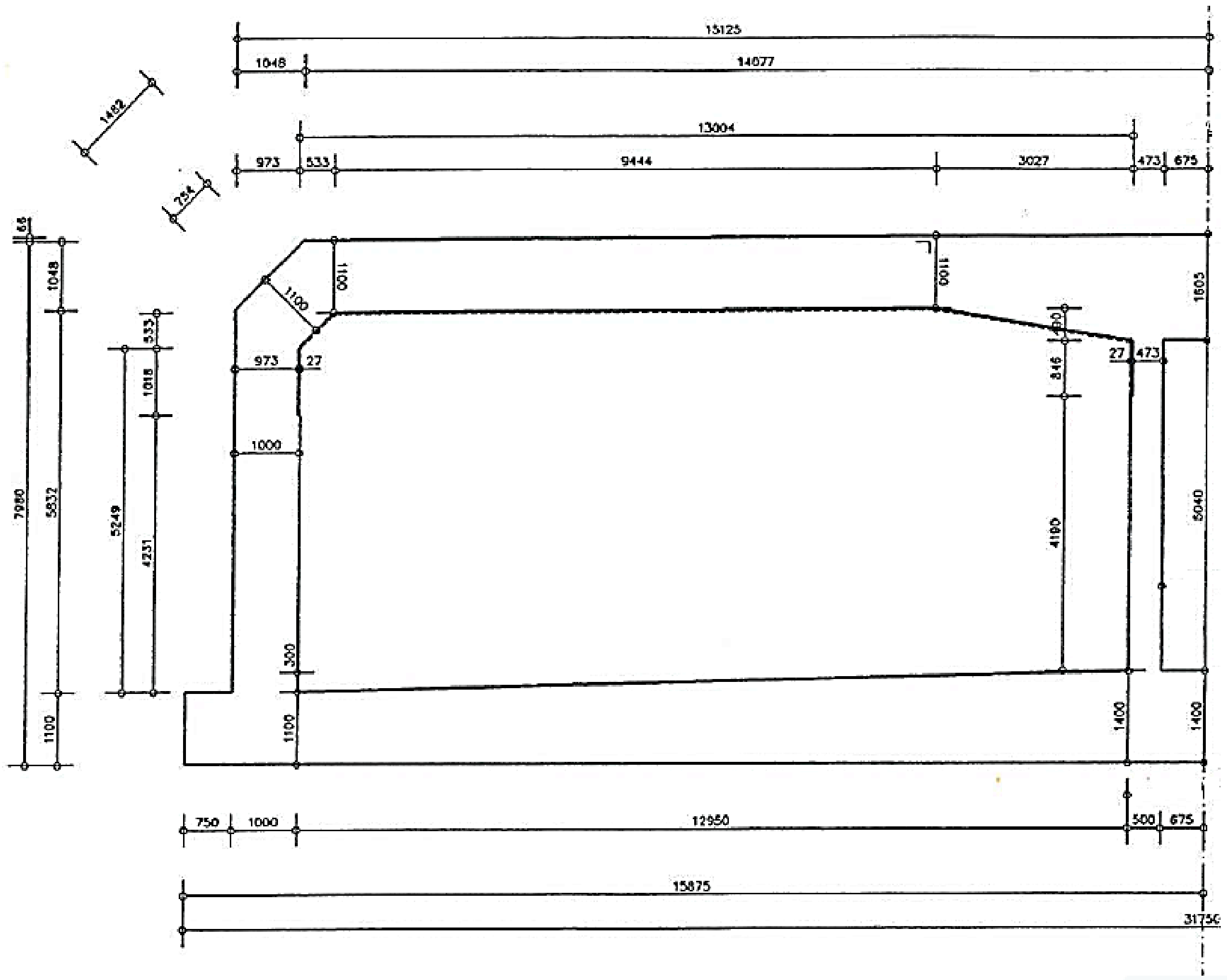


Figure 87 - Dimensions Wijkertunnel

7.2 Representative sunken ship load

In this paragraph a characteristic load from a sunken ship is determined. To determine this load, first an overview of the type of ships passing the Wijkertunnel is given. That gives an overview of the distribution of the type of ships.

7.2.1 Determining representative ship

In Figure 88 an overview is given from the type of ships which are passing the Wijkertunnel.

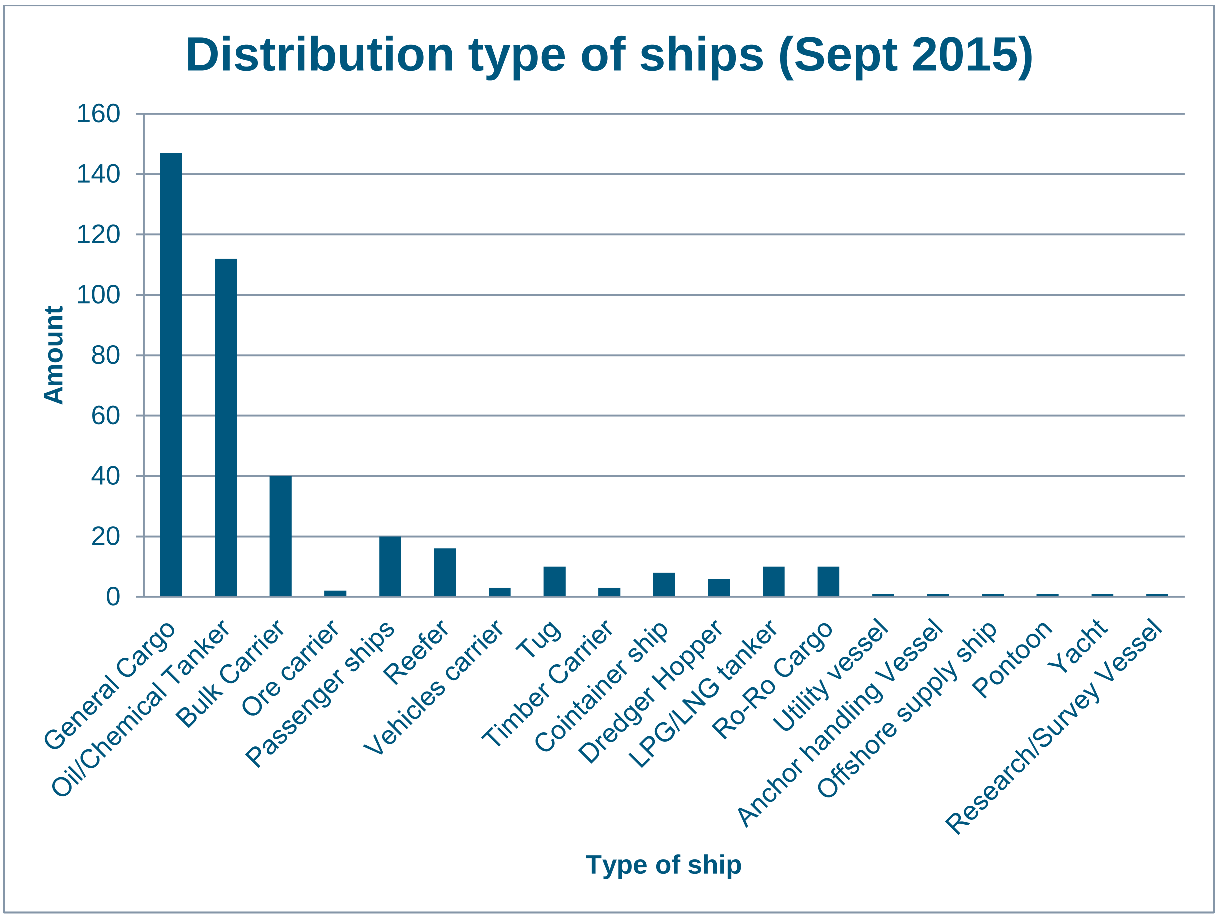


Figure 88 - Distribution type of ships passing Wijkertunnel[44]

As explained in §5.2 *Relevant types of ships*, the ships which carry iron ore, are the most important ships. Because they induce the biggest load on the tunnel. Therefore the presented ships are evaluated with respect to this item, if they can carry iron ore or not.

From the above presented figure, it can be seen that the biggest amount of ships are of the General Cargo type. This type of ship can carry a big range of different type of goods. One of the possibilities is that such a ship carries bulk cargoes (William I. Milwee, 1996). This implies that such a type of ship can also carry iron ore.

The second type of ship which can carry iron ore, are the bulk carriers. This type of ship is less present in the statistical data, but is still of importance. The Ore carriers are here presented as a different category. In fact are they also bulk carriers, but then only used for carrying iron ore.

As can be seen from the figure, there are also a lot of Oil/Chemical Tankers passing the Wijkertunnel. The density of oil is however lower than water, so if such a ships fails, it will not sink. Only at the moment that a substantial amount of the oil is leaked into the water, the ship sinks on the tunnel. But the maximum load

[44] *Here the assumption is made, that each ship in the North Sea canal passes the Wijkertunnel. The showed ships are from http://www.portofamsterdam.nl/Lijst-aangekomen-HAP-schepen. Those are the ships in the North Sea canal which deliver its waste material. Every ship is obliged to do that. Some ships are however excluded through using this data. When comparing the amount of ships as here presented (514 ships) with the average amount of ships arriving at the port of Amsterdam per month (570 ships), it can be seen that it gives a good indication of the actual distribution.*

induced on the tunnel will then only be the load from an empty ship. Which is a very small load compared to the load from a ship with iron ore.

The other types of ships are all of almost no importance. Both with respect to the amount, as well as with respect to the load if such a ship sinks[45].

Based on these considerations, it can be said that the change that a general cargo ship sinks on the tunnel is most probable. Therefore the load from such a ship (loaded with iron ore) is evaluated. As a second (worst case) scenario, the load from a bulk carrier loaded with iron ore is evaluated.

7.2.2 Load from representative ship

In this paragraph the characteristic loads for a general cargo ship and a bulk carrier are determined.

7.2.2.1 General Cargo ship

The size distribution (in DWT) of the general cargo ships is shown in Figure 89.

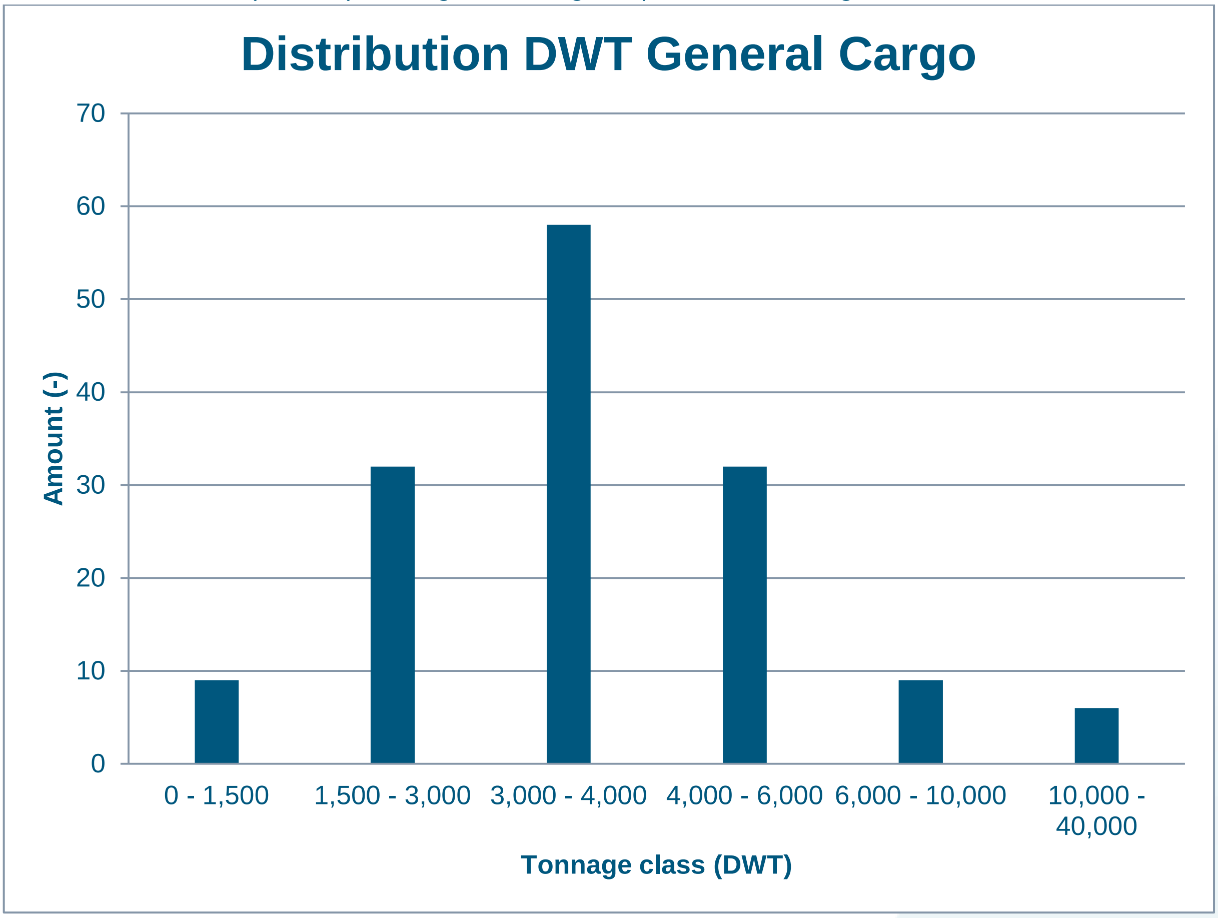


Figure 89 - Size distribution (in DWT) of General Cargo ships

Based on this size distribution, a representative general cargo ship can be determined. That’s done through taking the 95-percentile of the size distribution (Figure 90).

[45] *A tug boat is an exception to this, but will not be evaluated in this research (see §5.2 for clarification).*

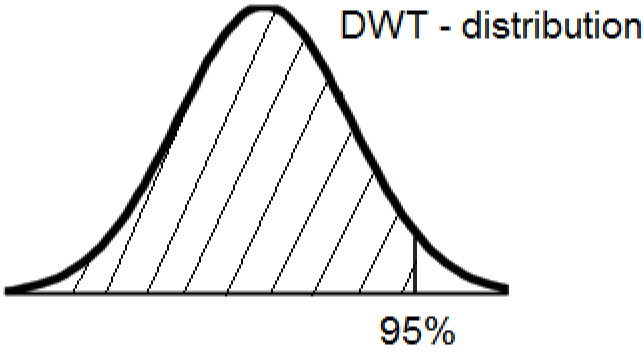


Figure 90 - Indication of 95 percentile in size distribution

This 95 – percentile value gave a value of about 4,600 DWT. As a representative general cargo ship is now the SWE-carrier chosen, which has a carrying capacity of 4,560 DWT. This ship has the characteristics as shown in Table 22.

Table 22 - Characteristics SWE - Carrier[46]

Parameter	Amount	Unit	Formula	Description
L	92.5	m		Length
L_{load}	85	m	Assumption	Loaded length
B	13.8	m		Width
H	7.4	m		Moulded depth
T	5.7	m		Draught
DWT	4,555	ton	Dead weight ton	Maximum carrying capacity of ship
Δ	6,186	ton		Volume displacement

Now the loads from this ship need to be determined.

In chapter 5 (§5.3.3 *Sinking*, p.25) it is assumed that a ship sinks if (at least) three compartments become flooded. When estimating the length of one compartment at 10% of the ship length, 30% of the ship is flooded with water, which is equal to 0.3*92.5 ≈ 28m. So that's the minimum amount of compartments which is flooded.

The load is obtained by increasing the amount of the ship which is flooded (starting from the bow) until a U.C. of 1.0 is found for the shear capacity. This value was achieved for X = 51m (≥ 28, OK). The unity check for the moment capacity is then 0.80. The load for this situation is about 60kN/m^2.

If the ship rests however only on half the tunnel width, the load increases even more. For that situation a U.C. of 1.0 for the shear capacity was found for X = 41m (≥ 28, OK). Now the load becomes 120kN/m^2. This situation is governing over the situation that the ship is supported by the full tunnel width. This situation will therefore be used when evaluating the structure for the General Cargo ship load. A load of 120kN/m^2 results in a load of 101kN/m^2 for block 1 and 34kN/m^2 for block 2 ([47]). The load for the longitudinal analysis is found by dividing the total load by the width of the ship: 1,050kN/m. The results are summarized in Table 23.

[46] *See for information about this type of ship: peakgroup.no/mv-swe-carrier/*
[47] *For explanation of the block loads see Appendix A2 (§A2.1.3.2.8* Load on tunnel*, p. 139)*

Table 23 - Magnitude of loads for General Cargo carrier

Load	**Cross sectional analysis (kN/m²)**		**Longitudinal analysis (kN/m)**
	Block 1	Block 2	
General cargo carrier	101	34	1,050

7.2.2.2 Bulk Carrier

For the bulk carrier, the same procedure is followed as for the general cargo ship. In Figure 91 an overview of the size distribution (in DWT) of the Bulk Carriers is given.

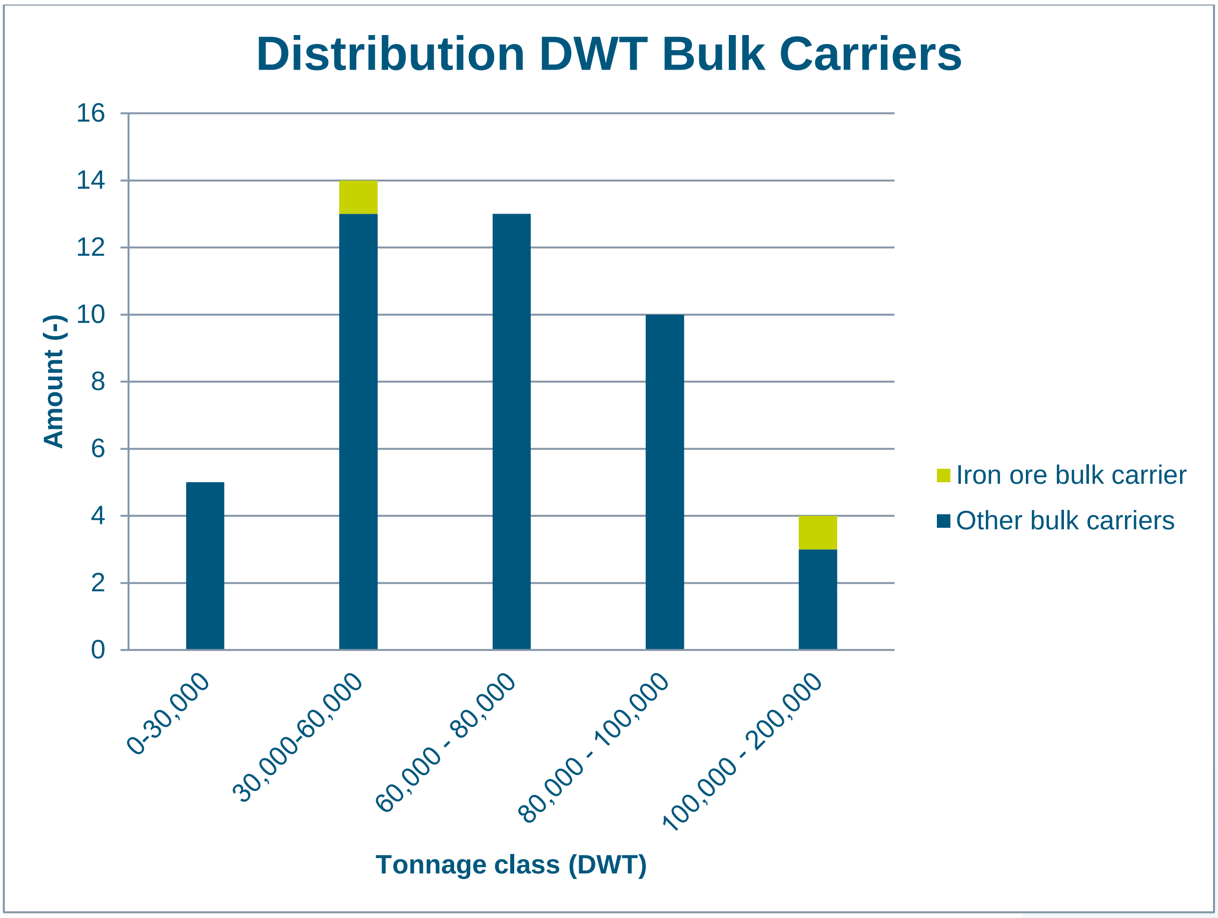


Figure 91 - Size distribution (in DWT) of Bulk Carriers

The 95-percentile value, gives now a DWT of about 82,600. As a characteristic bulk carrier, the Nord Sun is chosen, with a maximum carrying capacity of 82,100 DWT. The characteristics of this ship are given in Table 24.

Table 24 - Characteristics of Nord Sun

Parameter	**Amount**	**Unit**	**Formula**	**Description**
L	220	m		Length
L_{load}	200	m	Assumption	Loaded length
B	32.3	m		Width

H	17.3	m	1.2T ([48])	Moulded depth
T	14.4	m		Draught
DWT	82,146	ton	Dead weight ton	Maximum carrying capacity of ship
Δ	90,000	ton		Volume displacement

The draught of the ship is 14.4m. The maximum draught allowed in the North Sea Canal is however only 13.75m ([49]). Ships with a higher draught needs to be lowered to enter the Canal. Therefore for this ship the amount of iron ore is lowered from 95%*DWT to 90%*DWT.

For this type of ship the minimum length of the ship which is flooded is assumed to be 0.3*220=66m.

For the ship being supported over the full tunnel width, a U.C. of 1.0 for the shear capacity is found for X = 60m. This is a little bit smaller than the stated 66m, but will be hold on as being valid to be conservative. This is done, because the length of the compartments is now assumed to be 10%, but it is not known whether this assumption is correct or not. But it gives an indication. Therefore it is assumed that due to this restriction, it is not possible that the ship becomes supported by only half of the tunnel width.

The load obtained for this situation is about 275kN/m^2. The U.C. for the bending moment capacity is 0.37. This load of 275kN/m^2 results in a load of 257kN/m^2 for block 1 and 86kN/m^2 for block 2.The load for the longitudinal analysis is 4464kN/m. These results are summarized in Table 25.

Table 25 - Magnitude of loads for iron ore bulk carrier

Load	**Cross sectional analysis (kN/m^2)**			**Longitudinal analysis (kN/m)**
	Load on tunnel deck		Load on tunnel wall	
	Block 1	Block 2		
Iron ore bulk carrier	257	86	129	4464

7.3 Structural behaviour

In this part of the chapter the structural behaviour of the tunnel is examined. First an overview of the loads is given which were taken into account for the design. Also the governing load combination is presented. After that it is clarified which part of the tunnel is most relevant with respect to a sunken ship load. For that part of the tunnel the structural behaviour is examined.

The structural behaviour is examined for the cross section and for the longitudinal direction. This both for the loads under normal conditions as well as when applying a sunken ship load.

7.3.1 Loads

7.3.1.1 Loads taken into account in the design

In this paragraph the loads which were taken into account for the design of the Wijkertunnel are evaluated. That loads can be divided in permanent, variable and accidental loads.

Permanent loads:

- Self-weight
- Water pressure
- Ballast concrete

[48] *The factor of 1.2 is a guide number for the ratio between the moulded depth and the draught (J. Koning, Mei 1992).*
[49] *http://www.portofamsterdam.nl/vaarweginformatie.html*

- Load from soil
- Adhesive forces from soil

Variable loads:
- Temperature T1 (inside -10°C, outside +5°C)
- Temperature T2 (inside +15°C, outside +5°C)

Accidental loads:
- Explosion

7.3.1.2 Load combinations

Based on the loads as stated above, different load combinations are made:
- Comb A: All permanent loads
- Comb B: Comb A + Temperature T1
- Comb C: Comb A + Temperature T2
- Comb D: Comb A + Explosion

These four combinations are basically all load combinations. There are also other load combinations, but those contain only variations based on the load combinations as stated above. One variations is made with respect to the minimum and maximum water level. Another variation is made with respect to the adhesive forces from the soil. In certain load combinations those adhesive forces are taken into account, while for other combinations they aren't.

7.3.2 Location of governing segment

The tunnel consists out of different segments. Each segment has its own loads. Therefore also the reinforcement differs. For this tunnel the same reinforcement cage is applied for each segment in a complete element. For each element it holds that the segment which is at the lowest position, carries the biggest load. Therefore for those segments the loads are determined and based on the loads the reinforcement cage. Due to symmetry, this needs only to be done three times. Because element 1 is equal to element 6, 2 to 5 and 3 to 4.

For the evaluation of the load of a sunken ship, it is important to know where the navigable waterway is. Because that determines the position of the ship when passing the tunnel. The Dutch Ministry of Transport gives the following data about the North Sea Canal[50]:

- Width: 270m
- Depth: 15.1m

The North Sea Canal at the position of the Wijkertunnel has not a water depth of 15.1m over a distance of 270m. Therefore the navigable waterway is assumed to be over the full width where a water depth of 15.1m is available. This is indicated in Figure 95. The width of the navigable waterway becomes then about 200m.

[50] *http://www.rijkswaterstaat.nl/water/vaarwegenoverzicht/noordzeekanaal.aspx*

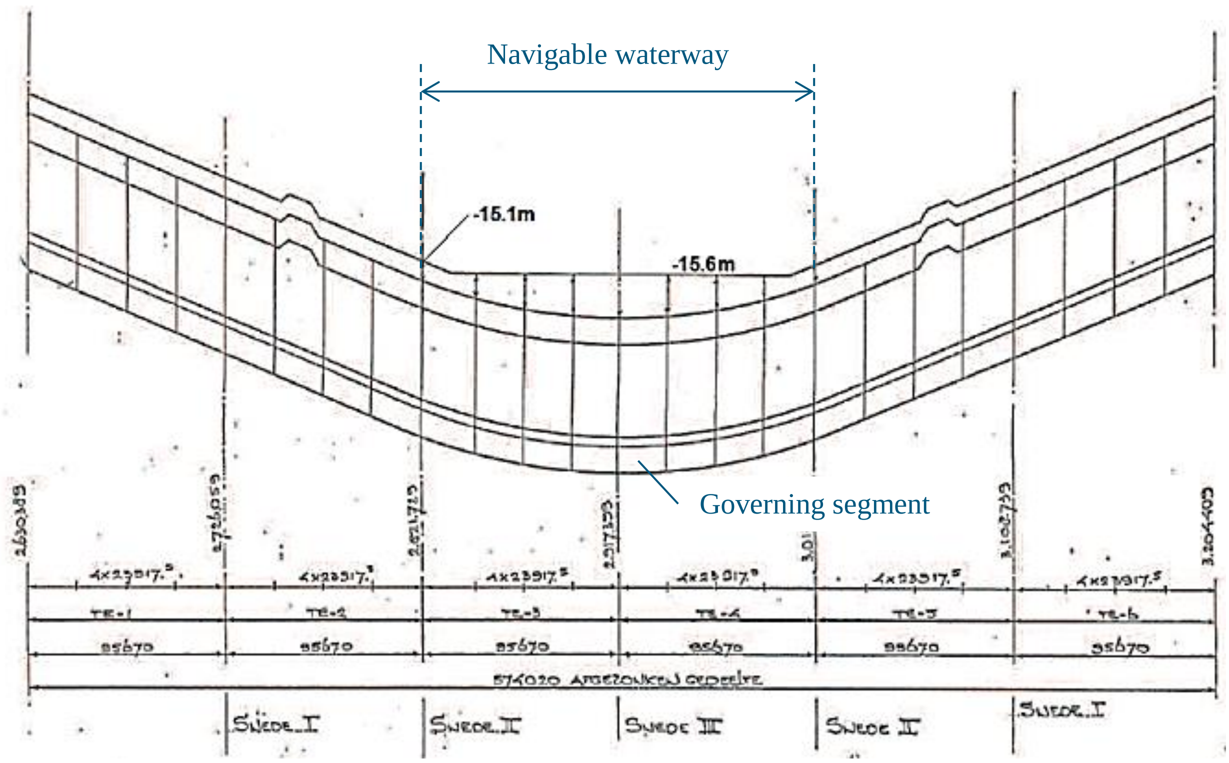


Figure 92 - Indication of navigable waterway and governing segment

From Figure 92 it can be seen that the navigable waterway lies only above element 3 and 4. As explained before, the segments in these elements has all the same reinforcement cage. That facilitates the calculations, because no differences in reinforcement cage needs to be taken into account now. With respect to the loads, as said before, the lowest positioned segment takes the biggest loads. That means that those segments need to be evaluated with respect to a sunken ship load. That segment is also indicated by 'governing segment' in Figure 92.

7.3.3 **Cross sectional behaviour**

In this part the cross sectional behaviour is examined. Due to the fact that a sunken ship is an accidental load situation (ALS), all load factors are one in this paragraph. This holds both for the loads in the normal situation as well as for the sunken ship loads.

7.3.3.1 Schematisation of structure

The schematisation of the Wijkertunnel is given in Figure 93.

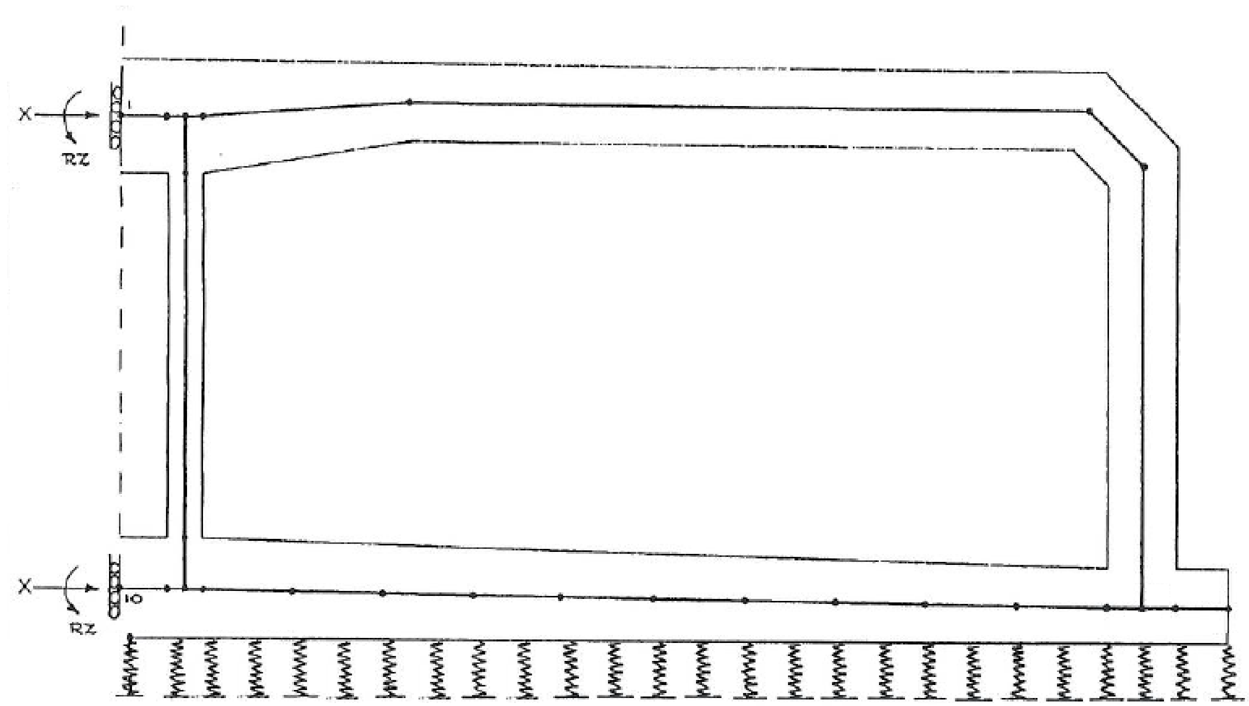


Figure 93 - Schematisation of Wijkertunnel

As can be seen from the picture above, only half of the tunnel is presented. That's done because of the symmetry of the tunnel. This symmetry does not hold for the explosion load only. Therefore some changes in the boundary conditions were made for that load.

The bars which represent the structure are located in the core of the elements. To each bar the corresponding dimensions and properties are added. Some of them are made infinitely stiff[51]. All bars are rigidly connected.

A next item which is remarkable, are the numerous bars used for the floor. That's done for a schematisation of the subsoil by discrete springs. The schematisation of the subsoil most frequently used is however an equal distributed elastic foundation. That schematisation is also used for the research. Be aware that those springs can take up only compression forces and no tensile forces.

For the bedding stiffness a value of 30.000kN/m^2 is used. That was the value as given by the Dutch ministry of Transport. The designers however had a different opinion. They thought that a value of 3.000kN/m^2 should be more realistic for the first years. Because the foundation consists out of disturbed ground. The expectation of the designers was that the value of 30.000kN/m^2 will be reached after several years, when the subsoil is more settled. The Wijkertunnel was ready for use in 1996. So at this moment we are 20 years further. Therefore it is assumed that the subsoil has settled so much that a stiffness of 30.000kN/m^2 is a realistic value for now.

7.3.3.2 Behaviour under loads from design

Under this heading the response of the tunnel is evaluated under normal load conditions. The results are validated with the aid of the existing design calculations.

[51] That are the parts which have a very large height. For example the two small bars of the floor just located under the inner wall.

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7.3.3.2.1 **Behaviour**

Combination A is used as governing load combination for the design. Combination B and C are however governing over combination A for certain locations. Therefore the reinforcement is based on load combination A and after that checked for combination B and C. Combination A is totally governing over combination D, therefore combination D is not evaluated at all.

Due to this, it is tried to calculate back the results from the design calculations for combination A. The bending moment diagram of combination A is given in Figure 94. These results are found by making use of Scia Engineer.

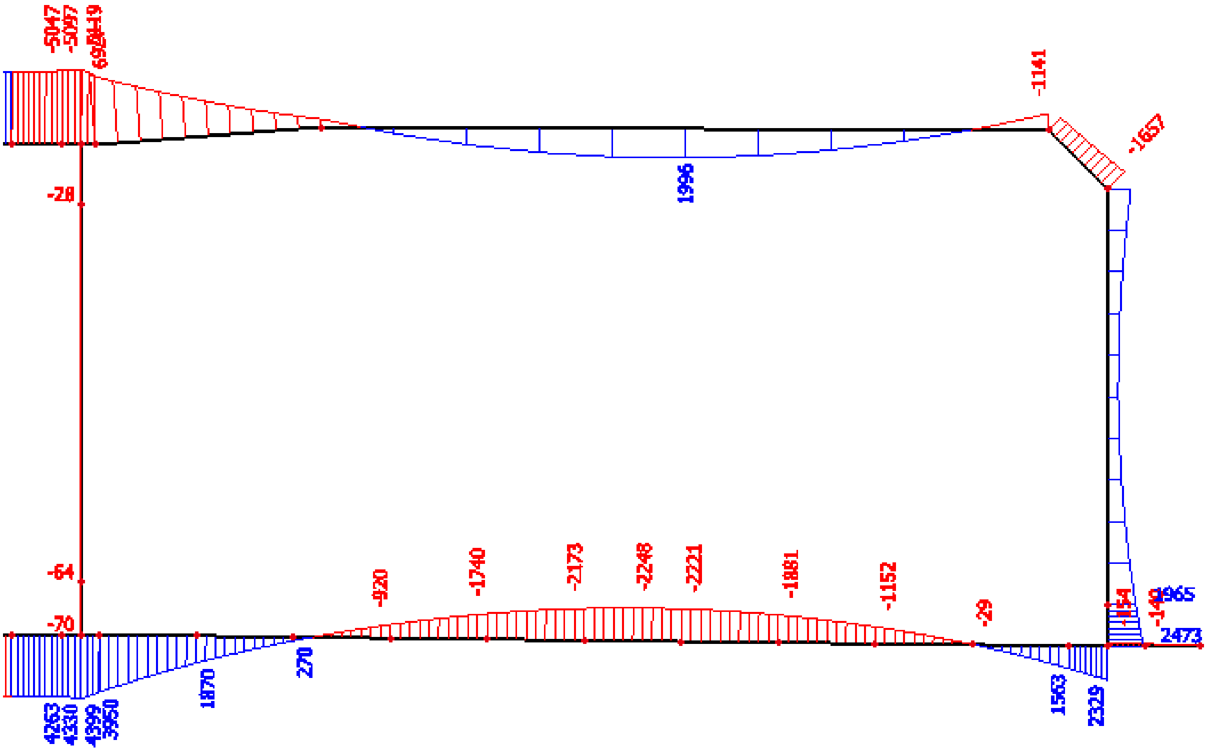

Figure 94 – Bending moment diagram in kNm of combination A, found by Scia

7.3.3.2.2 **Validation**

To validate the found results, they are compared with the values as found in the design. The bending moment diagram of combination A from the design calculations is given in Figure 95. This figure includes the shifted m-line. The shifted m-line is used when determining the required amount of reinforcement.

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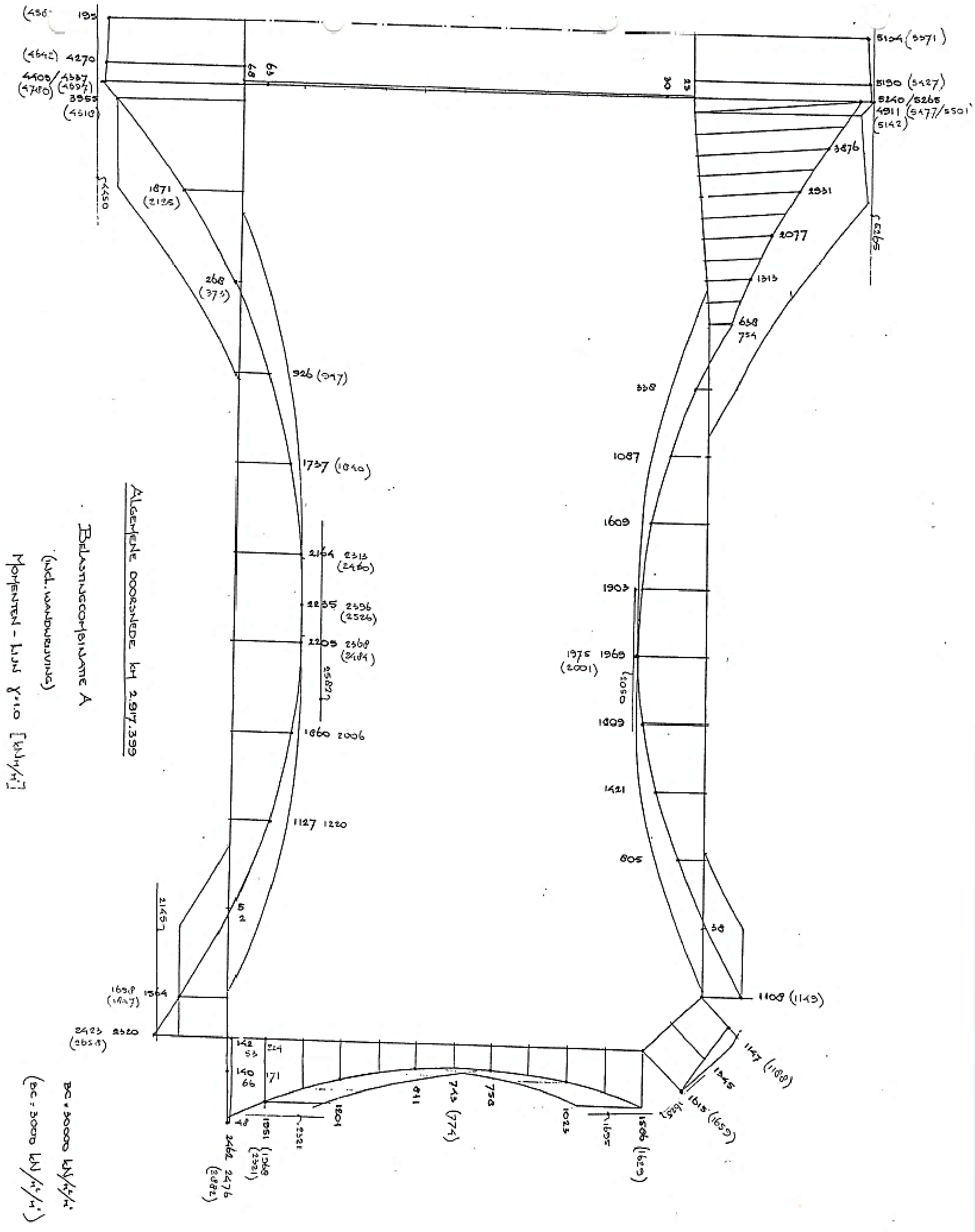

Figure 95 - Bending moment diagram of combination A from design calculations (with shifted m-line)

It can be seen that the results for the deck and the bottom compare quite well. For the corners a little bit more differences are found, but they differ only for about 2%. So it's assumed that the results of the model as made in Scia engineer are reliable.

7.3.3.3 Behaviour under sunken ship load

In this paragraph the tunnel is evaluated with respect to a sunken ship load. The load from a sunken general cargo carrier and an iron ore bulk carrier are applied in addition to the governing load combination. In this paragraph only the bending moments are shown. This is done to give an indication of the behaviour. But also the strength of the tunnel with respect to the shear forces is evaluated later on.

7.3.3.3.1 **General cargo carrier**

In Figure 96 a schematisation of the load from a general cargo carrier is given. The load configuration as showed in Figure 96 has a higher block at the left side, and the lower block at the right side. This situation is governing over the situation when the block loads are positioned the other way around.

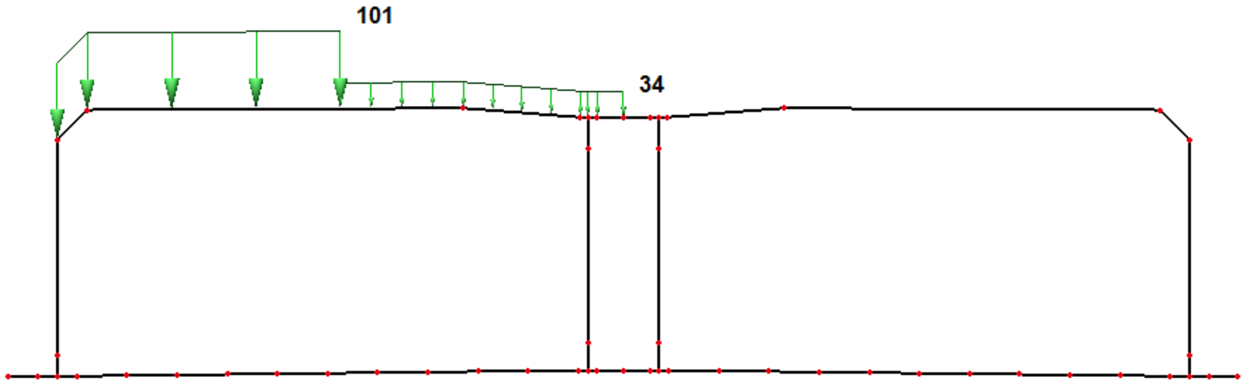

Figure 96 - Load from general cargo carrier in kN/m² (sinking under an angle)

Figure 97 shows the resulting bending moment diagram when applying the sunken ship load together with the governing load combination.

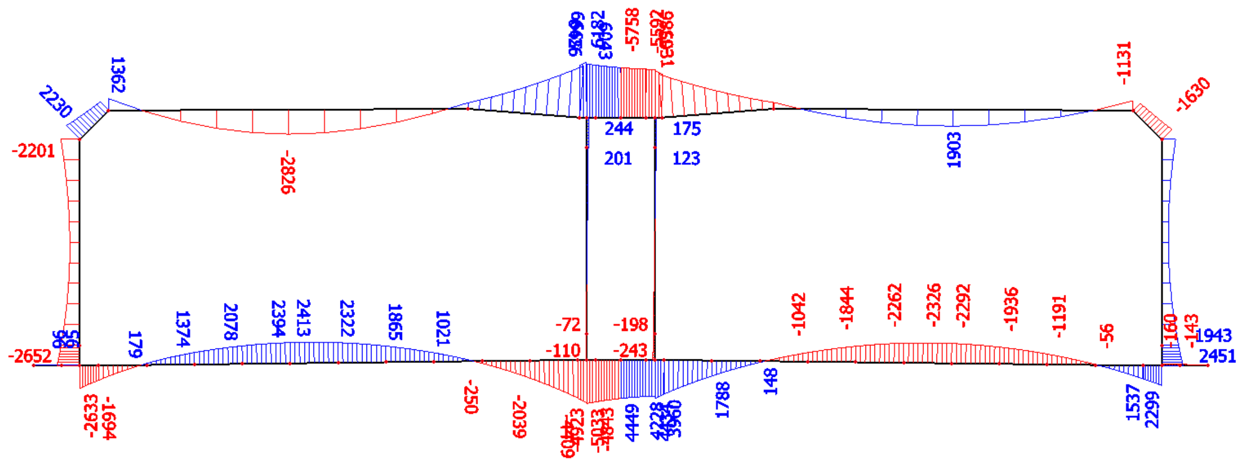

Figure 97 - Bending moment diagram in kNm: comb A + load from general cargo carrier

From the resulting bending moment diagram, it can be seen that the left tube is the governing one. Therefore only that tube is evaluated later on.

7.3.3.3.2 **Iron ore bulk carrier**

For the iron ore bulk carrier, two load situations are evaluated. One of them is the ‘normal’ load situation of a ship sinking under an angle on top of the tunnel. The other situation is if the ship sinks just next to the tunnel. There is then no load on top of the tunnel, but there will be a load induced on the wall of the tunnel.

Sinking on top of the tunnel

The load of the iron ore bulk carrier is presented in Figure 98.

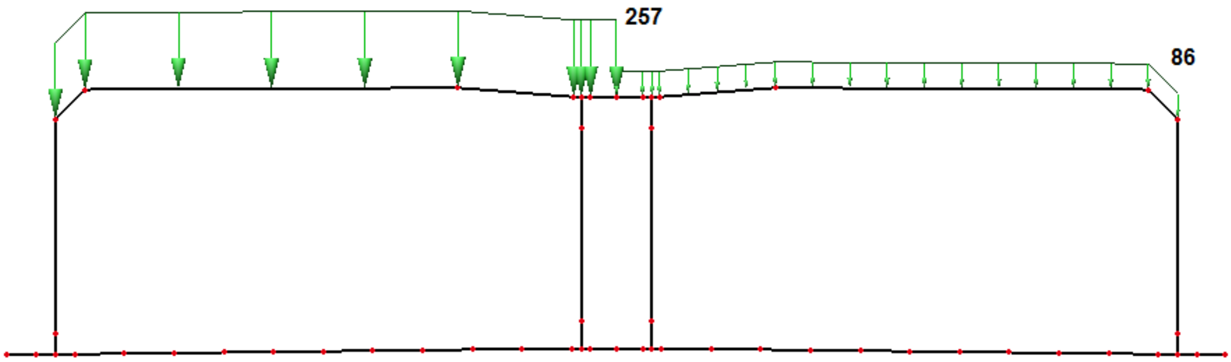

Figure 98 - Load from big iron ore bulk carrier in kN/m^2 (sinking under an angle, on deck)

The resulting bending moments are presented in Figure 99.

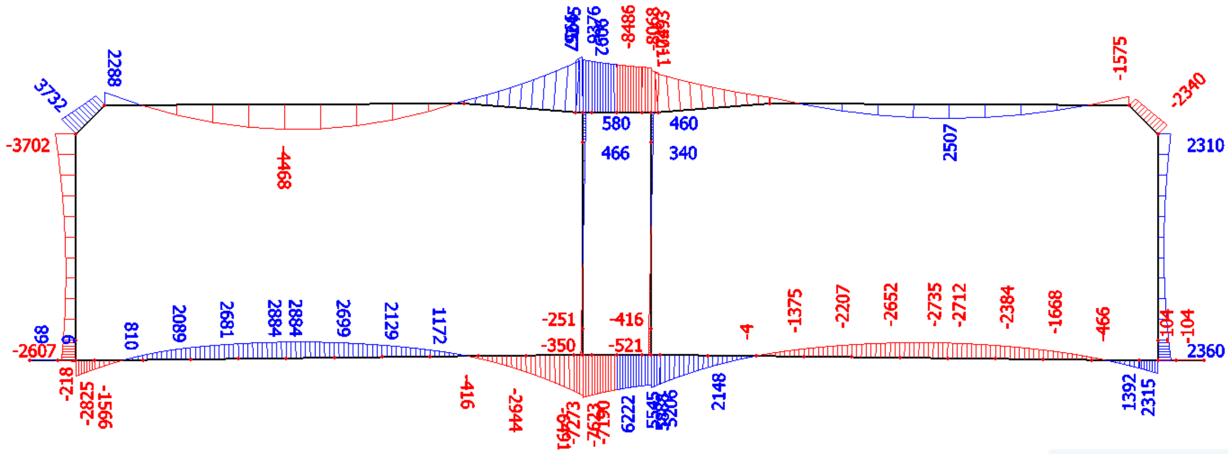

Figure 99 - Bending moment diagram in kNm: comb A + load from iron ore bulk carrier (on tunnel deck)

Also here the maximum bending moments occur in the left tube of the tunnel. Therefore only that tube will be checked later on.

Sinking next to tunnel

The load exerted on the wall of the tunnel is assumed to be 50% of the vertical load (257*1/2=129). The load is also assumed to be equally spread over the height of the tunnel.

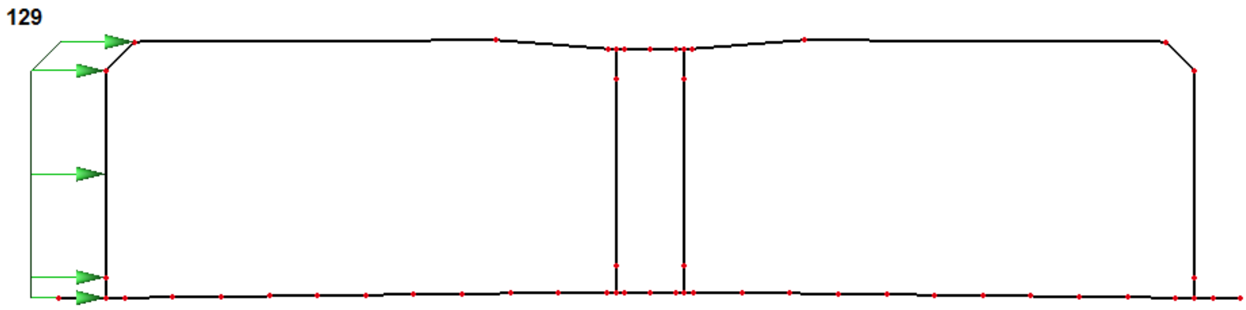

Figure 100 - Load from iron ore bulk carrier in kN/m² (sinking under an angle, next to tunnel)

The resulting bending moment diagram is given in Figure 101.

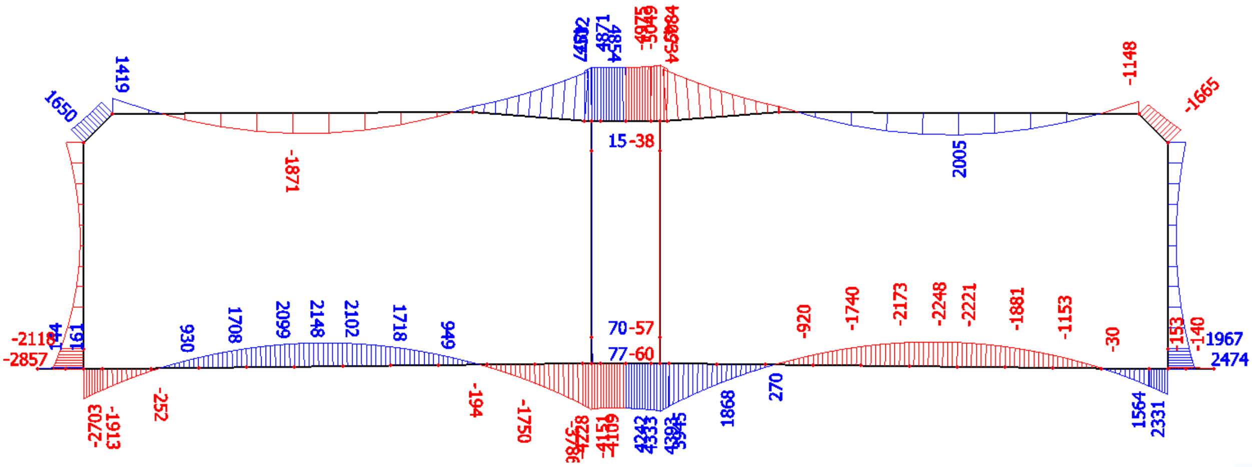

Figure 101 - Bending moment diagram in kNm: comb A + load from iron ore bulk carrier (on tunnel wall)

Also here only the left tube is checked later on.

7.3.4 **Longitudinal behaviour**

In this part the longitudinal behaviour is examined. Also in this paragraph, all load factors are one. This holds both for the loads in the normal situation as well as for the sunken ship loads.

7.3.4.1 Schematisation of structure

In Figure 102 a schematisation of the structure is given as used in the design documents.

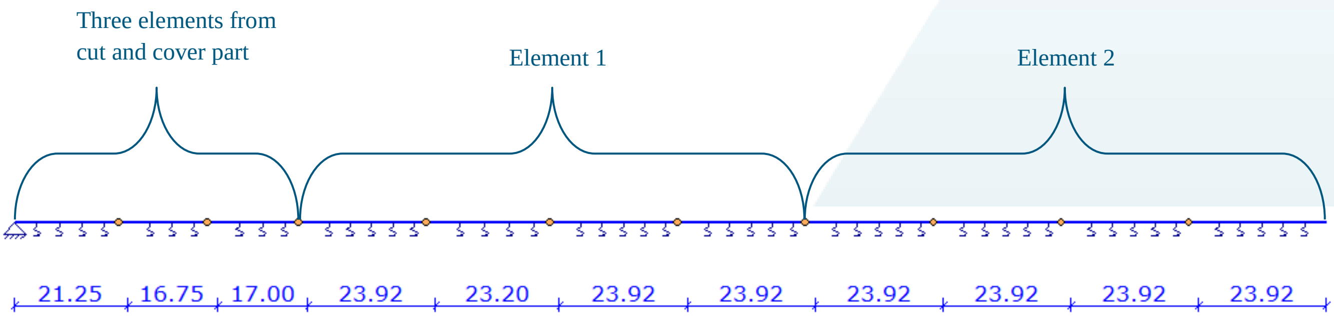

Figure 102 - Schematisation of tunnel by design documents

The first three elements in this model are from the cut and cover part of the tunnel. These three elements are taken into account in the model, because they influence the force distribution in the immersed tunnel segments. The other elements from the cut and cover part are founded on piles, hence the fixed support at the beginning of the model. The elements from the cut and cover part have also different lengths compared to the segments. The length of each segment is 23.92m ([52]).

Each segment has the following characteristics:

- $A = 100m^2$
- $E = 32{,}000{,}000kN/m^2$
- $I = 1000m^4$

The model is only needed to calculate the shear forces in the joints. This means that the surface area (A) is not of any importance. Therefore it doesn't matter that the chosen surface area differs a little bit from the real value: $91m^2$.

The E-modulus corresponds with a concrete strength of B35.

The moment of inertia (I) is in reality $904m^4$. For the longitudinal behaviour of a segmented tunnel the stiffness plays a minor role in the force distribution (which was concluded in the design documents). The used value of $1000m^4$ instead of $904m^4$ give only differences in the order of magnitude of 0.2%. Such a difference is not of any importance.

The bedding stiffness K is not mentioned. That's because the bedding stiffness was variated in the design documents when calculating the shear forces.

This model was used in the design to calculate the shear forces in the transition from the cut and cover part to the immersed elements. This model is now extended to the full tunnel as presented in Figure 103.

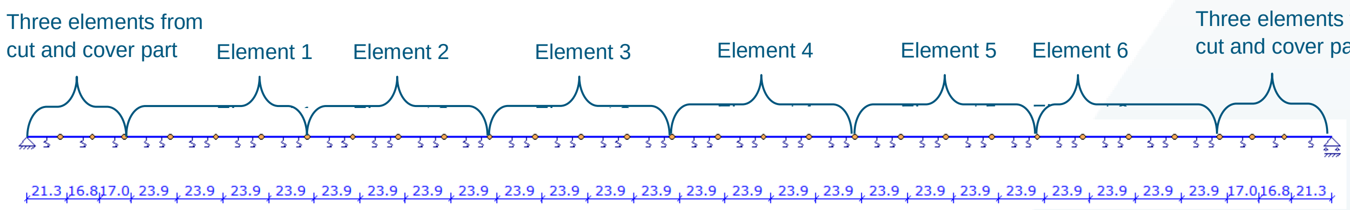

Figure 103 - Schematisation of tunnel for research

This tunnel as presented in Figure 103 is used for evaluation of the sunken ship loads in the research. For the segments, the same characteristics for the A, E and I are used as used in the design documents. For the bedding stiffness a value of $30.000kN/m^2$ is used.

7.3.4.2 Behaviour under loads from design

7.3.4.2.1 **Behaviour**

For the longitudinal direction, only the permanent forces are taken into account in the design. The other loads do not have any (significant) influence on the forces in longitudinal direction of the tunnel. The variable loads (temperature loads) cause only changes in normal forces in the structure. Those normal

[52] *There is one element in the model which has a length of 23.20m. This was an error in the model from the design which is taken over to be able to validate the results. In the model, which is used for this research, this flaw is corrected.*

forces are not evaluated for the longitudinal direction. The accidental load (explosion load) is only important for the cross sectional analysis.

The load configuration as used to calculate the shear force at the transition between cut and cover versus immersed tunnel is given in Figure 104.

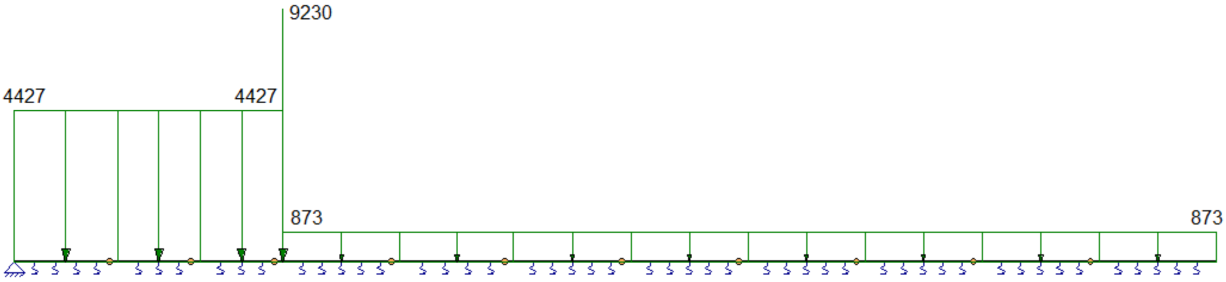

Figure 104 - Loads from design to calculate shear force at transition cut and cover ↔ immersed tunnel

Such a load configuration gives a shear force diagram as shown in Figure 105.

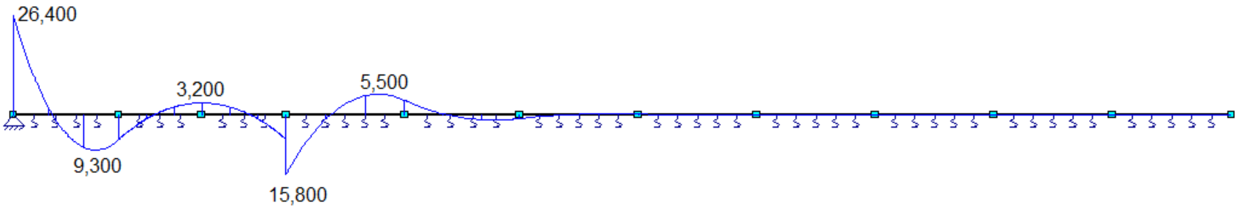

Figure 105 - Shear force diagram under permanent loads

When extending the tunnel to the full length, the loads become as depicted in Figure 106.

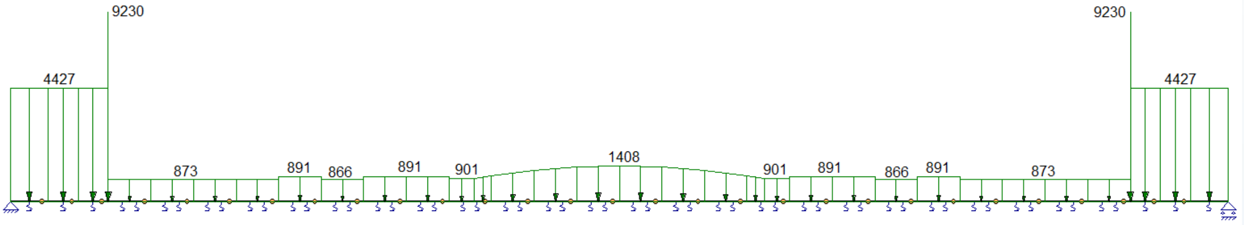

Figure 106 - Loads from design, full tunnel length

That results in a shear force diagram as given in Figure 107.

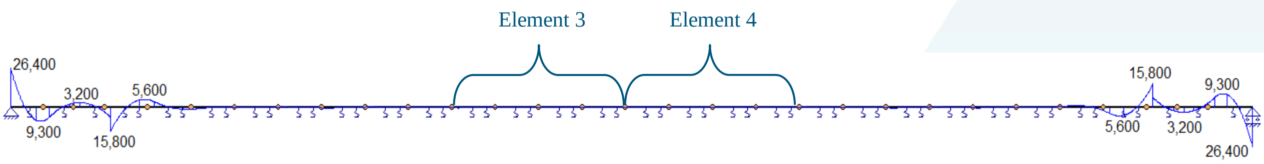

Figure 107 - Shear force diagram, full tunnel length

From this figure it can be seen that the major shear forces occur near the cut and cover part of the tunnel. The shear forces in element 3 and 4 (which are the potential locations where a ship can sink) are however almost zero. This means that, when evaluating the sunken ship loads, the shear forces from the design will not be taken into account.

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7.3.4.2.2 **Validation**

The model will be validated with the aid of the results from the model as used in the design (Figure 104). This is done by calculating the shear forces back as given in the design documents. The design documents give the shear force between the cut and cover part and the immersed part for different soil conditions. The results are given in Table 26.

Table 26 - Shear forces from model from design and own used model

Stiffness soil (kN/m^3)	**Shear force in joint between cut and cover and immersed part (kN)**	
	Model from design	Own used model
30,000	15,476	15,476
3,000	16,028	16,028
300	16,088	16,088
Cut and cover: 6,000 **Immersed part: 3,000**	9,586	9,586

From Table 26 it can be seen that the results from the own used model correspond exactly with the results as presented in the design documents. This result validates the model.

7.3.4.3 Behaviour under sunken ship load

7.3.4.3.1 **General cargo carrier**

The load in longitudinal direction is calculated by dividing the total reaction force (which follows from the model to calculate the sunken ship loads) by the width of the ship (see also §A2.1.3.2.8 *Load on tunnel*, p.164). The load is applied just next to a joint, because that's the location that the maximum shear force occurs in a joint (see also §6.3.3.2.1 *Forces* on p.68).

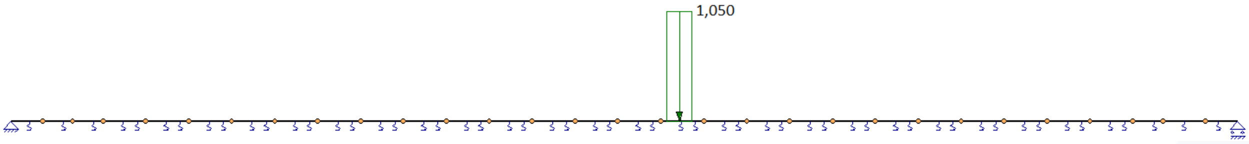


Figure 108 - Load from general cargo carrier (kN/m)

The resulting shear force diagram is given in Figure 109.

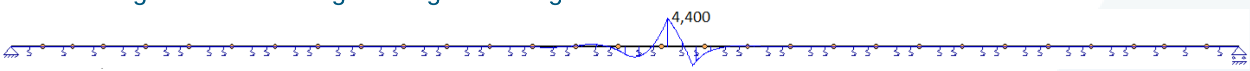


Figure 109 - Shear force diagram from general cargo carrier (kN)

The (maximum) shear force which is occurring in the joint equals 4.4MN.

7.3.4.3.2 **Iron ore bulk carrier**

Sinking on top of the tunnel

The load from the iron ore bulk carrier is determined in the same manner as for the general cargo carrier. The tunnel loaded with the iron ore bulk carrier is displayed in Figure 110.

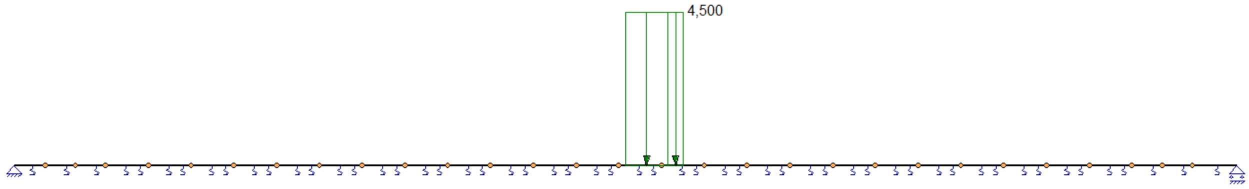


Figure 110 - Load from iron ore bulk carrier (deck loaded)

The resulting shear force diagram is given in Figure 111.

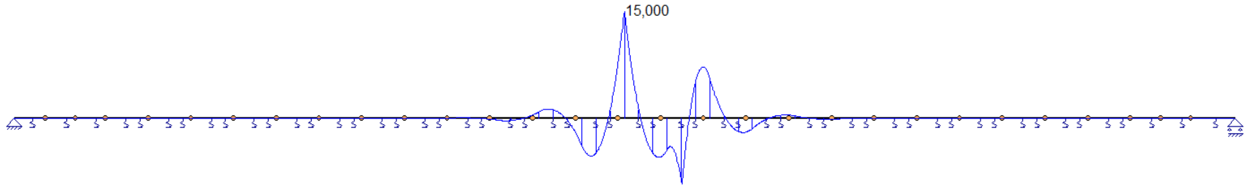


Figure 111 - Shear force diagram from iron ore bulk carrier (deck loaded)

The forces are now a way higher compared to the general cargo carrier. The maximum shear force in the joint now reads 15,0MN.

Sinking next to tunnel

For the situation of sinking under an angle, the same model is used, but now with different parameters. The stiffness of the soil is now 30,000*8=240,000kN/m^2 and I = 8000m^4. The load follows from the equal distributed load on the tunnel wall times the height: 129*8 $\approx$ 1,000kN/m.

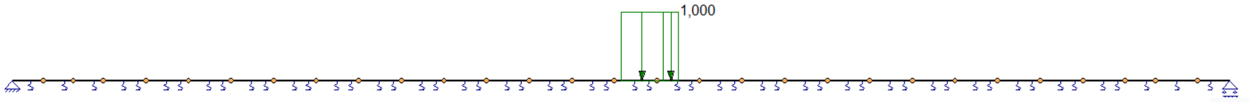


Figure 112 - Load from iron ore bulk carrier (wall loaded)

This results in the shear force diagram as shown in Figure 113.

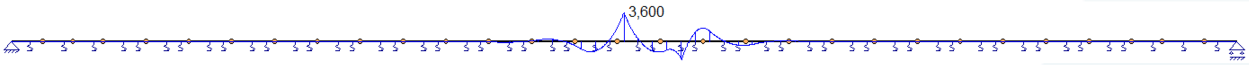


Figure 113 - Shear force diagram from iron ore bulk carrier (wall loaded)

The maximum shear force now equals to 3.6MN.

7.4 Verification

In this part the verification with respect to the bending moment capacity and the shear force capacity is carried out. This holds for the cross sectional analysis. For the longitudinal analysis only the shear forces and the deformations of the water seals in the joints are verified.

7.4.1 Cross section

For the cross section first an description of the build-up of the reinforcement cage is given. After that the verification rules which are used for checking the bending moments and shear forces are presented. At last the U.C.'s are given for the different load events.

7.4.1.1 Capacity

7.4.1.1.1 **Applied reinforcement**

For determining the required amount of reinforcement w.r.t. strength, an overall safety factor of 1.7 is used for the bending moments and the shear forces. For the normal forces a factor 1.4 is used. However, for durability reasons, the amount of reinforcement is increased over the full cross section. The increase varies from a factor 1.08 to 1.34. That based on a maximum allowable crack width varying between 0.42 and 0.50mm, depending on the location.

The amount of reinforcement applied to take up the cross sectional forces, is not equal over the full length of a segment. There are two strips in each segment near the joint which are more heavily reinforced (Figure 114). From these strips is strip 1 most heavily reinforced and strip 2 a little bit less. Those strips are present over the full cross section of the tunnel in the dilation joint. For the immersion joint is strip 2 only present in the floor and not in the wall and deck.

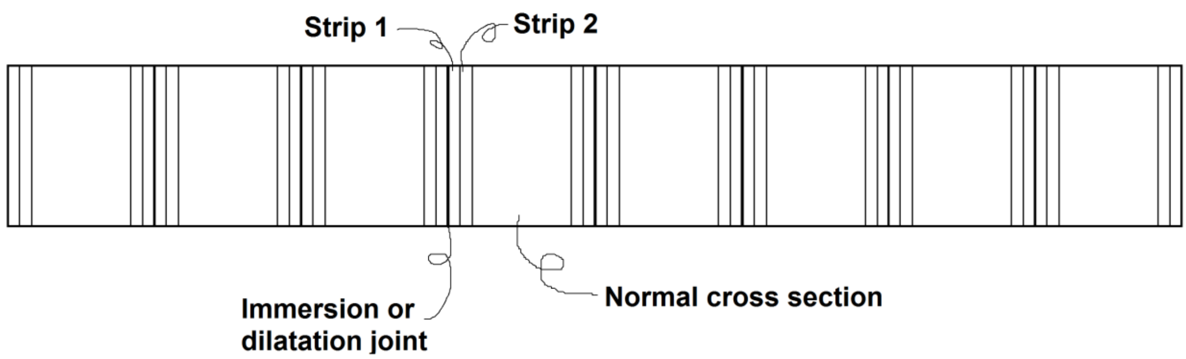
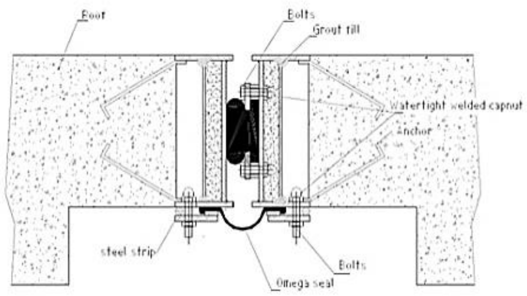
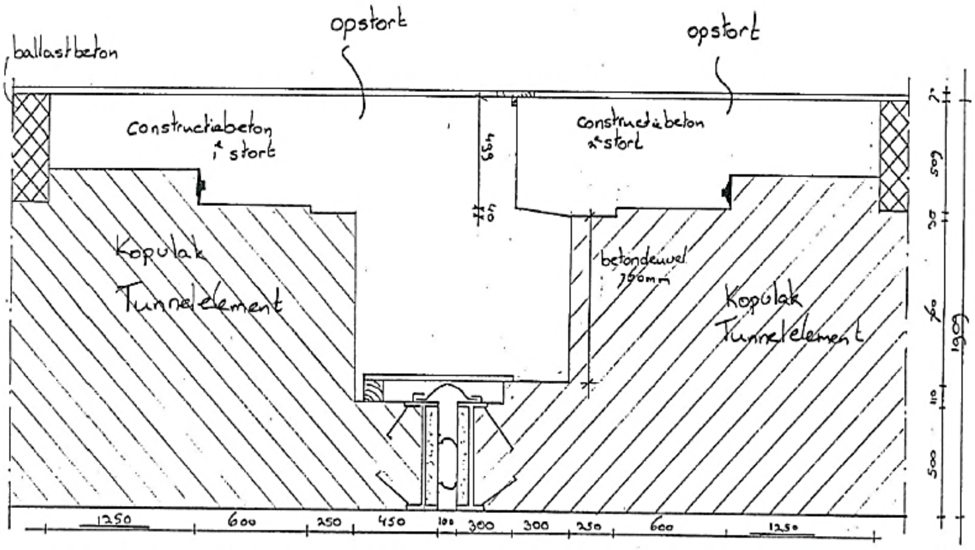


Figure 114 - Build-up of segments

These strips are more heavily reinforced due to the reduced cross section at the position of the joints (see Figure 115 for the immersion joint and Figure 116 for the segment joint). Another item is that the forces in the shear keys (which follow from the longitudinal analysis) cause an increase in the forces in the cross section.



a)



b)

Figure 115 - Lay out of immersion joint [a) deck, b) floor]

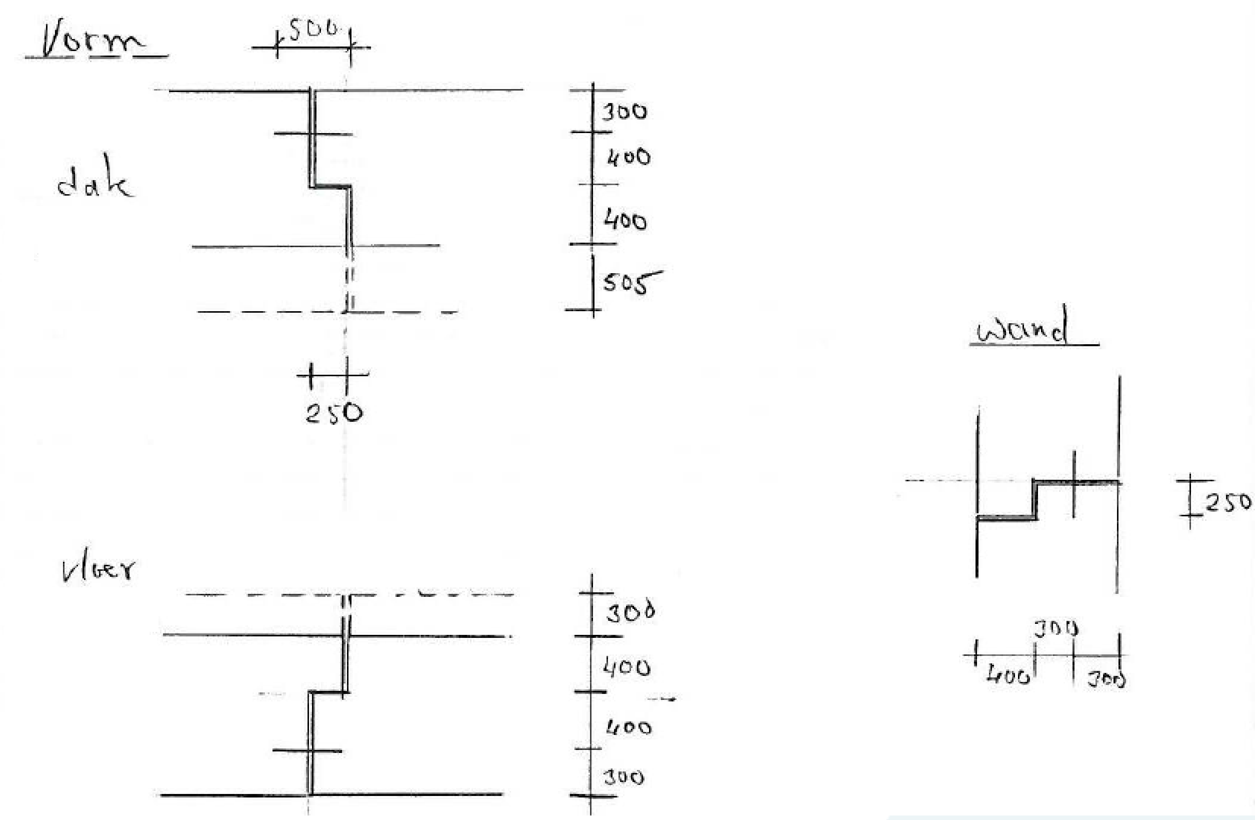


Figure 116 - Lay out of dilatation joint

7.4.1.1.2 **Bending moments**

The bending moment capacity is determined in the following way:

$$M_{Rd,tot} = M_{Rd,reinf} + M_{Rd,N_{Ed}}$$

In which:

$$M_{Rd,reinf} = A_l f_{yd} z$$

$$z = d - 0.39 x_u$$

$$x_u = \frac{f_{yd} A_l}{0.75 f_{cd} b}$$

$$M_{Rd,N_{Ed}} = \sigma_{cp} W$$

$$\sigma_{cp} = \frac{N_{Ed}}{db}$$

$$W = \frac{1}{6} bh^2$$

In which the following definitions are used:

A_l	the longitudinal reinforcement in mm^2
f_{yd}	yield strength of steel, equal to 500N/mm^2
z	internal lever arm
d	effective height
x_u	is the height of the compression zone
f_{cd}	the design strength of concrete in the accidental limit state: 28/1.2=23.3N/mm^2
b	effective width, equal to 1000mm, because the construction is evaluated for one meter length
σ_{cp}	normal stress due to the normal force N_{Ed}
N_{Ed}	normal force
W	moment of resistance
h	height of the construction element

7.4.1.1.3 **Shear force**

The shear capacity is determined with the aid of the Eurocode (EC) and the TNO-IBBC method. That is done, because the EC tend to be very conservative with respect to the shear capacity. Those design methods have different approach in predicting the shear capacity. The EC is based on a strut and tie model. The TNO-IBBC method is based on compression arches and deep beams.

Eurocode

For the shear capacity, the maximum of the shear resistance with and without shear reinforcement is used. The shear capacity without shear reinforcement yields:

$$V_{Rd,c} = \left[C_{Rd,c} k (100 \rho_l f_{ck})^{1/3} + k_1 \sigma_{cp} \right] bd$$

With a minimum of

$$V_{Rd,c} = \left(v_{\min} + k_1 \sigma_{cp} \right) bd$$

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In which:

$$C_{Rd,c} = \frac{0.18}{\gamma_c} = \frac{0.18}{1.2} = 0.15$$

$$k = 1 + \sqrt{\frac{200}{d}} \leq 2$$

$$\rho_l = \frac{A_l}{bd}$$

$$\sigma_{cp} = \frac{N_{Ed}}{A_c} < 0.2 f_{cd} = 0.2 \cdot 23.3 = 4.7$$

$$v_{\min} = 0.035 k^{3/2} \sqrt{f_{ck}}$$

d	effective height
ρ_l	reinforcement ratio ≤ 0.02
A_l	the longitudinal reinforcement in mm^2
b	effective width, equal to 1000mm, because the construction is evaluated for one meter length
f_{ck}	the cylinder characteristic strength of concrete: 28N/mm^2
k_1	0.15
σ_{cp}	normal stress due to the normal force N_{Ed}
N_{Ed}	normal force

The shear capacity with shear reinforcement yields:

$$V_{Rd} = V_{Rd,s} + V_{ccd} + V_{td}$$

In which:

$$V_{Rd,s} = \frac{A_{sw}}{s} z f_{ywd} \cot\theta$$

V_{ccd} and V_{td} are defined as shown in Figure 117.

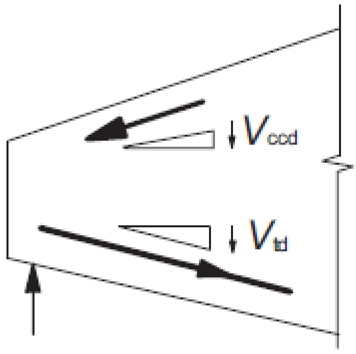


Figure 117 - Definition V_{ccd} and V_{td} (NEN, 2011)

Furthermore:

$\frac{A_{sw}}{s}$ applied shear reinforcement per unit of length

z internal lever arm

f_{ywd} yield strength of steel, equal to 500N/mm^2

θ internal angle of crack as defined in Figure 118.

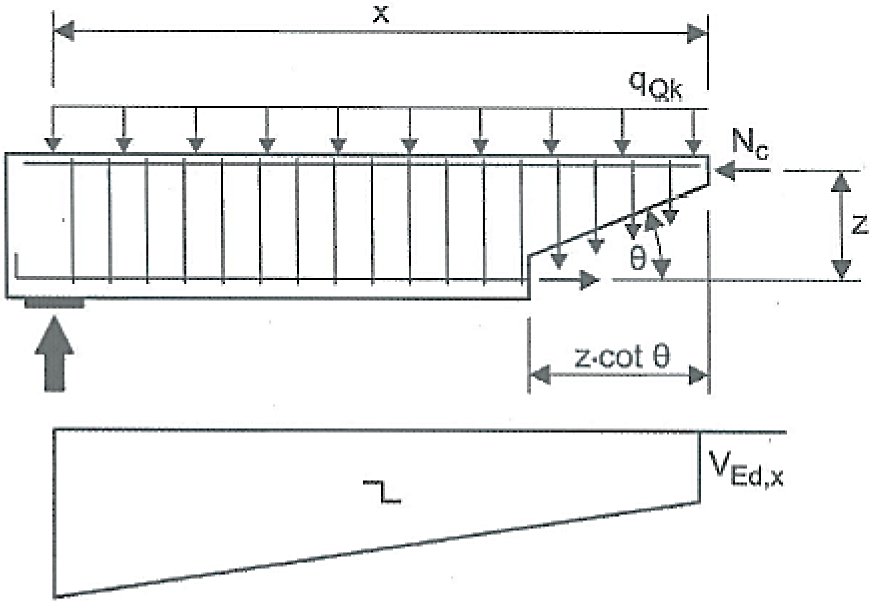


Figure 118 - Definition of angle of cracking θ (Walraven, 2011)

The angle θ changes over time during failure of the structure. This development is shown in Figure 119.

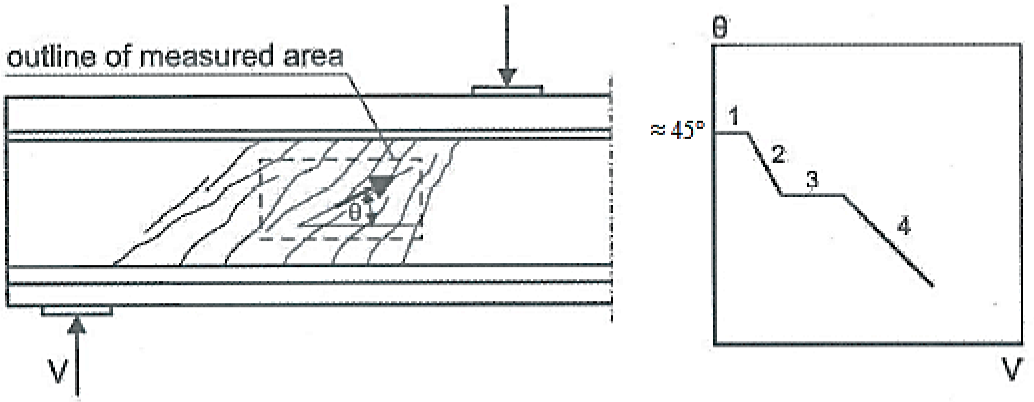


Figure 119 - Development of θ during failure (under shear) of the structure (Walraven, 2011)

The angle θ starts around 45°. After that θ decreases gradually. The lowest angle which the structure almost always achieves is 21.8°. A decrease in the angle θ causes an in increase in the shear capacity (Figure 119). That's due to the longer distance of the crack from top to bottom, in which more reinforcement bars are present then. So it is only allowed to use the high shear strength (for θ = 21.8°) if over the full length of the crack reinforcement bars are present.

For the Eurocode check it holds that the shear force doesn't need to be checked over a distance *d* from the support. With *d* being the effective height.

TNO-IBBC

For the TNO-IBBC method two different formulas can be used. The first of them are directly derived from the test results. Those formulas do not take into account any model uncertainties and long term effects. Therefore those formulas are indicated here as 'short term strength'. From those formulas certain design formulas are derived. Those design formulas do take into account any possible model uncertainties and long term effects. Those formulas are indicated here as 'long term strength'.

Short term strength:

For $\omega_0 < 1\%$

$$\tau_{11} = 0.263(1+0.0125\,f'_{cm})(1+\omega_0)(1+1.213\left|\frac{1}{\lambda_x}\right|)\left(\frac{d}{d_0}\right)^{-\frac{1}{4}} f_1(N)$$

$$\tau_{12} = 0.739(1+0.06\,f'_{cm})(1+\omega_0)\left|\frac{1}{\lambda_x}\right| f_{vout}(n)\left(\frac{d}{d_0}\right)^{-\frac{1}{4}} f_2(N)$$

For $\omega_0 > 1\%$

$$\tau_{11} = 0.455(1+0.0125\,f'_{cm})(1+0.156\omega_0)(1+1.213\left|\frac{1}{\lambda_x}\right|)\left(\frac{d}{d_0}\right)^{-\frac{1}{4}} f_1(N)$$

$$\tau_{12} = 1.386(1+0.06\,f'_{cm})(1+0.067\omega_0)\left|\frac{1}{\lambda_x}\right| f_{vout}(n)\left(\frac{d}{d_0}\right)^{-\frac{1}{4}} f_2(N)$$

Long term strength:

$$\tau_{11} = 0.17(1+0.0125\,f'_{ck})(1+\omega_0)(1+1.213\left|\frac{1}{\lambda_x}\right|)\left(\frac{d}{d_0}\right)^{-\frac{1}{4}} f_1(N)$$

$$\tau_{12} = 0.45(1+0.06\,f'_{ck})(1+\omega_0)\left|\frac{1}{\lambda_x}\right| f_{vout}(n)\left(\frac{d}{d_0}\right)^{-\frac{1}{4}} f_2(N)$$

In which:

$$\lambda_x = \frac{M_x}{V_x d}$$

$$f_1(N) = (1 - 0.12\frac{N_{Ed}}{bd}),\ \text{for -10} \leq \frac{N_{Ed}}{bd} \leq 0$$

$$f_2(N) = (1 - 0.045\frac{N_{Ed}}{bd}),\ \text{for -10} \leq \frac{N_{Ed}}{bd} \leq 0$$

$$\frac{d}{d_0} \leq 5$$

$$f_{chamfer}(n) = (1 - \left|\frac{1}{n}\right|),\ \text{n} \geq 3$$

In which n is defined as showed in Figure 120.

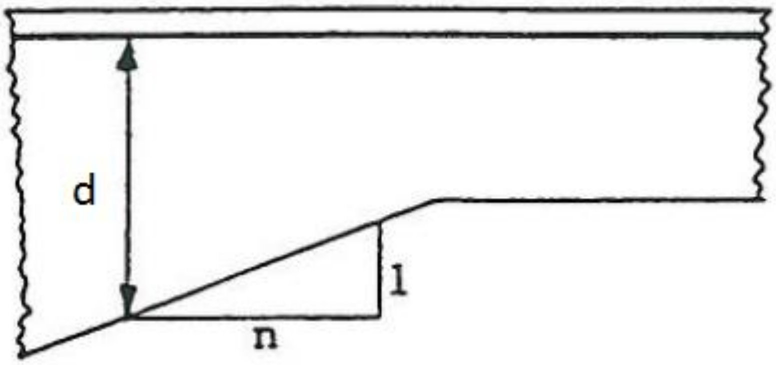


Figure 120 - Definition of n in $f_{chamfer}$ (design documents)

Furthermore:

d	effective height
d_0	reference height equal to 300mm
b	effective width, equal to 1000mm, because the construction is evaluated for one meter length
f'_{ck}	the cube characteristic strength of concrete: 35N/mm^2
ω_0	reinforcement ratio (≤ 1% for long term strength)
N_{Ed}	normal force
M_x	actual bending moment at position x
V_x	actual shear force at position x

The differences in τ_{11} and τ_{12} will not be explained in detail here. For detailed information see for example (A. van den Beukel, 1985) or (F.B.J.Gijsbers, 2009). In this research τ_{11} is used for M > 0 and τ_{12} for M < 0 ([53]).

At the location of a clamping the magnitude of V may be reduced over a distance x_u. The definition of x_u is shown in Figure 121. Over this distance only a shear force equal to V_{Ed} at x_u needs to be taken into account.

[53] *By which a bending moment halfway the deck is positive, and a bending moment near the inner wall negative.*

$$x_u = 0.5 \frac{M_s}{V_s} \frac{1}{1 - tan\varphi}$$

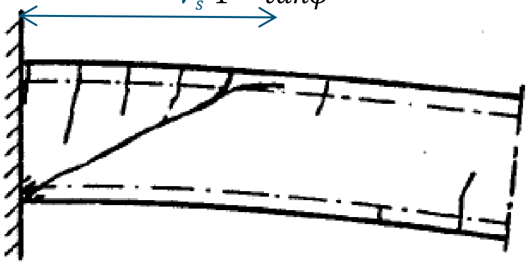


Figure 121 - Definition x_u (A. van den Beukel, 1985)

In which the symbols are defined as follows:

M_s	bending moment at the clamping
V_s	shear force at the clamping
φ	Angle of chamfer (if present)

7.4.1.2 Verification

Now the structure is checked according to the formulas as given in the previous paragraph (§7.4 *Verification*). To be able to indicate which position in the cross section is meant, certain locations are marked with a number (Figure 122).

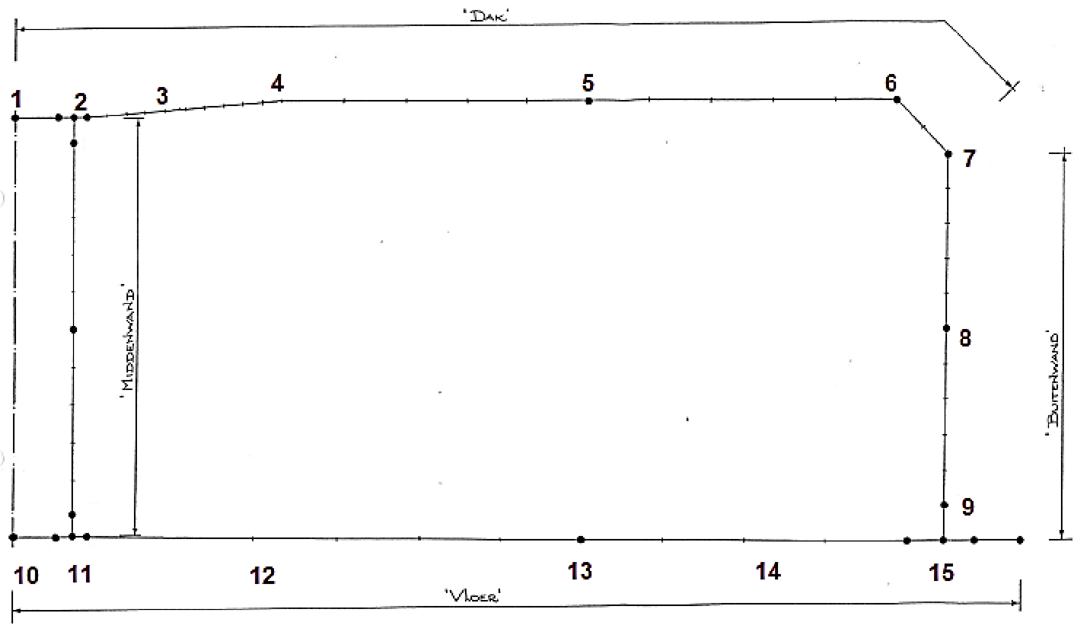


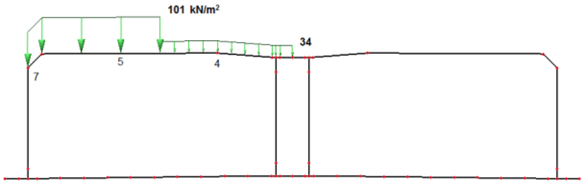
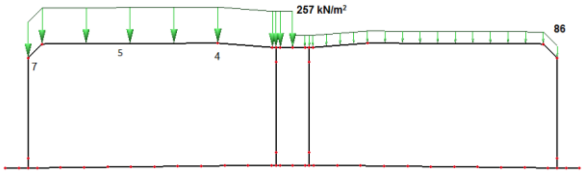
Figure 122 - Indication of positions in cross section tunnel

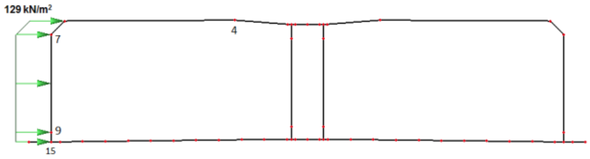
The results of the verification are shown in Table 27. In this table is also indicated at what location that Unity Check is obtained. The position in the cross section is indicated with a number (see Figure 122). For the longitudinal position the normal cross section is indicated with the character *N*, the immersion joint with

I and the dilatation joint with *D*. A ‘1’ indicates strip 1, and a ‘2’ indicates strip 2. For example I-2, means strip 2 from the immersion joint (see also Figure 114).

For the verification of the shear force different methods are used. The differences are already explained in the previous paragraph (§7.4.1.1). From the TNO-IBBC method the short term strength may be used. That’s because the load configuration of a sunken ship resting with its bow on the tunnel maintains probably only a few days. This was explained in chapter 5 (§5.3.3.2 Sinking under an angle, p.29).

Table 27 - Governing Unity Checks

	Unity Check				
	Shear force				**Bending moments**
	Eurocode		**TNO-IBBC**		
	θ = 45°	**θ = 21,8°**	**Long term strength**	**Short term strength**	
Normal situation	I-1 1.8 (4)	N 0.97 (4)	N, D-1 1.09 (7)	N, D-1 0.59 (7)	N 0.77 (9)
General Cargo carrier  	I-1 2.23 (4)	N 1.14 (4)	D-1 1.99 (7)	D-1 1.10 (7)	N 0.87 (5)
Iron ore bulk carrier, load on tunnel deck  	I-1 3.62 (4)	N 1.93 (4)	D-1 3.60 (7)	D-1 1.94 (7)	N 1.35 (5)

Iron ore bulk carrier, load on wall 	D-1 1.44 (4)	D-1 1.26 (9)	D-1 1.35 (7)	D-1 0.73 (7)	N 0.83 (15)

From Table 27 a few conclusions can be drawn. At first it is noted that for each situation the governing location corresponds with the loaded side[54]. That's an easy check for the validity of the results.

Secondly, a remarkable item is that (almost) all Unity Checks with respect to the shear force are bigger than 1.0. Even for the normal situation. That a U.C. > 1.0 is found for the normal situation can be explained when looking more carefully to the design calculations.

For the design, the shear capacity was determined with the TNO-IBBC method (long term strength). It was decided by the designers that no shear reinforcement should be applied if not more than 707mm^2/m^2 was needed. Secondly, the situation occurred that only over a very small region (about 0.5m) shear reinforcement should be applied at the upper half of the wall (the position indicated with number 7). Therefore the designers neglected that amount of reinforcement. That explains why location 7 often becomes the most critical location with respect to the shear capacity. As can be seen, that is always the case for the TNO-IBBC check.

For the EC-check however, location 4 becomes often critical. That has to do with the different approaches of the EC and the TNO-IBBC method. The EC assumes a 'constant' shear capacity, irrespective of the load conditions (excepted for the normal forces). Contrarily, the IBBC-method estimates the shear capacity based on the moment to shear force ratio. And is therefore dependent on the loading conditions. When using the EC-approach, location 4 is a weak spot, but when using the IBBC-method, location 7 is a critical location.

This differences in 'weak spot' explains also why the differences in U.C. between the Eurocode and the TNO-IBBC differ not that much. It can be seen that the EC – θ = 45° corresponds quite well with the TNO-IBBC method for the long term strength. Also the EC – θ = 21.8° corresponds quite well with the TNO-IBBC method for the short term strength. Although the TNO-IBBC method tend to predict a lower U.C, especially for the normal situation.

The bending moment capacity is not always bigger than one. Only for the situation of the tunnel loaded by the iron ore bulk carrier a U.C. larger than one is found.

A last item which will be discussed here is the failure mechanism. Although some U.C.'s > 1.0 are found for the normal situation, the real tunnel isn't collapsed yet, so no attention will be paid to those U.C.'s. For the general cargo carrier and the iron ore bulk carrier (loaded on the deck), all U.C.'s for shear are bigger than for the bending moment. So for those two situations it is assumed that shear failure will be the governing failure mechanism. For the last event, the tunnel being loaded from aside, there is only one U.C. for the shear force (TNO-IBBC, short term strength) smaller than the U.C. of the bending moment. That U.C. and also that of the bending moment are both smaller than one. That means that the tunnel does not collapse under such a load.

[54] An exception to this is the value for the situation of loaded from aside. Here location 4 becomes critical for the EC-check (θ = 45°). That's because that location was already critical in the normal situation. In this situation is the U.C. reduced from 1.8 to 1.44, but remains still the most critical one.

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7.4.2 **Longitudinal direction**

In this section the strength of the joints and the deformations of the water seals are evaluated. First an overview of the capacity of the joints together with the requirements to the water seals are given. After that the real occurring shear forces and deformations will be checked against the capacity.

7.4.2.1 Capacity

7.4.2.1.1 **Strength**

The strength of the shear key is determined by its reinforcement. These reinforcement is determined based on a strut and tie analysis. An example of a part of a strut and tie model is shown in Figure 123. F_v and F_h indicate the vertical and the horizontal force respectively, acting on the shear key.

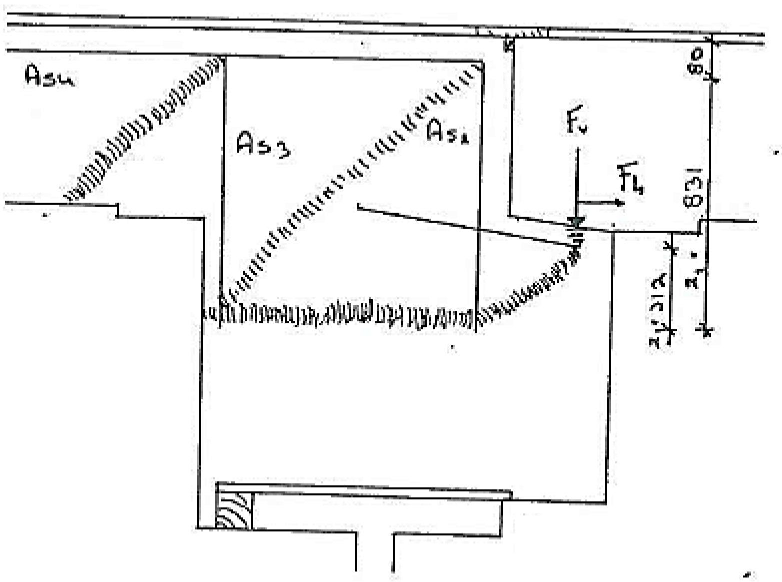

Figure 123 - Example of strut and tie model in joint (design documents)

Based on the assumed configuration of the strut and tie model, a reinforcement cage as displayed in Figure 124 is obtained. The reinforcement in that picture holds for immersion joint 4 (the joint between element 3 and 4).

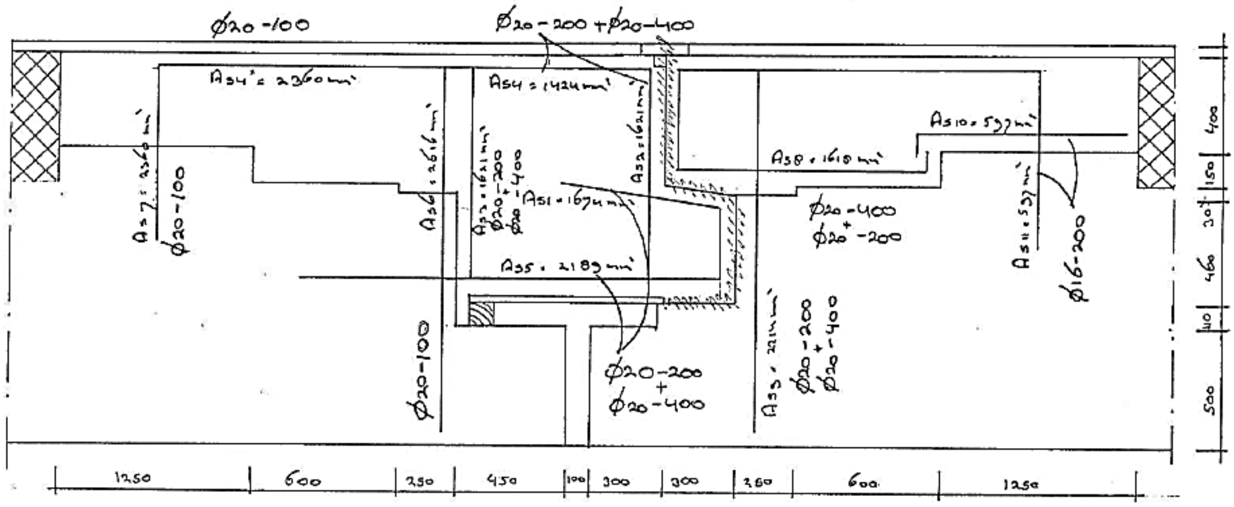

Figure 124 - Reinforcement in immersion joint 4 (the joint between element 3 and 4)

The same strategy is used for determining the required amount of reinforcement for the dilatation joint.

Based on the applied reinforcement and the configuration of the strut and tie model, the capacity of the joint can be calculated back. This can be done both for the immersion joint as well as for the dilatation joint. Keep in mind that there should be made a distinction between the different load configurations. If the tunnel is loaded from above, on the deck, the capacity of the joints in the floor or the deck is of importance. But for the event of the tunnel being loaded from aside, the capacity of the joint in the wall is of importance.

A second check, besides that of the strut and tie model, needs to be carried out for the longitudinal reinforcement. Because a loaded shear key induces also longitudinal bending moments (Figure 125).

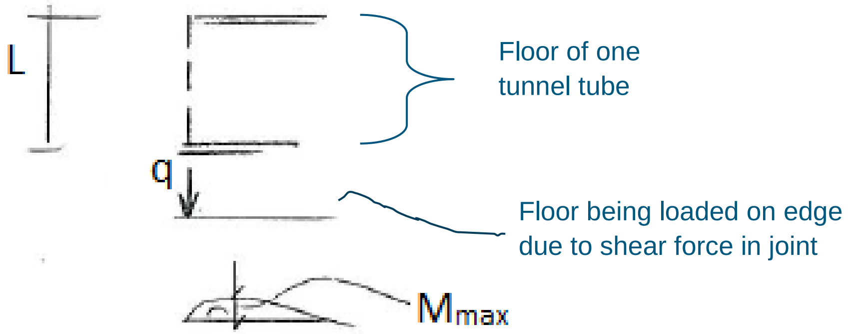

Figure 125 - Bending moments in longitudinal direction (design documents)

The value of M_{max} follows from: $M_{max} = 0.041qL$ ([55]).

7.4.2.1.2 **Deformations**

The requirements for the water seals depend on which type are used. The type of Omega seal what is used is unknown. Therefore the smallest type will be used to verify the results (OS 240-40). The type of water stop what is used, is the W9U-I. The requirements with respect to those water seals are given in Table 28.

[55] *Given by design documents. That formula follows from design figures for plates with different boundary conditions.*

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Table 28 - Requirements water seals in joint

	Maximum elongation allowed in ULS (mm)
Omega profile OS 240-40	60
Water stop W9U-I	46

7.4.2.2 Verification

7.4.2.2.1 **Strength**

When comparing the load with the capacity of the joint, the results as shown in Table 29 are obtained. Those results are all for the strut and tie model. The check for the longitudinal reinforcement (Figure 125) seems not to be decisive.

Table 29 – Unity Checks for the shear keys

	Unity Check
General cargo carrier	0.24 (immersion joint)
Iron ore bulk carrier, load on deck	0.81 (immersion joint)
Iron ore bulk carrier, load on wall	1.81 (dilatation joint)

From these results the conclusion can be drawn that the joints are able to handle the loads if the ship sinks on the tunnel deck. For the situation of the tunnel being loaded from aside, the U.C. become larger than one. That means that here the dilatation joint in the wall fails.

When deriving these results, it is assumed that the immersion joint has enough capacity to take up the load from aside. It is known that the immersion joint is only located under the roadways and not under the gallery. It is now assumed that the gallery acts as a kind of dowel between those two parts of the joints under the roadways. Such a connection will highest probably have enough capacity to take up the loads.

7.4.2.2.2 **Deformations**

The maximum elongation from the water seals is 3.7mm. This is under the load from the iron ore bulk carrier, loaded on the deck. This is a very small value. That has mainly to do with the very high bedding stiffness what is used for this design: 30.000kN/m^3. Therefore with respect to the deformations of the water seals, it can be concluded that no problems will occur.

7.5 Consequences

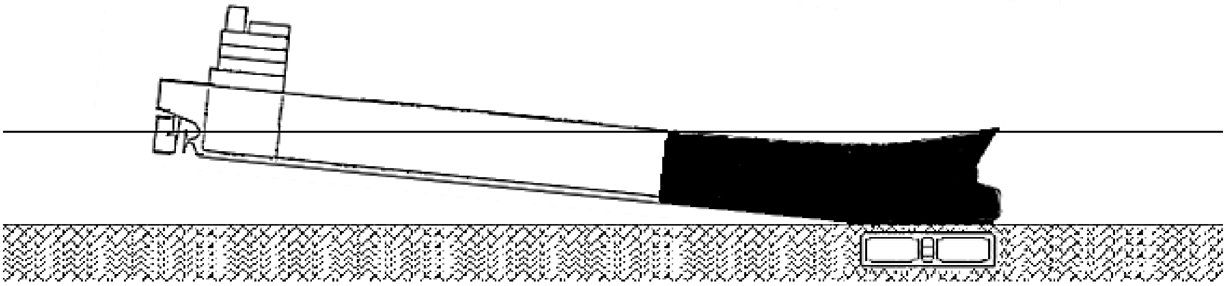
7.5.1 Cross section

From §7.4*Verification* it was concluded that the tunnel does fail under the general cargo carrier, and also under the load from the iron ore bulk carrier, if loaded on the deck. For both situations the U.C. for the shear capacity is bigger than for the moment capacity. It was therefore concluded that shear failure is the governing failure mechanism.

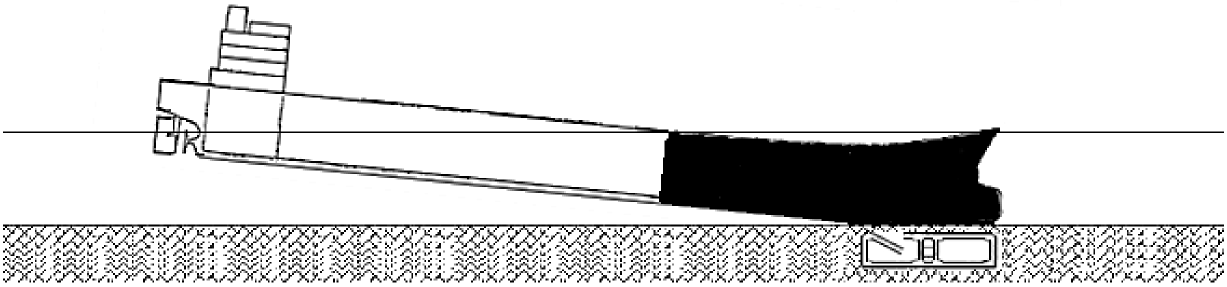
There are two different locations where the tunnel does fail. For the general cargo carrier it is location 4 and for the iron ore bulk carrier it is location 7. Those two possibilities are worked out below.

7.5.1.1 Failure at location four

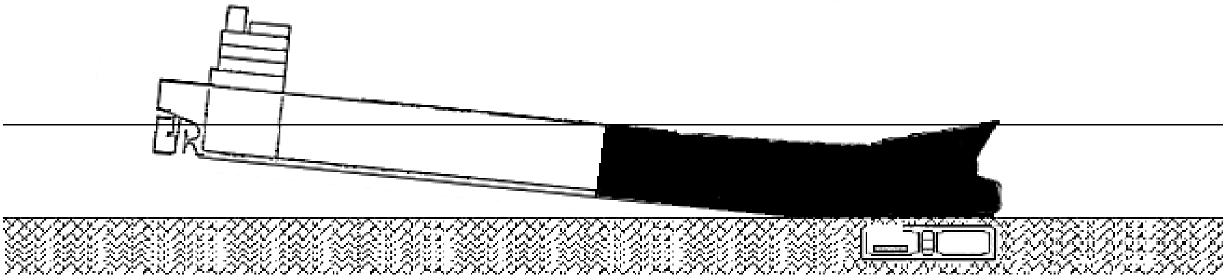
1) First the ship sinks on the tunnel deck. The bow of the ship is deformed (see Figure 35) until the situation is reached as shown below. Due to the deformations of the bow before that equilibrium situation is reached, it is assumed that the initial deformations of the tunnel deck will be followed by the bow. That means that such initial deformations of the tunnel deck do not have any influence on the force distribution.



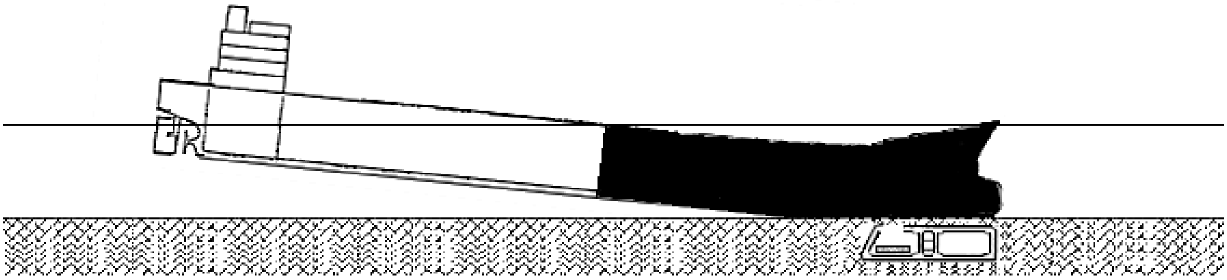
2) The deck fails at location four. Shear failure is a brittle failure mechanism. Hence no redistribution of forces occurs, but the deck loses its integrity.



3) The deck collapses and the ship needs new support at the left end. Therefore the ship will enlarge its supporting area over the sand bed. This is accompanied with more sinking of the back side of the ship, and hence a larger part of the ship becomes flooded. The larger supporting area causes that now also a load on the wall is exerted.



4) Due to the water pressure on the wall, together with the load of the ship, the wall fails also.



5) Now one tunnel tube is completely collapsed. The ship is supported by one tunnel tube, and mainly by the river bed at the right hand side of the tunnel. The supporting area increases again compared to the previous situation. A lot of water (and sand) is penetrating now into the tunnel.

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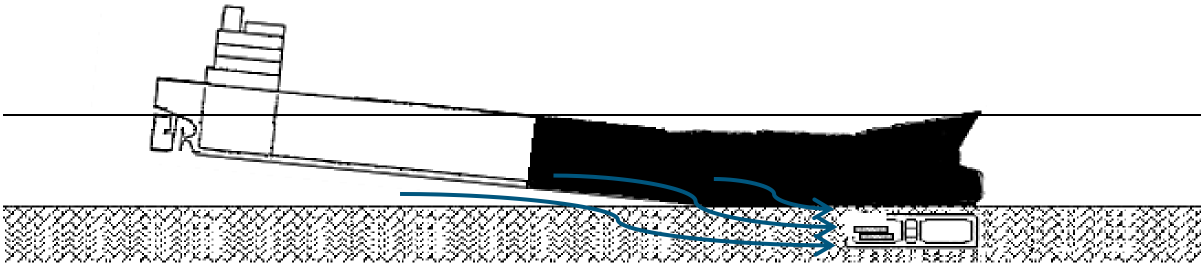
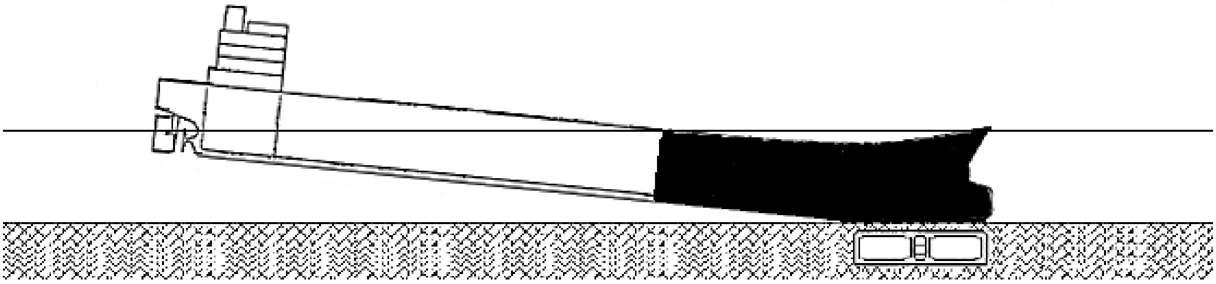


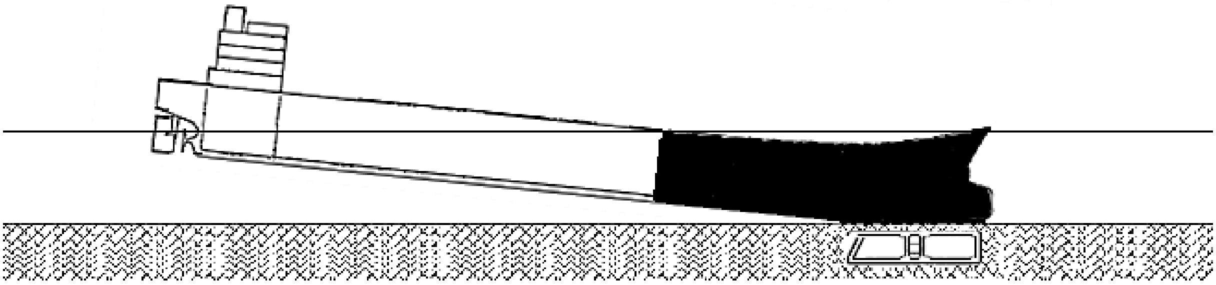
7.5.1.2 Failure at location seven

Now the situation is worked out if location seven fails.

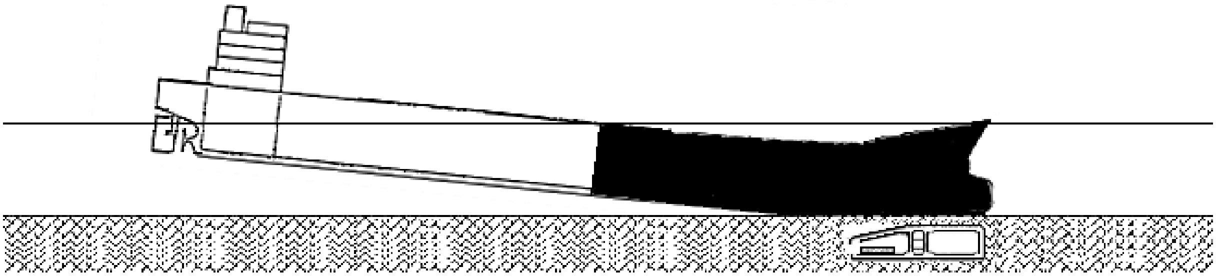
1) The ship sinks on the tunnel.



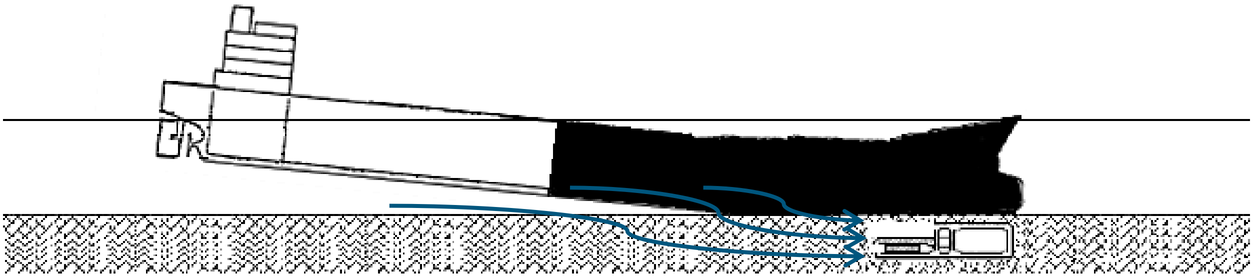
2) Failure of tunnel wall (shear being the governing failure mechanism).The wall will fall down due to the water pressure.



3) Due to the collapse of the wall, the tunnel deck collapses also. The ship needs new support at the left hand side now. Therefore the ship will enlarge its supporting area over the sand bed. This is accompanied with more sinking of the back side of the ship, and hence a larger part of the ship becomes flooded.



4) Now one tunnel tube is completely collapsed. The ship is supported by one tunnel tube, and mainly by the river bed at the right hand side of the tunnel. The supporting area increases again compared to the previous situation. A lot of water (and sand) is penetrating now into the tunnel.



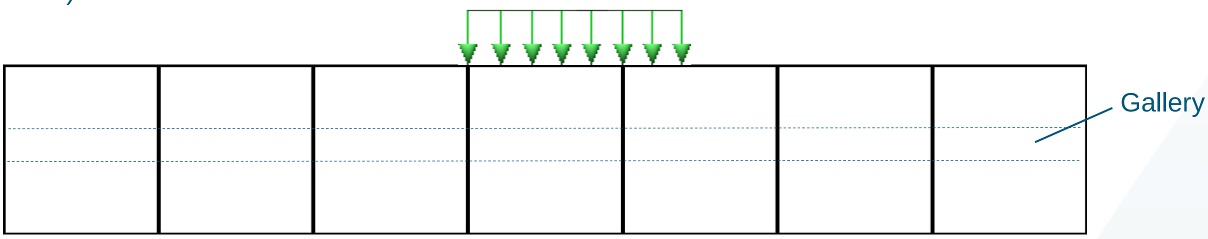
7.5.1.3 Conclusion

In the previous paragraph two possible scenarios were worked out in more detail. From these pictures it can be seen that each scenario ends in a collapse of the tunnel. Through the collapse of the tunnel, a lot of water from the North-Sea Canal (with sand) will penetrate into the tunnel. That means that nobody is safe anymore in the tunnel.

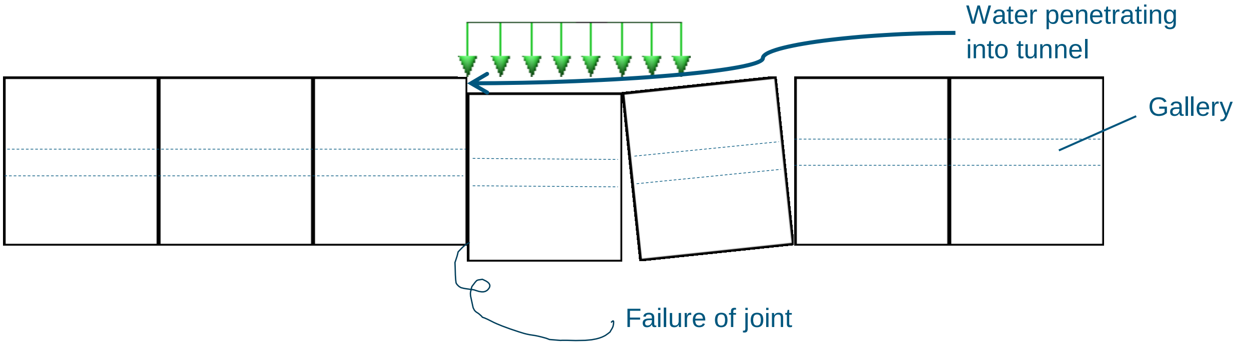
7.5.2 **Longitudinal direction**

For the longitudinal direction, only the situation that the tunnel was loaded from aside leads to failure of the joint. This situation is worked out in the following two pictures. When evaluating this event, it is assumed that the cross section of the tunnel remains intact. That the cross section does not fail can be derived from Table 27.

1) Tunnel loaded from aside.



2) The joint fails under the load. Therefore the loaded segment moves over a certain distance. This is accompanied with deformations of the soil. That means that the soil at the backside of the tunnel will be activated (passive ground pressure). The active ground pressure however (which is the load from aside) will decrease. This will go on until new equilibrium is achieved. It is assumed that under those deformations, the water seals in the failed joint also fail. Water is able to penetrate into the tunnel then.



From these two pictures it resulted that water will penetrate into the tunnel through the failed joint. The question is how much water will penetrate into the tunnel. When removing the joint in the model, a displacement of 4mm was found. The thickness of the wall is 1000mm. That means that the tunnel elements do not translate that much.

To make an assumption of the amount of leakage, a calculation is carried out similar as presented in Table 69 (p.207). For this calculation a water column of 20m is assumed and a gap of 4mm and over the height of the tunnel (6m). The volume (of one tunnel tube) is assumed to be 900*12.95*6 = 70,000m^3. This results in 91 hours before the tunnel is fully flooded.

If people are halfway the tunnel at the moment of failure, they need to travel about 450m to reach the exit of the tunnel. If they are running with a speed of 10km/h (=2.8m/s), they need only about 3 minutes to travel that distance. That's more than enough time to bring themselves in a safe environment.

7.6 Statistical consideration

To be able to interpret the results in a broader perspective, a small statistical consideration is added. One is based on the statistical data available about the casualties in the Dutch waterways. The other one is based on statistical considerations for the Øresund link.

The chance of a sunken ship is thereafter compared with the chance of other accidents.

7.6.1 Chance of a sunken ship

7.6.1.1 Chance based on casualties Dutch waterways

The Wijkertunnel is part of the Dutch waterways. Therefore there will be said something about the amount of ships sinking in the Dutch waterways.

In Figure 126 an overview is given of the amount of sinking ships in the Dutch waterways (dark blue line).

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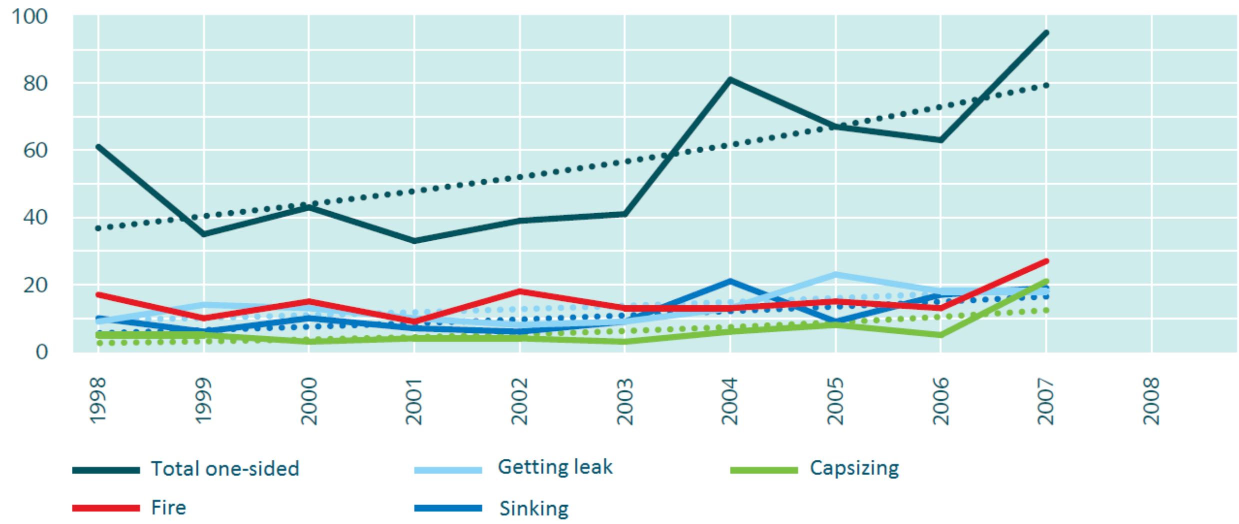

Figure 126 - Amount of one-sided accidents, divided into categories (Inspectie Verkeer en Waterstaat, 2008)

From this picture it can be seen that every year (on average) about 12 ships sink. That holds for all accidents together in the Dutch waterways. Important is now, to know how much casualties happen around the Wijkertunnel.

The Dutch waterways are categorized in different management areas. The area West-Netherland North contains the North-Sea Canal (and hence the Wijkertunnel). As can be seen in Figure 126, a sunken ship is categorized under the one-sided accidents. The Dutch Ministry of Transport registers that 0.8% of the total amount of one-sided casualties is located in the area West-Netherland North (Dutch Ministry of Transport, 2013). From Figure 126 it can be derived that the category 'sinking' is about 22% of the total amount of one-sided accidents. This means that every year 0.008*0.22*12=0.021 sunken ship casualties take place in the area West-Netherland North.

There is also a spread over that area (West-Netherland North) where the casualties take place. An indication of the spreading is given in Figure 127.

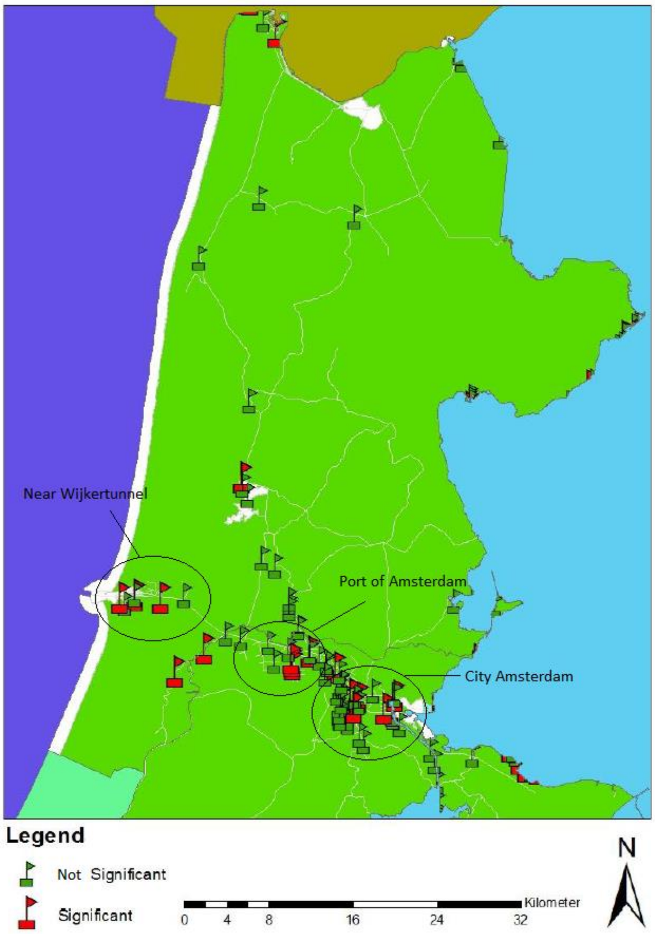

Figure 127 - Locations of accidents in the area North-Netherland West (Dutch Ministry of Transport, 2013)

Based on this picture a guess is made that about 10% of the casualties take place near the Wijkertunnel. That area (what is indicated with 'near Wijkertunnel') contains about 7km waterway.

The length of the critical area (d_{crit}, the area where a ship can hit the tunnel) is defined by $d_{crit} = 2*L_{ship} + B_{tunnel}$ (Øresund Konsortiet, 1994). For the Wijkertunnel this length is assumed to be around 300m. When assuming now an equally casualty rate over this 7km, 300/7000*100%=4.3% of the ships sinking in that area will hit the Wijkertunnel.

All this information together results in $0.021*0.1*0.043=9.1*10^{-5}$ sinking ships on the Wijkertunnel per year. That corresponds with a return period of about 11,000 years, which is quite a lot.

7.6.1.2 Chance based on statistical data Øresund

For the Øresund Link (located between Sweden and Denmark) certain studies were carried out about grounding and sinking ships. Based on those studies the frequency of a sunken ship was estimated to be 1.7*10-4 (Øresund Konsortiet, 1994). That frequency was based on the data available of the year 1990. In 1990 the total amount of ships passing (the future location of) the Øresund tunnel was about 18,700. So the chance of sinking on the tunnel, for every individual ship becomes then on average $1.7*10^{-4}/18{,}700=9.1*10^{-9}$. The amount of ships passing the Wijkertunnel is about 6,850 (Port of Amsterdam, 2015). This gives a frequency of $9.1*10^{-9}*6{,}000=6.2*10^{-5}$. That corresponds with a return period of 16,000 years.

7.6.1.3 Chance of a sunken ship leading to failure of the tunnel

Both return periods for the chance of a sunken ship (11,000 and 18,200) lay in the same order of magnitude. The chance of a sunken ship in general is now assumed to be around $(6.2 + 9.1)*10^{-5} / 2 = 7.7*10^{-5}$.

Now an assumption should be made about the amount of ships which can lead to failure of the tunnel. For this an assumption is needed about the amount of ships carrying iron ore and having a large enough size.

The port of Amsterdam registers that dry bulk is around 4% of its total transhipment (Port of Amsterdam, 2015). Iron ore is a dry bulk. Assumed is that iron ore is half of the total amount of dry bulk. That implies that iron ore is 2% of the total transhipment goods.

Therefore, it is assumed that 2% of the total amount of ships carry iron ore. The total amount of ships per year is about 6,850 ships (Port of Amsterdam, 2015). That implies that 0.02*6850 = 137 ships carry iron ore.

From Figure 88 can be derived that the ratio general cargo ↔ bulk carrier is about 1:3. That gives 0.25*137 = 34 bulk carriers and 137 – 34 = 131 general cargo ships. It is now assumed that all bulk carriers lead to failure of the tunnel and also 10% of the general cargo ships. That gives 34 + 0.1*131 = 47 ships which can lead to failure of the tunnel. 47 ships is about 0.7% of the total amount of ships.

Not every ship sinks with its bow on the tunnel. It is also possible that the ship sinks in a straight horizontal position. In §5.3.3 *Sinking* (under *Longitudinal stability*, p.26) it was stated that those two options have approximately the same probability of occurrence.

All this information together leads to the following chance of a critical sunken ship: $0.5 * 7.7*10^{-5} * 0.007 = 2.7*10^{-7}$ per year. That corresponds with a return period of about 3,8 million year.

7.6.2 Chances of other accidents

In this chapter the chance of a big fire and a BLEVE are evaluated. This is done to be able to compare the chance of a critical sunken ship with the chance of other accidents.

7.6.2.1 Big fire

The chance of a big (lorry-) fire in a tunnel is determined as $1.5*10^{-10}$ per motor vehicle kilometer (TNO, 2013). To determine what the chance of such a big fire in the Wijkertunnel is, the traffic characteristics need to be known.

The A22 is the main road way which passes through the Wijkertunnel. The CBS registers that around 1,400 vehicles pass the A22 every hour (CBS, 2014)[56]. That gives $1,400*24*365=12.3*10^{6}$ vehicles per year passing the Wijkertunnel.

The length of the Wijkertunnel is around 900m (immersed and cut and cover part, see Figure 86). That gives $12.3*10^{6} * 0.9 = 11.1*10^{6}$ motor vehicle kilometres per year.

The chance of a big fire in a tunnel becomes now: $1.5*10^{-10} * 11.1*10^{6} = 1.67*10^{-3}$ per year. That corresponds with a return period of about 600 years.

[56] *http://statline.cbs.nl/StatWeb/publication/?VW=T&DM=SLNL&PA=82855NED&LA=NL*

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7.6.2.2 Explosion of an LNG road tanker (BLEVE)

An explosion of a LNG road tanker occurs only if there is fire. The statistics in the previous paragraph were based on a large fire. The chance of a fire (independent of the size) in a lorry is $2.3*10^{-8}$ per lorry kilometer (TNO, 2013).

Now should be determined how much LNG road tankers pass the Wijkertunnel every year. It is assumed that 10% of the traffic consists out of lorries. That gives $0.1*12.3*10^{6} = 12.3*10^{5}$ lorries per year. It is however not known how much lorries an LNG road tanker are.

It is known that there are around 20 LNG gas stations[57]. It is also known that around 400 lorries use LNG as fuel[58]. Based on this information it is assumed that approximately 10 LNG road tankers are driving over the Dutch motor ways. The total amount of lorries is about 75,000 ([59]). LNG road tankers are then 0.013% of the total amount of lorries.

All this information leads to $0.00013 * 12.3*10^{5} * 0.9 = 144$ LNG road tanker kilometres per year. In which the factor 0.9 is the length of the Wijkertunnel (in km).

The probability of occurrence of a BLEVE in case of a fire is 40% (TNO, later than 2011).

The chance of a BLEVE in a tunnel becomes now: $0.4 * 144 * 2.3*10^{-8} = 1.3*10^{-6}$ per year. That corresponds with a return period of about 755,000 year.

7.6.3 Comparing chances

Now the chance of a critical sunken ship is compared with those of other accidents.

The chance of sunken ship leading to failure of a tunnel is $2.7*10^{-7}$ per year. The chance of a big fire in the tunnel is $1.7*10^{-3}$ per year. The chance of a BLEVE is $1.3*10^{-6}$ per year. When comparing those values, it can be seen that the chance of a critical sunken ship load is the lowest.

A BLEVE in a tunnel implies partly or full collapse of the tunnel (TNO, later than 2011). A sunken ship leads to partly collapse of the tunnel cross section (see §7.5 *Consequences*, p.105). That means that the consequences of a sunken ship are the same as for a BLEVE or even less.

The risk of a certain event is determined by multiplying the chance with the consequence. The chance of a critical sunken ship is smaller than for a BLEVE and the consequences are assumed to be the same. This information together gives a lower risk for a critical sunken ship compared to a BLEVE.

The load from a BLEVE is that high (peak pressure of 2,000 kN/m^2), that it is almost impossible to design a tunnel for such a load. Therefore there is an escape route in Appendix B of NEN-EN 1991-1-7 *Information for risk assessment* (COB)[60]. This part of NEN-EN 1991-1-7 prescribes a risk analysis, with *risk acceptance* as possible outcome. If that is the outcome, a tunnel should not be designed for a BLEVE. None of the tunnels so far is designed for such loads. Only tunnel which lie very deep or in a mountain are

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[57] *http://www.rolandelng.nl/nl/lng-cng-tanken.htm*
[58] *https://www.energyvalley.nl/energy-valley/nieuws/stand-van-zaken-lng-november-2015*
[59] *http://auto-en-vervoer.infonu.nl/diversen/55775-autofeiten-en-cijfers.html*
[60] *http://www.handboektunnelbouw.nl/home/ontwerpaspecten/ontwerpaspecten-definitieve-constructie/belastingen/belasting-door-explosie/*

resistant to certain loads. That means that for all those tunnels (through which LNG tankers are passing[61]) the risk of a BLEVE is accepted.
If the risk of a BLEVE is accepted, the risk of a critical sunken ship can be accepted even more. Because the risk of a critical sunken ship appeared to be lower than the risk of a BLEVE. Therefore it is concluded that the risk of a sunken ship can be accepted.

7.7 Conclusion

From a Multi Criteria Analysis it followed that the Wijkertunnel is a good candidate to be evaluated for sunken ship loads. The most relevant types of ships which can sink on the tunnel are a general cargo carrier and a large iron ore bulk carrier. From those two types of ships, the loads are evaluated if those ships sink on the tunnel deck. For the iron ore bulk carrier, also the load on the tunnel wall is evaluated, when the ship sinks just next to the tunnel.

It appeared that the biggest problems occur for the cross section. If the general cargo carrier or the iron ore carrier sinks on the tunnel deck, the tunnel collapses. If the tunnel collapses, the tunnel is no longer structural safe. That means that the users of the tunnel become in danger.

For the longitudinal direction, the strength of the shear keys are sufficient if the tunnel is loaded on the deck. If the tunnel however is loaded from aside, the shear keys are loaded in the wall. The tunnel is not designed for such kind of loads. Therefore the shear capacity in the walls seems to be insufficient. Failure of the shear key in the wall leads to water penetrating into the tunnel. But the severity of that event is less compared to failure of the cross section.

The risk of a sunken ship leading to failure of a tunnel is lower than a BLEVE. The risk of a BLEVE is accepted for a tunnel until now. It is therefore concluded that the risk of a critical sunken ship can be accepted too.

[61] There are tunnels with restrictions to the transportation of dangerous goods. In the Netherlands none of the tunnels have any restriction to the transportation of dangerous goods (Dutch Ministry of Transport, 2015).

8 Design guide

In this paragraph a guide line will be given about how to take a sunken ship load into account for the design of a certain tunnel. This is done through a simple roadmap. This roadmap is only applicable for concrete immersed tunnels. Exceptional situations are not covered. In an exceptional case, the situation of sinking under an angle is not the governing load event. Then the steps of chapter 5 needs to be done again.

1. **Determine the distribution of the ships which are passing the tunnel**

As a first step, determine the distribution of ships which are passing the tunnel. An example of such a distribution is given in Figure 128.

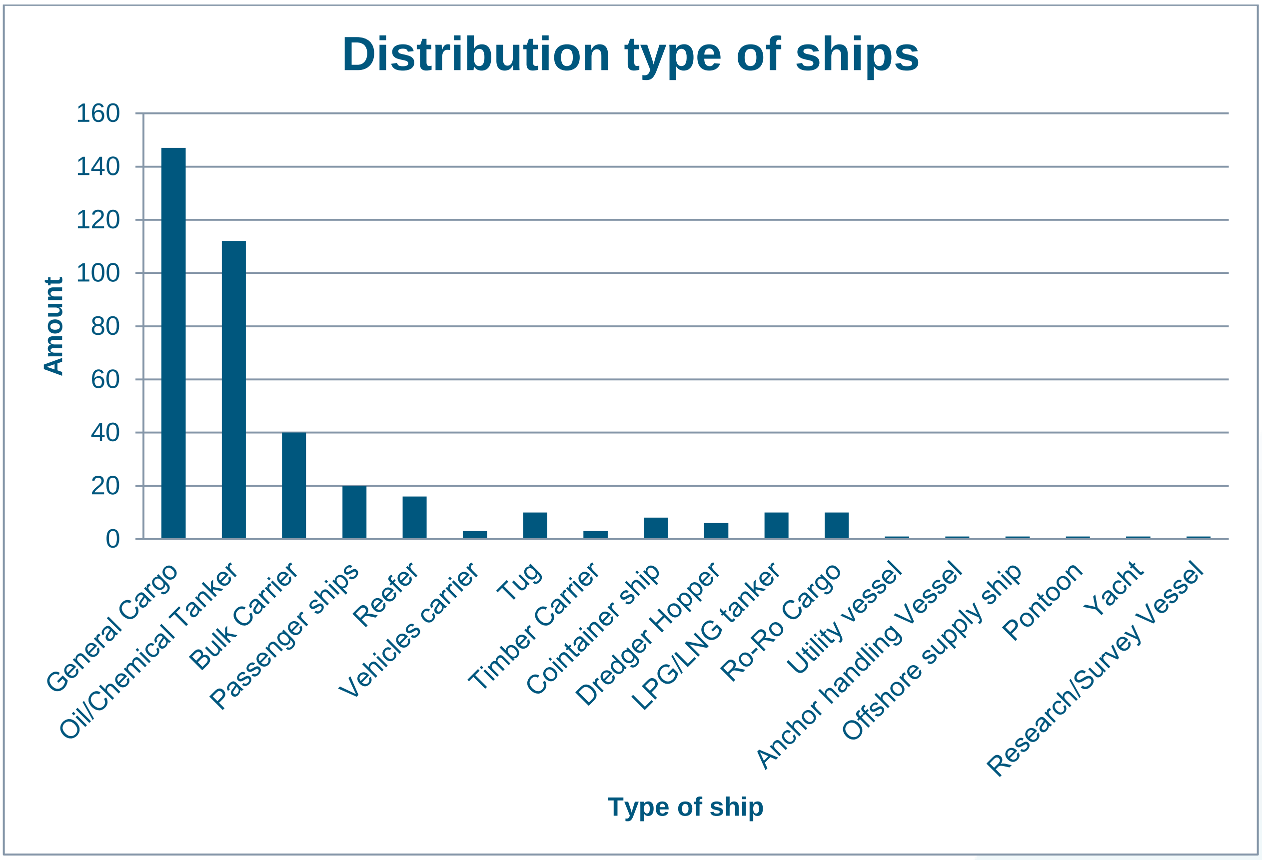

Figure 128 - Distribution type of ships passing the immersed tunnel

2. **Determine the normative ship**

The next step is to determine the normative ship. The normative ship should be based on the rate of occurrence, the density of the carried mass and the size of the ships. So taking Figure 128 as a starting point, it can be decided by the designers that only the first three types of ships are of any importance for example. From these three types, it should be determined what the maximum density of the carried mass is. Also the characteristic size of these three types of ship should be determined. That can simply be done by making a size distribution and taking the 95th percentile of those (Figure 129).

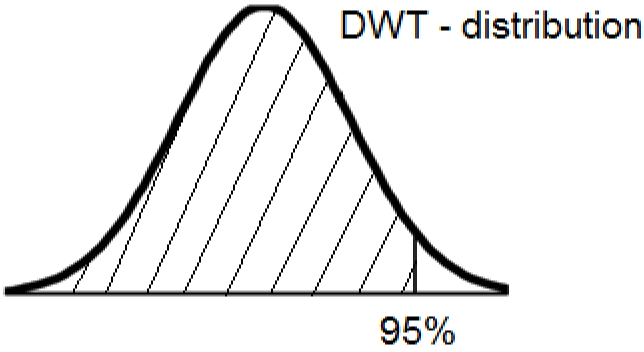

Figure 129 - Determining characteristic size of a certain type of ship

Having now the characteristic size of the ship and also the maximum density of the carried mass, an estimation of the load can be made by using the model as presented in Appendix 2 (§A2.1 *Determining ship load on tunnel*, on p.144)[62]. Based on the estimation of load for each type, it can be said what type of ship is the governing one. Depending on the distribution of the type of ships, it can also be decided to take more than one ship type into account. This was also done in this research (§7.2.1).

3. Determine the load with the aid of the model

Having determined a normative ship (or ships), the load can be determined with the aid of the model as presented in Appendix 2 (§A2.1 *Determining ship load on tunnel*, p.144). In that model a distinction is made between horizontal sinking and sinking under an angle. In chapter 5 (§5.5 *Conclusion*, p.43) it was concluded that the event of sinking under an angle is the governing one (Figure 130). Therefore only that load needs to be determined.

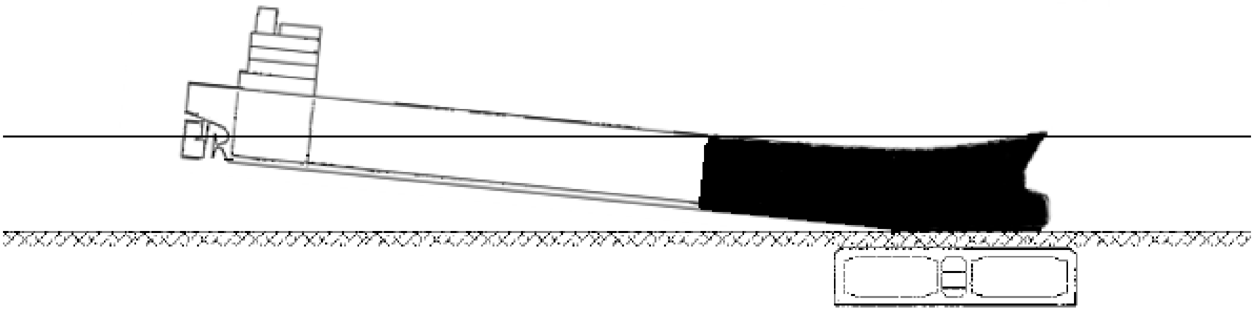

Figure 130 - Governing load event

The Amber Alena is chosen as an example for a normative ship. This is a bulk carrier with a carrying capacity of about 53,000DWT. This is a more or less common size for a bulk carrier.

To determine the load with the model, the characteristics of the normative ship should be filled out (Table 30). Also the width of the tunnel and the depth of the waterway need to be known (Table 31).

Table 30 - General characteristics of Amber Alena

Parameter	Amount	Unit	Formula	Description
L	190	m		Length

[62] *The governing load situation is not known yet, but when using that model, a good estimation of the differences in load between the different types of ships can be given.*

L_{load}	170	m		Loaded length
B	32.3	m		Width
H	15.1	m		Moulded depth
T	12.6	m		Draught
DWT	53,193	ton	Dead weight ton	Maximum carrying capacity of ship
Δ	70,000	ton	Assumption	Volume displacement
W_{ship}	16,807	ton	Δ-DWT	Mass of ship
$W_{iron\ ore}$	50,533	ton	0.95DWT	Mass of iron ore
$W_{supplies}$	2,660	ton	0.05DWT	Mass of supplies
$\rho_{iron\ ore}$	3,000	kg/m^3		Density iron ore
ρ_{water}	1,000	kg/m^3		Density water
ρ_{ship}	7,000	kg/m^3	Ship is made out of steel	Density material ship (steel)

Table 31 - Width tunnel and depth waterway

Parameter	Amount	Unit	Formula	Description
B_{tunnel}	30	m		Width tunnel
$D_{waterway}$	15	m	Variable	Depth waterway

In chapter 5 (§5.3.3 *Sinking*, p.25) it is assumed that a ship sinks if (at least) three compartments become flooded. When estimating the length of one compartment at 10% of the ship length, 30% of the ship is flooded with water, which is equal to 0.3*190 ≈ 57m. So that's the minimum amount of compartments which is flooded.

The load of the ship will now be obtained by increasing the amount of flooded compartments (= changing the parameter X, with a = 0) until a unity check for the shear force of 1.0 is found[63]. This value was achieved for X = 58m (≥ 57, OK).The load for this situation is about 285kN/m^2.

This load from the bow of the ship needs now to be translated to a load configuration for the cross sectional analysis and the longitudinal analysis. For the cross sectional analysis, use is made from 'block loads' (Figure 131). See Appendix A2 (§A2.1.3.2.8 *Load on tunnel*, p. 164) for clarification of this principle and how to determine those 'block loads'.

[63] *The moment is not checked. In §A2.1.4.3.2* External validation, *it was concluded that the shear force unity check is highest probably always governing over the moment unity check.*

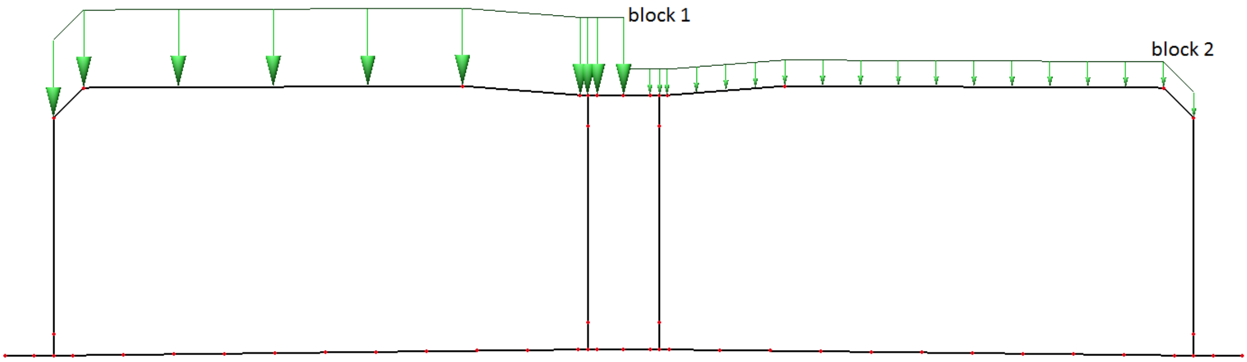

Figure 131 - Loads for cross sectional analysis (loaded on the deck)

To determine those loads also the length of a segment needs to be known. It is not necessary that the load is present over the full width of the tunnel as shown in Figure 131. If the ship is only supported by half of the tunnel for example, it can lead to a more unfavourable load situation for the tunnel. Such a load situation is however only possible if the requirements are fulfilled. The requirements with respect to the minimum amount of flooded compartments and the U.C. for the shear force.

For this situation is the load present over the full width of the tunnel. Because if the supporting area is decreased, the requirement of the minimum amount of flooded compartments is no longer fulfilled.

Besides that the ship can sink on the tunnel deck, it is also possible that the ship sinks just next to the tunnel. Then a load on the tunnel wall is exerted (Figure 132). Depending on the requirements from the client such a load can also be taken into account. The magnitude equals 0.5*block 1.

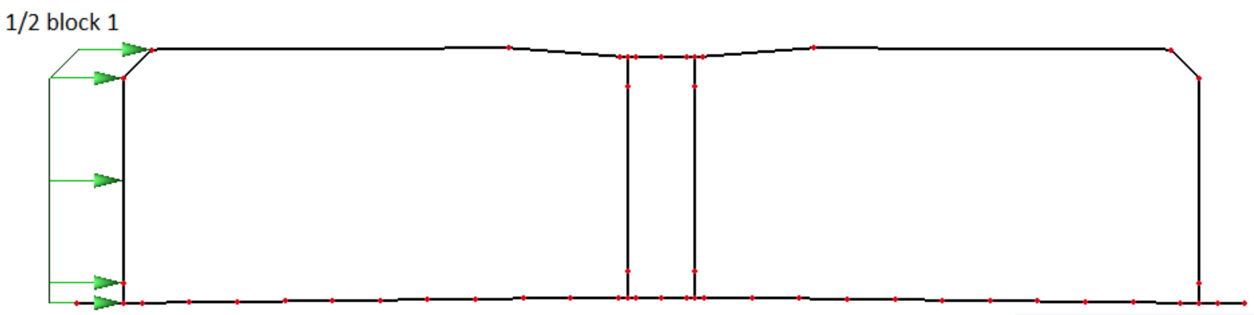

Figure 132 - Load for cross sectional analysis (loaded on the wall)

The load for the longitudinal analysis can simply be found by dividing the total reaction force (R) by the width of the ship (Figure 133).

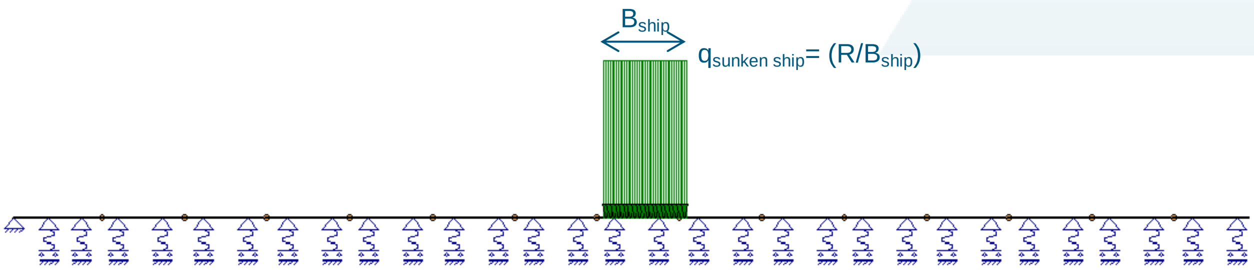

Figure 133 - Load for longitudinal analysis

For the Amber Alena, the loads are obtained as presented in Table 32.

Table 32 - Loads from Amber Alena

Load	**Cross sectional analysis (kN/m^2)**			**Longitudinal analysis (kN/m)**
	Load on tunnel deck		Load on tunnel wall	
	Block 1	Block 2		
Iron ore bulk carrier	267	89	134	3,970

9 Conclusions and recommendations

9.1 Conclusions

In this chapter an answer is formulated to the research question. This answer is build up out of the sub-questions, which are answered first.

9.1.1 Sub questions

1. ***What are the design criteria for an immersed tunnel in relation to a sunken ship load?***

For the cross sectional analysis holds only that the tunnel structure may not collapse. Water tightness and deformations are no problem as long as the tunnel remains intact.

For the longitudinal analysis it holds that the joint may not fail with respect to strength and not deform that much that the water seal fails. To prevent leakage, the forces in the structure may not cause through cracks in the concrete structure.

2. ***What are representative loads from a sunken ship on an immersed tunnel?***

A representative load from a sunken ship depends on a lot of parameters. It depends on the mass density of the carried cargo, the size of the ship, the depth of the waterway, and the way how a ship sinks.

Ships carrying iron ore and sinking with its bow on the tunnel cause the biggest loads.

To predict the corresponding load, a model is developed. In that model the ship and tunnel characteristics can be filled out, from which the corresponding load results. A sunken ship load varies between 50 – 300 kN/m^2.

3. ***What is the structural behaviour of an immersed tunnel when subjected to a sunken ship load?***

The structural behaviour of an immersed tunnel depends on the type of tunnels. Concrete tunnels appear to be the most important ones. The research is therefore restricted to concrete tunnels.

Concrete tunnels are evaluated for a sunken ship load of 300kN/m^2 and a bedding stiffness of 2,000kN/m^3.

For the cross sectional analysis, it appeared that the U.C. globally increases with a factor 1.3 for shear and decreases with a factor 0.7 for the bending moment.

For the longitudinal analysis, monolithic tunnels can obtain shear forces in the joints which are three times bigger than the strength. The bending moments cause no cracking of the tunnel structure. The deformation of the water seals remain below the requirements.

The shear forces in the joints for a segmented tunnel lie in the same order of magnitude as the strength. The bending moments remain small and cause no through cracking of the tunnel structure. The deformations of the water seals can become a factor 1.2 higher than allowed but do not fail.

4. *What is the structural behaviour of an existing tunnel when subjected to a sunken ship load?*

This sub-question is divided in two separate questions.

a. What is the structural behaviour?

The Wijkertunnel appears to be a good candidate to be evaluated for a sunken ship load. That tunnel is evaluated for the load of a small type of ship (a general cargo carrier) and a big one (an iron ore bulk carrier).

For the cross sectional analysis a U.C. of 1.1 was found for the general cargo carrier if sinking on the deck. For the iron ore bulk carrier a U.C. of 1.93 was found if sinking on the deck, and a U.C. of 0.73 if sinking just next to the tunnel. Shear failure is the governing failure mechanism for both events with a U.C. > 1.0.

The Wijkertunnel is a segmented tunnel. For the longitudinal analysis, a U.C. of 0.24 was found for the shear key when loaded by the general cargo carrier. Under the load from the iron ore bulk carrier a U.C. of 0.81 was found if sinking on the deck. In case of sinking just next to the tunnel gives a U.C. of 1.81 was found. The maximum deformation of the water seals is 3.7mm. The maximum allowable deformation is 46mm.

b. What are the consequences of the sunken ship loads for that immersed tunnel?

Failure of the tunnel cross section implies that a huge amount of water and sand penetrates into the tunnel. People who are using the tunnel at that moment are in great danger. If the joint fails, water penetrates into the tunnel. This event is less severe compared to failure of the cross section. People are still able to leave the tunnel.

The chance of a sunken ship leading to failure of the Wijkertunnel is $2.7 \cdot 10^{-7}$ per year. That very low chance leads to such a low risk, that a sunken ship not needs to be taken into account of the design.

5. *How should a sunken ship load be taken into account in the design of an immersed tunnel?*

In the previous chapter a guide line is given about how to take a sunken ship load into account. In short, that can be done by taking the following steps:

- Determine the distribution of the ships which are passing the tunnel
- Determine the normative ship
- Determine the load of the normative ship with the aid of the developed model

9.1.2 Main question

What are representative loads from a sunken ship on an immersed tunnel and how does an immersed tunnel behave under such loads? Does an existing tunnel still met the design criteria and if not, is the tunnel still structural safe?

A representative load from a sunken ship depends on a lot of parameters. Ships carrying iron ore and sinking with its bow on the tunnel, cause the biggest loads. A sunken ship load varies between 50 – 300 kN/m^2.

Concrete tunnels on a typical Dutch subsoil give for the cross sectional analysis a U.C. of 1.3 for shear and a U.C. of 0.7 for the bending moment. This holds for a sunken ship load of $300kN/m^2$.

For the longitudinal analysis, monolithic tunnels obtain shear forces in the joints which are three times bigger than the strength. The bending moments cause no cracking of the tunnel structure. The deformation of the water seals remain below the requirements.

The shear forces in the joints for a segmented tunnel lie in the same order of magnitude as the strength. The bending moments remain small and cause no through cracking of the tunnel structure. The deformations of the water seals can become a factor 1.2 higher than allowed but do not fail.

One tunnel tube of the Wijkertunnel collapses when subjected to a sunken general cargo carrier (U.C. = 1.1) and an iron ore bulk carrier (U.C. = 1.93). If the iron ore bulk carrier sinks next to the tunnel, the shear key fails in the wall.

In case of failure of the cross section, the tunnel is no longer structural safe. Users of the tunnel are in great danger. In case of failure of the joint, the tunnel is still structural safe. Users are able to leave the tunnel.

The chance of a sunken ship leading to failure of the Wijkertunnel is $2.7*10^{-7}$ per year. That very low chance leads to such a low risk, that a sunken ship not needs to be taken into account of the design.

9.2 Recommendations

- **Doing a non-linear analysis**

The Wijkertunnel is in this research only evaluated with a linear analysis. A non-linear analysis can demonstrate if there is redistribution of stresses possible. Redistribution of stresses is only possible for the cross sectional analysis.

This research found that shear failure is the governing failure mechanism. Shear failure is a brittle failure mechanism. A non-linear analysis can demonstrate that bending moment will be the governing failure mechanism. In case of bending moment failure, there is redistribution of stresses possible due to the formation of plastic hinges. The formation of plastic hinges has an influence on the load configuration of the ship. This is illustrated in the next subparagraph.

It is assumed that one plastic hinge occurs halfway the tunnel deck, at the position of its maximum bending moment. It is also assumed that two plastic hinges occur at the outmost ends of the tunnel deck. That means that the tunnel deck will undergo large deformations. Such deformations cause probably unloading of the tunnel deck halfway, but the load increases more near the outer and inner wall. This illustrates that the interaction between the ship and the tunnel needs careful attention.

This non-linear analysis should prove if the tunnel structure does not collapse. If the tunnel structure does not collapse, the tunnel remains still structural safe.

- **Looking more into detail to chances**

In §7.6 *Statistical consideration* (p.109) a small statistical evaluation was carried out. Based on that evaluation it was concluded that the risk of a sunken ship, leading to failure of the tunnel, is smaller than for a BLEVE.

A BLEVE is nowadays not taken into account for the design due to its low risk. This is called *risk acceptance*. This risk acceptance is gained with the aid of the procedure given in Appendix B of NEN-EN 1991-1-7 *Information for risk assessment*.

One should search out if with the aid of Appendix B in NEN-EN 1991-1-7 it can be concluded that the risk of a sunken ship also can be accepted. If that will be the outcome, many tunnels doesn't need to take a sunken ship load into account. That favours the design, because a sunken ship load is often governing the design.

- **Length and amount of compartments of ship being flooded when sinking**

In this research a little bit is said about the amount of compartments which are flooded when sinking. It was said that there are two possibilities. A ship sinks if three or four compartments become filled with water. It is however not known to what type of ship those requirements correspond.

The amount and length of compartments filled with water determines (among others) the magnitude of load, as well as the loaded area. An increase in the length of the ship being flooded results in an increase in the total reaction force (kN). But the supporting area increases also. In general it can be said that the ultimate load (kN/m^2) decreases. If it can be found out that for example large ship only sink if four compartments become filled with water, this will give a decrease in load compared to the now maintained value.

- **3D analysis about interaction between ship load and tunnel behaviour**

The interaction between the ship and the tunnel is now evaluated in 2D. In reality it is 3D behaviour. This holds both for the tunnel as well as for the ship.

The load from the bow of the ship is now assumed to be equally spread over a triangular area (Figure 160). If this is a true representation of reality, depends on the stiffness distribution of the bow of the ship. It is well possible that the side walls of the ship induce the load for a major part and the hull of the ship only for a very small part. The distribution of the load depends also on the stiffness of the cover layer on the tunnel. An example of that is given in Appendix 2 (§A2.1.5.2 *Loads due to irregularities in river bottom*, p.179). The differences in stiffness resulted for that example in a difference of 30% for the maximum bending moment.

Such a research to the differences in stiffness can also verify if the line load is a correct assumption for the longitudinal analysis. If for example the load from the iron ore bulk carrier is taken as a pyramid shaped load (2D), a 40% higher shear force is found. That's quite a big difference.

The other side is the 3D – effect of the tunnel. Because the triangular shaped load of the bow (Figure 160) was now transferred to a triangular shaped load in 2D (Figure 161). A 3D – analysis predicts the behaviour of the tunnel better compared to a 2D analysis.

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Appendix 1

A1 Design Criteria

A1.1 Partial load factors

The following factors are taken from the book *Immersed tunnels,* written by *R. Lunniss* and *J. Baber*.

Table 33 - Combination factors

Load	ψ_0	ψ_1	ψ_2
Earth pressure (surchage)	0.7	0.5	0.3
Road and rail traffic loading	0.6	0.75 [64] 0.4 [65]	0.0
Wind	0.6	0.4	0.0
Water	0.8	0.55	0.3
Temperature	0.7	0.5	0.2
Wave & Current	0.8	0.7	0.6
Temporary construction loads	1.0	0.7	0.6

Table 34 - Partial load factors ULS

Load	Permanent (1)	Permanent (2)	Temporary	Accidental/seismic
Permanent loads				
Self-weight of structure	0.9/1.25	1.0/1.35	1.2	1.0
Ballast concrete	0.9/1.25	1.0/1.35	1.2	1.0
Road pavement, furniture	0.9/1.25	1.0/1.35		1.0
Hydrostatic load	1.0/1.25	0.9/1.35	1.2	1.0
Earth pressure	1.0/1.25	0.9/1.4	1.2	1.0
Settlements	1.0/1.25	0.9/1.4	1.2	1.0
Prestressing, creep, and schrinkage	1.0	1.0	1.0	1.0
Variable loads				
Earth pressure	1.5		1.35	1.0
Road traffic	1.5			1.0
Wind	1.5		1.35	1.0
Water level variation	1.2		1.2	1.0
Temperature				1.0
Wave and Current loads			1.35	
Temporary construction loads			1.35	

[64] *Concentrated*
[65] *Uniformly distributed*

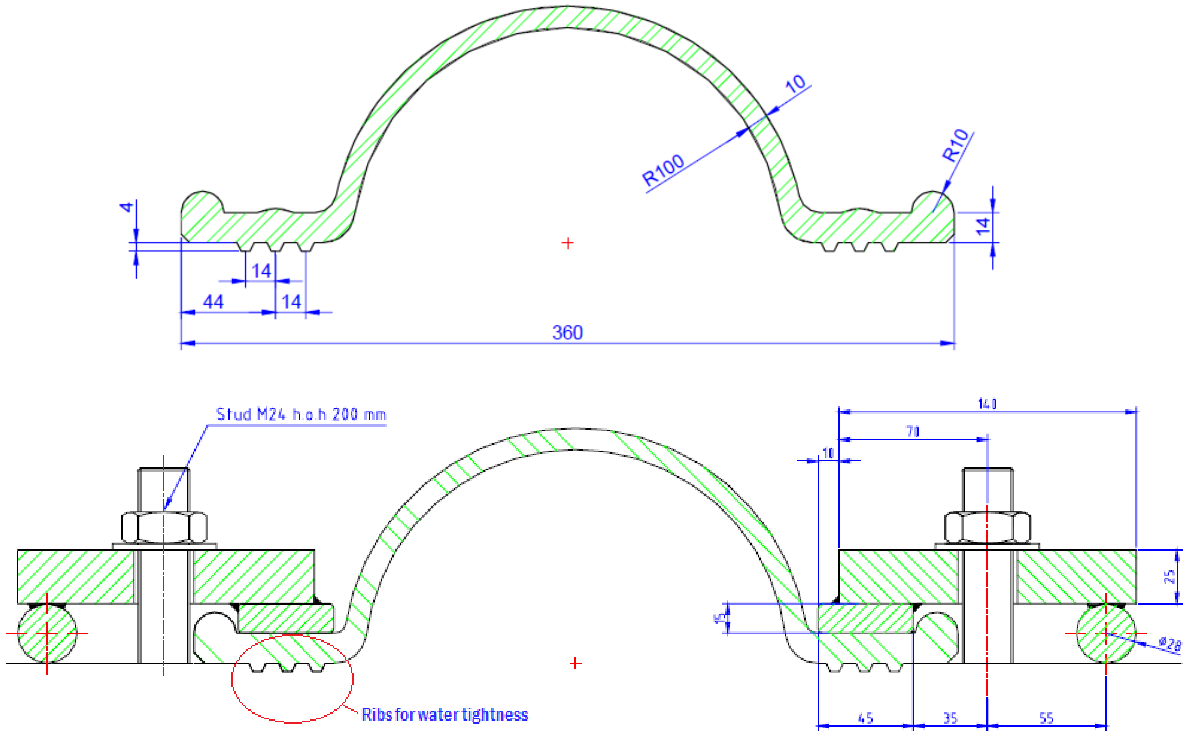
Accidental loads	
Explosion	1.0
Collision from road traffic	1.0
Sunken ship	1.0
Falling anchor	1.0
Earthquake	1.0
Tunnel flooding	1.0
Extreme high water and waves	1.0

A1.2 Joints

A1.2.1 Immersion joint

A1.2.1.1 Omega profile

In Figure 134 a detailed overview is given from an Omega profile (os 360-100). In part *a* the configuration of the omega seal is shown. In part *b* the configuration of the clamping system is shown. The three ribs from the omega seal which are under de clamping system are indicated with a red circle (in part *b*). This ribs should provide the required water tightness of the seal.



a)

b)

Figure 134 – a) Configuration of Omega OS 360-100, b) Typical clamping system of Omega OS 360-100 (after (Trelleborg))

The allowable water pressures of an Omega profile (type OS 360-100) are given in Figure 135. For this relation a safety margin of a factor 2.5 is taken into account for the fracture strength.

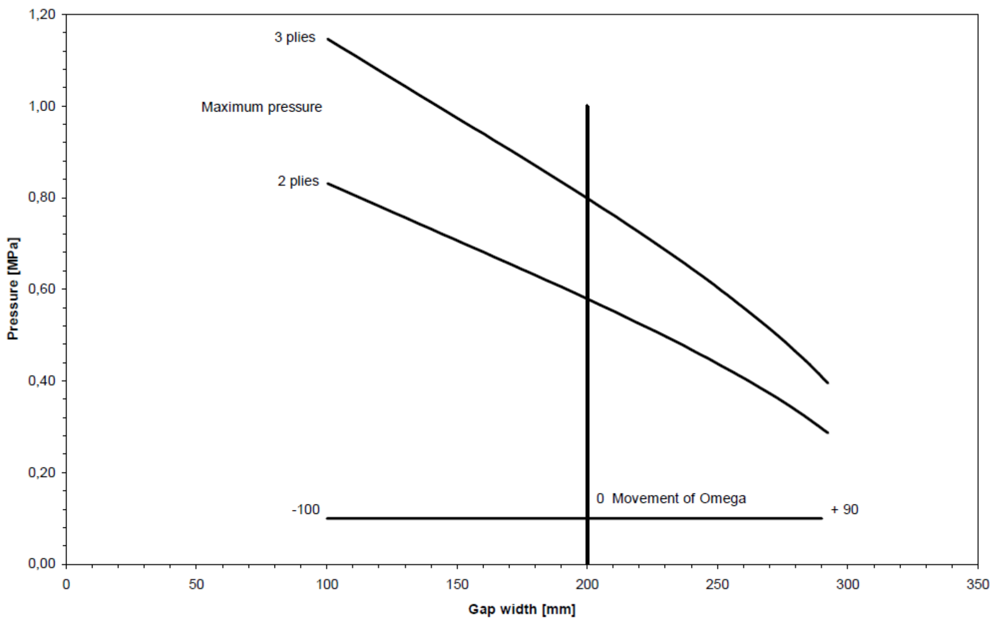


Figure 135 - Allowable pressure omega profile OS 3600-100, including safety factor 2.5 (Trelleborg)

In Figure 135 the movement of the Omega is drawn up to + 90mm at the right hand side, which seems to indicate that the maximum allowable elongation of the omega is 90mm. The real maximum elongation of the Omega is restricted by the arc of the Omega. For the shown profile, the maximum elongation reeds: 0.5*200π-200=114mm. More is not possible, because the elongation of the rubber is prevented by reinforcement in the rubber (Trelleborg).

Table 35 - Maximum elongations possible for different standard types of omega profiles

Standard Omega profile	Elongation at break (mm)
OS 240-40	45
OS 300-70	80
OS 360-100 & OS 400-100	110

A1.2.1.2 Gina gasket

The behaviour of two typical Gina-profiles is set out in Figure 136 and Figure 137.

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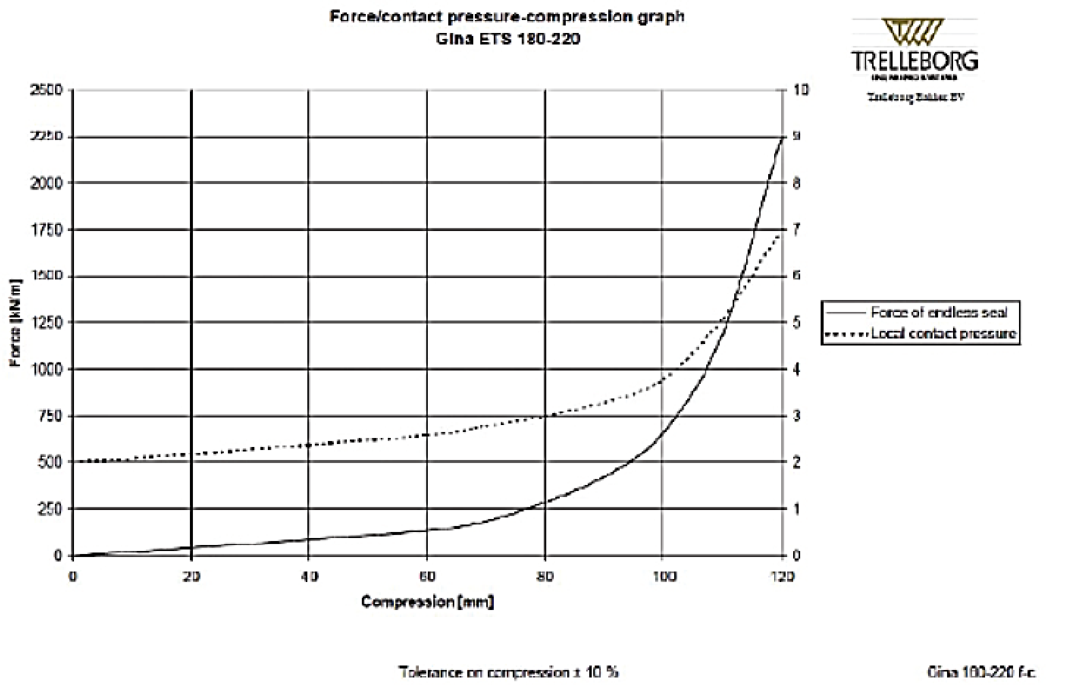

Figure 136 – Force-deformation diagram Gina-profile type ETS 180-220 (COB, 2014)

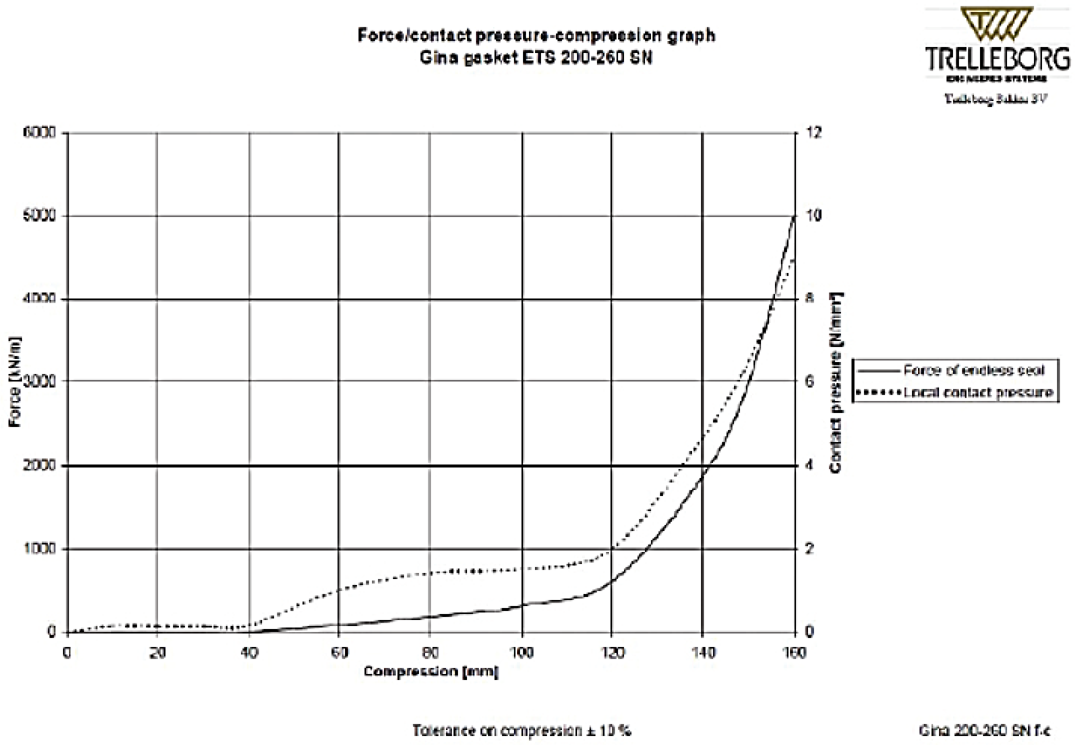

Figure 137 - Force-deformation diagram Gina-profile type ETS 200-260 (COB, 2014)

The second Gina-profile has a more soft behaviour for the first 50mm compression of the profile. This favours the water tightness of the profile in the initial phase.

A1.2.2 Segment joint

In Figure 138 the dimensions of two typical waterstops are given.

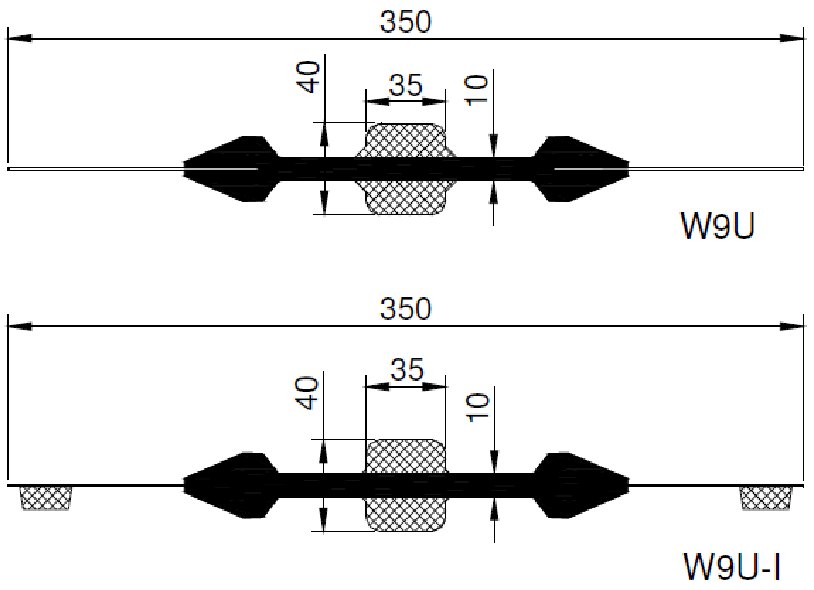

Figure 138 - Two types of water stops (Trelleborg)

The allowable pressures on these waterstops by a certain elongation are given in Figure 139 and Figure 140.

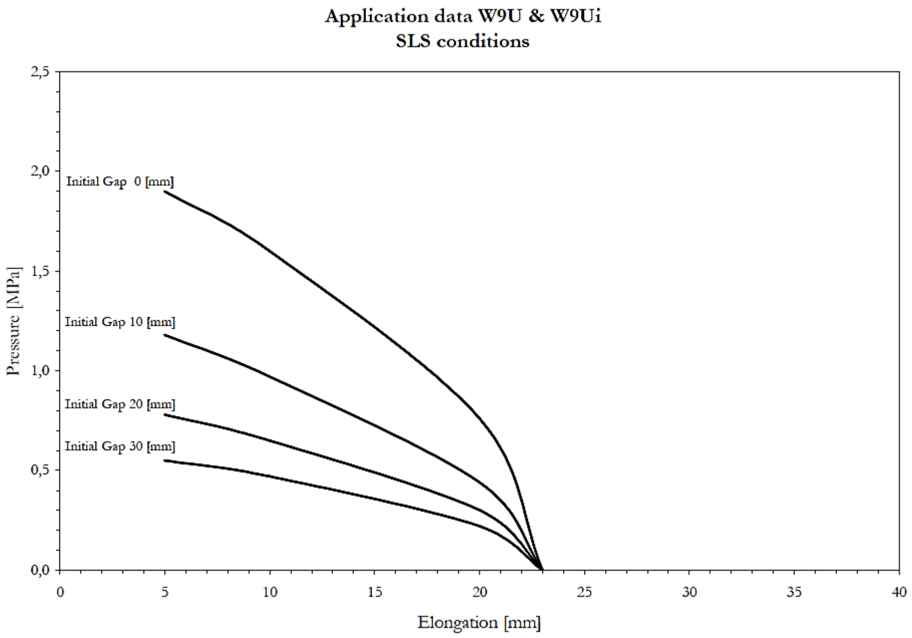

Figure 139 - Design application data (Trelleborg)

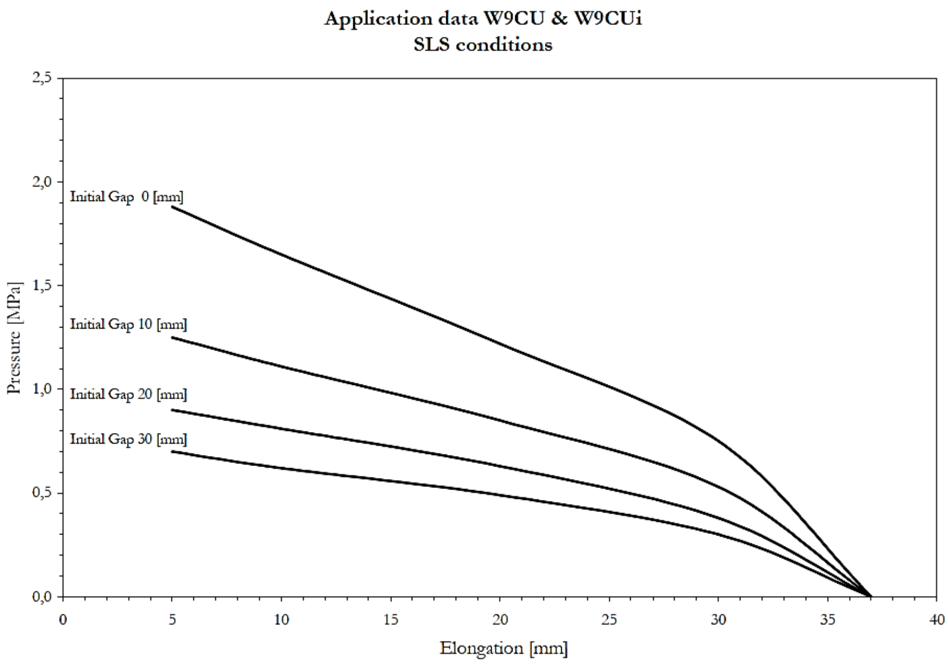

Figure 140 - Design application data (Trelleborg)

For interpreting these graphs, be aware that this is for SLS conditions. For ULS conditions much higher elongations are allowed. In the documentation of Trelleborg about the waterstops, it is stated that the elongation at break should be higher than 375% (Trelleborg). When taking the length of the waterstop which can stretch as 35mm (see Figure 138), the elongation at break is then 35*3.75=131mm. So that is much more compared to the 37mm which is allowed in SLS conditions.

Table 36 - Maximum elongations possible for different standard types of water stops

Standard water stop type	Elongation allowed[66] in ULS (mm)	Elongation at break (mm)
W10U	38	75
W9U & W9U-I	46	130
W9CU & W9CU-I	74	260

[66] Only the maximum elongation in ULS conditions for a W10U profile is given by Trelleborg. The other values are calculated by assuming the same ratio between ULS and SLS as for the W10U profile.

Appendix 2

A2 Ship loads on an immersed tunnel

A2.1 Determining ship load on tunnel

A2.1.1 Introduction

The load from a sunken ship on a tunnel depends on the one hand on the mass of the ship minus its buoyancy and at the other hand on how that load is transferred to the tunnel deck. The load from the ship itself is determined by its configuration, type of mass etc. Also the strength of the ship has an influence on the magnitude of load. Therefore first an explanation is given how the load from the ship will be determined. This is done both for the situation of horizontal sinking as well as for the situation of sinking under an angle.

The model is validated with the aid of the results from a report of Gent University (Gent University, 13 november 2003). Therefore that model is explained also by a short description. In that report the load is assumed to be equally spread over the bottom area of the tunnel. This is also done in the model. The differences between the here presented model and the results from Gent University, are therefore only determined by the load from the ship itself and not by the transfer of the load to the tunnel.

The transfer of the load from the ship to the tunnel is mostly done by the cover on the tunnel. This cover layer is most of the time about one meter thick. That is not that big. Therefore the spreading of the load due to this cover layer is neglected. There are however certain side effects which causes an increase in the magnitude of load in addition to the load from the weight of the ship only. The treated side effects are impact loading, a higher stiffness of the tunnel compared to the surrounding soil and irregularities in the river bottom. These side effects are treated in a different paragraph and result in load factors which need to be taken into account for that certain side effect.

So, as a summary, the loads from the ship are calculated by the model. The increase in load due to the transfer of the load from the ship to the tunnel is covered by the side effects.

A2.1.2 Model for horizontal sinking

A2.1.2.1 Set up of model

A schematization of the model for horizontal sinking is given in Figure 141.

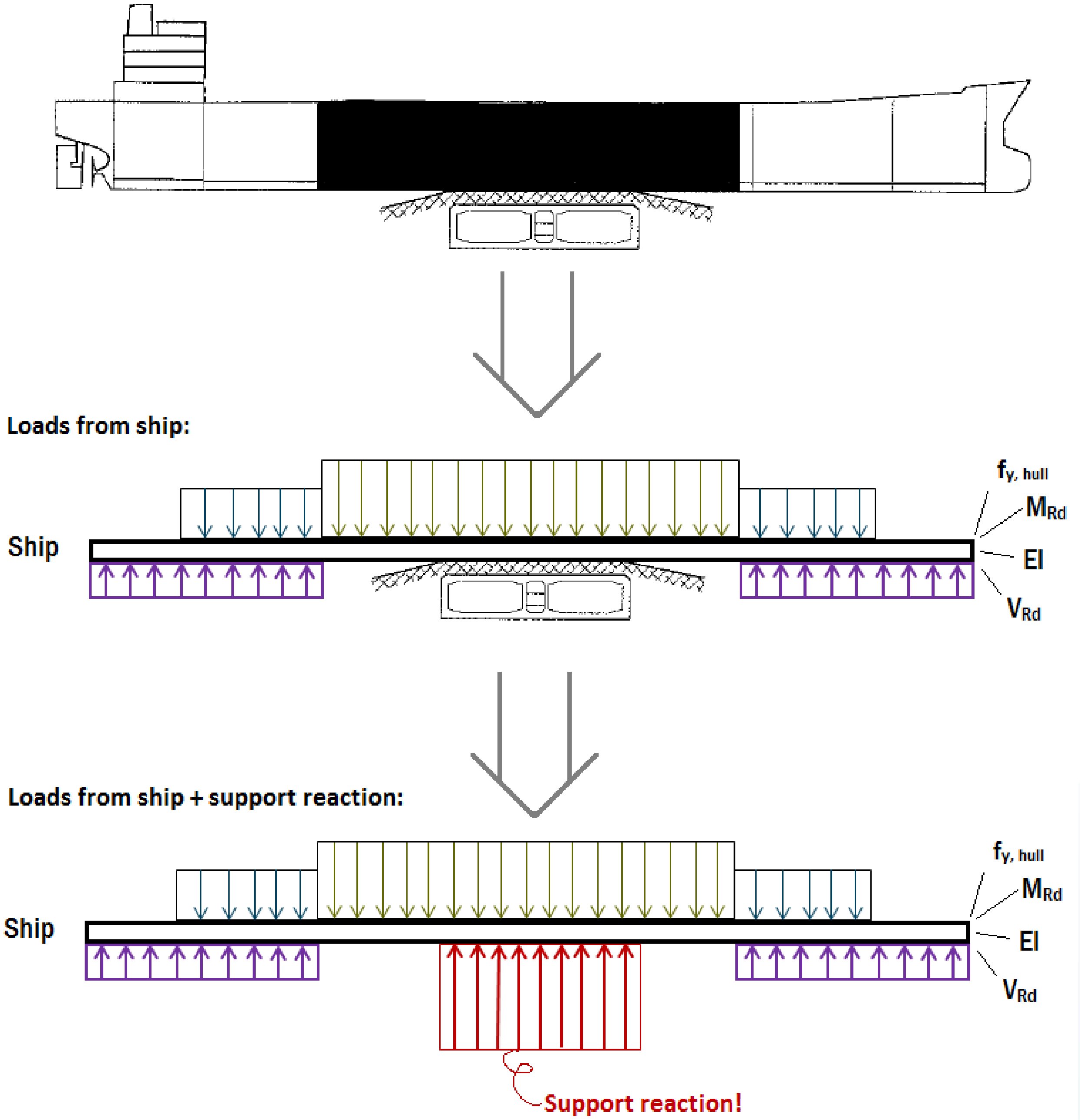

Figure 141 - Schematisation of ship only supported by the tunnel (tunnel above river bed)

From this figure it can be seen that the ship is schematised as a beam with a certain stiffness (EI), moment capacity (M_{Rd}) and shear capacity (V_{Rd}). Also the out of plane compression strength of the hull of the ship is taken into account ($f_{s,hull}$).

The loads which are acting on that beam are determined by the self-weight of the ship, the carried mass and the buoyancy. The self-weight is a simple given parameter, so there are no doubts about that.

The carried mass of the ship is determined by the amount of load which a ship can take, expressed in Dead Weight Tonnage (DWT). The major part of this total carrying capacity will be used for cargo, while another part will be used for supplies. There is not a general rule about the size of each part. For this model a division of 95% versus 5% is made, but that's not for sure. Also the density of the cargo differs from cargo to cargo. So that's a second item of uncertainty. In the report from Gent University it is not clarified which division between the parts is used. Also the density of the cargo is not given.

The buoyancy of the ship is determined by the configuration of the ship. There are certain coefficients for a ship which describes the characteristics of a ship. A very important coefficient is the block coefficient (C_B), see Figure 142. Gent University takes this into account through taking the width of the ship as a function of the position in longitudinal direction. But in the model, the reduction in volume (compared to L* B * T) is taken into account uniform over the whole length of the ship[67]. So this difference in approach will also cause differences in results between the here presented model and the model of Gent University.

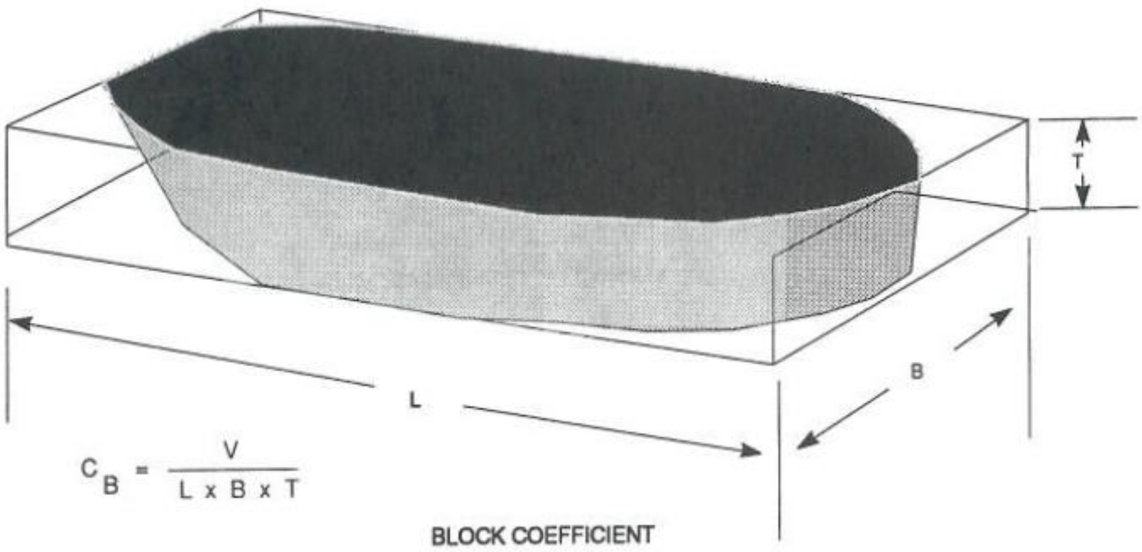

Figure 142 - Spatial representation of the block coefficient (William I. Milwee, 1996)

Based on the loads which are described so far, the load on the tunnel results simply from vertical equilibrium. The reaction load is assumed to be an equally distributed load over the full tunnel width.

When having determined the loads, it should be checked, whether the bending moment capacity, the shear capacity or the ship's hull strength is not exceeded. For calculating the bending moment and shear forces, a mechanical schema is used as presented in Figure 143. Be aware that the support reactions are zero, because the reaction forces from the tunnel are also taken into account as a load in the model. This means that there is vertical equilibrium. So in reality the supports can be seen as not present.

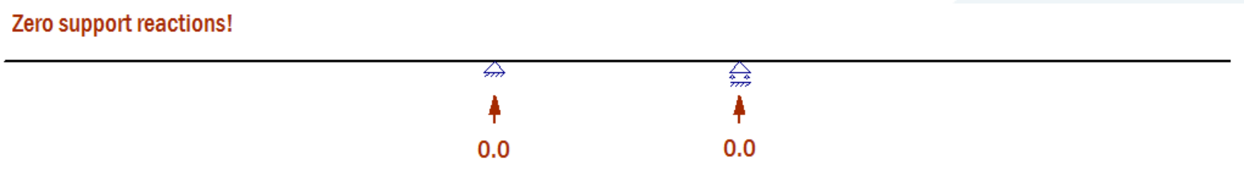

Figure 143 - Mechanical schema

[67] *Only for horizontal sinking. Because for sinking under an angle an different approach is used.*

A typical bending moment diagram and shear force diagram are presented in Figure 144 and Figure 145 respectively. The maximum bending moment occurs halfway the ship length. This value can be calculated simply by taking the sum of all moments (from each part of the load) around that point.

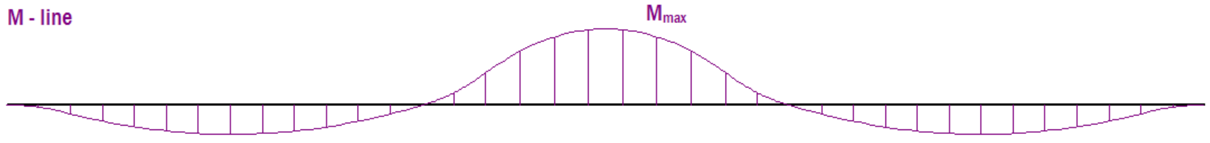

Figure 144 - Typical example of moment diagram

The maximum shear force can occur at two different positions, depending on the loading conditions. They are indicated in Figure 145. V_{max} (1) is the shear force just next to the tunnel. V_{max} (2) is the shear force at the transition between the flooded and not flooded part of the ship.

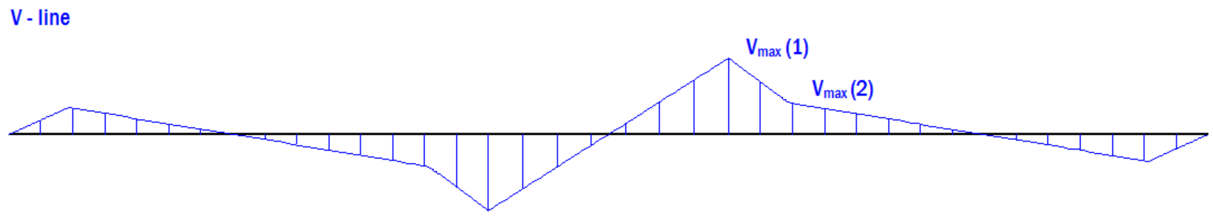

Figure 145 - Typical example of shear force diagram

At last, it should also be checked whether the out of plane compression strength of the ship's hull is exceeded or not (Figure 144).

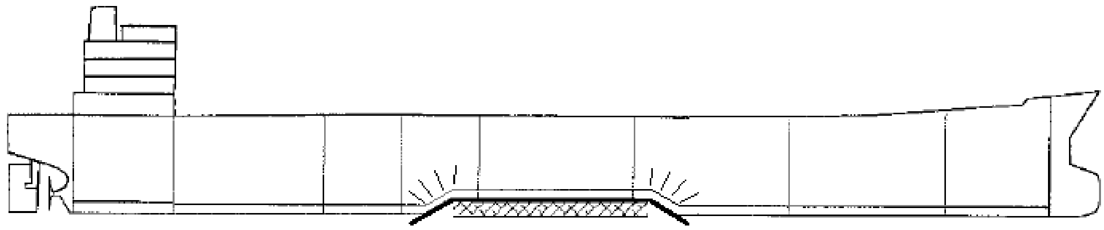

Figure 146 - Failure compression strength of ship

So far, this is all for the situation of a tunnel which lies above the river bed. The situation becomes different for the situation that the tunnel lies under the river bed. Then the ship becomes fully supported. That's the case for both sinking in transverse direction as well as for sinking in longitudinal direction, see Figure 147.

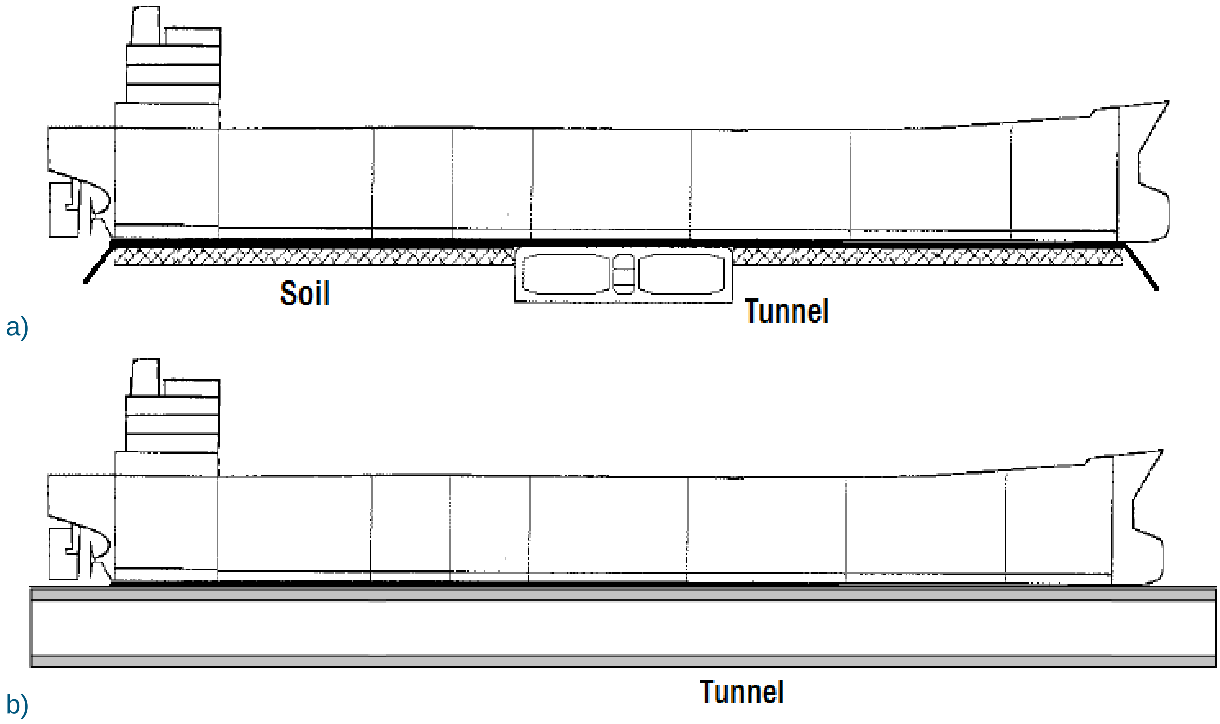

Figure 147 - Overview of ship fully supported by a) the tunnel and soil (sinking in transverse direction) or b) only the tunnel (sinking in longitudinal direction)

For this situation the ship is fully supported by the underground, so no (big) bending moments and shear forces will occur. Therefore for this situation, no checks need to be done with respect to strength.

It is assumed that the load from each part is directly transferred to the underlying subsoil (or tunnel). The biggest load on the tunnel is then caused by the part of the ship which induces the biggest load. That's the part of the ship which is flooded, because that part has no buoyancy.

A2.1.2.2 Working out of model

The model is made in Excel. The details are worked out below. For every part a table with parameters is given. For each parameter a formula is given how the parameter is defined. If nothing is said under the heading ´formula´ this parameter is a given parameter. Also a description is given what the parameter implies.

A2.1.2.2.1 General parameters

In Figure 148 an overview of the used distances are given.

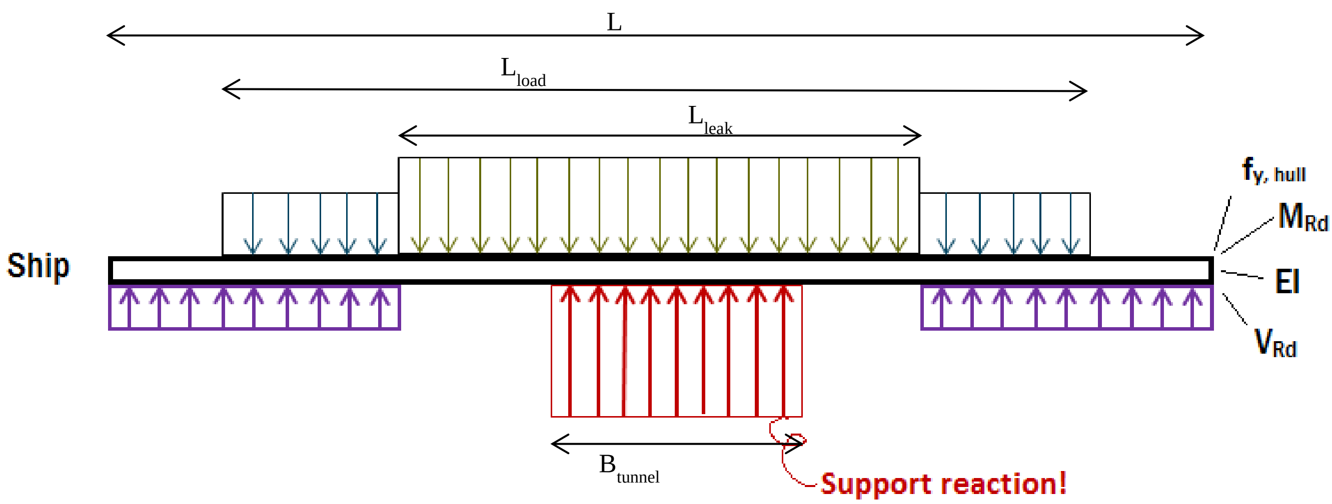

Figure 148 - Definition of distances

In Table 37 and Table 38 the general parameters for respectively the ship and the tunnel are given.

Ship

Table 37 - General parameters of ship

Parameter	Amount	Unit	Formula	Description
L	200	m		Length
L_{load}	180	m	Variable	Loaded length
B	28	m		Width
H	15.6	m		Moulded depth
T	11.5	m		Draught
DWT	40,000	ton	Dead weight ton	Maximum carrying capacity of ship
Δ	54,100	ton		Volume displacement
W_{ship}	14,100	ton	Δ - DWT	Mass of ship
$W_{iron\ ore}$	38,000	ton	0.95 DWT	Mass of iron ore
$W_{supplies}$	2,000	ton	0.05 DWT	Mass of supplies
$\rho_{iron\ ore}$	3,000	kg/m^3	Assumption	Density iron ore
ρ_{water}	1,000	kg/m^3	Assumption	Density water
ρ_{ship}	7,000	kg/m^3	Ship is made out of steel	Density material ship (steel)
L_{leak}	60	m	Variable	Length of leak

The width (B) of the ship is assumed to be a constant value over the height (see Figure 187). In this model the width is also constant over the length of the ship. This in contrast to the report from Gent University, where the width is a function of the length of the ship.

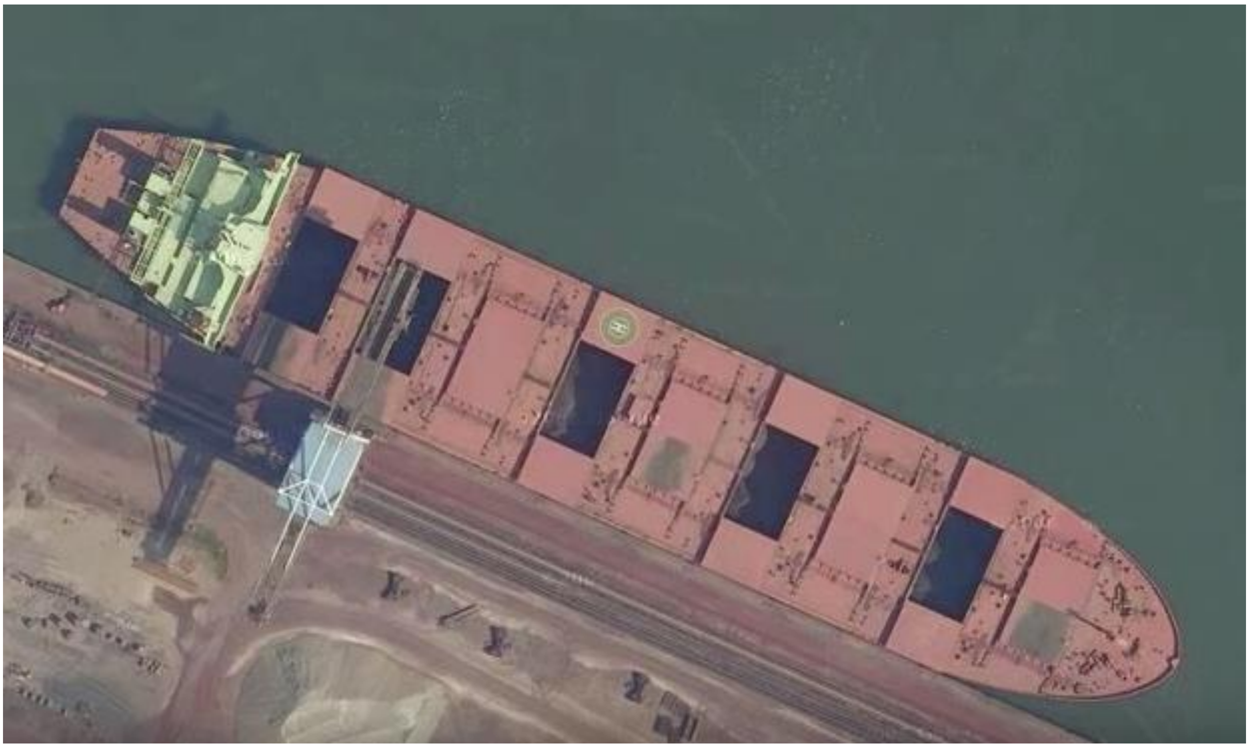

Figure 149 - Top view iron ore bulk carrier

As can be seen from Figure 149 the assumption from a constant width over the length is justified for the main part of the ship. Only at the end and the front this assumption is not correct. Therefore an effective length should be chosen, such that the length (L) times the width (B) gives approximately the same area as the real area.

The definition of the moulded depth is given in Figure 150. This is the distance between the uppermost continuous deck and the keel line.

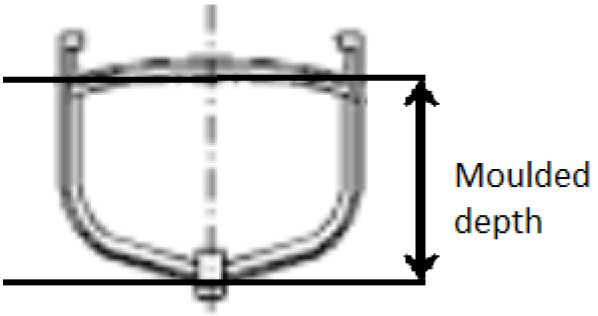

Figure 150 - Definition moulded depth

Important to notice is that the moulded depth not should be confused with the height of the ship. Because between the upper edge of the ship and the upper continuous deck, certain drainage holes are present. So this part of the ship cannot be taken into account to contribute to the buoyancy of the ship.

The volume displacement represents the volume displaced by the total weight of the ship. The DWT is a measure for the maximum weight which a ship can carry. So the difference between the volume displacement and the DWT is the self-weight of the ship.

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For the density of the iron ore a value of 3,000 kg/m^3 is assumed. There are also type of iron ores with a higher density, but this is a more representative value.

Tunnel

Table 38 - General parameters of tunnel

Parameter	Amount	Unit	Formula	Description
B_{tunnel}	40	m		Width tunnel
$D_{waterway}$	7	m	Variable	Depth waterway

The water level can be varied, because the load from the ship changes during tidal fluctuations.

A2.1.2.2.2 Loads from ship

An overview of the used loads is presented in Figure 151.

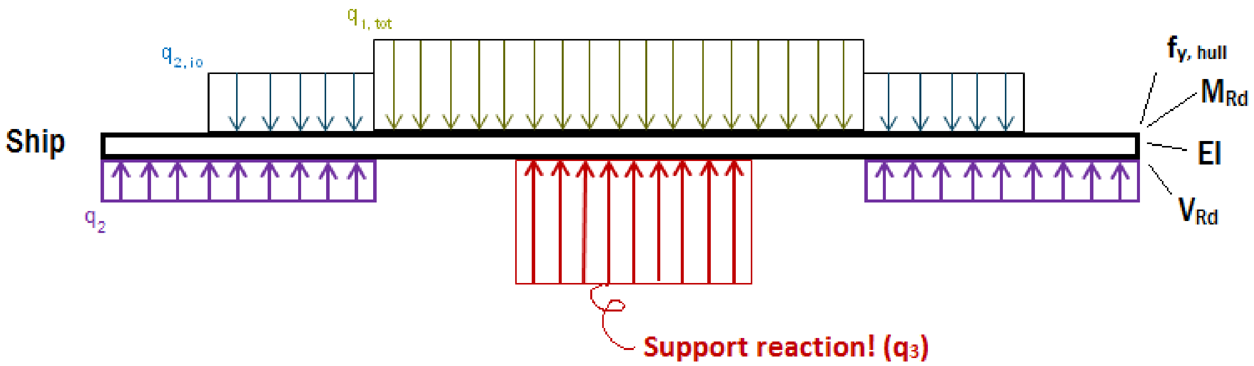

Figure 151 – Definition of used loads

In this schematisation a distinction is made between the different parts. The green load ($q_{1,\ tot}$) represents the load from the flooded part of the ship. The subscript ‘tot’ stands for ‘total’, because this load is built up from a flooded and a non-flooded part. The purple load (q_2) represents the dead weight of the ship itself + the supplies – the buoyancy of the ship. The blue load ($q_{2,\ io}$) represents the load from the iron ore. Hence the addition ‘io’ in the subscript (iron ore). The load from the support reaction (q_3) is indicated with red in the figure above.

All loads are calculated in Table 39. Notice that (as said) a distinction is made for q_1 between the part which is above the water level and the part which is below the water level. The subscript ‘uw’ stands for: under water. Also the permeability is taken into account. This can take the influence of certain secluded compartments into account.

Table 39 - Loads from ship

Parameter	Amount	Unit	Formula	Description
V_{ship}	120,900	kN	$W_{ship}(\rho_{ship}-\rho_{water})/\rho_{ship}10$	Load of ship under water per m
$V_{iron\ ore}$	253,300	kN	$W_{iron\ ore}(\rho_{iron\ ore}-\rho_{water})/\rho_{iron\ ore}10$	Load of iron ore under water per m
P	100%		Variable	Permeability
$q_{1,\ uw,\ p\ =\ 100\%}$	900	kN/m	$(V_{ship}D_{waterway}/H)/L+(V_{iron\ ore}D_{waterway}/H)/L_{load}$	Load from leaky compartments, fully flooded
$q_{1,\ uw,\ p\ =\ 0\%}$	-340	kN/m	$((W_{ship}+W_{supplies})10/L + W_{iron\ ore}10/L_{load})*(D_{waterway}/H) - C_B B D_{waterway}10$	Load from leaky compartments, not flooded

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$q_{1,\ uw,\ p=P}$	900	kN/m	$Pq_{1,\ uw,\ p=100\%} + (1-P)q_{1,\ uw,\ p=0\%}$	Load from leaky compartments, with P% flooded
$q_{1,\ above\ water\ level}$	1,610	kN/m	$((W_{ship}+W_{supplies})(H-D_{waterway})/H)10/L+(W_{iron\ ore}(H-D_{waterway})/H)10/L_{load}$	Load from leaky compartments, above water level
$q_{1,\ tot}$	2,510	kN/m	$q_{1,\ uw,\ p=P} + q_{1,\ above\ water\ level}$	Load from leaky compartments
q_2	840	kN/m	$-((W_{ship}+W_{supplies})10/L - C_B B D_{waterway} 10)$	Load from intact compartments
$q_{2,\ io}$	2,100	kN/m	$W_{iron\ ore}10/L_{load}$	Load from iron ore
q_3	7,200	kN/m	$(q_1L_{leak}+q_2(L-L_{leak})+q_{2,io}(L_{load}-L_{leak}))/B_{tunnel}$	Load on tunnel deck

A2.1.2.2.3 Moments from load

The moments from the load are calculated in Table 40. The maximum moment acts in the middle of the ship. The moments form each part of the load contributing to the total moment are calculated separately and ultimately summed up.

Table 40 - Moments from load

Parameter	Amount	Unit	Formula	Description
M_1	-3,829,000	kNm	$q_2*(L-L_{leak})/2*((L-L_{leak})/2/2+(B_{tunnel} - L_{leak})/2$	Moment from q_2
M_2	628,000	kNm	$q_{1,tot}*(L_{leak}-B_{tunnel})/2*((L_{leak}-B_{tunnel})/2+B_{tunnel}/2)$	Moment from $q_{1,tot}$
M_3	-929,000	kNm	$0.5(q_{1,tot}-q_3)*(B_{tunnel}/2)^2$	Moment from q_3
M_4	7,600,000	kNm	$q_{2,\ io}*(L_{load}-L_{leak})/2*((L_{load}-L_{leak})/4+L_{leak}/2)$	Moment from $q_{2,\ io}$
M_{tot}	3,489,000	kNm	$M_1+M_2+M_3+M_4$	Total moment

A2.1.2.2.4 Shear forces from loads

The shear loads are calculated in Table 41. The shear force is calculated at two points. Both at the transition of the intact ship to the leaky compartments and at the edge of the tunnel. Depending on the water depth ($D_{waterway}$) the maximum shear force will occur at the first or the second point (see also Figure 145).

Table 41 - Shear loads

Parameter	Amount	Unit	Formula	Description
$Q_{Ed,\ support}$	93,000	kN	$q_2(L-L_{leak})/2+q_{2,\ io}*(L_{load}-L_{leak})/2+q_1(L_{leak}-B_{tunnel})/2$	Maximum shear force near support
$Q_{Ed,\ leak}$	68,000	kN	$q_2(L-L_{leak})/2+q_{2,\ io}*(L_{load}-L_{leak})/2$	Maximum shear force near leak

A2.1.2.2.5 Moment resistance of ship

The moment resistance of the ship is calculated in Table 42. The moment (and shear) resistance of ships must be conform the requirements given by the classification societies for ships.

The block coefficient C_B comes from the IACS (International Association of Classification Societies LTD, 2010) and was also given already in Figure 142 (William I. Milwee, 1996).

The other formulas given come from SNAME (The Society of Naval Architects and Marine Engineers, 2003). The formulas for the wave induced bending moment capacity are equal in different documents. These values are based on a return period of 20 year.

About the formulas for the still water bending moment there is more uncertainty. The values presented are given by SNAME, with the comment that these formulas are according to the major Classification Societies. In other documents as from DNV (Det Norske Veritas, 2003), which is also a classification society, other values are given. But with the comment that those are minimum values and that a different value can be specified, according to the spread of the loading in the ship. Those values as given by DNV, are also given by Gent University (Gent University, 13 november 2003). When comparing those formulas with those given by SNAME it is striking that there is a difference of a factor 10. Because of the fact that it is stated that the values as given by DNV are minimum values, it is assumed that the values given by SNAME are more common values. Therefore those values are used for the research.

Table 42 - Moment resistance of ship

Parameter	Amount	Unit	Formula	Description
C_B	0.84	-	$\Delta/(LBT)$	Block coëfficiënt
C	9.75	-	$10.75-((300-L)/100)^{1.5}$	Coëfficiënt
$M_{SW,\ hogging}$	1,200,000	kNm	$CL^2B(122.5-15C_B)$	Still water bending moment, hogging
$M_{SW,\ sagging}$	1,093,000	kNm	$CL^2B(45.5+65C_B)$	Still water bending moment, sagging
$M_{WV,\ hogging}$	1,743,000	kNm	$190CL^2BC_B$	Wave induced bending moment, hogging
$M_{WV,\ sagging}$	-1,850,000	kNm	$-110CL^2B(C_B+0.7)$	Wave induced bending moment, sagging
$M_{Rd,\ hogging}$	2,943,000	kNm	$M_{SW,\ hogging} + M_{MV,\ hogging}$	Total hogging bending moment resistance
$M_{Rd,\ sagging}$	2,943,000	kNm	$M_{SW,\ sagging} + ABS(M_{MV,\ sagging})$	Total sagging bending moment resistance

A2.1.2.2.6 Shear capacity of ship

The shear resistance of the ship is calculated in Table 43. For the design wave shear force capacity no formulas are given by SNAME. The formula for the wave shear force capacity is given by Gent University, with the comment that it is according to the classification societies. The values for the still water shear force as given by Gent University and DNV are linked to their values given for the still water bending moment capacity. Those values for the bending moment capacity were minimum values. Therefore it is assumed that also these values for the shear force capacity are minimum values. Therefore, due to lack of information, the same ratio as for $M_{SW,\ hogging}$ / $M_{MV,\ hogging}$ is used to make an estimation for the still water shear force capacity.

Table 43 - Shear resistance of ship

Parameter	Amount	Unit	Formula	Description
K_1	0.70	-	0.4 L < x < 0.6 L, for positive shear force	Coëfficiënt
K_2	1	-	= 1 for unrestricted sea-going service condiditons	Coëfficiënt
Q_{w0}	25,000	kN	$0.3CLB(C_B+0.7)$	
Q_{WV}	18,000	kN	$K_1K_2Q_{W0}$	Design wave shear force
Q_{SW}	12,000	kN	$Q_{WV}(M_{SW,\ hogging} / M_{MV,\ hogging})$	Design still water shear force
Q_{Rd}	30,000	kN	$Q_{SW} + Q_{WV}$	Total shear force resistance

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A2.1.2.2.7 Checks for bending moments and shear forces

The unity checks for the bending moments and shear forces are given in Table 44.

In a research, it is stated that there is some spare capacity left (about 10-50% for double bottom vessels, as an iron ore carrier is) at the resistance side (Valsgaard & Steen, 1991). In the Report of Gent University (Gent University, 13 november 2003) it is stated that ships are often over dimensioned with respect to the shear force (they assume the shear capacity to be twice as high). Because of these factors, it can be said that there is most of the time more capacity than assumed beforehand.

At the other hand, a ship sinks due to a certain amount of damage. The location of that damage (in length direction) will be somewhere halfway the ship. This location is somewhere halfway of the ship, because the ship is sinking horizontally, and that corresponds with a leak somewhere halfway the ship (see §5.3.3 *Sinking*, p.25). That is the same location as where the maximum bending moment and shear force occurs. Therefore this is of importance.

That damage reduces the bending moment as well as the shear capacity. Assumed is (see §A2.4 *How an iron ore tanker fails*, p. 188) that the ship fails through colliding of ships. The damage location is then positioned in the side of the ship's hull. The bending moment capacity is mainly achieved by the bottom area and the sides of the ship. That due to the absence of a deck structure which can take up longitudinal forces. The shear force capacity is mainly achieved by the sides of the ship's hull. Therefore it can be said that damage in the side of the ship's hull affects the strength. Now an assumption will be made for the amount of reduction in strength.

The damage location in the ship's hull is assumed to be at the upper side. Because the bow of the ship extends most forward at the upper side of the ship. So that part will touch the struck ship first. When now neglecting the upper two meter of the ship's side hull structure, this reduces the bending moment capacity for about 25% (of one side) and the shear capacity of about 10% (also one side).

It is now assumed that this reduction in strength compares with the amount of spare capacity which is present in the ship. That means that no reduction factors will be taken into account.

Table 44 - Unity checks for moments and shear forces

Parameter	Amount	Unit	Formula	Description
$m_{hogging}$	1.18	-	$M_{Ed}/M_{Rd,\ hogging}$	Moment check for hogging bending moments
$m_{sagging}$	1.18	-	$M_{Ed}/M_{Rd,\ sagging}$	Moment check for sagging bending moments
$q_{support}$	2.27	-	$Q_{Ed,\ support}/Q_{Rd}$	Shear check edge tunnel
q_{leak}	3.11	-	$Q_{Ed,\ leak}/Q_{Rd}$	Shear check end leak

A2.1.2.2.8 Load on tunnel

Ultimately the forces acting on the tunnel deck are determined (Table 45). The total reaction force was given by R. The load on the tunnel deck is obtained by dividing this force by the area of the tunnel deck. This is for the situation if the tunnel lies above the river bed. The loads from the ship if the tunnel lies under the riverbed or if the ship is fully submerged are also given. With the phrase 'load under ore' for the latter one is meant that the load from the ship under the ore is taken. Because the part where iron ore is present in the ship causes (locally) the biggest load if a ship is fully submerged.

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In this model only the vertical loads on the tunnel deck are calculated. If the tunnel lies under the riverbed, also a load on the wall of the tunnel is present equal to half of the vertical load. One may decide to take that load also into account when evaluating a sunken ship load for an immersed tunnel.

Table 45 - Load on tunnel

Parameter	Amount	Unit	Formula	Description
R	286,000	kN	$q_3 B_{tunnel}$	Total reaction force
$q_{sunken\ ship\ load}$	280	kN/m^2	$R/((B-2)B_{tunnel})$	Ground pressure if tunneldeck > riverbed
$q_{sunken\ ship\ load}$	55	kN/m^2	$R/((B-2)L)$	Maximum ground pressure if tunneldeck < riverbed
$q_{sunken\ ship\ load,\ fs}$	77	kN/m^2	$(V_{ship}/L+V_{iron\ ore}/L_{load})/(B-2)$	Fully submerged, load under ore

A2.1.2.2.9 Check for out of plane compression strength

A last check is the out of plane compression strength of the ship. In §A2.2 *Out of plane compression strength of ship* an elaboration is given about this topic. In that paragraph it is concluded that a load higher than 300kN/m^3 probably will lead to failure of the bottom structure. When comparing this value with Figure 166, it can be seen that for the lower water depths, this value of 300kN/m^3 is exceeded. For that water depth however, the U.C. of shear and bending moment are most probably more critical than the out of plane compression strength. It is therefore assumed that the out of plane compression strength will not be the governing failure parameter.

A2.1.3 Model for sinking under an angle

A2.1.3.1 Model set up

A schematisation for the situation of sinking under an angle is given in Figure 152. From that figure it can be seen that the ship is schematized as being in a horizontal position. In reality lies the ship under an angle. That gives a difference in load of about 0.5% and is therefore neglected.

Due to that same inclination of the ship, the question can arise if it is reasonable to assume that the ship is supported over the full tunnel width. Because if the ship lies under an angle, the ship imposes its load only by its bow. As explained in §5.4.2.2.1 (p. 38), the bow is not able to withstand such high loads. Therefore the bow will deform until internal equilibrium in the ship is achieved. In this model it is assumed that the length of the support is always equal to the width of the tunnel[68].

[68] *If the tunnel is in reality 40m and the load in case of a support of only 20m length needs to be evaluated, the tunnel width in the model can simply be adjusted to 20m.*

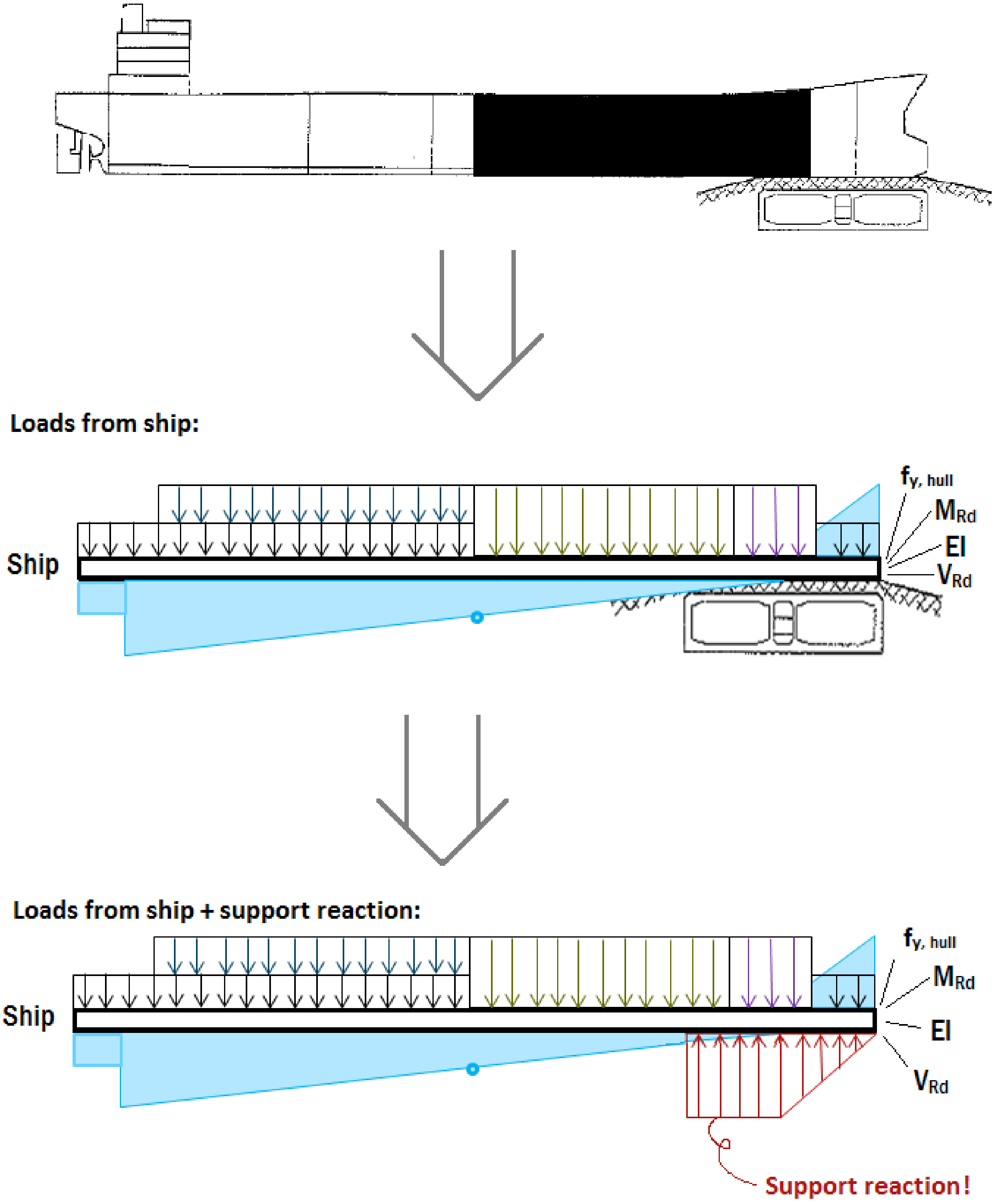


Figure 152 - Schematisation of ship supported by tunnel at the position of the bow

A typical example of the loads which are acting on the beam is given in the lower part of Figure 152. The same parts as for horizontal sinking (self-weight of ship, cargo and buoyancy) are taken into account, but now in a different configuration.

The mechanical schema which is used is given in Figure 153. Also now the support reactions are zero, due to taking the reaction force from the tunnel as a load into account in the model. So here again the supports can be seen as not present.

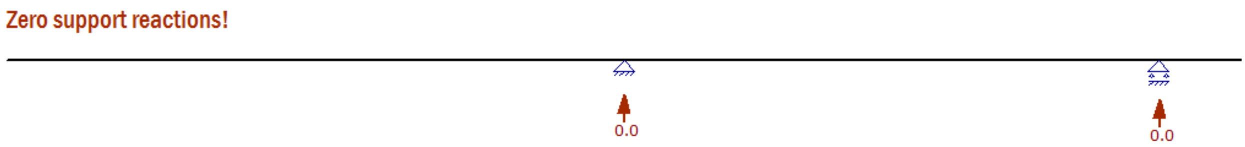


Figure 153 - Mechanical schema

This model will be checked in the same way as for horizontal sinking.

A typical example of the bending moment diagram is given in Figure 154. The location of the maximum bending moment cannot be said exactly on beforehand, but lies in the front part of the ship.

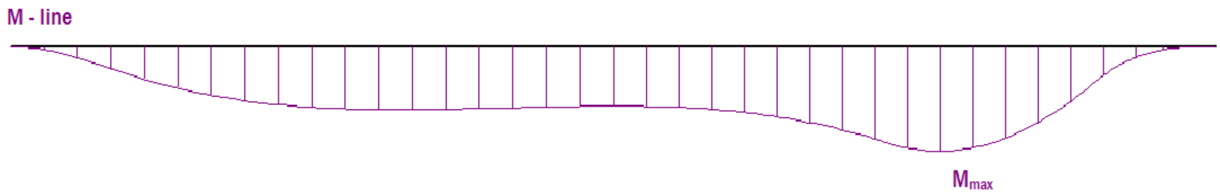


Figure 154 - Typical example of moment diagram

A typical example of the shear force diagram is given in Figure 155. The position of the maximum shear force is known. That's exactly near the edge of the tunnel (at the left hand side of the tunnel).

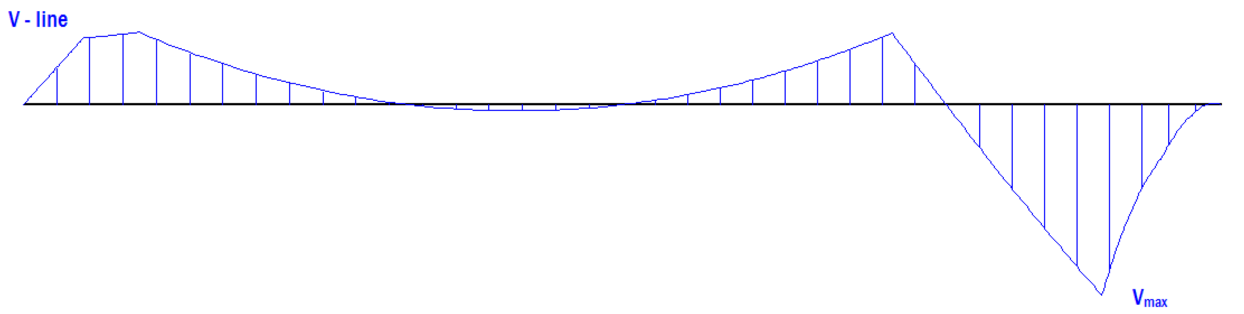


Figure 155 - Typical example of shear force diagram

At last the out of plane compression strength of the ship's hull structure of the bow is checked.

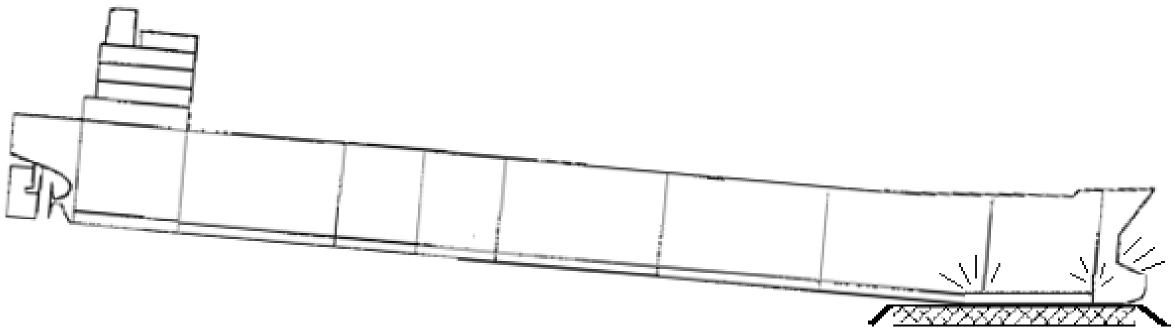


Figure 156 - Failure through exceeding out of plane compression strength bow of ship

A2.1.3.2 Working out of model

A2.1.3.2.1 General parameters

In Figure 157 an overview is given of the used distances.

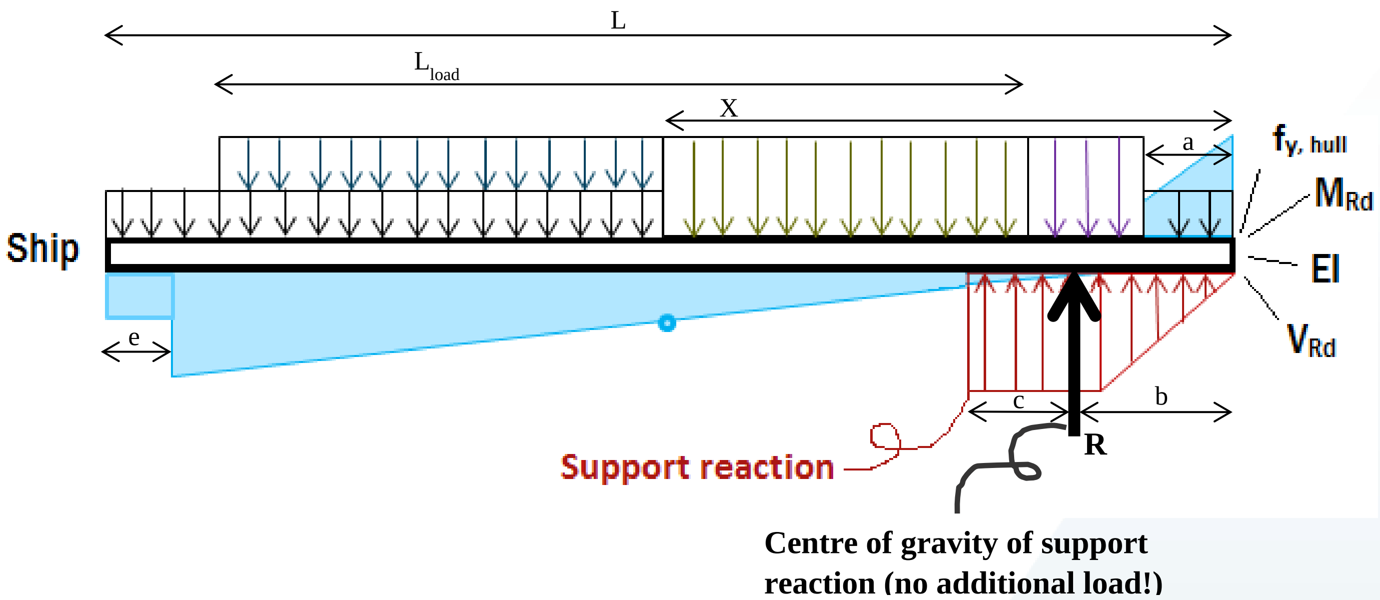


Figure 157 - Definition of distances

As for horizontal sinking, first the general parameters of the ship and after that the general parameters of the tunnel are given (Table 46 and Table 47).

Ship

Table 46 - General parameters of ship

Parameter	Amount	Unit	Formula	Description
L	200	m		Length
L_{load}	180	m	Variable	Loaded length
B	28	m		Width
H	15.6	m		Moulded depth

T	11.5	m		Draught
DWT	40,000	ton	Dead weight ton	Maximum carrying capacity of ship
Δ	54,100	ton		Volume displacement
W_{ship}	14,100	ton	Δ - DWT	Mass of ship
$W_{iron\ ore}$	38,000	ton	0.95 DWT	Mass of iron ore
$W_{supplies}$	2,000	ton	0.05 DWT	Mass of supplies
$\rho_{iron\ ore}$	3,000	kg/m^3	Assumption	Density iron ore
ρ_{water}	1,000	kg/m^3	Assumption	Density water
ρ_{ship}	7,000	kg/m^3	Ship is made out of steel	Density material ship (steel)

The general parameters are the same as before. Only the length of the flooded compartments (L_{leak}) is missing. The amount of flooded compartments are now determined by the parameters X and a, as defined in Figure 157, and are given in Table 48.

Tunnel

Table 47 - General parameters of tunnel

Parameter	Amount	Unit	Formula	Description
B_{tunnel}	20	m		Width tunnel
$D_{waterway}$	7	m	Variable	Depth waterway

The tunnel is actually 40m. But in the report of Gent University only half of the tunnel width is used for support. Therefore a value of 20m is given (see also footnote 68 on page 155).

A2.1.3.2.2 Loads from ship

An overview of the used symbols for the different types of loads is given in Figure 158.

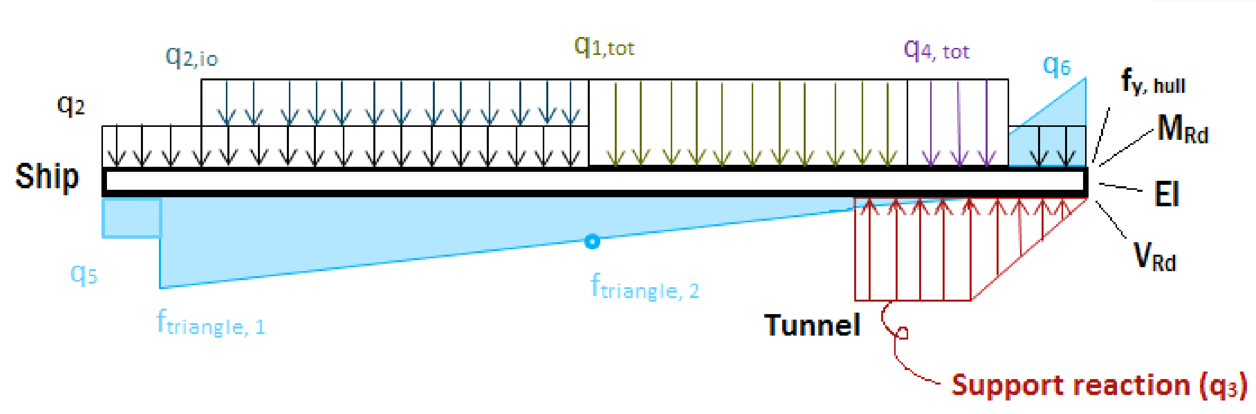


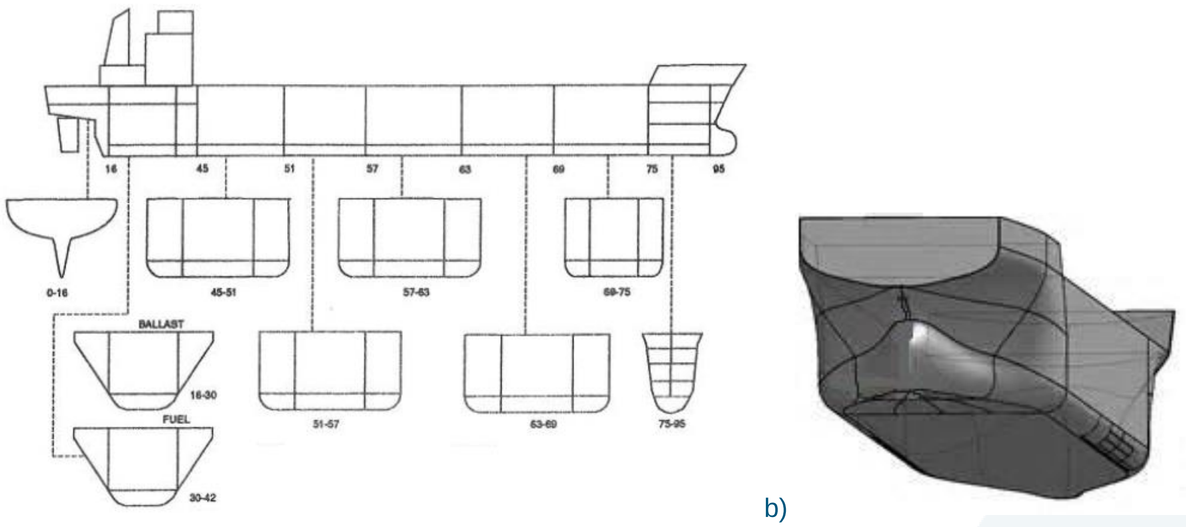
Figure 158 – Definition of used loads

The loads $q_{1,tot}$, q_2 and $q_{2,io}$ are (almost) the same as before. Almost, because the block coefficient is now taken into account in a different way, and is no longer present in this loads. How the block coefficient is taken into account is explained below. The purple load ($q_{4,\ tot}$) represents the part of the ship which is flooded, but contains no bulk.

The block coefficient is now taken into account in a little bit different way. As already said, the block coefficient takes into account the difference in the real displaced volume of the ship and the volume enclosed by B*T*L (Figure 142). This difference in volume is now assumed to be caused only by the bow and stern. Factually this means that the cross section everywhere equals to B*T except for the stern and the bow. This assumption is taken into account through a reduction in buoyancy at the stern (load q_5) and at the bow (load q_6). The load q_5 reduces the buoyancy by a half, over a distance *e*. In reality this load should have the same inclination as $f_{traingel\ 1}$ (and $f_{triangle2}$), but is taken as a block load, with a value equal to the mean value. The load q_6 subtracts the buoyancy from the original buoyancy, which is incorporated in q_2. This is a triangle, due to the configuration of the bow (Figure 160) over a distance B. But it stops at the position of the first leaky compartment, because each leaky compartment has no buoyancy at all.

The blue triangle loads ($f_{triangle,\ 1}$ and $f_{triangle,\ 2}$) represents the additional buoyancy of the ship gained through its rotation in longitudinal direction. The load $f_{triangle,\ 2}$ has to do with the permeability and takes the effect into account if there are enclosed compartments in the flooded areas. Because when the permeability is not 100% this should be taken into account for the load. For how this is done, see Table 48.

The load q_3 still represents the reaction force, but the configuration differs a little bit. This due to the different configuration of the bottom which is used. An indication how the bottom of a ship looks like is given in Figure 159. Part *a)* is an iron ore bulk carrier; part *b)* shows a general ship. But it gives a good indication of the layout of the bottom.



a) b)

Figure 159 – a) Cross sections from ship (William I. Milwee, 1996), b) bottom configuration of hull ship[69]

For this case of the ship sinking under an angle, it is important to model the bow of the ship in the right way. Because this part rests on the tunnel and the configuration of the bow determines the magnitude of load. The configuration of the bottom is assumed to be as presented in Figure 160.

[69] *Drawing from http://cadcamcae.eafit.edu.co/conference.html.*

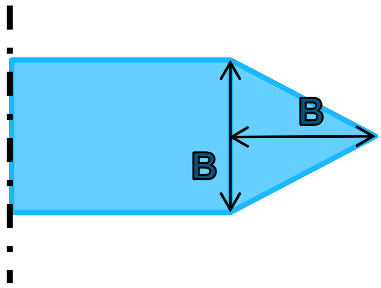


Figure 160 - Schematisation bottom bow of ship

The total reaction force on the tunnel is assumed to be equally spread over the bottom area. This clarifies that the load q_3 is partly block wise and partly a triangle (Figure 158).

As said before, the rationale behind the blue triangle load is that this represents the additional buoyancy of the ship to get equilibrium. The magnitude of this load is calculated by setting the sum of the moments around the centre of the reaction force (R) equal to zero. Another advantage of such a model is that the draught of the ship at its back side can simple be calculated back form the increase in buoyancy.

The loads are calculated in Table 48. The same distinction which is made for $q_{1,tot}$ (submerged part and not submerged part) is now also made for $q_{4,\ tot}$. The distance *a* accounts for the distance where the leaky compartments start, seen from the bow of the ship. *X* gives the end point of the leaky compartments. f_{rad} is the value which represents the increase in buoyancy per unit of length. $f_{triangle,\ 1}$ gives the magnitude of load at the position as given in Figure 157. $f_{triangle,\ 2}$ is represents the reduction in buoyancy if the permeability is smaller than 100%. If the permeability is 100%, $f_{triangle,\ 2}$ is zero. The capital values F represent the total loads from the corresponding 'triangle'.

The distances *a*,*b*,*c* and *e* are as defined in Figure 157.

Sometimes there are certain values given which are needed for MatrixFrame. These values are needed to check the model for the bending moments, which is done in MatrixFrame.

The parameter d_{stern} gives the additional draught of the ship at the backside of the ship, measured from the top side of the tunnel. The total draught at that point (d_{tot}) is the distance measured from the water level.

Table 48 - Loads

Parameter	Amount	Unit	Formula	Description
V_{ship}	121,000	kN	$W_{ship}(\rho_{ship}-\rho_{water})/\rho_{ship}10$	Load of ship under water per m
$V_{iron\ ore}$	253,000	kN	$W_{iron\ ore}(\rho_{iron\ ore}-\rho_{water})/\rho_{iron\ ore}10$	Load of iron ore under water per m
P	100%			Permeability
$q_{1,\ un\ wtr,\ p\ =\ 100\%}$	900	kN/m	$(V_{ship}D_{waterway}/H)/L+(V_{iron\ ore}D_{waterway}/H)/L_{load}$	Load from leaky compartments, fully flooded
$q_{1,\ uw,\ p=0\%}$	-650	kN/m	$((W_{ship}+W_{supplies})10/L + W_{iron\ ore}10/L_{load})(D_{waterway}/H) - BD_{waterway}10$	Load from leaky compartments, not flooded
$q_{1,\ uw,\ p=P}$	900	kN/m	$Pq_{1,\ uw,\ p\ =\ 100\%} + (1-P)q_{1,\ uw,\ p\ =\ 0\%}$	Load from leaky compartments, with P% flooded
$q_{1,\ above\ water\ level}$	1,600	kN/m	$((W_{ship}+W_{supplies})(H-D_{waterway})/H)10/L+(W_{iron\ ore}(H-D_{waterway})/H)10/L_{load}$	Load from leaky compartments, above water level

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$q_{1, tot}$	2,510	kN/m	$q_{1, under\ water} + q_{1, above\ water\ level}$	Load from leaky compartments
$q_{4, un\ wtr, p = 100\%}$	270	kN/m	$(V_{ship}D_{waterway}/H)/L$	Load from leaky compartments, fully flooded
$q_{4, uw, p=0\%}$	-1,600	kN/m	$((W_{ship}+W_{supplies})10/L)(D_{waterway}/H) - BD_{waterway}10$	Load from leaky compartments, not flooded
$q_{4, uw, p=P}$	270	kN/m	$Pq_{4, uw, p = 100\%} + (1-P)q_{4, uw, p = 0\%}$	Load from leaky compartments, with P% flooded
$q_{4, above\ water\ level}$	440	kN/m	$((W_{ship}+W_{supplies})(H-D_{waterway})/H)10/L$	Load from leaky compartments, above water level
$q_{4, tot}$	720	kN/m	$q_{4, under\ water} + q_{4, above\ water\ level}$	Load from leaky compartments
q_2	-1,200	kN/m	$(W_{ship}+W_{supplies})10/L - BD_{waterway}10$	Load from intact compartments
$q_{2, io}$	2,100	kN/m	$W_{iron\ ore}10/L_{load}$	Load from iron ore
q_6	1,960	kN/m	$BD_{waterway}10$	See schematisation
$q_{6, leak}$	1,610	kN/m	$(B-a)/Bq_6$	Needed for MatrixFrame
a	5	m	Variable	Distance from end which is empty
X	55	m	Variable	Distance from end which is flooded
A	200	m^2	$(B_{tunnel}-B)B+0.5B^2$	Supporting Area
c	6.7	m	$(0.5B(B_{tunnel}-B)^2+0.5B^2(B_{tunnel}-B+B/3))/A$	See Figure 157
b	13.3	m	$B_{tunnel}-c$	See Figure 157
$V_{red, tot}$	10,300	m^3	$(1-C_B)BTL$	Reduction of volume
$V_{red, bow}$	6,100	m^3	$0.5B^2H$	Reduction of volume at bow
$V_{red, stern}$	4,200	m^3	$V_{red, tot} - V_{red, bow}$	Reduction of volume at stern
e	19.2	m	$V_{red, stern}/(0.5BH)$	Distance at stern over which reduction is taken into account
f_{rad}	7.55	kN/m/m	$(q_2(L-X)((L-X)/2+X-b)+q_{1, tot}(X-MAX((L-L_{load})/2;a))((X-MAX((L-L_{load})/2;a)/2-(b-(L-L_{load})/2))+q_{2,io}(L_{load}-X+(L-L_{load})/2)((L_{load}-X+(L-L_{load})/2)/2+X-b)+q_{4, tot}MAX((L-L_{load})/2-a;0)(((L-L_{load})/2-a)/2-(b-a))-q_2a(b-a+a/2))/(0.5*2/3((L-b-e)^3+(1-P)(X-b)^3-q_5e-0.5q_6b+0.5q_6(B-a)^2/B(2/3(B-a)-(B-b))))$	Amount of increase in force
$f_{triangle\ 1, halfway}$	660	kN/m	$(L/2-b)f_{rad}$	Needed for MatrixFrame
$f_{triangle\ 1}$	1,270	kN/m	$(L-b-e)f_{rad}$	See schematisation
$f_{triangle\ 2}$	0,0	kN/m	$(1-P)*(X-b)f_{rad}$	See schematisation
$F_{triangle,1}$	106,000	kN	$0.5f_{triangle\ 1}(L-b-e)$	Total load from triangle 1
$F_{triangle,2}$	0,0	kN	$0.5f_{triangle\ 2}(X-b)$	Total load from triangle 2
R	118,000	kN	$q_2(L-X+a)+q_{2, io}(L_{load}-X+(L-L_{load})/2)+q_{1, tot}(X-MAX((L-L_{load})/2;a))+q_{4, tot}MAX((L-L_{load})/2-a;0)-F_{triangle,1}+F_{triangle, 2}-q_5e+0.5q_6b-0.5q_6(B-b)^2/B$	Total reaction force
σ_3	590	kN/m^2	R/A	Ground pressure

q_3	11,800	kN/m	$\sigma_3 B$	Load on tunnel deck
$q_{3, 2/3th\ of\ length}$	7,900	kN/m^2	$2/3q_3$	Needed for MatrixFrame
q_5	670	kN/m	$0.5(L-b-0.5e)f_{rad}$	Additional buoyancy intact compartments at stern
d_{stern}	5	m	$(L-b)f_{rad}/(10B)$	Additional immersion back side of ship
d_{tot}	12	m	$d_{stern} + D_{waterway}$	Total immersion back side of ship

A2.1.3.2.3 Moments from load

In Table 49 the maximum bending moment is given. It is not possible to say at forehand at which position the maximum moment will occur. Therefore this moment is calculated by MatrixFrame.

Table 49 - Moments from load

Parameter	Amount	Unit	Formula	Description
M_{tot}	2,171,000	kNm	MatrixFrame	Maximum moment

A2.1.3.2.4 Shear force from loads

The shear force is calculated (Table 50) just next to the edge of the tunnel. There occurs the maximum shear force.

Table 50 - Shear force from loads

Parameter	Amount	Unit	Formula	Description
Q_{Ed}	87,000	kN	$q_3B_{tunnel} - L_{load}-q_{1,tot}(B_{tunnel} - (L-L_{load})/2))-q_{4,tot}((L-L_{load})/2-a)-q_2a$	Maximum shear force

A2.1.3.2.5 Moment resistance of ship

The moment capacity (Table 51) is exactly the same as in the model for horizontal sinking. For further clarification see §A2.1.2.2.3 on page 152.

Table 51 - Moment resistance of ship

Parameter	Amount	Unit	Formula	Description
C_B	0.84	-	$\Delta/(LBT)$	Block coëfficiënt
C	9.75	-	$10.75-((300-L)/100)^{1.5}$	Coëfficiënt
$M_{SW, hogging}$	1,200,000	kNm	$CL^2B(122.5-15C_B)$	Still water bending moment, hogging
$M_{SW, sagging}$	1,093,000	kNm	$CL^2B(45.5+65C_B)$	Still water bending moment, sagging
$M_{WV, hogging}$	1,743,000	kNm	$190CL^2BC_B$	Wave induced bending moment, hogging
$M_{WV, sagging}$	-1,850,000	kNm	$-110CL^2B(C_B+0.7)$	Wave induced bending moment, sagging
$M_{Rd, hogging}$	2,943,000	kNm	$M_{SW, hogging} + M_{MV, hogging}$	Total hogging bending moment resistance
$M_{Rd, sagging}$	2,943,000	kNm	$M_{SW, sagging} + ABS(M_{MV, sagging})$	Total sagging bending moment resistance

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A2.1.3.2.6 Shear capacity of ship

The shear capacity (Table 52) is exactly the same as in the model for horizontal sinking. For further clarification see §A2.1.2.2.4 on page 152.

Table 52 - Shear capacity of ship

Parameter	Amount	Unit	Formula	Description
K_1	0.70	-	0.4 L < x < 0.6 L, for positive shear force	Coëfficiënt
K_2	1	-	= 1 for unrestricted sea-going service condiditons	Coëfficiënt
Q_{w0}	25,200	kN	$0.3CLB(C_B+0.7)$	
Q_{WV}	17,700	kN	$K_1K_2Q_{W0}$	Design wave shear force
Q_{SW}	12,200	kN	$Q_{WV}(M_{SW, hogging} / M_{MV, hogging})$	Design still water shear force
Q_{Rd}	29,800	kN	$Q_{SW} + Q_{WV}$	Total shear force resistance

A2.1.3.2.7 Checks

The Unity Check for the bending moment capacity is the same as in the model for horizontal sinking. The strength of the shear capacity is however increased by a factor two.

In §A2.2 *Out of plane compression strength of ship* it is explained that the bow of the ship is a strengthened part of the ship. Because it should be able to resist loads from slamming. Strengthening of the hull's structure implies also a higher shear capacity of the ship at that location. Because of the fact that the maximum shear force for this situation occurs at the position of the bow, it seems to be reasonable to increase the shear capacity. The amount of strengthening due to this effect is however unknown. Gent University proposes a factor two[70]. Therefore also that value is used.

The results are presented in Table 53.

Table 53 - Unity checks for bending moments and shear forces

Parameter	Amount	Unit	Formula	Description
$m_{hogging}$	0.74	-	$M_{Ed}/M_{Rd, hogging}$	Moment check for hogging bending moments
$m_{sagging}$	0.74	-	$M_{Ed}/M_{Rd, sagging}$	Moment check for sagging bending moments
$q_{support}$	1.46	-	$Q_{Ed, support}/(2Q_{Rd})$	Shear check edge tunnel

A2.1.3.2.8 Load on tunnel

Ultimately the forces acting on the tunnel deck are determined (Table 54).

Table 54 - Load on tunnel

Parameter	Amount	Unit	Formula	Description
R	118,000	kN	As under: loads from ship	Total reaction force
$q_{sunken\ ship\ load}$	590	kN/m^2	$R/((B-2)B_{tunnel})$	Ground pressure

[70] *This value in that report is not based on the reasoning as stated before, but there it is stated that ships most of the time are over-dimensioned with respect to the shear strength.*

As said before, the load is assumed to be equally spread over the full bottom area of the ship. As can be seen from Figure 160 the bow of the ship is schematized as a triangle. That means that the load cannot simply be taken into account as a uniform distributed load of over the full tunnel width (for the cross sectional analysis). In reality the load looks like more or less as presented in Figure 161. In this figure a certain part is uniformly distributed (representing the part of the ship after the bow) and a part is evenly descending (representing the bow of the ship).

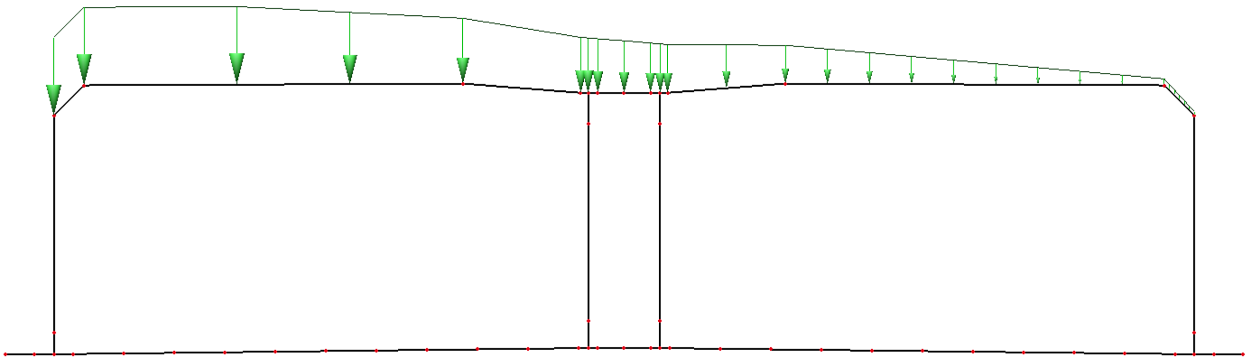

Figure 161 - Load configuration s.u.a.a.(triangular shape)

Such a load configuration is difficult to take into account for the design. Therefore the load configuration is changed to the configuration as shown in Figure 162.

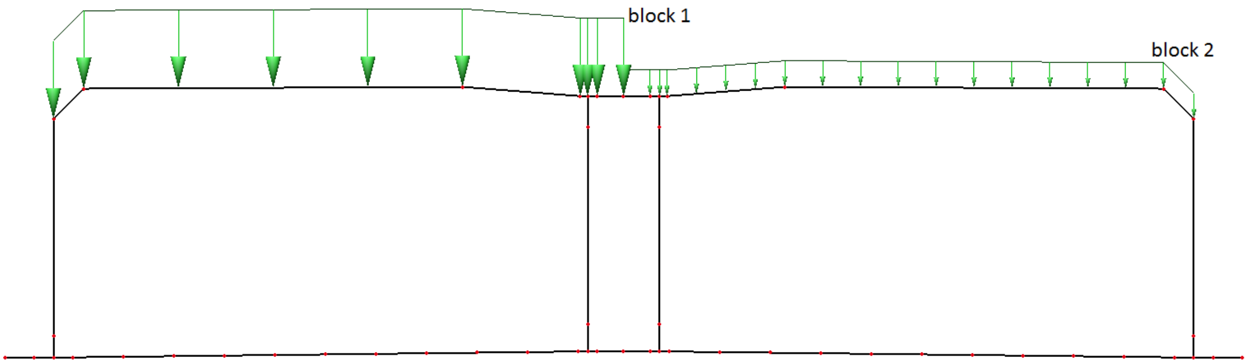

Figure 162 - Block loads representing triangular shaped load

The values of the blocks can be calculated as presented in Table 55.

Table 55 - Determining magnitude of block loads

Parameter	Amount	Unit	Formula	Description
$q_{sunken\ ship\ load}$	275	kN/m^2		Load from ship
$L_{element}$	23.9	m		Length of element
B_{ship}	32.3	m		Widht ship
B_{tunnel}	31.75	m		Widht tunnel
f	1.25	-	2-MIN($L_{element}$;B_{ship})	Factor
r_1	0.75	-		Ratio block 1

r_2	0.25	-		Ratio block 2
$q_{block,1}$	257	kN/m^2	$r_1 f q_{sunken\ ship\ load}$	Load block 1
$q_{block,2}$	86	kN/m^2	$r_2 f q_{sunken\ ship\ load}$	Load block 2

This block loads give of course a little bit a different force distribution. Therefore the differences were compared for a few load configurations. The differences in results were in the order of magnitude of 2%.

This model focusses on the load on the tunnel deck. If a ships sinks however just next to the tunnel, a load is exerted on the tunnel wall. The magnitude of load on the tunnel wall is equal to half of the vertical load. See Figure 132 as an example.

For the longitudinal analysis such an approach as for the cross sectional analysis is not followed. The load is still assumed as an equal distributed load present over a length which is equal to the width of the ship (Figure 163). The value of the load can be determined by R/B_{ship}. Keep in mind that 'B_{ship}' in the model is just denoted as 'B'.

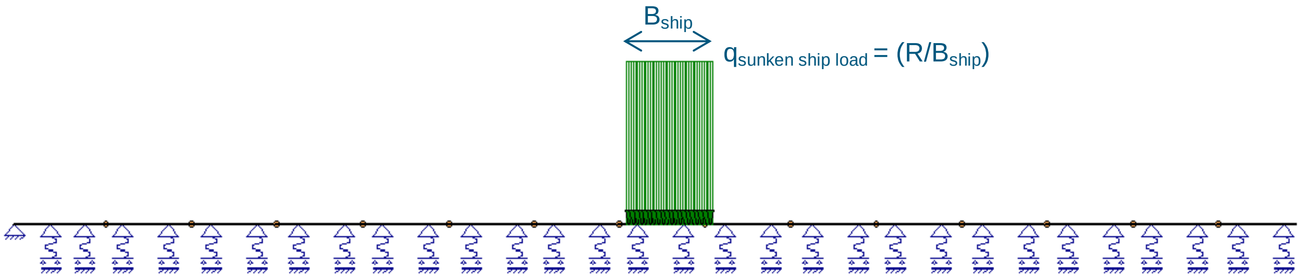

Figure 163 - Load for longitudinal analysis

A2.1.3.2.9 Check for out of plane compression strength

A last item is the out of plane compression strength of the ship. In §A2.2 *Out of plane compression strength of ship* it is concluded that probably shear failure will be governing over the out of plane compression strength of the bow. Therefore the check for the out of plane compression strength is not needed for this situation of sinking under an angle.

A2.1.4 Validation of model

The model is validated to show that the results are reliable. For validation use is made from a report published by Gent University. That report presents rather detailed information about sunken ship loads. Before the model is validated, first a short description is given of the model used by Gent University. In the next paragraph that model of GU is validated with a simple check. After that the model from this research is validated through comparing the found results with those of GU. This both for horizontal sinking as well as for sinking under an angle.

A2.1.4.1 Model of Gent University

A2.1.4.1.1 Description

Gent University calculates the loads from a sunken ship on an immersed tunnel based on equilibrium equations with the aid of numeric methods. They start from the point that the ship gets leak, which leads to an increase in the total mass of the ship and hence an increase in draught. From this point on all other parameters can be determined. For example: the change in trim of the ship, the forces which are acting at the governing cross section and the total load on the tunnel. In that way all results are calculated by simply increasing the amount of water which is flooding into the ship step by step.

The bending moment capacity of the ship together with the shear capacity is calculated after that. For the acting bending moment, the influence of the distribution of the cargo over the length of the ship is also taken into account. Because an uneven distribution of the cargo causes additional moments in the ship. There are also values given for the amount of strengthening of the bow of the ship due to slamming, but nothing more is said about that.

A2.1.4.1.2 Validation results of Gent University

To validate the model, use is made from the iron ore bulk carrier presented in the report with a DWT of 40,000. The results are validated at the moment that the ship lies in a horizontal position. That for both horizontal sinking, as for sinking under an angle. Because for the case of sinking under an angle, there is also a moment that the ship lies in a horizontal position (in case that the tunnel lies above the river bed). This position is at a water depth of 12m.

By checking the validity of the model, use is made from the fact that if a ship is fully loaded, the ship achieves its maximum draught (without any leaking compartment). This is an equilibrium position by definition, which is good starting point. For the mentioned iron ore bulk carrier that is for 11.5m.

The differences compared to that equilibrium position are now as follows. The water depth is now 12m, leading to an increase in buoyance of 0.5m. This gives a decrease in load. There are also some compartments filled with water now. That leads to an increase in the load on the tunnel. The difference between the increase in load due to the flooded compartments and the decrease in load due to the additional buoyance must give the load on the tunnel.

The results are presented in Table 56. For the case of horizontal sinking the length of the leak (L_{leak}) = 60, and for sinking under an angle the length of the leak (L_{leak}) = 50m. Clarification of the symbols can be found under A2.1.2.2.1 *General parameters*. For $\rho_{supplies}$ a value of 1000kg/m^3 is taken.

The description '*Real load'* is set between brackets, because there are certain assumptions made which are not stated in the report. This applies to the iron ore density used (taken as 3,000kg/m^3) and the amount of the load carrying capacity of the ship which is used for cargo (taken as 95%).

Table 56 - Validation Model Gent University

Parameter	Amount	Unit	Formula	Description
$R_{real, horizontal\ sinking}$	96	MN	$(1000\Delta/\rho_{water}-(W_{ship}/\rho_{ship}+W_{supplies}/\rho_{supplies}+W_{iron\ ore}/\rho_{iron\ ore})*1000*12/H)*L_{leak}/L*10-(12-T)BL\rho_{water}*10$	'Real load'
$R_{real, sinking\ under\ an\ angle}$	75	MN	$(1000\Delta/\rho_{water}-(W_{ship}/\rho_{ship}+W_{supplies}/\rho_{supplies}+W_{iron\ ore}/\rho_{iron\ ore})*1000*12/H)*L_{leak}/L*10-(12-T)BL\rho_{water}*10$	'Real load'
$R_{GU, horizontal}$	115	MN	Presented[71]	Calculated load by GU

[71] *There is an error in the graph which is used, because the position of the bottom of the ship is there not equal to the water depth (which should be the case, because the ship is in a horizontal position). The presented load of 115kN is taken for the bottom of the ship being at a depth of 12m. When taking the water depth as reference (at 12m), the load is about 140kN (which seems unrealistic).*

sinking $R_{GU, sinking}$ under an angle	105 MN	Presented	Calculated load by GU

From the table it can be seen that the model of Gent University tents to predict a higher value than what is expected. This information can be used when comparing the results from this report with those of Gent University.

A2.1.4.2 Validation of the model (horizontal sinking)

The model is validated both internally and externally. Internally to see if there is not something wrong in the Excel sheet which describes the model. The external validation (with the aid of the results of GU) is used to see if the model gives reliable results.

A2.1.4.2.1 Internal validation

For internal validation, it should be checked whether there is vertical equilibrium or not. This check is carried out by filling out the values in the model in MatrixFrame. MartrixFrame should give zero support reactions then. The result as shown in Figure 164 was obtained.

Figure 164 - Support reactions

This result shows that there vertical equilibrium. That's the result which should be obtained. Therefore it can be concluded that there is no error in the Excel sheet which describes the model.

A2.1.4.2.2 External validation

For external validation a comparison is made between the reaction forces, pressures on the bottom and the Unity Checks for the moments and shear forces. See Figure 165 up to Figure 168.

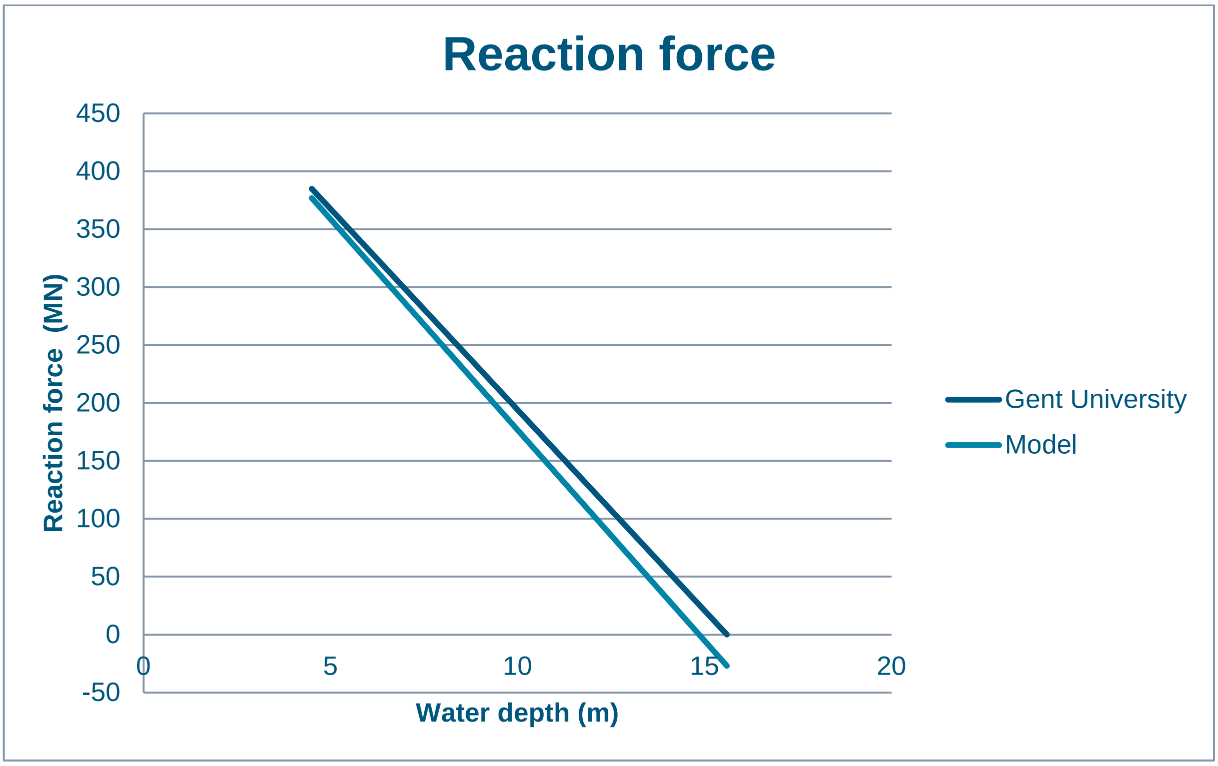

Figure 165 - Comparison reaction force

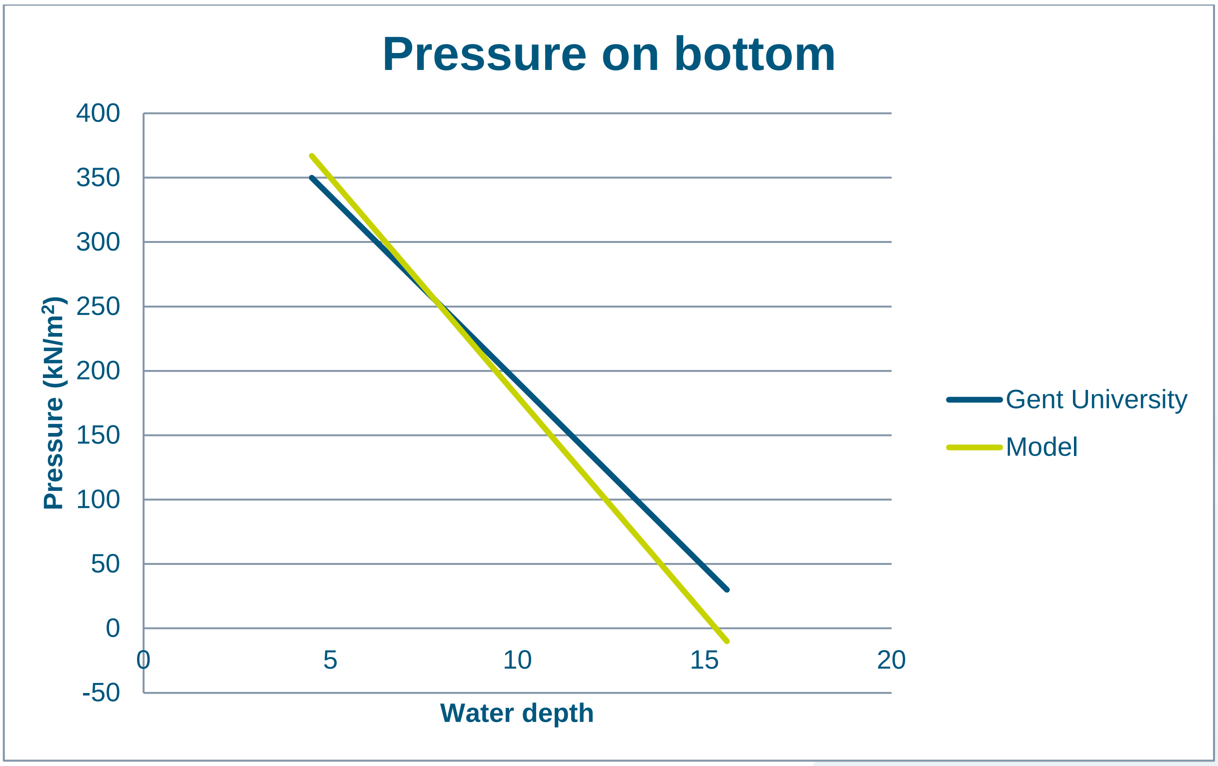

Figure 166 - Comparison pressure on bottom

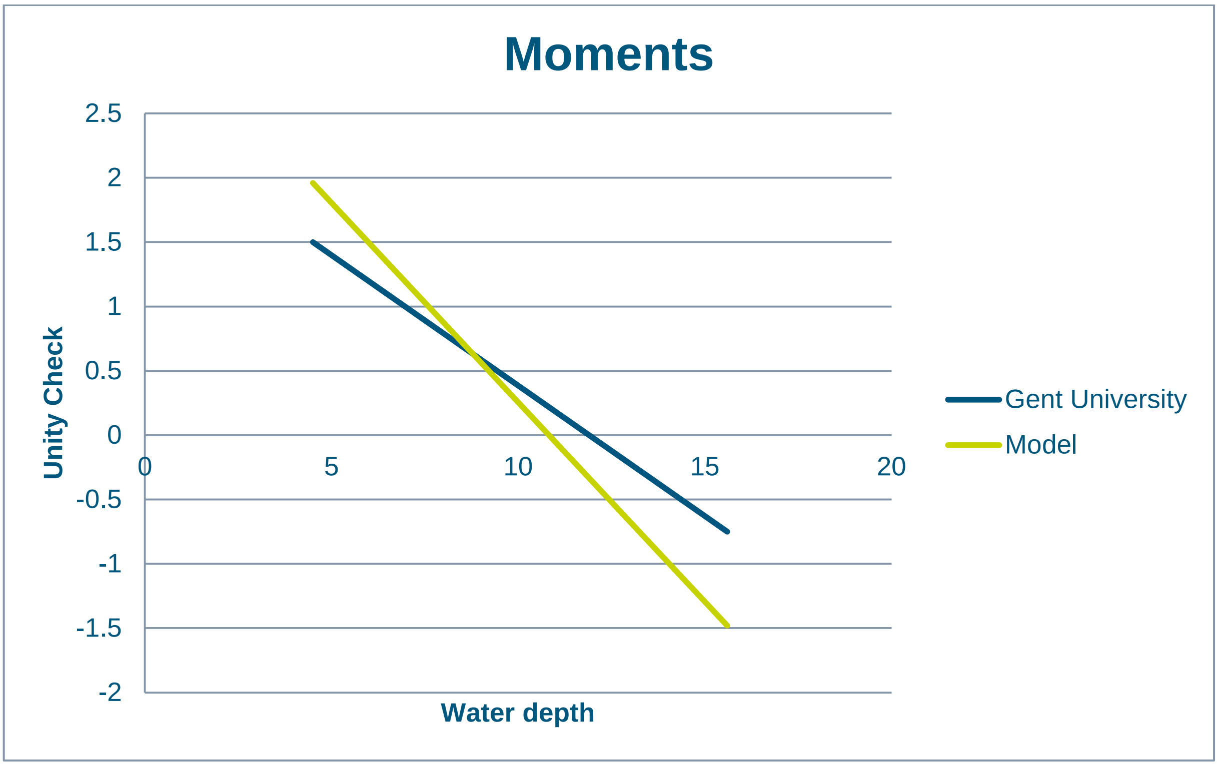

Figure 167 - Comparison moments

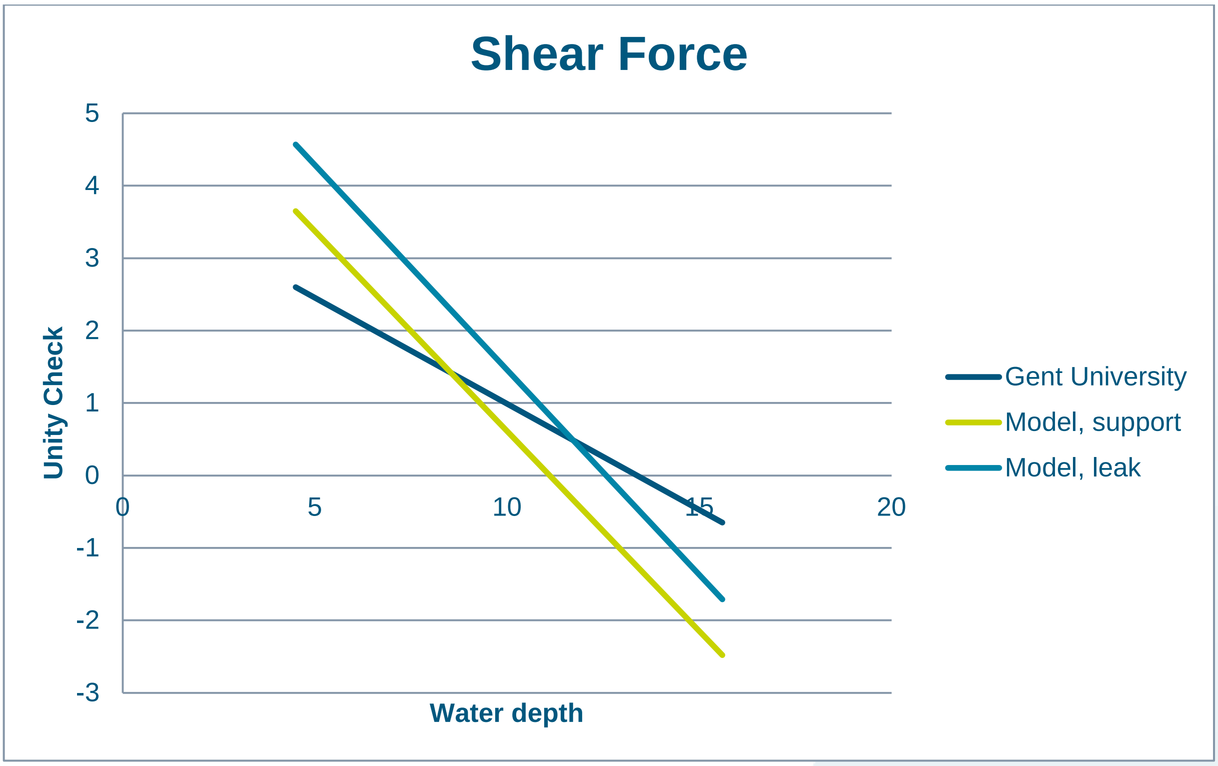

Figure 168 - Comparison shear force

There are differences in reaction force, but not that big. In Table 56 there is a difference found of about 20 kN. This is approximately the mean difference in value between the here presented model and that from Gent University.

The main differences in reaction force between the two models are caused by how the configuration of the ship is taken into account. An important parameter with respect to the configuration of the ship is the block coefficient C_B. This block coefficient takes into account the difference in volume between a square box and the real configuration of a ship (Figure 142). The main differences between the box and the real differences are at the back side and front side of the ship. The square box to which the block coefficient refers is related to the (maximum) draught of the ship and not the total hull height. In this model however the block coefficient is taken into account equally over the full length and the full height of the ship. This clarifies the main differences between the model and the results from Gent University.

The pressure on the bottom follows directly from dividing the reaction force by the supporting area. Although Gent University predicts higher values for the reaction force at a low water depth, the model predicts a higher pressure on the bottom. This means that the supporting area which is taken into account for the model is smaller compared to that of Gent University.

The differences in Unity Checks for both the moments as well as the shear forces are quite substantial. This has three reasons. Gent University assumes a reserve capacity of 37% between the design steel stresses and actual stresses. They use also other design formulas as which were used for the model. As third, the way how the bending moments are calculated differ between the model and Gent University. This differences cause in general a lower U.C. for Gent University comparted to the model. A lower U.C. implies a higher load. It can therefore be said that Gent University in general predicts a higher load compared to the model[72].

A2.1.4.3 Validation of the model (sinking under an angle)

Also here the model is validated both internally and externally.

A2.1.4.3.1 Internal validation

To see if there is vertical equilibrium, as well as moment equilibrium around the middle of the support, all loads from the model are put in MatrixFrame (Figure 169). In this model resembles the bar the ship structure. Also here holds that in reality the supports may be seen as not present.

[72] Gent University takes also the bending moments into account which are caused by an uneven distribution of the cargo over the length of the ship. These additional moments can be a hogging or a sagging bending moment. Gent University takes both scenarios into account. The U.C. lines which are presented here from Gent University are without this additional bending moments. This item cause also that Gent University predicts higher loads compared to the model.

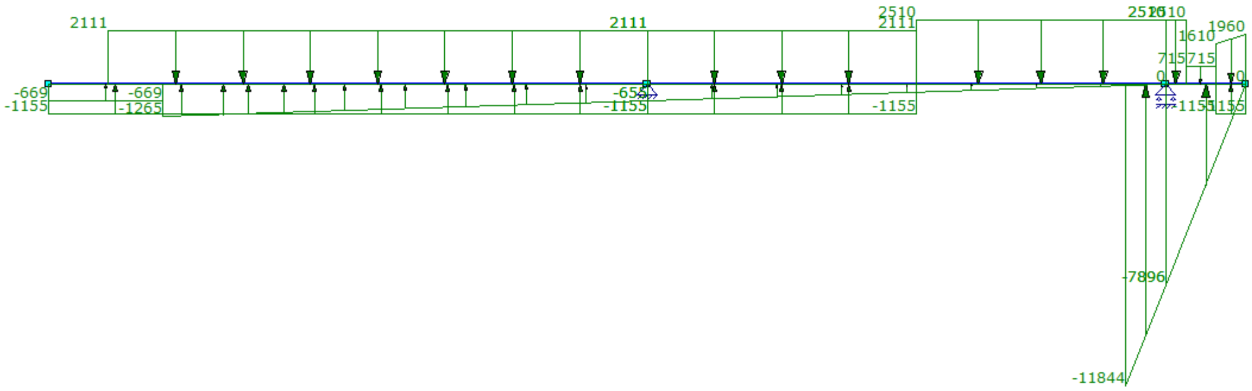

Figure 169 - Loads in MatrixFrame

By having the loads in applied on the ships structure in MatrixFrame, the result of Figure 170 is obtained for the support reactions.

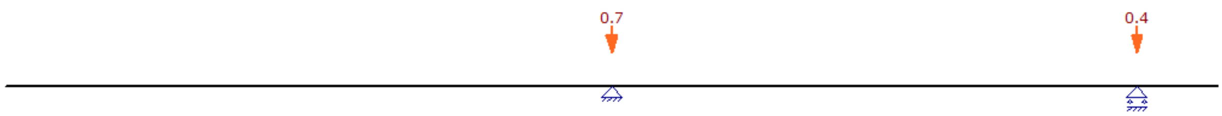

Figure 170 - Support reactions

The almost zero loads which are acting on the supports means that there is vertical equilibrium by the loads which are acting on the bar (= ship). And also that the sum of moments around the middle of the tunnel (= right support) is equal to zero. That is the situation to be reached.

A2.1.4.3.2 External validation

For external validation of the model again a comparison is made between the reaction forces, pressures on the bottom and the Unity Checks for the moments and shear forces. See Figure 171 until Figure 175.

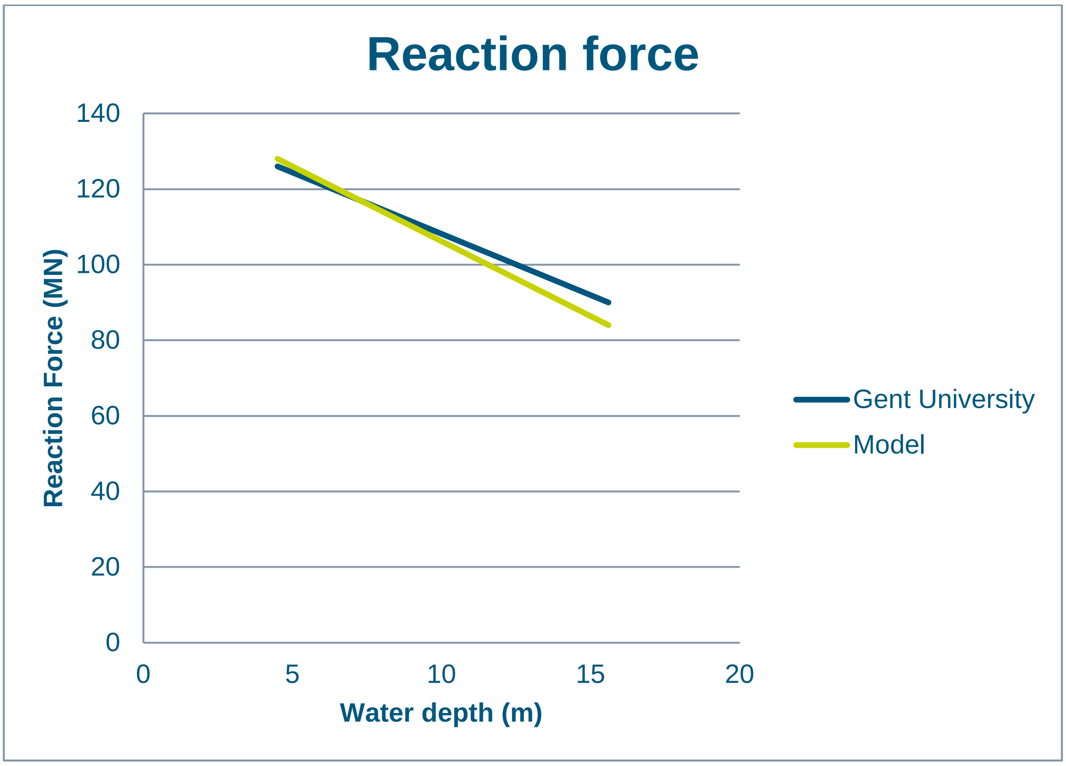

Figure 171 - Comparison reaction force

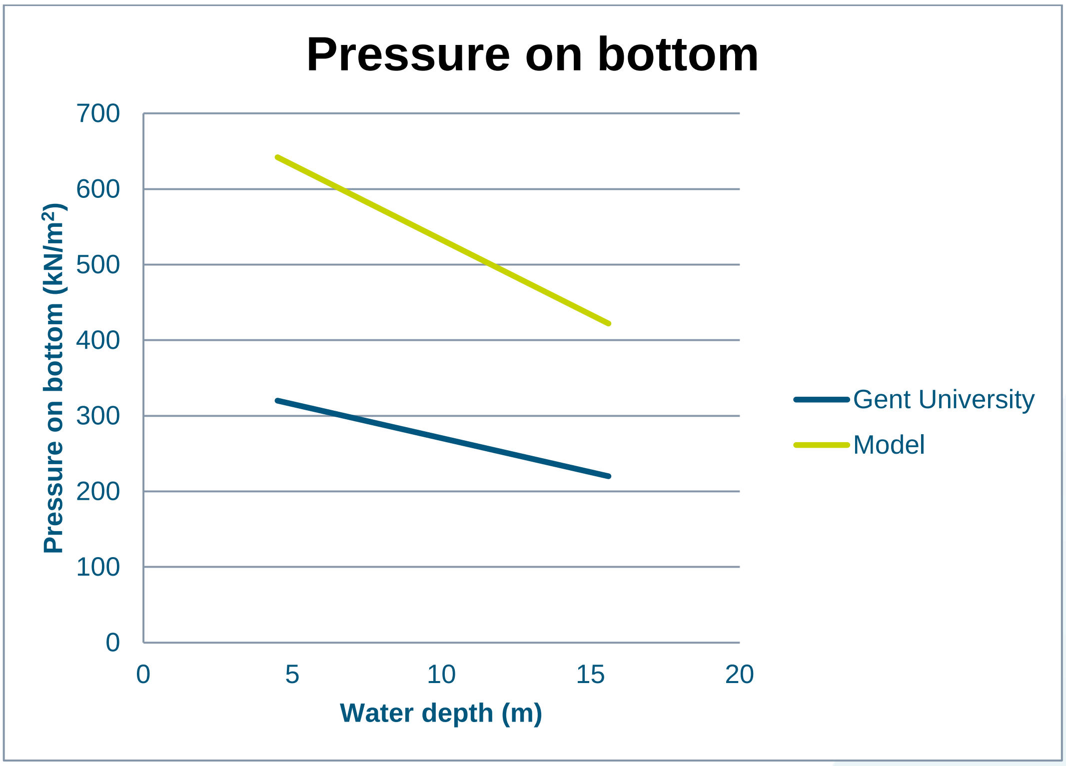

Figure 172 – Comparison pressure on bottom

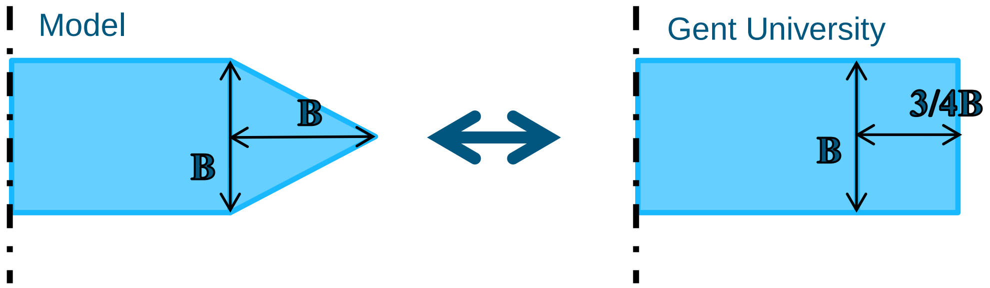

Figure 173 - Differences in bottom area bow

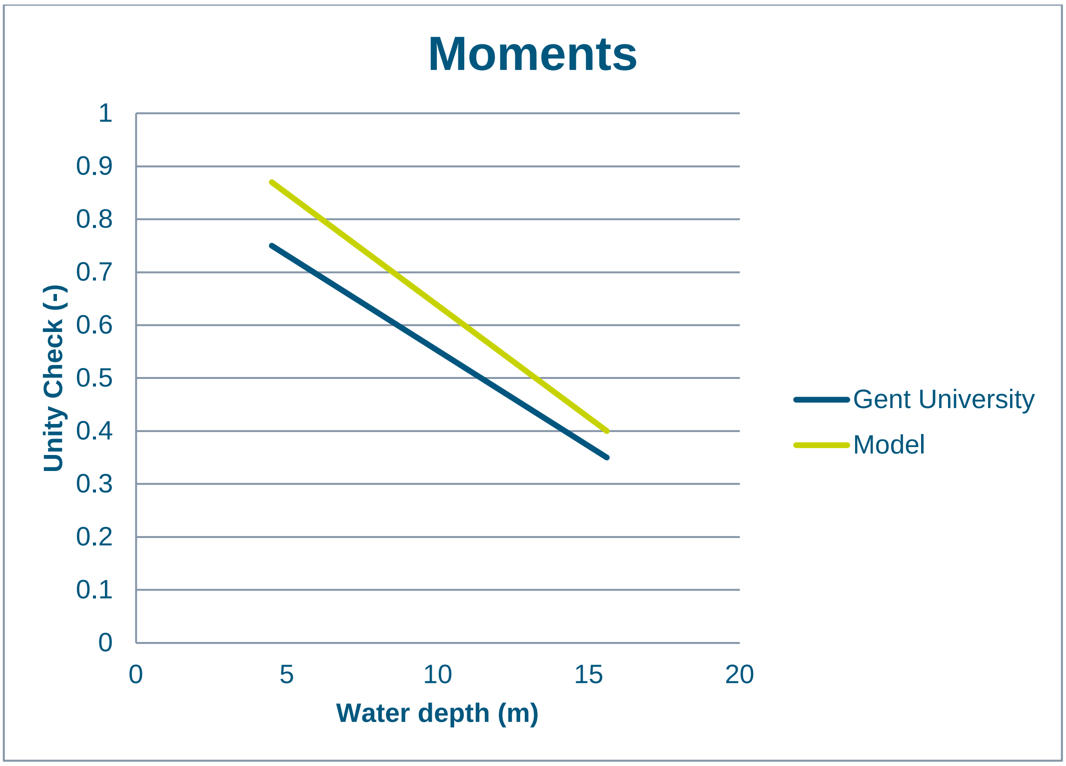

Figure 174 – Comparison moments

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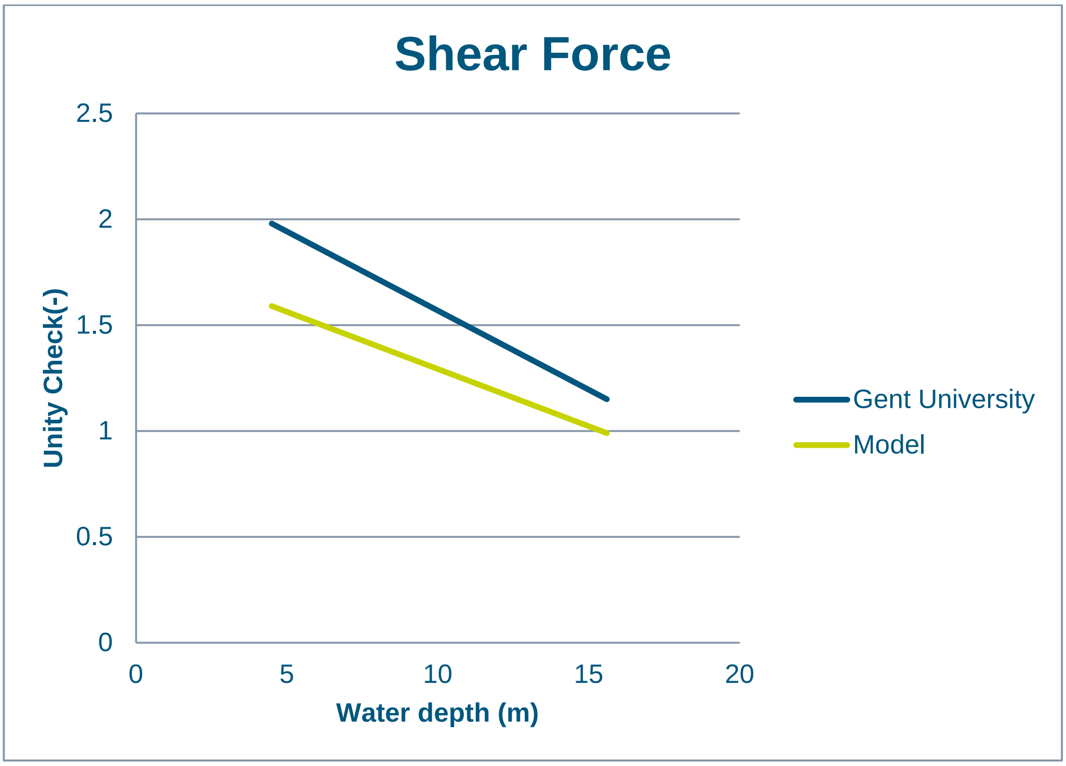

Figure 175 – Comparison shear forces

As can be seen from Figure 171, the reaction forces are almost the same. When looking at the results from Table 56, one would expect that the model predicts a lower load compared to Gent University. This is however not the case. It is therefore assumed that the model also over predicts the real load.

The main differences are now with respect to the pressure on the bottom. The model predicts a much higher load compared to the results from Gent University. That's because the bottom area taken into account by Gent University is the full bottom width together with a reduction of 5m in length (Figure 173). For this case this gives an area of 28*(20-5) = 420m^2, while the model predicts only 200m^2. So that's a big difference. That explains the difference in pressure.

The moment checks (Figure 174) and the shear force checks (Figure 175) lie in the same order of magnitude. It can be seen that the unity check for the shear capacity is always more than 1.0. While the unity check for the bending moments is smaller than 1.0 for all water depths. From this it can be concluded that shear failure will be the governing failure mechanism (over bending moment failure) for a ship sinking under an angle[73].

[73] Although Gent University presents U.C.'s for the shear capacity, they don't use them as check. They assume that bending moment always will be the governing failure mechanism. This is in contrast to the here given opinion. This difference in opinion cause that Gent University often predicts a higher load compared to the model.

A2.1.5 Side effects which influence the magnitude of load

In this paragraph certain side-effects are treated, which cause an increase in the load exerted on the tunnel from the ship. The side-effects which are treated here are impact loading, loads due to irregularities in river bottom and stiffness tunnel. With the latter is meant that the tunnel has a higher stiffness compared to the surrounding soil.

A2.1.5.1 Impact loading

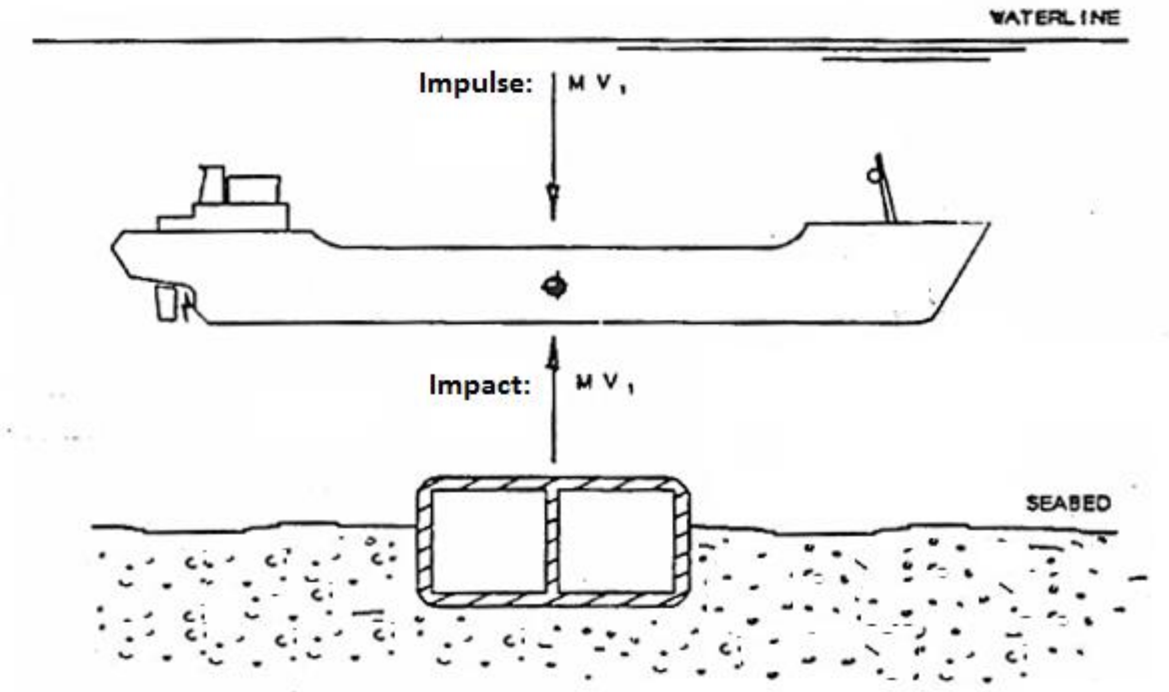

Figure 176 - Schematization impact loading (after (J. Koning, Mei 1992))

The loads as treated so far are all static loads. In case of a deep sea strait, the ship can reach a substantial vertical velocity before reaching the tunnel. For those situations impact loading plays a role. This leads to a load exerted on the tunnel which is a factor higher than only the static load.

In *Zinkende schepen boven een tunnel tracé in de pas van Terneuzen*[74] (J. Koning, Mei 1992) diagrams are given which illustrate the accelerations, velocities and displacements over time from a sinking ship. Some results are presented in Figure 177 till Figure 179.

[74] *In English: Sinking ships above a tunnel route in the pass of Terneuzen.*

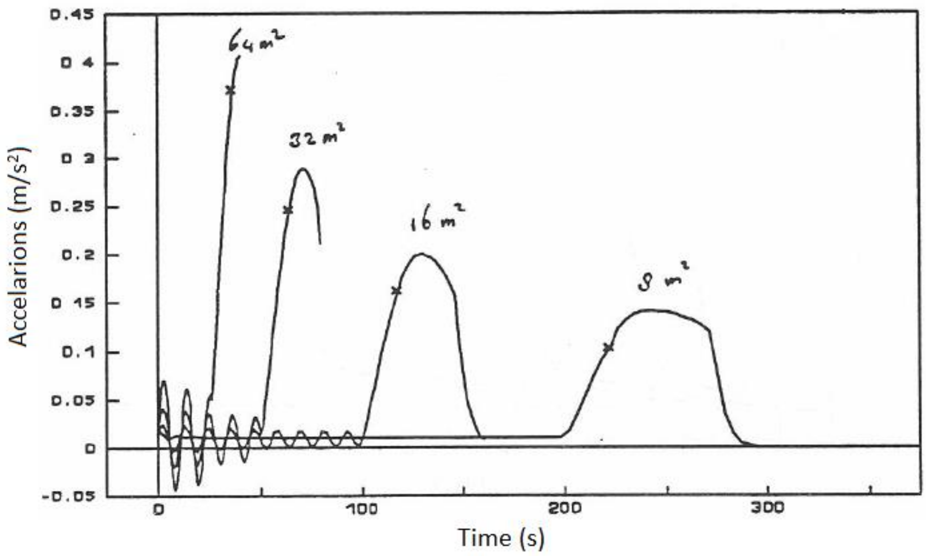

Figure 177 – Accelerations, ship of 200m, horizontal sinking (J. Koning, Mei 1992)

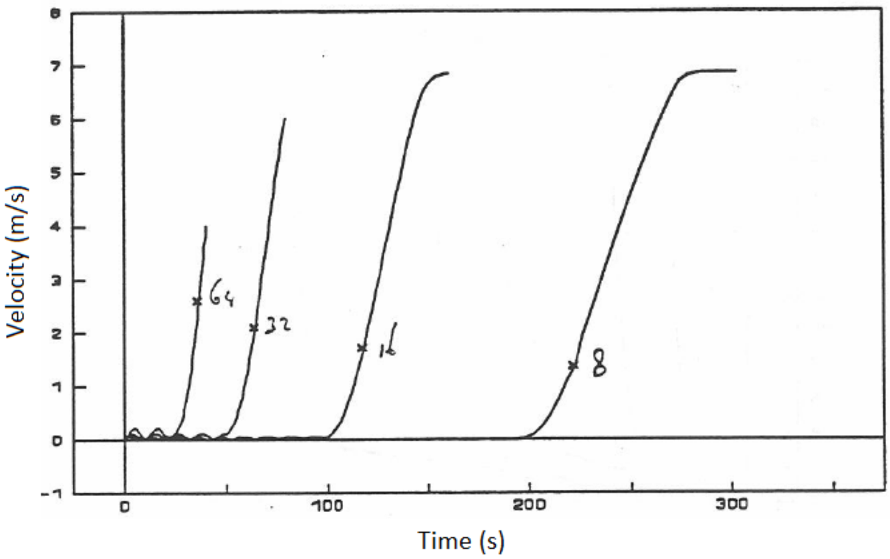

Figure 178 – Velocities, ship of 200m, horizontal sinking (J. Koning, Mei 1992)

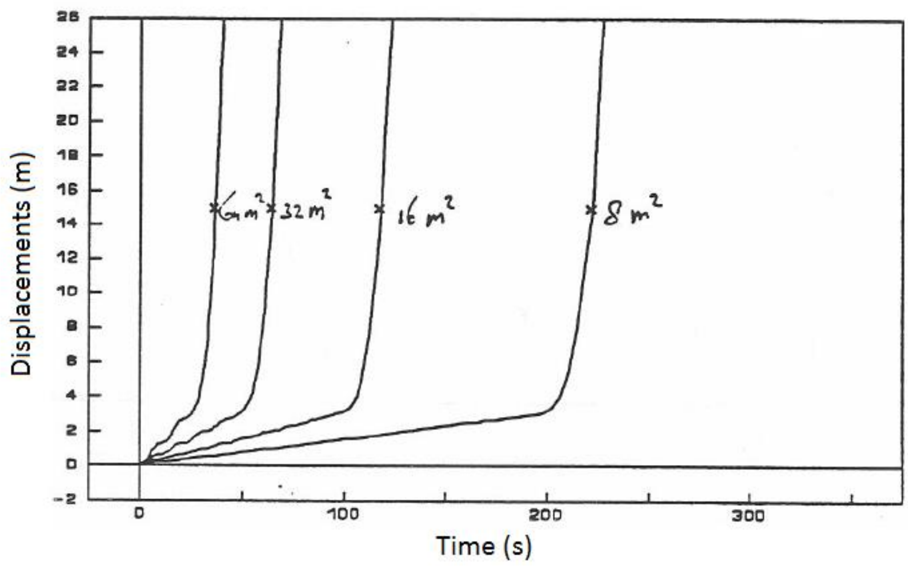

Figure 179 – Displacements, ship 200m, horizontal sinking (J. Koning, Mei 1992)

The areas in the figures indicate the size of the leak in the ship. The higher the leaking gap, the faster the ship is totally submerged. From Figure 179 it can be seen that after a displacement of about 4m the displacements increase very fast. This 4m is approximately the free board[75] of the ship. So the irregularities during the first seconds are due to the process of water flooding into the ship. After the ship is fully submerged, the ship starts to accelerate.

Then the question arises how big impact loads will be. A ship of about 100m induces forces which lie in the same order of magnitude as the static load of the ship, when reaching velocities of about 5 m/s. A ship of 200m causes an impact loading which is only a fraction (about 0.3 times) the static load of the ship, when reaching a velocity of about 2 m/s (J. Koning, Mei 1992).

These results are obtained when taking into account the buckling strength of the hull of the ship and an out of plane compression strength ranging from 0.5 – 1.5MN/m^2. The velocity of 5m/s for the 100m ship corresponds with a sinking distance over 22m and the 2m/s of the 200m ship with a distance of 15m. Compare this with the Marmaray tunnel in Istanbul (Turkey) which is the deepest immersed tunnel at the moment. This tunnel lies with its deck at a water depth of 56m. When taking 18m for the draught of a big iron ore bulk carrier (L = 294m), the sinking distance becomes 38m. This is more than the mentioned 15m. So here impact loading in all probability will be of importance.

When comparing the impact loads from a long ship (as a 200m ship is) with a somewhat shorter one (one of 100m length), the following considerations are made. A big ship of 200m will weigh approximately eight (2^3) times the weight of a ship of 100m. Assume that the impact load of a 100m ship is 2 times the static load of the ship. The total load is then three times the static load. The static load of the 200m ship is then still more than the static load + impact loading of the 100m ship. From this reasoning, together with the previous statement that the impact load for a long ship is a factor lower compared to a shorter ship, it is concluded that impact loading plays a minor role for big ships (> 200m) and a sinking distance smaller than 15m.

Important to notice is that impact loading from sunken ships is a very difficult subject. Also experts don't really know how big such loads are. '*Everybody will be very glad if you can explain how big such loads*

[75] *The free board of a ship is the difference between the height and the draught.*

are' (Ms. Stroo-Moredo, Appendix A2.2). Ms. Stroo-Moredo advised to take only the static loading into account.

A2.1.5.2 Loads due to irregularities in river bottom

All loads presented so far are all based on a flat bottom of the river. But in reality the river will never be totally flat, but a kind of a small hilly area. This leads to local stress concentrations.

In the ROK (Rijkswaterstaat, 2013) p.199, the possibility is given to take a varying soil stiffness into account. This principle (in a modified manner) is used to evaluate the effect that a river bottom never will be flat. In a modified manner, because in the ROK it is set up to take the different soil stiffness into account for the tunnel element foundation. But in this research it is used to evaluate the irregularities from the river bottom.

How this is done is presented in Figure 180 and Figure 181. The factor α which is presented in that figure, takes the difference in soil stiffness into account.

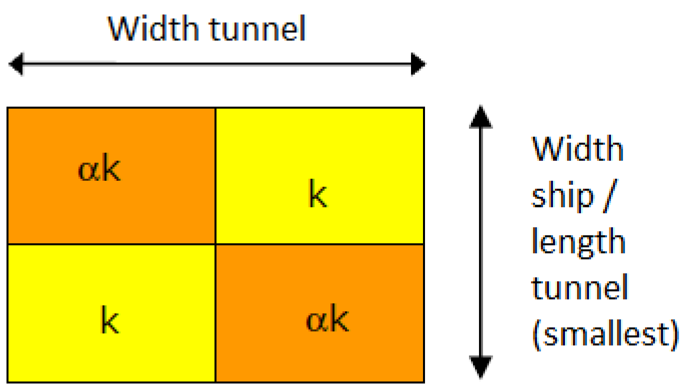

Figure 180 - Varying bedding stiffness (seen from above)

In the ROK there are certain values for α given. A value of 0.9 is given for a gravel foundation, and a value of 0.5 for a sand foundation. These values are also used.

It is easy to calculate the increase in stresses for the different parts. It is assumed that the deformations of the soil will be equal over the whole area. This means that the yellow parts take 2/3th (= k / (k+α)) of the total load. So 2/3th of the load is taken by half of the total area. This gives an increase in stresses of a factor (2/3) / 0.5 =4/3. This is an increase of 33%. At the other hand, the load for the orange parts decreases with 33%. For the gravel layer the increase/decrease in stresses is smaller, namely: (1/1.9) / 0.5 = 1.05, so that's only 5%.

This principle is applied to one segment of the Wijkertunnel (Figure 181). This picture shows a schematisation of the tunnel deck. For this schematisation a plate of 23.92 * 30 * 1.1m (=length * width * height) is used. Under x = 14 and 16m a support is added. That represents the walls of the gallery. The supports at the side have a rotational stiffness of 1.72*10^6 kNm*rad. That represents the stiffness of the walls. The magnitude of the load is just arbitrarily chosen. The differences are based on a sand layer, because the Wijkertunnel is covered with sand.

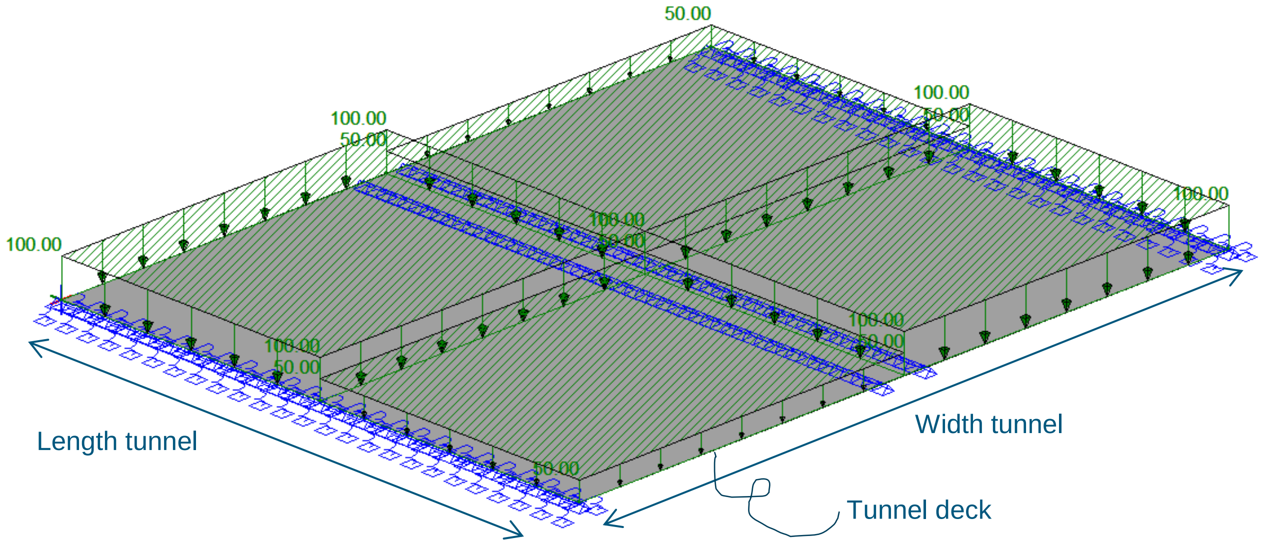

Figure 181 – Application of varying bedding stiffness

From this load configuration the bending moments are evaluated. That's also done for the same plate loaded with an equal distributed load of $75kN/m^2$ over the full deck. When taking the results from the latter case to be 100%, an increase in bending moments of about 30% is obtained. That's quite a lot.

This side effect needs a 3D analysis for evaluation of the forces. This research focuses on a 2D analysis for the cross section and the longitudinal direction. It is therefore concluded that this side effects falls beyond the scope of the research. But it is important to be aware of this effect.

A2.1.5.3 Stiffness tunnel

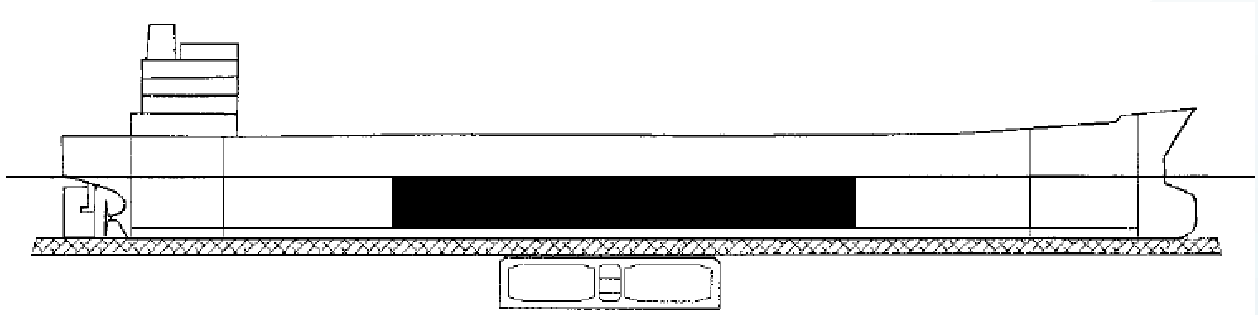

Figure 182 - Ship stranding in transverse direction on tunnel, tunnel under riverbed

For the situation in Figure 182 a ship is positioned in transverse direction on the tunnel. For this case the tunnel lies under the river bed. The ship will be supported partly by the tunnel and partly by the riverbed. But the tunnel behaves more stiff compared to the surrounding soil. Therefore the part of the load taken by the tunnel will be more than assuming the load to be equally spread over the full bottom area of the ship.

To take this additional stiffness into account, the stiffness of the tunnel is dived into two parts. One is the stiffness of the gravel[76] layer on the tunnel, the second one is the stiffness of the tunnel itself (Figure 183).

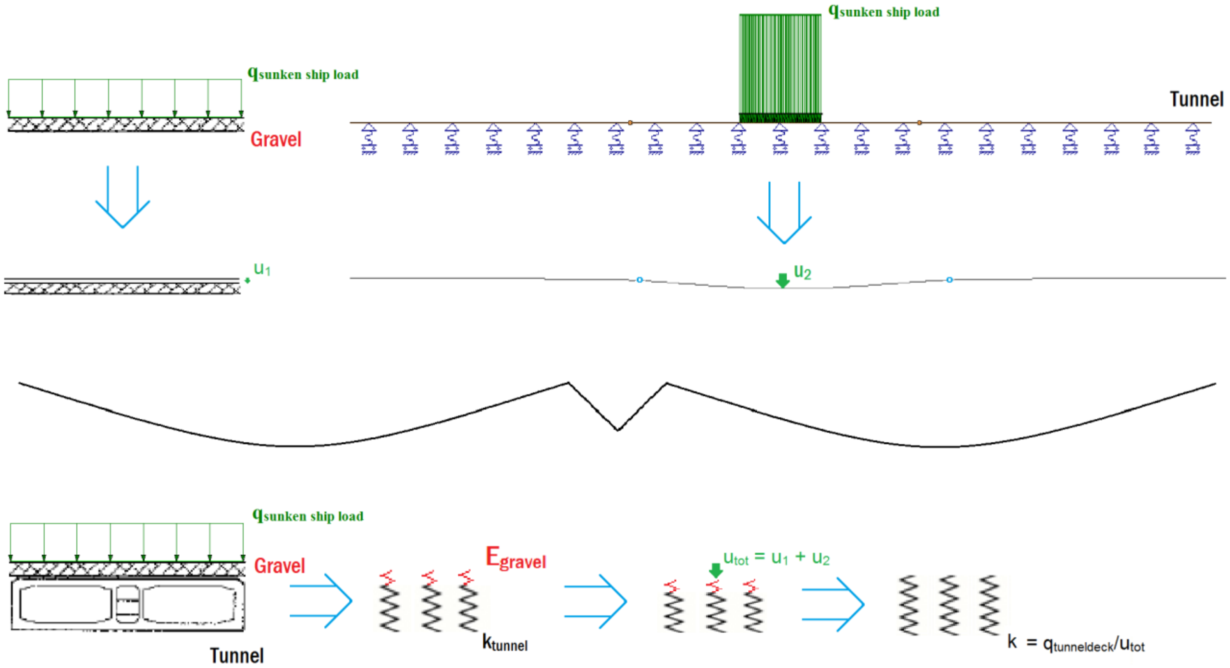

Figure 183 – Determining equivalent bedding stiffness

This equivalent bedding stiffness (k) is determined in Table 57. In this table represents $q_{\text{sunken ship load}}$ the load from a sunken ship, when equally spread over the bottom.

The stiffness of the gravel layer is taken into account with its E-modulus. Soil has a certain E-modulus which can be used for a one dimensional situation. This E-modulus can be determined in a triaxial test, or indirectly from an oedometer test. This E-modulus can be seen as a spring stiffness of the gravel. The used value is a rough estimation, for each case the corresponding value should be used.

The value u_2 follows from a tunnel which consists out of 3 elements of 100m and 30m width[77]. For the E-modulus of the tunnel a value of 36000N/mm^2 is used, and a moment of inertia of 1.05*10^{12} mm^4. The tunnel is resting on a soil with a bedding stiffness of 2000kN/m^3. The length of the load follows from the width of the ship, which is here equal to 28m.

Table 57 - Determining equivalent stiffness tunnel

Parameter	Amount	Unit	Formula	Description
$q_{\text{sunken ship load}}$	100	kN/m^2		Ground pressure
E_{gravel}	100,000	kN/m^2		E-modulus gravel layer
ε_{gravel}	1.00E-03	-	q/E	Strain gravel layer
D_{gravel}	1	m		Thickness gravel layer
u_1	1.00E-03	m	$\varepsilon_{gravel} D_{gravel}$	Displacement gravel layer

[76] It is better to speak about protection layer, because the protection layer consists not always out of gravel. But for now it is assumed that the protection layer consists out of gravel.
[77] The tunnel as shown in Figure 183 is a monolithic tunnel, but can also be a segmented tunnel.

Monolithic				
u_2	0.033	m	Follows from MatrixFrame	Displacement tunnel
u_{tot}	0.034	m	u_1+u_2	Total displacement tunnel
k	2920	kN/m^3	$q_{sunken\ ship\ load}/u_{tot}$	Equivalent bedding stiffness
Segmented				
u_2	0.041	m	Follows from MatrixFrame	Displacement tunnel
u_{tot}	0.042	m	u_1+u_2	Total displacement tunnel
k	2360	kN/m^3	$q_{sunken\ ship\ load}/u_{tot}$	Equivalent bedding stiffness

This equivalent spring stiffness is used to determine the increase in load at the positon of the tunnel. A schematisation is given in Figure 184. The ship which is evaluated now, is equal to the one as used in Chapter 5 in general to evaluate the sunken ship loads. For details see §5.4 *Loads on tunnel*, p.30. For the moment of inertia of the ship a value of

$$I = \frac{M\,z}{\sigma} = 96m^4$$

is taken. With *M* the bending moment capacity of the ship, *z* the distance from the neutral axis to the outer fibre and σ the yield strength of the ship[78]. The E-modulus is taken from steel: 210.000N/mm^2.

The loads which are acting on the ship correspond to a water depth of 7m.

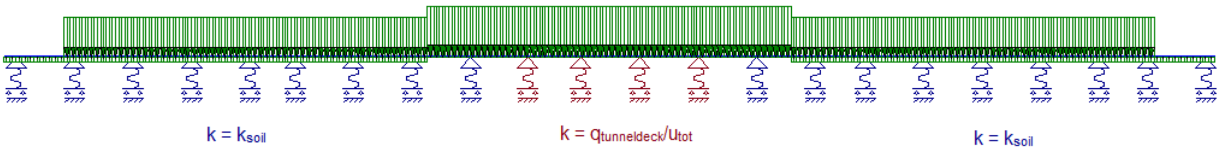

Figure 184 - Schematisation ship transverse on tunnel

This model gives an average displacement of 0.034m of the monolithic tunnel and 0.038m for the segmented tunnel. With the aid of the bedding stiffness the load on the tunnel can be calculated. This is done in Table 58.

Table 58 - Determining increase in load

Parameter	**Amount**	**Unit**	**Formula**	**Description**
Monolithic				
u	0.034	m		Average displacement of springs (which represent the tunnel)
k	2920	kN/m^3		Modified bedding stiffness
F_{new}	100	kN/m^2	ku	Load with modified bedding stiffness
F_{old}	55	kN/m^2		Load if equally spread
F_{new}/F_{old}	1.82	-	F_{new}/F_{old}	Increase in load
Segmented				

[78] *Taken as 240N/mm^2.*

u	0.038	m		Average displacement of springs (which represent the tunnel)
k	2360	kN/m^3		Modified bedding stiffness
F_{new}	89	kN/m^2	ku	Load with modified bedding stiffness
F_{old}	55	kN/m^2		Load if equally spread
F_{new}/F_{old}	1.62	-	F_{new}/F_{old}	Increase in load

From the table it can be seen that the increase in load due to this side effect is about 80% for a monolithic tunnel and about 60% for a segmented tunnel. This is a substantial value. Therefore it is concluded that it is important to take this increase in load into account when determining representative sunken ship loads.

Keep in mind that this increase in load due to this side effect only holds for horizontal sinking. In case of sinking under an angle, this side effect needs not to be taken into account.

A2.1.6 Conclusion

The models which are developed for the most important load scenarios compare quite well with the results as given by Gent University. The main difference is found for the bottom pressure in case of sinking under an angle.

For horizontal sinking, it depends much if the tunnel lies under or above the river bed. If the tunnel lies above the river bed, the loads are substantial higher. The governing failure mechanism is then failure of the bending moment capacity. But the situation of a tunnel above the river bed is seldom.

The situation of sinking under an angle leads to high forces. The forces are most of the time higher compared to horizontal sinking. For sinking under an angle, shear failure of the hull is most of the time the governing failure mechanism.

The side effects which are treated are all of different importance. Impact loading plays most of the time no significant role and is also a very difficult subject. This side effect is therefore not taken into account. The increase in load due to the irregularities in the river bottom depends on the soil characteristics. This side effect needs a 3D analysis of the tunnel, which falls beyond the scope of the research. Therefore also this side effect is not taken into account. The increase in load due to the higher stiffness of the tunnel compared to the surrounding soil, depends on the characteristics of the tunnel and the protection layer. This side effect needs only to be taken into account for horizontal sinking and not for sinking under an angle.

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A2.2 Out of plane compression strength of ship

An uncertain factor is the out of plane compression strength of the ship. Because it is possible in certain situations that neither the bending moment capacity nor the shear capacity is exceeded, but that the out of plane compression strength is exceeded. It is therefore important to be able to say something about that strength.

A minimum value for the compressive strength is constituted by the load which the hull must be able to resist from water pressure (David Prentice, Appendix A2.5). Suppose a draught of 20m (which is well possible for a big iron ore bulk carrier), the water pressure is then 200kN/m^2. Over this value a safety margin is present (magnitude unknown).

At the same time the ship must be able to resist the maximum bending moment. This induces additional longitudinal forces in the hull structure. So in case there is no bending moment, the out of plane compression force of the hull is higher.

The bow of the ship is strengthened for slamming induced loads. Prof. dr. ir. Marc Vantorre presents in the report of Gent University some general rules to compute the additional amount of strengthening. This strengthening is expressed in an additional water column. The results (for the 200m ship) are presented in Table 59.

Table 59 - Strengthening bow of ship

Parameter	Amount	Unit	Formula	Description
T_{FB}	3.00	m	$(\Delta\text{-DWT})/(C_B BL)$, $0.01L < T_{FB} < 0.045L \longrightarrow 2 < T_{FB} < 9 \longrightarrow$ OK	Minimum draught
F	1.42	-	$5.95\text{-}10.5(T_{FB}/L)^{0.2}$	Definition
h_{max}	166	m	$130F\text{*}\exp(-0.0125(L\text{-}180)^{0.705})$, for L > 180m	Maximum additional water column
$h_{s,\,1}$	83	m	$0.5h_{max}$, for $0.95L < x < 1.0L$, $C_B > 0.8$	Additional water column
$h_{s,\,2}$	166	m	h_{max} for $0.875L < x < 0.95L$, $C_B > 0.8$	Additional water column
$p_{\ hs,1}$	831	kN/m^2	$10h_{s,\,1}$	Additional water column pressure
$p_{\ hs,2}$	1,662	kN/m^2	$10h_{s,\,2}$	Additional water column pressure

The minimum draught of the ship T_{FB} is calculated based on the weight of an empty ship. The value for T_{FB} should lie in a certain range. This check is carried out under the heading *formula* by T_{FB}. Also the strengthening varies over the length of the ship. Not everywhere the maximum additional water column (h_{max}) has to be taken into account. This is specified through making a distinction between $h_{s,1}$ and $h_{s,\,2}$. The first part (0.95L – 1.0L = 0 - 10m, measured from the bow of the ship) of the bow falls under the definition of $h_{s,\,1}$ and the second part (0.85L – 0.95L = 10 – 25m) under $h_{s,\,2}$. From the additional water columns the corresponding increase in stress is calculated (p).

So, based on the results as presented in Table 59 Gent University propose an increase in strength of more than 800kN/m^2 for the first part of the bow and even more than 1,500kN/m^2 for the second part. These are quite big loads and seams unrealistic.

By the American Bureau of Shipping a guide for slamming induced loads is given (American Bureau of Shipping, 2011 (updated 2013)). In this guide a maximum pressure of about 400kN/m^2 is presented (at page 23, figure 2 from that report). That seems more realistic. When adding this value to the static value of 200kN/m^2 a value of 600kN/m^2 is obtained.

The arguments used so far, approach this topic from the loading side. The other side is the strength side. The strength can only be calculated with the aid of the real configuration of the ship's hull structure or when testing it in experiments. J. Koning reports that from results from TNO experiments, the strength tend to be in the order of 1.5 – 2.0 MN/m^2 (J. Koning, Mei 1992).

Now some assumptions are made for the case of horizontal sinking and sinking under an angle. For the case of horizontal sinking, the ship's hull structure halfway the ship is of importance. Because that's the location where the load is acting on the ship. This part is the not strengthened part of the ship. This part is assumed to have therefore a strength of minimum 200, say 300kN/m^2. This based on the first reasoning from the water pressure which the ship must be able to resist.

For sinking under an angle, we're talking about the bow of the ship, which is the strengthened part. For this part a strength of 600kN/m^2 is assumed. This is based on the values presented by guide of the American Bureau of Shipping. This was the lowest value presented here compared to the other values from literature. When looking not to Figure 172, it can be seen that such a value of 600kN/m2 is only exceeded for very low water depths. When looking now simultaneously to the U.C. for the shear capacity (Figure 175) it can be seen that the shear capacity is much more critical compared to the out of plane compression strength. It is therefore assumed that shear failure is governing over failure of the bottom of the ship for sinking under an angle.

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A2.3 Conversation with Ms. Stroo-Moredo

Ms. Elena Stroo-Moredo works for the Netherlands Maritime Technology institute. Previously she worked for the TUDelft, at the 3mE faculty. Her expertise lies in the field of marine salvage. That discipline deals with the salvage of ships.

Ms. Stroo-Moredo says that it is very difficult to keep the scope of the research very wide. She advises to focus on one situation. It is important to map the naval activities around the tunnel, to be able to say something about the load of a sunken ship on a tunnel.

In the ITA report, a value of 90% is assumed for the bulk of the total DWT. I asked whether that is a representative value. She says: that's not possible to say. Each ship is different. When calculating the loads of a ship, most of the time difference is made between the bulk, the light weight / supplies and the fuels.

Container ships are most of the time not fully loaded. Only up to 70%. And whether this induces a high load when sinking, depends a lot on the density of the products in the containers. There is a maximum to the amount which can be carried in containers. Important for container ships are the tidal fluctuations. Containers will be slowly filled with water after sinking of the ship. But when the tide drops, the containers will not be emptied as fast as the tide drops.

Impact loading is a very difficult object. Even experts (as she is) don't know the magnitude of impact loads. '*Everybody will be very glad if you can explain how big such loads are*' she says.

After a ship fails, directly the emergency response is activated. That means that if a ship fails above a tunnel, a tugboat will be called to pull the ship away from the dangerous place. Tugboats will almost always be present, because immersed tunnels are in civilized areas. From this perspective it can be said that if a ship sinks on a tunnel, it sinks in a short period of time.

With respect to ships, there are many, many types. Each with its own characteristics. Companies which are specialized in salvage of ships need even months before they can start with their work. They had to do a lot of engineering work, before they can start with salvage of the ship. And that are really experts. And in emergency cases, the company aims at helping the majority (≈70%) of the cases. The message what she will give with this, is that there is a lot of uncertainty, and a lot of assumptions have to be made. For the study, the iron ore tanker is the most important ship. This gives some handhold.

If one ship hits another ship amidships, and the struck ship get leak, it will be filled with water transversely, due to the compartmentation of the ship. This is the case if it works as it should work. Because in the walls which divide the ship in compartments, certain shutters are present. These shutters should be always closed, but often it happens that there are some shutters open. This causes flooding of the ship in both transverse as well as in longitudinal direction. Due to this phenomenon there are a lot of ships sunken, which was not necessary.

In every ship are water tanks. Those tanks are needed for the stability of the ship. In certain ships this water tanks are situated at the side of the ship. If in case of a collision only the water tank is damaged, the ship will not sink.

There are two and three compartment ships, which not mean that they consist out of only two or three compartments, but that two or three compartments can be filled with water without sinking of the ship. The ship should be able to reach a harbour with this damage.

The hull of the ship is stronger at its bottom than at the side. The bottom of a ship is often double layered (two plates with stiffeners in between, with a total height of about 20cm), while the side has only one plate with stiffeners. The thickness of the steel plate is not constant over the height of the ship. The thickness decreases from bottom to top. Also the strength of the bottom is not equal over the length. There are some 'hard points' were the ship can be docked in a yard. But the supports cannot be placed at every position. Especially the bottom amidships forms the weakest part. Also with respect to dimensions: if a ship sinks with his middle on a tunnel, and the tunnel is only 30m wide, while the ship is almost 300m long, it can be seen more or less as point load acting on the ship. In her opinion the tunnel will penetrate through the ship. The ship will not be able to withstand such a force.

Although not very important for the research, but ships which are empty have their centre of gravity more towards the engine room. In normal cases is attempted to keep the ship horizontal. But, as said, in case of an empty ship, there may be deviated from this principle.

Important to notice is that there are always venting holes in a ship. These are holes through which the water which the ship enters runs away. These holes are always present in the free board of the ship. The free board of the ship is the height minus its maximal draught. The deck of the ship lies a certain distance under the top of the ship, but higher than the maximal draught of the ship. The venting holes will lie always above the deck, but it is not possible to say how much. That differs per ship. Important to notice is that it is therefore not possible that the buoyancy of the ship increases until the top of the ship.

In case of a ship loaded with iron ore, be aware that if the iron ore gets wet, the behaviour of the iron ore becomes different. It is no longer dry bulk which stays in place, but it will become more or less a muddy substance, a sort of viscous mass. After the ship gets leak, the ship often comes to lie oblique in a certain amount. Due to this, the iron ore will not stay in place, but start to slide to the side. This aggravates the inclination of the ship, so the ship will therefore capsize more and more.

In the Report of Gent University (Gent University, 13 november 2003) is spoken about a strength of the ship of 240N/mm^2. I asked whether this is a usually steel strength for the ship. Nowadays, most of the time, High Tensile Steel (HTS) is used.

With respect to the ultimate hull girder strength, the requirements which a ship has to fulfil are prescribed by classification societies. One can think of Lloyd Register, Det Norske Veritas or American Bureau of Shipping. These requirements have to be fulfilled by shipbuilders.

With respect to the configuration of a ship, the bottom is most of the time flat. So for the width of the bottom the overall width of the ship can be taken, minus up to two meter. For the length to width (L/B) and draught to width ratio (D/B) there are standard rules.

The bow of the ship is a strong part (if undamaged!) of the ship. If the ship strands on his bow, the bow will exert initially a big force on the tunnel, but after that the bow will fail in a short period of time. So if a ship strands with its bow on the tunnel, it is not possible to say that the bow will carry the total load of the ship over time. At a small distance from the front of the ship, a collision bulkhead is present. Probably after this bulkhead the bulk can be stored in the ship.

A2.4 **How an iron ore tanker fails**

An iron ore tanker can get leak at its bottom or at the side. The cause from getting leak at the bottom is mainly through grounding. So in case of sinking, the ship gets mostly leak at the side. To be able to say something about the cause of getting leak at the side, it is important to know which types of accidents occur most frequently. In Figure 185 the causes of accidents for the Dutch waterways over a certain period are presented.

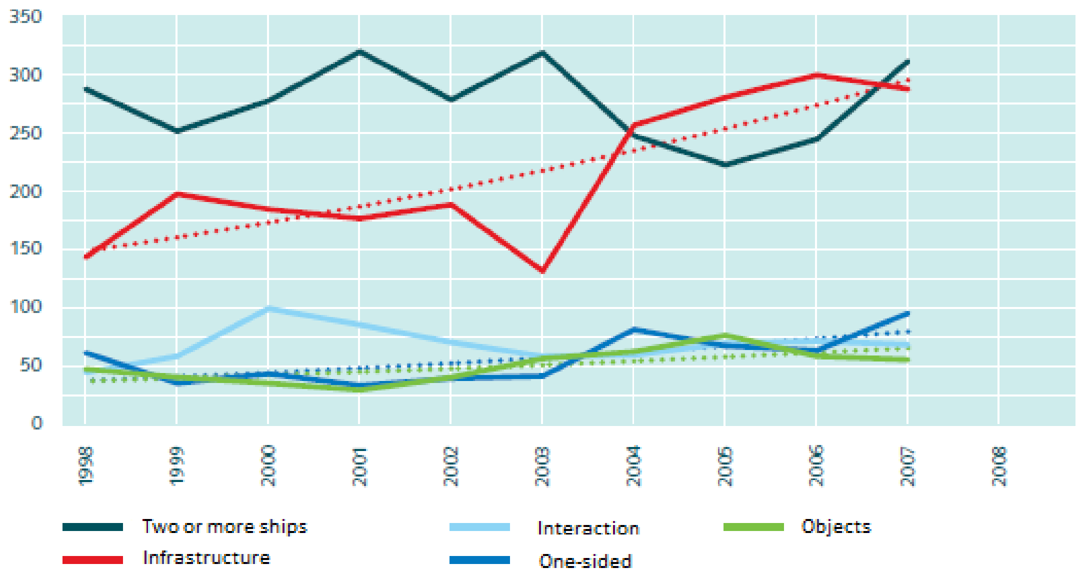

Figure 185 – The development in nature of shipping accidents on the Dutch waterways between 1998 and 2007. The statistically significant trend lines are shown as dotted lines (Inspectie Verkeer en Waterstaat, 2008).

From Figure 185 it can be seen that most of the accidents are from two colliding ships. Also a major part of the accidents is indicated as 'infrastructure'. This type of failure contains mostly grounding (Figure 186). From this perspective it can be assumed that most of the accidents with result in sinking of a ship are caused by colliding of ships.

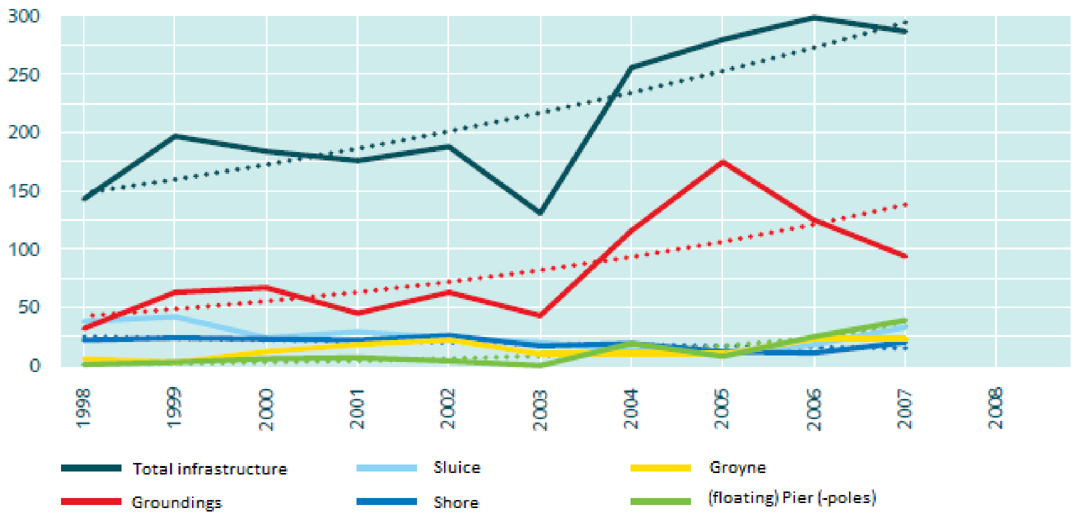

Figure 186 - The collisions with the infrastructure split up into several categories. The statistically significant trend lines are shown as dotted lines (Inspectie Verkeer en Waterstaat, 2008).

As said, if two ships collide, the hull of the ship is damaged at the side. To give insight in what happens with a struck ship from aside, a cross section of an iron ore bulk carrier is presented in Figure 187.

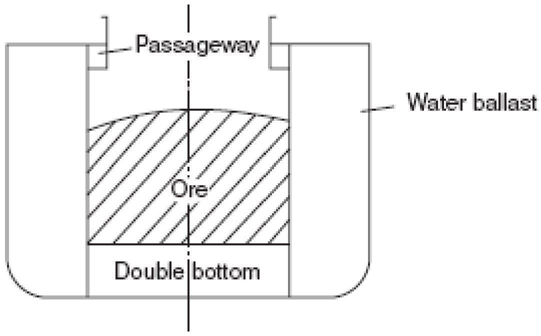

Figure 187 - Typical cross section of an iron ore bulk carrier (Ventura)

An iron ore bulk carrier has a double skin at the side. This in contrast to a cargo bulk carrier which has a single skin, see Figure 188. In this figure a general cross section of a cargo bulk carrier is given.

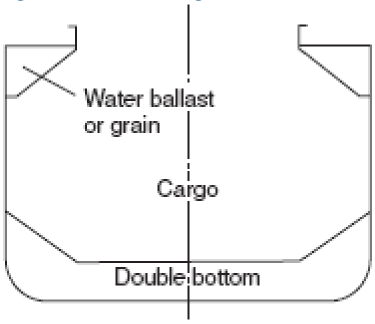

Figure 188 - Typical cross section of cargo bulk carrier (Ventura)

It is possible that a cargo ship carries iron ore. But heavy cargo (as iron ore) causes relatively large deformations and stresses in the side frame of the hull structure (Elsevier, 2001). Therefore most of the time iron ore is transported with an iron ore bulk carrier which has a stronger side hull structure.

If a ship has a double side skin, the chance that the ship gets leak is smaller than for a single side skin. Because if the outer skin of the double side skin fails, only the water ballast tank is filled with water (if the tank was empty) and causes not sinking of the ship. If the single side skin of the cargo bulk carrier fails, directly the total compartment is filled with water. From this it can be concluded that an iron ore bulk carrier is safer than a cargo bulk carrier.

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A2.5 **E-mail from Lloyd's Register's employee**

1. Thanks for your interest. Andy passed your enquiry to us in the Lloyd's Register Ship Emergency Response Service. We handle ship casualties, including groundings so can make some comment based on that. Then perhaps I can offer the following thoughts.

2. The grounding reaction force acting on an intact floating ship is according to the change in floating position. So, if a vessel is aground at a point (e.g. your immersed tunnel) then the force will reduce the mean draught and change trim and heel. This is how we calculate the grounding force by considering the change in draughts. (If there is flooding then this has to be taken into account). If the ship has sunk then weight will be that in air less weight of water displaced. These forces will depend on the size of vessel, depth of water/tide and bottom/grounding configuration (single/two-point or shelf etc.) It is difficult to generalise.

3. Sometimes the limiting factor is hull girder strength, e.g. if a grounded vessel breaks her back. Are you trying to relate the reaction forces to the ultimate strength. There are some published data, including on the internet, on hull girder ultimate strength that perhaps you may use to make simple approximations.

4. As far as localised crushing strength is concerned, then there are models such as those of Kinkaid and Minorsky that I remember from the past, but probably many since, that are used in collision modelling. Perhaps they may be adapted for localised collapse if sitting on your tunnel structures.

5. Finally an observation that the vessel hull is designed to resist certain pressure loads. Consider the bottom. A water ballast tank will be designed to be filled to the air pipe vents that are usually just above the deck – in a worst case the vessel is at light draught so there would be no external pressure. Externally, wave action will present a similar loading and internally there could be no pressure. In other words the net design head of the bottom of a ship is roughly the depth (keel to deck) of water. Suppose depth is 10m then this is 0.1MN. Then there will be a margin on normal design loads. And in addition, the ship bottom is designed to carry the hull girder (longitudinal) loads. This compares with your 0.5 to 2 MN. You might also wish to consider hard points – when a vessel is docked then the supporting blocks are placed under the longitudinal and transverse bulkheads.

6. I hope that offers some ideas.

Best Regards,

David

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A2.6 **Punching bow through tunnel deck**

If a ship sinks on the tunnel with its bow, the bow can plastically deform, or the bow of the ship can punch through the tunnel deck (Figure 189). Therefore a check is carried out to see which of the failure mechanisms will occur.

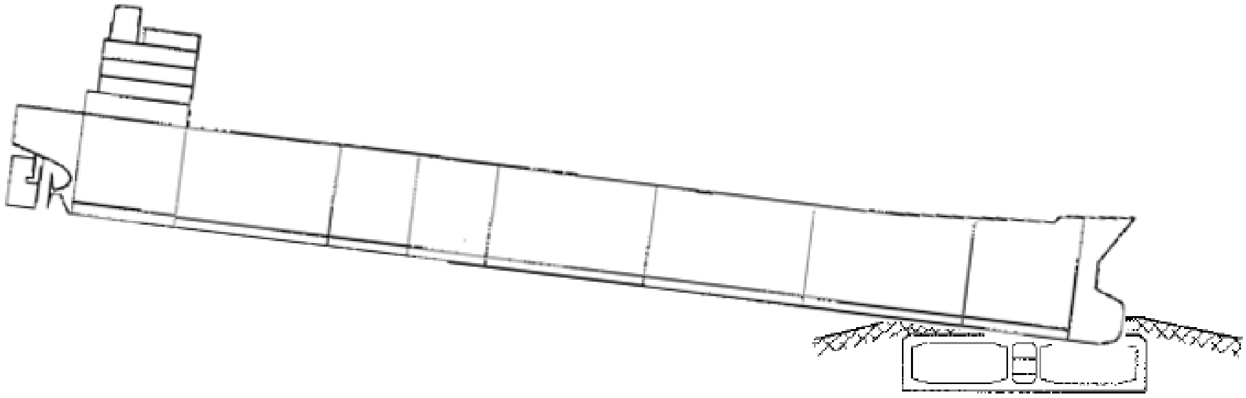

Figure 189 - Punching through tunnel deck

For the calculation of the punching shear resistance, the reinforcement and normal forces needs to be known. That information is known from the Wijkertunnel, which is worked out later on (Chapter 7). Therefore that tunnel is used for the required information.

To calculate the punching shear resistance, its makes difference whether there is shear reinforcement present or not[79]. Halfway the tunneldeck from the Wijkertunnel, no shear reinforcement is present. Therefore the resistance is calculated both for the part of the tunnel with and without shear reinforcement.

For the calculation, a few assumptions are made. One of them is that the bow of the ship is of the bulbous bow type (Figure 190).

Figure 190 - Bulbous bow[80]

A next assumption is made with respect to the dimensions of such a bulbous bulb (Figure 191). In this figure also an indication of the failure behaviour and spreading of the load is given. The load area is assumed to be of a circular shape.

[79] *Normally the term punching shear reinforcement is used, but for this calculation the shear reinforcement is used as punching shear reinforcement.*
[80] *Picture taken from https://www.flickr.com/photos/cuxclipper1/4718464908*

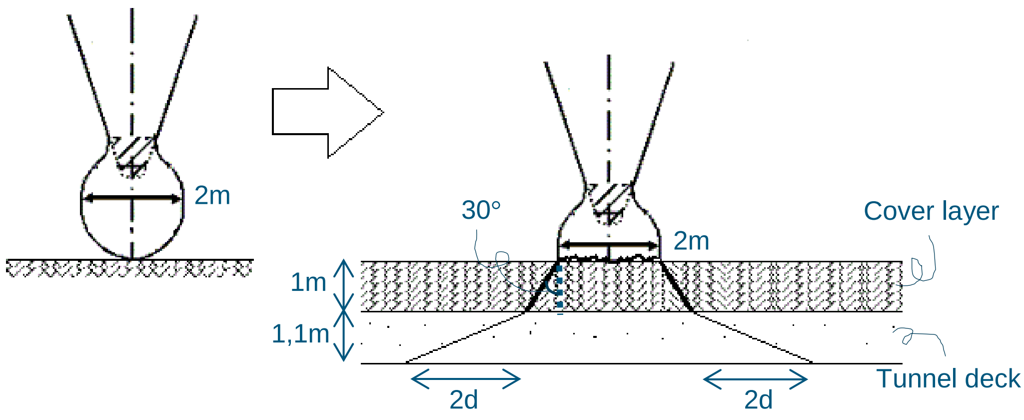

Figure 191 – Left: dimensions bow, Right: failure of bow & assumed spreading of the load

The calculation for the punching shear resistance (without reinforcement) is shown in Table 60. This calculation is based on nen-en1992-1-1+c2=2011, §6.4.4.

Table 60 - Punching shear resistance without reinforcement

Parameter	Amount	Unit	Formula	Description
γ_c	1.2	-		Material factor
$C_{Rd,c}$	0.15	-	$0.18/\gamma_c$	Factor
ρ_{ly}	0.01	-		Transverse reinforcement ratio
ρ_{lx}	0.002	-		Longitudinal reinforcement ratio
ρ_l	0.003	-	$(\rho_{ly}\rho_{lx})^{1/2}$	Reinforcement ratio
f_{ck}	28	N/mm^2		Characteristic strength concrete
k_1	0.10	-	= 0.1 for compression	Factor
σ_{cy}	1.00	N/mm^2		In transverse direction
σ_{cz}	0.12	N/mm^2		In longitudinal direction
σ_{cp}	0.56	N/mm^2	$(\sigma_{cy}+\sigma_{cz})/2$	Resulting normal stress
d	1,000	mm		Effective depth deck
k	1.45	-	$1+(200/d)^{0.5}$	Factor
$\nu_{Rd,c}$	0.50	N/mm^2	$C_{Rd,c}k(100\rho_l f_{ck})^{1/3}+k_1\sigma_{cp}$	Punch resitance (without shear reinforcement)
check	0.38	N/mm^2	$0.035k^{2/3}f_{ck}^{1/2}+k_1\sigma_{cp}$	$\nu_{Rd,c} \geq$ check
r	1,000	mm		Radius
d_{cover}	1,000	mm	Assumption	Thickness of cover on tunnel
u	22,477	mm	$2\pi(r+d_{cover}\tan30°+2d)$	Perimeter
V_{Rd}	11,178	kN	$\nu_{Rd,c}ud$	Total punch resitance (without shear reinforcement)
A	3,141,600	mm^2	πr^2	Loaded area
σ	3,600	kN/m^2	V_{Rd}/A	Stress between bulb and cover layer

From this calculation it follows that at the moment of failure of the tunnel deck a stress of 3.6MN/m^2 is present against the steel bulbous bulb. This is however in the situation that the bulb is deformed. That means that the bulb does no longer have its original strength.

In the previous paragraph was stated that the out of plane compression strength can be up to 2MN/m^2. The bow of the ship is a more strengthened part of the ship. Therefore its original strength is assumed to be twice as high: 4MN/m^2. When now assuming that the deformations of the prow reduce the strength again with a factor two, the strength becomes 2MN/m^2.

When comparing this strength with the calculated load of 3.6MN/m^2 it is concluded that the bow of the ship highest probably does not punch through the deck. A more detailed analysis should found out whether this conclusion is correct or not.

The calculation of the punching shear resistance with shear reinforcement is based on nen-en1992-1-1+c2=2011nl, §6.4.5. For the results see Table 61.

Table 61 - Punching shear resistance with reinforcement

Parameter	Amount	Unit	Formula	Description
s_r	450	mm	Assumption	Radial spacing of punch reinforcement
s_t	500	mm	Assumption	Tangential spacing of punt reinforcement
Ø	16	mm	Taken equal as shear reinforcement	Bar diameter punching shear reinforcement
A_{sw}	9039	mm^2	$\pi Ø^2 u/s_t$	Total amount of punching shear reinforment available over perimeter
$f_{ywde,ef}$	500	N/mm^2	$250+0.25d \leq f_{ywd}$	Effective design value of the yield strength of the punching shear reinforcement
α	1.57	rad		Angle between punching reinforcement and the plane of the plate
$v_{Rd,c}$	1.04	N/mm^2	$0.75v_{Rd,c}+1.5(d/s_r)A_{sw}kf_{ywd,ef}(1/(u_1d))\sin\alpha$	Punching shear resistance (with shear reinforcement)
$V_{Rd, cs}$	23,447	kN	$v_{Rd,c}ud$	Total punching shear resistance (with shear reinforcement)
σ	7,500	kN/m^2	$V_{Rd, cs}/A$	Stress between bulb and cover layer

From this table it can be seen that the stress (7.5MN/m^2) is now far more compared to the previous situation. So for this situation, the situation with (punching) shear reinforcement, it is assumed that the bow of the ship will fail.

This analysis is based on a bow from a very large ship. Smaller ships give even higher stresses between bulb and cover layer (and hence earlier failure of the bow). So, with increasing ship size, the chance of punching shear failure increases. From the analysis above it can be concluded that highest probably also for a large ship the bow of the ship will fail instead of punching through the deck. This leads to the conclusion that failure of the bow most likely will be the governing failure mechanism.

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Appendix 3

A3 Structural behaviour

This appendix contains information concerning Chapter 6 *Structural behaviour*. It shows several calculations which are used for additional support. The conclusions based on these calculations are put in the main text. In the main text references are made to the parts of this appendix.

A3.1 Script for determining crack width

A3.1.1 Introduction

For evaluation the deck of an immersed tunnel is used. A typical thickness of the deck of an immersed tunnel is 1m. For the calculations of the crack width, use is made from the book C*oncrete Structures under Imposed Thermal and Shrinkage Deformations* (Braam, Breugel, Veen, & Walraven, 2013). The here presented values are for the tunnel subjected to permanent loads, with a water column of 30m on top of the deck of the tunnel (see Figure 46 and Figure 49). The reinforcement is determined in such a way that the water tightness criterion is fulfilled (assumed that it is 0.2mm).

First the cracking moment is determined. If the actual bending moment is exceeding this cracking moment, the concrete structure goes from the not fully to the fully developed crack pattern.

A3.1.2 Calculations

The cracking moment is calculated in Table 62. This cracking moment determines the minimum amount of reinforcement.

Table 62 – Cracking moment (M_{cr})

Parameter	Amount	Unit	Formula	Description
f_{yk}	40	N/mm^2	C40/50 is used	Characteristic cilinder compressive strength
f_{ctm}	3.5	N/mm^2	For C40/50	Tensile strength
f_{cflm}	3.5	N/mm^2	$=f_{ctm}$, for h > 600	Mean flexural tensile strength
f_{ck}	50	N/mm^2		Characteristic cube compressive strength
f_{ccm}	58	N/mm^2	f_{ck}+8	Mean concrete cube compressive strength
f_{cd}	26.7	N/mm^2	f_{ck}/1.5	Design strength concrete
b	1000	mm		Width of element
h	1000	mm		Height of element
d	900	mm	0.9h	Effective depth
z	810	mm	0.9d	Internal lever arm
W	1.67E+08	mm^3	1/6bh^2	Moment of resistance
M_{cr}	58	kNm	Wf_{cflm}	Cracking moment

For calculation of the crack width, it should be checked whether the beam is in the fully or not fully developed crack pattern (Figure 192). The stage of the not fully developed crack pattern is indicated with

Roman number 2 (II), and the stage of the fully developed crack pattern is indicated with the Roman number 3 (III).

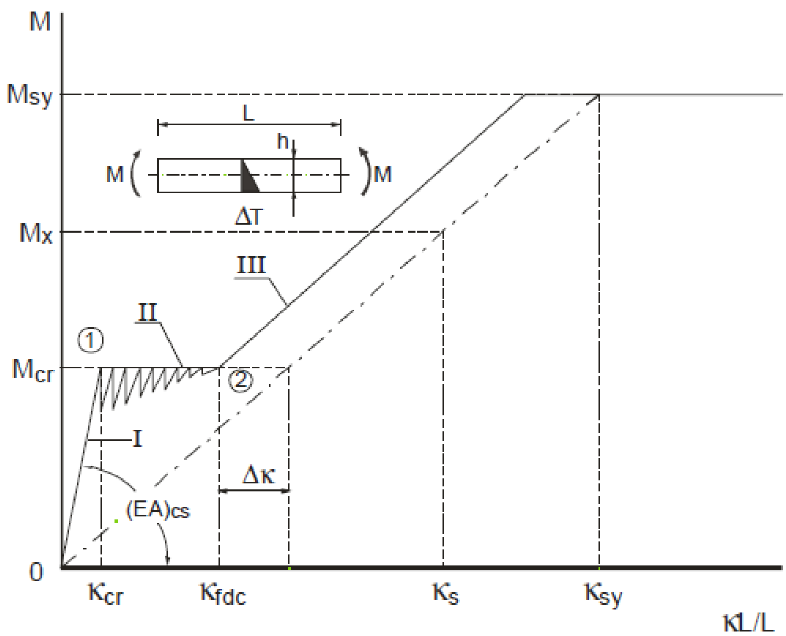

Figure 192 - Moment-curvature diagram of a reinforced concrete beam (Braam, Breugel, Veen, & Walraven, 2013)

The crack width for the not fully developed crack pattern is calculated in Table 63.

Table 63 – Crack width not fully developed crack pattern (w_{m0})

Parameter	Amount	Unit	Formula	Description
σ_{cr}	2.1	N/mm^2	$0.6f_{ctm}$	For slow loading
E_s	210,000	N/mm^2	Assumption	Modulus of elasticity of steel
E_s	30,000	N/mm^2	Assumption	Modulus of elasticity of concrete
α	7	-	E_s/E_c	Ratio E-modulus steel vs concrete
Ø	40	mm	Assumption	Bar diameter
s	99	mm	Assumption	Bar spacing
A_s	25,400	mm^2	$2*1/4\pi Ø^2 h/s$ (two rows of bars)	Area of steel
ω	2.9%		$A_s/(bd)$	Reinforcement ratio
f_{yk}	500	N/mm^2	B500	Characteristic steel strength
f_{yd}	435	N/mm^2	500/1.15	Design strength steel
x_u	560	mm	$A_s f_{yd}/(0.75bf_{cd})$	Concrete depth under compression
$\sigma_{s,cr}$	28	N/mm^2	$M_{cr}/(A_s z)$	Steel stress
w_{m0}	0.016	mm	$2\{0.4Ø/(f_{ccm}E_s)(\sigma_{s,cr}-\alpha\sigma_{cr})\}^{0.85}$	Mean crack with in a not fully developed crack pattern

The crack width for the fully developed crack pattern is calculated in Table 64.

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Table 64 - Crack width fully developed crack pattern (w_{mv})

Parameter	Amount	Unit	Formula	Description
M_{Ed}	4,400	kNm	MatrixFrame	Maximum moment from load
σ_s	210	N/mm^2	$M/(A_s z)$	Steel stress
Δl_m	214	mm	$1.8 w_{m0} E_s/\sigma_{s,cr}$	Mean crack distance
w_{mv}	0.200	mm	$\Delta l_m/E_s(\sigma_s-0.5\sigma_{s,cr})^{0.85}$	Mean crack with in a fully developed crack pattern

Based on the reinforcement needed to fulfil the water tightness criterion, the ratio between the amount needed for strength compared to the actual amount of reinforcement is calculated in Table 65.

Table 65 - Ratio between actual acting moment and ultimate strength

Parameter	Amount	Unit	Formula	Description
M_{Rd}	9120	kNm	$A_s f_{yd} z$	Moment resistance with respect to strength
M_{Ed}/M_{Rd}	0.48	-	M_{Ed}/M_{Rd}	Unity check

A3.1.3 Conclusion

The amount of reinforcement needed for water tightness can be substantially more than needed for strength. Depending on the depth of the tunnel, the capacity utilized for strength is only 50% or even less.

A3.2 Shear force in joints under a sunken ship load

A3.2.1 Introduction

In this part the shear forces in the joints are examined under different loading conditions. These shear forces in the joints are determined by making several influence lines. When making this influence lines, certain parameters are variated to see the influence of those parameters on the forces in the joints. Parameters which are variated are the bedding stiffness, and the length of the load. Ultimately an indication of the capacity of a shear key is given, to see if the forces are larger than the strength.

A3.2.2 Loads in a joint

As said, for evaluation of the shear forces in the joints, use is made from influence lines. To make such influence lines, the load is moved over the tunnel in the way as shown in Figure 193 and Figure 194. The characteristics of those tunnels are the same as presented in the main text (see Table 21).

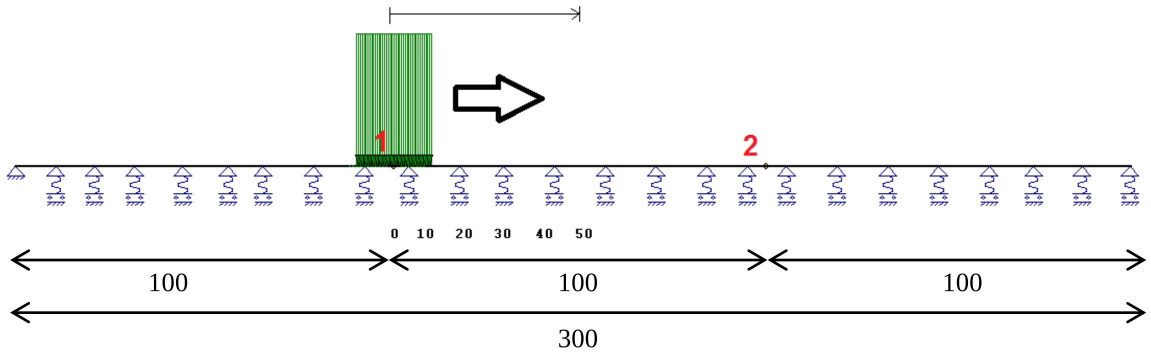

Figure 193 - Load moving over monolithic tunnel

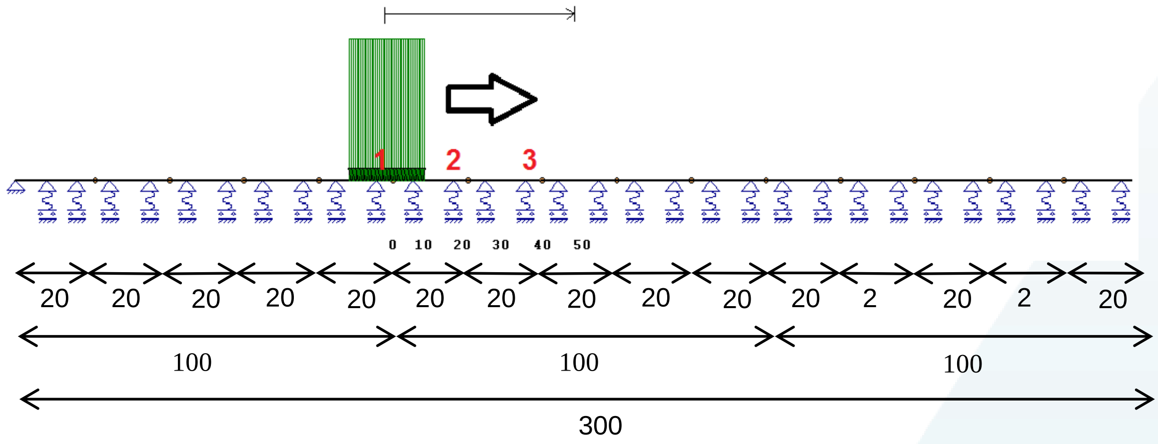

Figure 194 - Load moving over segmented tunnel

The values 0 – 50 in the figures above, indicate the position (in meters) on the middle element. This indicated range corresponds with the values on the x-as when presenting the influence lines. As already mentioned in the main text, only the behaviour of the middle elements is evaluated, because in this way the influence of the neighbouring elements on the structural behaviour is taken into account by the first and the third element. It is also the case that the results for position 50 till 100m on the middle element are the same as for 0 – 50, but then in a mirrored way. Therefore it is only relevant to evaluate the shear forces in the joint for the position 0 – 50.

There are different parameters which influence the magnitude of shear force in the joint. Parameters which have an influence are the characteristic length (1/λ) and the length of the load. These parameters are variated, to see the influence of those parameters.

As already mentioned in the main text, the characteristic length is a measure which says something about the stiffness of the tunnel relative to the soil. This relative stiffness determines the amount of spreading of a load.

To see this effect, the characteristic length is variated by varying the soil stiffness. The results for a tunnel on a soft soil (clay) are presented in Figure 195 and for a stiff soil (sand) in Figure 196. In these figures is the denotation 'longitudinal position' on the x-axis the position on the element as denoted in Figure 193 and Figure 194 meant. This position indicates that the resultant of the load (which is halfway the length of the load) is at that position.

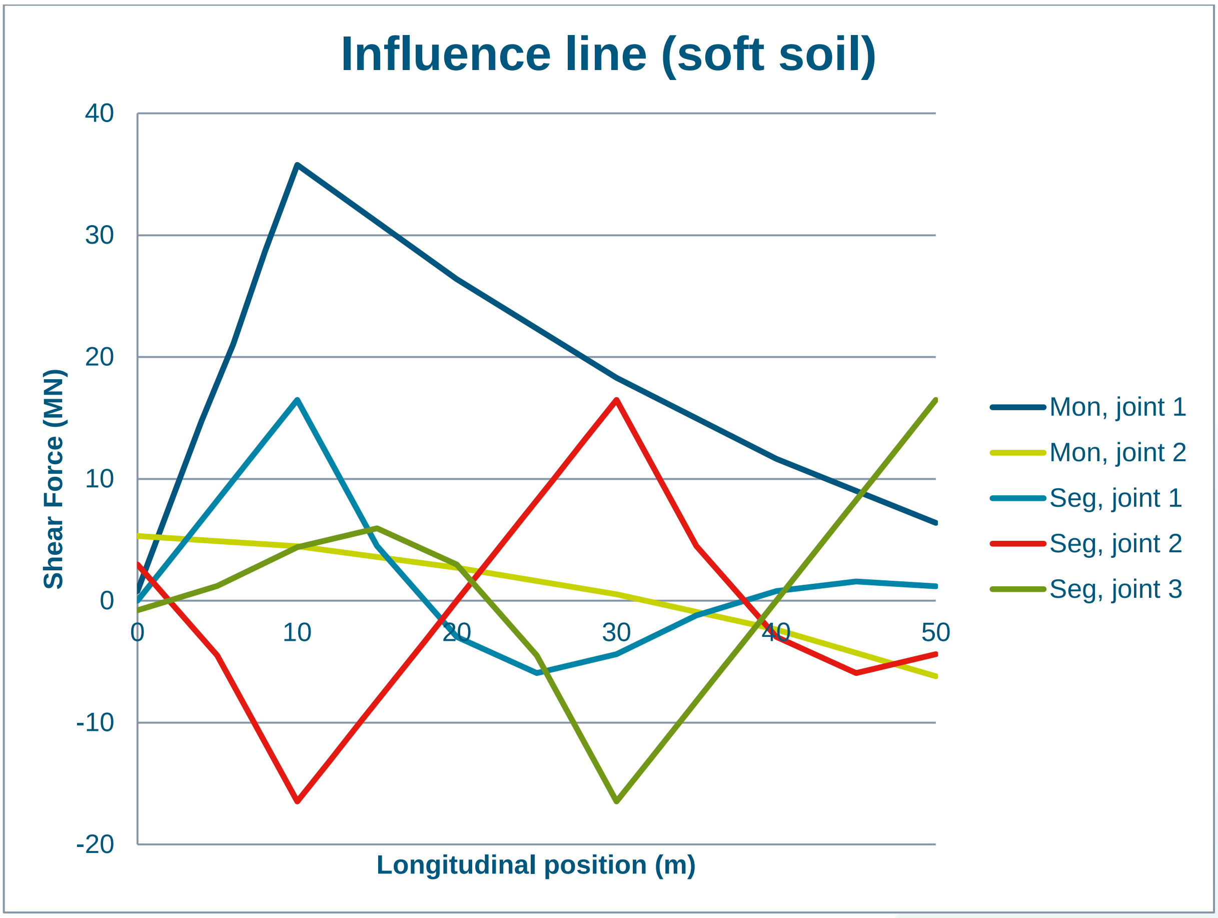

Figure 195 - Longitudinal behaviour tunnel on clay (k = 800kN/m^3) => 1/λ = 101m

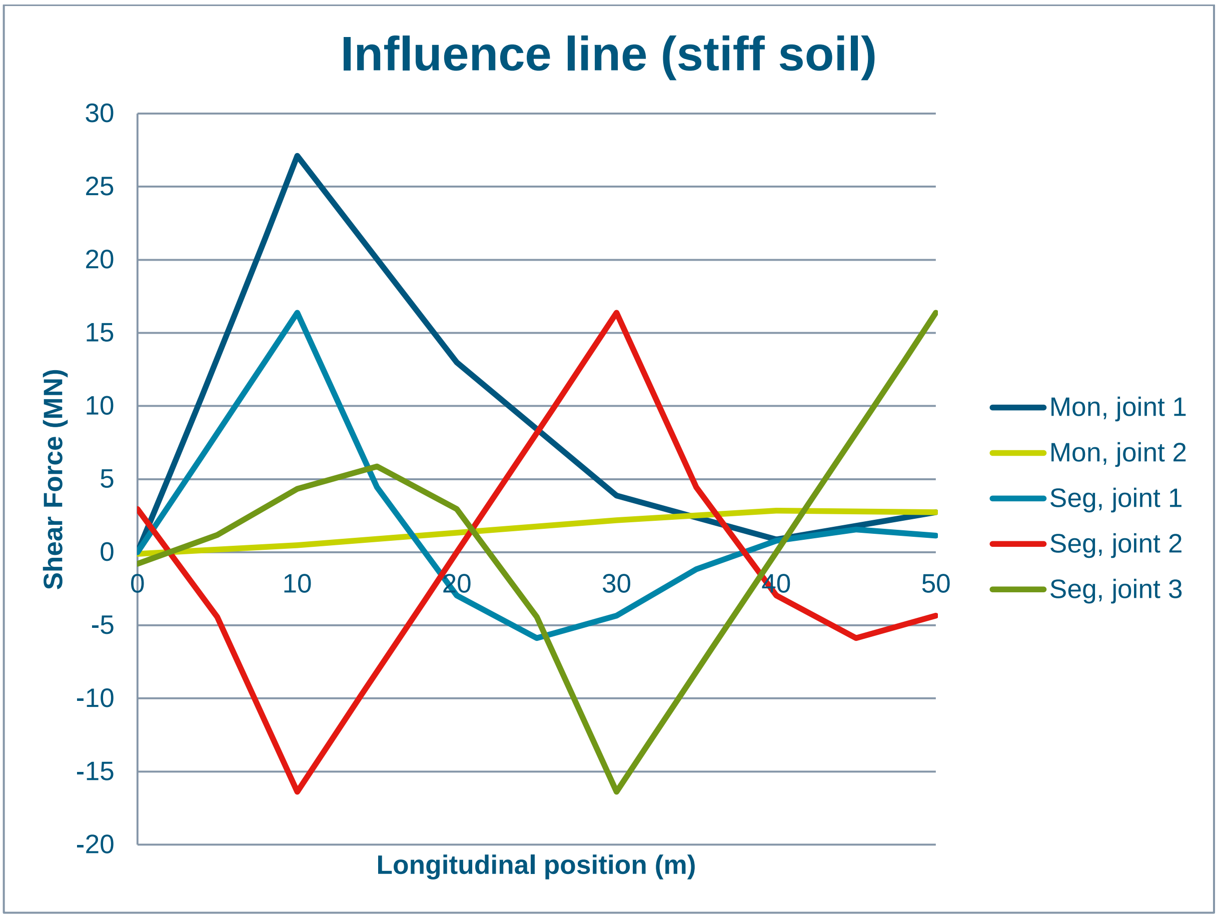

Figure 196 - Longitudinal behaviour tunnel on sand (k = 10,000kN/m^3) => 1/λ = 54m

When looking to the results, the first item what is notable is the difference in shear force between the monolithic and the segmented tunnel. The magnitude of shear forces for the monolithic tunnel is often higher than for the segmented tunnel. This holds especially for the tunnel on a weak soil.

It can also be seen that the graph for the segmented tunnel is repeating itself (in both figures) for the different joints. The influence line for joint 1 for example, starts again on 20m for joint 2. This is logical, because at x = 20, the load is then in the same position for joint 2 as in the situation at x = 0 for joint 1.

When comparing Figure 195 with Figure 196, it can be seen that a stiff bedding results in much less spreading of the load than for a monolithic tunnel. This is logical, because (as stated before) the spreading of the load is determined by the ratio between the soil and the tunnel stiffness. In this respective, a stiff soil underground gives a lower characteristic length (1/λ) and hence indicates less spreading of the load.

Striking is however that the differences in magnitude as well as the development of the influence lines for the segmented tunnel are negligible. This can be explained by looking to the classification of beams. This is measured by the factor λl (Simone, 2011). In this case, the elements can be classified as a short beam for both situations ($\lambda l < \pi/4$). This implies that the elements can be seen as a rigid body. And hence the differences in shear forces will be small.

The bedding stiffnesses used so far, are more or less upper and lower bound values[81]. A more common bedding stiffness for a typical Dutch soil is 2,000 kN/m^3. This value is used for further evaluation.

Up to now the length of load (l_{load}) is assumed to be 20m. This holds for many common ships, but a big iron ore bulk carrier can have a width of 40m. Therefore the response of the tunnel under such load is also examined. The results from a tunnel with a load length of 20m are given in Figure 197, and the results from a tunnel with a load length of 40m are presented in Figure 198.

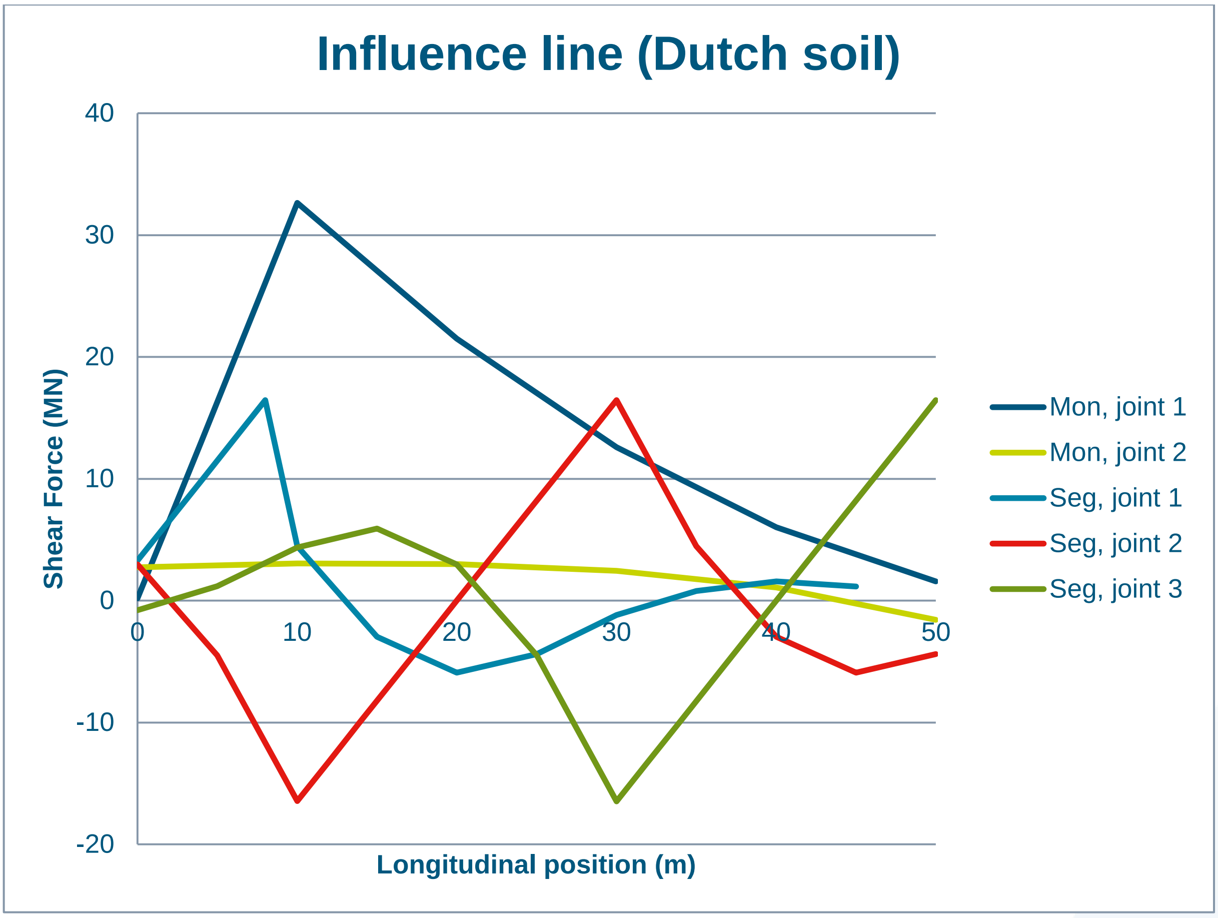

Figure 197 - Longitudinal behaviour tunnel on typical Dutch soil (k = 2,000kN/m^3) => 1/λ = 80m

[81] *In practice there are even higher values possible*

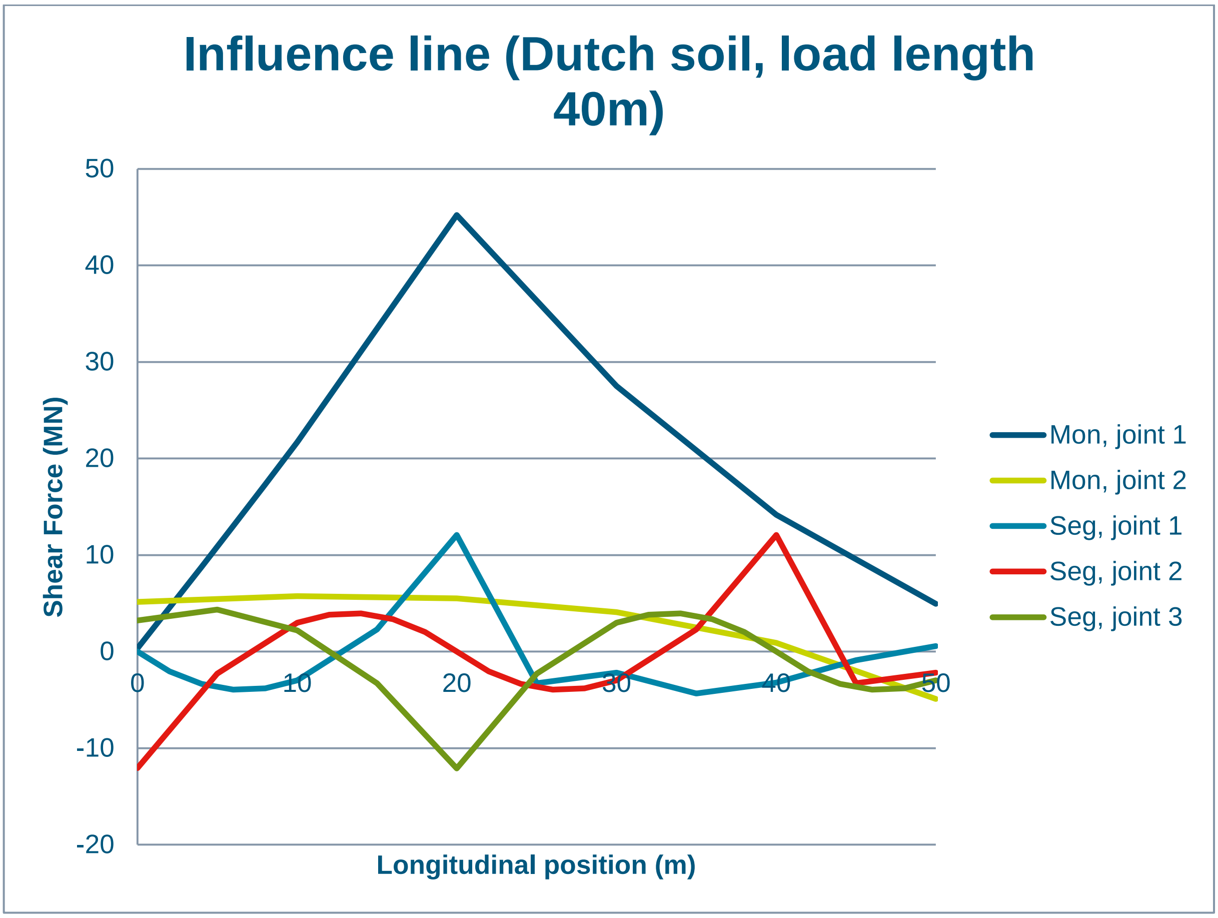

Figure 198 – Longitudinal behaviour tunnel on typical Dutch soil (k = 2,000kN/m³) => 1/λ = 80m, loaded length (L_{load}) is 40m

From Figure 198 it can be seen that the length of load has a major influence on the results. Whereas the results for the segmented tunnel remain almost the same (the forces decrease only a little bit) the results for the monolithic tunnel shows much difference. The monolithic tunnel gets much higher shear forces when changing the length of the load from 20 to 40m. In this situation, with a length of the load of 40m, a monolithic tunnel gives always a bigger shear force than a segmented tunnel.

A3.2.3 **Capacity of a joint**

To see whether the shear forces will be a problem in the joints, it is tried to say something about the shear capacity of a joint. The shear capacity of a joint is determined by the shear keys. There are different types of shear keys. Each of them has its advantages and disadvantages and has also an influence on the capacity. The shear key with probably the highest capacity possible is shown in Figure 199.

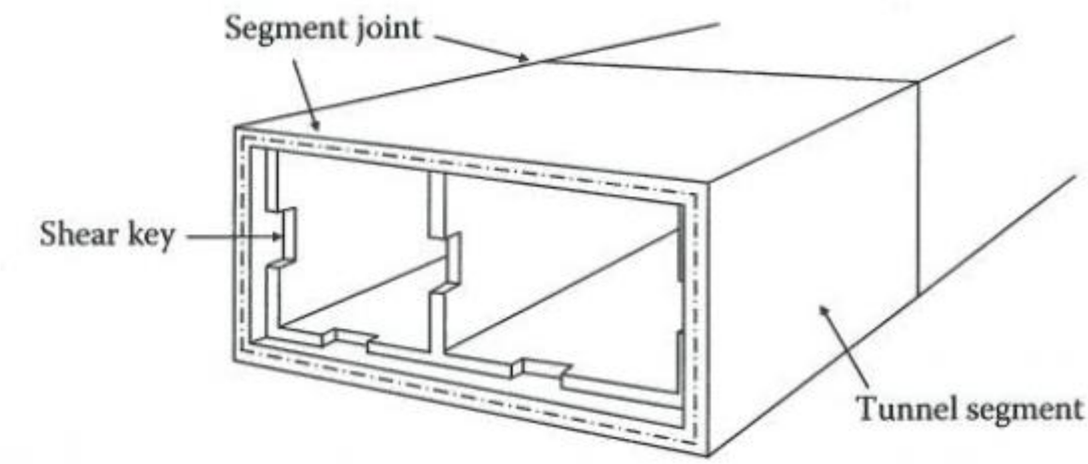

Figure 199 - Example of a shear key (Lunniss & Baber, 2013)

Each joint has more than one shear key. The total capacity of the joint is therefore determined by the sum of the capacities of all shear keys.

The capacity of a shear key is mainly determined by the amount of reinforcement. It is therefore difficult to say what a typical strength of a shear key is. A very dense reinforced shear key, with 5 x 4 Ø36, can have a capacity of 6.4MN (Bakker, 2013). When having three shear keys, the capacity of the joint becomes 19.2MN. The capacity of a more common reinforced shear key will be an order lower, say 3MN for example (and thus 9MN in total).

This shows that the capacity of the shear key can really become a problem in case of a ship sinking on a tunnel.

A3.2.4 **Conclusion**

The shear forces in a joint depend on different parameters. A monolithic tunnel gives most of the time a higher shear force in the joint compared to a segmented tunnel. This is in particular the case for a soft subsoil and a long length of the load.

A segmented tunnel shows very low differences in shear forces between different soil conditions. That's because of the short length of a segment in a segmented tunnel, which can be seen more or less as a rigid beam. The length of load leads to a (small) decrease in shear force for a segmented tunnel.

When comparing the shear forces which can occur in a joint with the capacity of the shear keys, it can be concluded that the strength of the shear keys really can be a problem.

A3.3 Cracking of concrete due to bending moments

To check whether a concrete element will crack under a sunken ship load, the cracking moment of a typical immersed tunnel is calculated in Table 66. For this calculation, the same characteristics for the tunnel are used as in the main text. They are also given again in the table below.

Table 66 - Cracking moment and ultimate moment

Parameter	Amount	Unit	Formula	Description
w	30	m	Assumption	Width tunnel
h	8	m	Assumption	Height tunnel
d	3	m	Assumption	Total width walls
I	580	m^4	Calculated by MatrixFrame	Moment of Inertia
E	36,000,000	kN/m^2	from C45/55	E-modulus
k	2,000	kN/m^3	Clay (CUR 166)	Bedding stiffness soil
$1/\lambda$	80	m	$1/((k/(4EI))^{0.25})$	Spreading length
h_{deck}	1	m	Assumption	Thickness of deck
h_{bottom}	1.5	m	Assumption	Thickness of bottom
W	184	m^3	$1/6(wh^2-(w-d)(h-h_{deck}-h_{bottom})^2)$	Moment of resistance
f_{yk}	40,000	kN/m^2	C45/55 is used	Characteristic cilinder compressive strength
f_{ctm}	3,800	kN/m^2	For C45/55	Tensile strength
f_{cflm}	3,800	kN/m^2	$=f_{ctm}$, for h > 600	Mean flexural tensile strength
M_{cr}	698,700	kNm	Wf_{cflm}	Cracking moment

From the table it can be seen that the cracking moment is bigger compared to the maximum bending moment (see Figure 80). That implies that the structure remains intact. The differences are however not that high. Important to notice therefore, is that the bedding stiffness as used is relatively low. A more stiff bedding results in lower bending moments. That means that the safety increases then. It is therefore assumed that a sunken ship load will not lead to failure for a monolithic tunnel.

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A3.4 Rotations in joints due to deformations

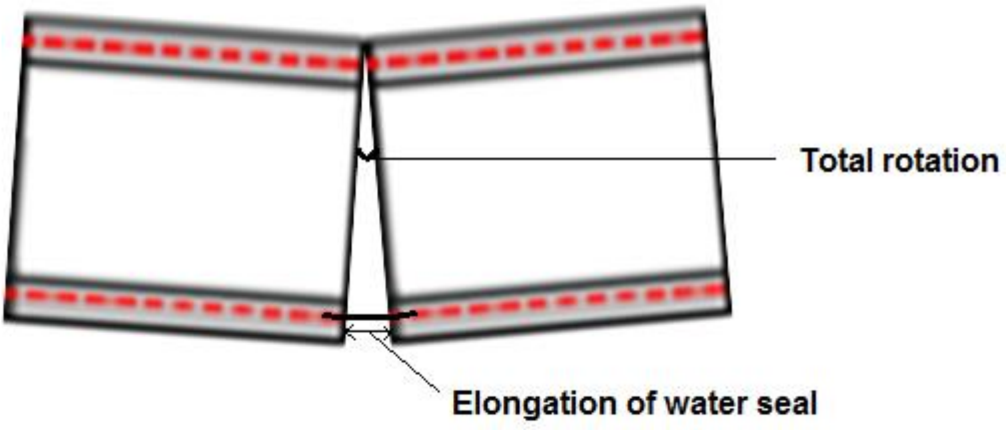

Figure 200 - Rotation and elongation of a water seal between two segments

The rotation and elongation between two segments is showed in Figure 200. The rotations in the joints should be checked, because both the rotations of the elements as well as the elongations of the water seals may not exceed the limit values as given in Chapter 4. Exceeding of the allowable rotation can lead to too big elongations of the water seals, so that it may lead to failure of the seals, with severe leaking as a result. Therefore the rotations and elongations of the water seals are calculated for a monolithic and a segmented immersed tunnel. The characteristic of those tunnels are given in Table 67 (which are still the same values as used in the other parts of this annex (A3).

Table 67 - Characteristics tunnel for determining rotations

Parameter	Amount	Unit	Formula	Description
$q_{sunken\ ship\ load}$	300	kN/m^2		Load on tunneldeck
l_{load}	20	m		Length load
w	30	m	Assumption	Width tunnel
h	8	m	Assumption	Height tunnel
d	3	m	Assumption	Total width walls
I	580	m^4	Calculated by MatrixFrame	Moment of Inertia
E	36000000	kN/m^2	from C45/55	E-modulus
k	2000	kN/m^3	Clay (CUR 166)	Bedding stiffness soil
1/λ	80	m	$1/((k/(4EI))^{0.25})$	Spreading length

To determine the rotations in the joints, again use is made from influence lines. It is done in exactly the same manner as shown in Figure 193 and Figure 194 for determining the shear forces. The results are given in Figure 201.

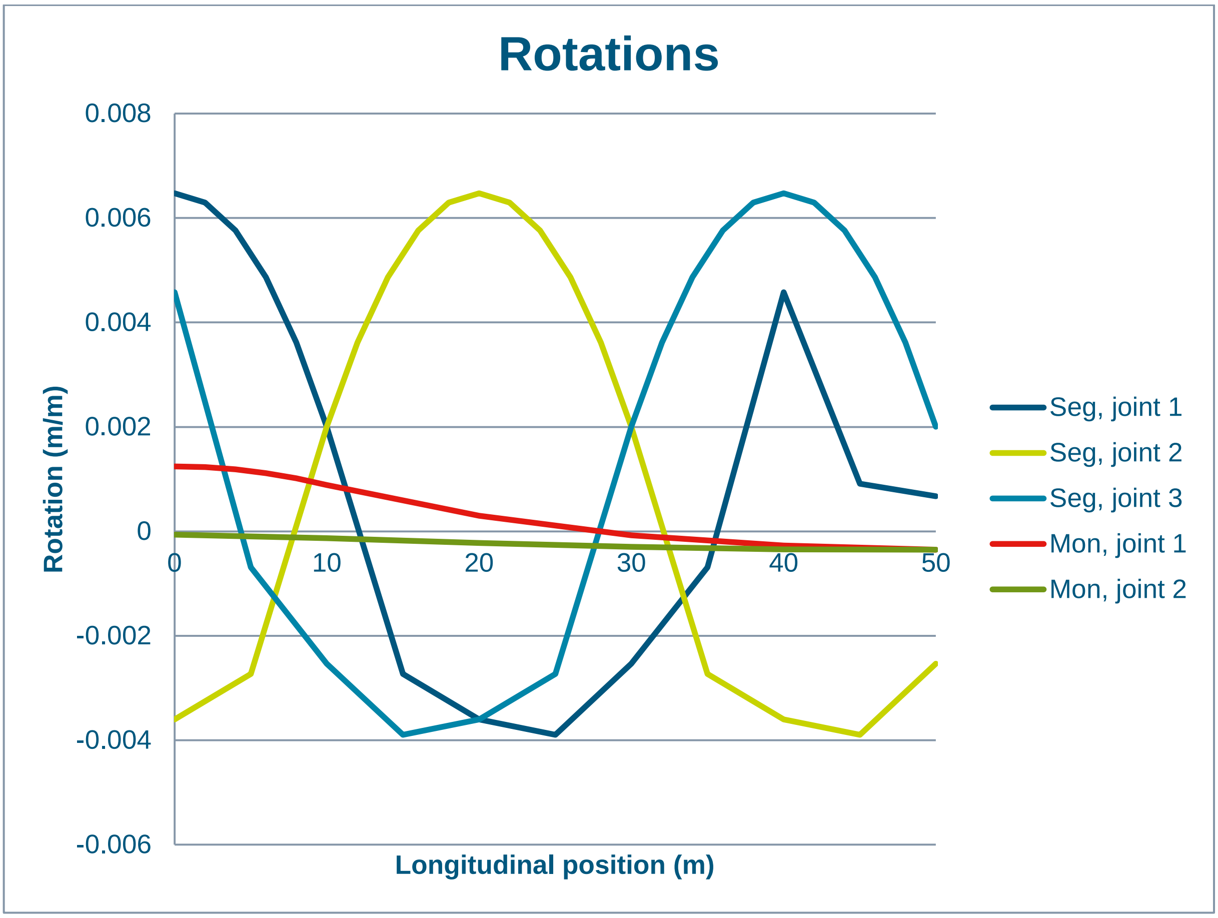

Figure 201 – Rotations between segments (k = 2,000kN/m^3) => 1/λ = 68m

It can be seen that the rotations for the segmented tunnel are much more than for the monolithic tunnel. The rotations for a segmented tunnel go up to about 0.0065 rad. This is well below the allowed value of 0.01 ([82]). Therefore segmented tunnels are probably not critical with respect to rotations. It can become a problem for tunnels on a very soft bedding. Monolithic tunnels will never face problems with respect to the rotations.

Based on the rotations of the joints, the elongations of the water seals can be calculated. Those are presented in Figure 202.

[82] *This value is an indication and will differ from project to project*

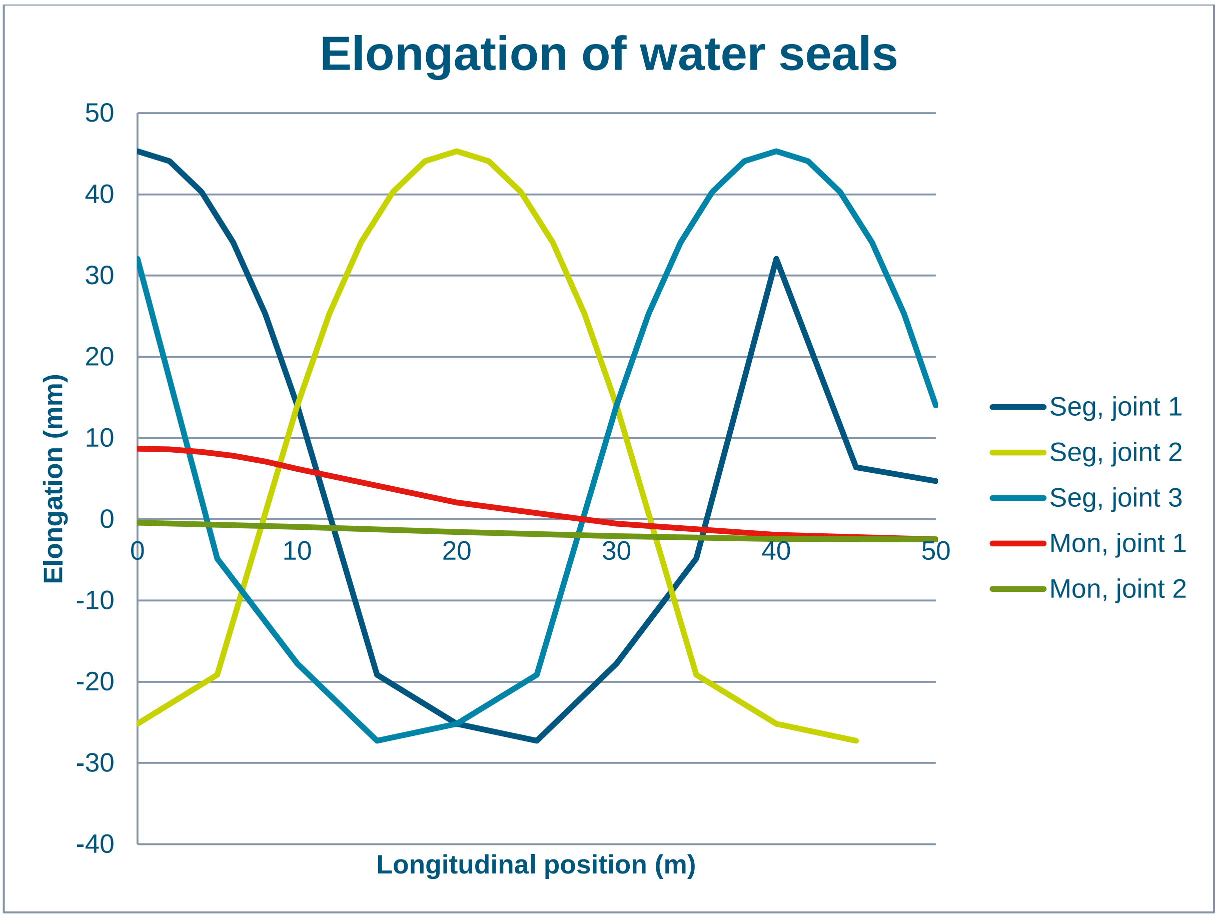

Figure 202 – Elongation of seals due to rotations (k = 2,000kN/m³) => 1/λ = 68m

Obviously, if the rotations of a segmented tunnel are higher than for a monolithic tunnel, the elongations of the water seals will also be larger for a segmented tunnel. The elongation goes up to about 45mm. When comparing this with an allowable elongation of 60-90mm for an Omega profile (§4.5.2.1 *Immersion joint* Table 2), or 40-75mm for a water stop (§4.5.2.2 *Segment joint,* Table 3), it is concluded that a sunken ship load can lead to too large deformations. When comparing it however with the elongation at break (80 - 110mm for an Omega profile and 75 – 260mm for a water stop) the waterstops does probably not fail.

A3.5 Flow rates through leaking joints and cracked concrete

In this paragraph an estimation is made of the amount of water flowing into the tunnel in case of failure of a water seal in a joint or through cracking of the concrete. To give an idea what the calculated amounts of flow rates implies, an estimation is made for the total volume enclosed by a tunnel. This volume is calculated in Table 68. For this calculation a tunnel of 1km length is assumed.

Table 68 - Estimation of free volume in tunnel

Parameter	Amount	Unit	Formula	Description
w	30	m		Widht tunnel
H_{tunnel}	8	m		Height tunnel
d_{tot}	3	m		Total widht walls
h_{tot}	2.5	m		Total height deck + bottom
A	176	m^2	$(w-d_{tot})*(H_{tunnel}-h_{tot})$	Open area tunnel
L	1	km		Length tunnel
V	148,500	m^3	A*L	Total volume in tunnel

A3.5.1 Leaking joints

To make an estimation of the amount of water flooded into the tunnel, use is made from Bernoulli's law[83]. For calculation of the gap width, use is made from the results as presented in Figure 202. In that figure it can be seen that the maximum elongation is about 45mm. The results are presented in Table 69.

Table 69 - Flow rate water through leaking joint based on Bernoulli 's Law

Parameter	Amount	Unit	Formula	Description
Δp	380	kN/m^2	Water column of 40m	Pressure potential
ρ	1,000	kg/m^3		Density water
v	28	m/s	$(2\Delta p/\rho)^{0.5}$	Velocity incomming water
Δl_{ws}	45	mm	Calculated	Maximum elongation water seal
Δu	45	mm	$=\Delta l_{ws}$	Width gap
w	30	m		Width tunnel
Q	37	m^3/s	$v*\Delta u*w$	Flow rate
t	67	min	V/Q	Time in which tunnel is totally flooded

This calculation is based on a constant pressure of 380kN/m^2 at the bottom side of the tunnel. However, due to resistance from the sand the pressure will be less. The total calculated time before the tunnel is fully flooded, is now 67min. It is however assumed that 90 min (one and a half hour) is more reasonable.

Now an estimation is made if people are able to leave the tunnel. It is assumed that people are able to leave the tunnel up to a water level of 1m. This 1m is reached in a quarter of an hour. Assume now that people are halfway the tunnel in case of failure of the water seal. They had to travel then for 500m. With a walking speed of 10km/h, this takes three minutes. These three minutes is far less compared to 15 minutes. It is therefore assumed that people can safely leave the tunnel.

[83] *$0.5\rho v^2 + \rho gh + p$ = constant. This is $z + p/\rho g + v^2/2g$ = constant for flowing liquids. For z = 0, this gives $v = (2\ \Delta p/\rho)^{0.5}$*

A3.5.2 Cracked concrete

Cracked concrete is caused if the cracking moment of a monolithic tunnel is exceeded under a sunken ship load. It is important to know then, if the steel is able to take up the bending moment after failure of the concrete.

Now an estimation of the ultimate bending moment resistance is made (the moment which the steel can take up after failure of the concrete). In normal conditions, the longitudinal bending moments are very small. Therefore the reinforcement in longitudinal direction is mostly not based on the maximum bending moments in longitudinal direction, but on the transverse stresses induced by the bending moments in the cross section. Or on practical reasons for keeping the reinforcement cage stable.

Due to this, the longitudinal amount of reinforcement is very small. Assumed is a ratio of 0.2%. The ultimate bending moment strength based on this reinforcement ratio, is still smaller compared to the cracking moment. It is therefore assumed that the cracking bending moment is also the ultimate bending moment strength.

Based on this reasoning, the tunnel (as given in Figure 80) is schematised with a hinge at the location of the cracked cross section. After that the rotation in the cracked cross section can be calculated and hence the gap in the bottom part of the tunnel.

For determining the flow rate through cracked concrete, normally use is made from Poiseuille's formula. But that formula is more applicable to crack widths up to 1.0mm. The here determined crack width is 12mm and is much more. Therefore also here use is made from Bernoulli's law.

The results are given in Table 70.

Table 70 - Flow rate water through big crack in concrete based on Bernoulli 's and Poiseuille's Law

Bernoulli's formula

Parameter	Amount	Unit	Formula	Description
Δp	380	kN/m^2		Pressure potential
ρ	1,000	kg/m^3		Density water
v	28	m/s	$(2\Delta p/\rho)^{0.5}$	Velocity incomming water
φ	1.54E-03	-		Rotation in joint
Δu	12	mm	$(H_{tunnel}-1)\varphi$	Width gap
w	30	m		Width tunnel
Q	10	m^3/s	$v*\Delta u*w$	Flow rate
t (uur)	4.0	uur	V/Q	Time in which tunnel is totally flooded

When comparing this result with those of a leaking joint, it can be seen that the consequences are a way less. This means such a crack does not lead to major problems.

Appendix 4

A4 Case

A4.1 Making choice for critical tunnel

A choice for a tunnel is made to evaluate the sunken ship loads. This tunnel should be most relevant for the research (question). To make a decision, first a framework is set up wherein a tunnel is searched. Otherwise too many tunnels should be analysed for making a choice.

A4.1.1 Framework

With this framework it is tried to exclude a lot of tunnels which are not relevant for the research. Therefore the boundaries which are set up in this framework are evaluated with respect to which types of tunnels are excluded and why that boundary is important.

A4.1.1.1 Starting points

The following points are used for the framework:

1. Enough information available about tunnel structure
    - Tunnel which is already built and
    - Tunnel built by TEC
2. Busy shipping area and not designed for sunken ship loads

These points are worked out below.

Enough information available about tunnel structure
Enough information about the tunnel ensures that it is a real case. When not enough information is available, some assumptions should be made. Making assumptions decreases the accuracy when investigating the structural behaviour. When choosing a tunnel which is already built, all information is in principle available.

A second item is that it should be possible to get all that information about a certain tunnel. Basically, from tunnels which are built by TEC all information is available. Therefore that restriction is made secondly.

Through this restriction double steel shell tunnels and tunnels with a circular cross section are excluded. In §6.2 *Types of immersed* tunnels it is concluded that such type of immersed tunnels are not of relevance for this research. Also almost all monolithic concrete tunnels are excluded. Because the majority of tunnels built by TEC are segmented. Based on §6.4 *Critical locations in concrete immersed tunnels* it is concluded that both monolithic as well as segmented tunnels show problems with respect to sunken ship loads. Therefore there is no preference for a monolithic tunnel neither to a segmented one. Monolithic tunnel being almost excluded from the framework is therefore not a big problem.

Busy shipping area and not designed for sunken ship loads
It is important that the tunnel lies in a busy shipping area, because the research question goes about the load from a sunken ship on a tunnel. Areas where not a lot of ships are passing are not relevant, because the change that a ship sinks on a tunnel is quite small. And then the research question becomes irrelevant for that situation.

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It also matters if such a tunnel is already designed for a sunken ship. Especially tunnels which are not that old and are in a busy shipping area are already designed for a sunken ship. Such tunnels are not relevant and should be excluded.

A4.1.1.2 Tunnels resulting from framework

The tunnels which result from the framework are listed below:

- Wijkertunnel, the Netherlands
- North-South Line, the Netherlands
- Hong Kong – Zhuhai – Macau Link (HZMB)[84], China
- Busan-Geoje Link, South Korea

A4.1.2 Multi criteria analysis

To make a choice for one of the tunnels, use is made from a Multi Criteria Analysis (MCA). In an MCA a choice is made for one of the possible options, based on different criteria. The criteria which are used here are explained first. After that the tunnels, which resulted from the framework, are worked out for those criteria. Based on that a choice is made for one of the tunnels.

A4.1.2.1 Criteria

The criteria are listed below:

- Type of ships passing the tunnel
- Spreading of the load
- Probability of failure of ships
- Enough information available about shipping traffic

Type of ships passing the tunnel
Through this criterion it should become clear what types of ships are passing the tunnel. Big ships with bulk of a high density will induce high loads on the tunnel after sinking. If there are no ships with high density bulk, the case will be less relevant.

Spreading of the load
A tunnel with a big cover on the tunnel causes more spreading of the load when a ship sinks on such a tunnel. Therefore such tunnels are less relevant. Tunnels without any cover or even which lie above the riverbed has to resist much bigger loads. Such tunnels are more relevant.

Probability of failure of ships
In case of heavy naval activities the chance of failure, and so the chance of sinking of a ship increases. It should be mapped what type of naval activities are present, to be able to give a qualitative estimation of the increase in probability of failure for a ship in that region.

When speaking about naval activities, one can think of an entrance of a harbour where a lot of manoeuvres take place, with increasing possibility of collisions. Or a quay wall where an accident can happen when the ships are loaded and unloaded.

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[84] *It is known that for the HZMB-tunnel the prestressing tendons are not cut through after the tunnel was build. This implies a different structural behaviour. This tunnel will be seen as a segmented tunnel from which the prestressing tendons are cut through.*

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Also the amount of ships plays a role. The more ships are passing a tunnel, the bigger the chance that ships collide and sink.

Enough information available about shipping traffic
It is important to have enough information available about the ships which are passing the tunnel. Because through this information it is possible to see what types of ships are passing the tunnel and how often. Also something can be said about the probability of failure of ships.

A4.1.2.2 Relative importance of criteria

Not every criteria has the same importance. The relative importance of each criterion is determined in Table 71 (and Table 72) .

Table 71 – Determining relative importance of criteria (1)

	Type of ships	Spreading of load	Probability of failure	Enough information	Total
Type of ships	x	1	1	1	3
Spreading of load	0	x	1	0	1
Probability of failure	0	0	x	0	0
Enough information	0	1	1	x	2

From Table 71 it can be seen that one of the criteria has a score of zero. That implies that such criterion does not have any influence on the total score for a tunnel. That’s of course not totally true, therefore the influence of that criterion is taken into account by multiplying all scores by a factor two and setting them for the third criterion to one (see Table 72).

Table 72 - Determining relative importance of criteria (2)

	Score	Weight
Type of ships	6	46%
Spreading of load	2	15%
Probability of failure	1	8%
Enough information	4	31%
Total	13	100%

A4.1.2.3 Tunnels evaluated for criteria

In this part all tunnels are evaluated with respect to the mentioned criteria.

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A4.1.2.3.1 Wijkertunnel, the Netherlands

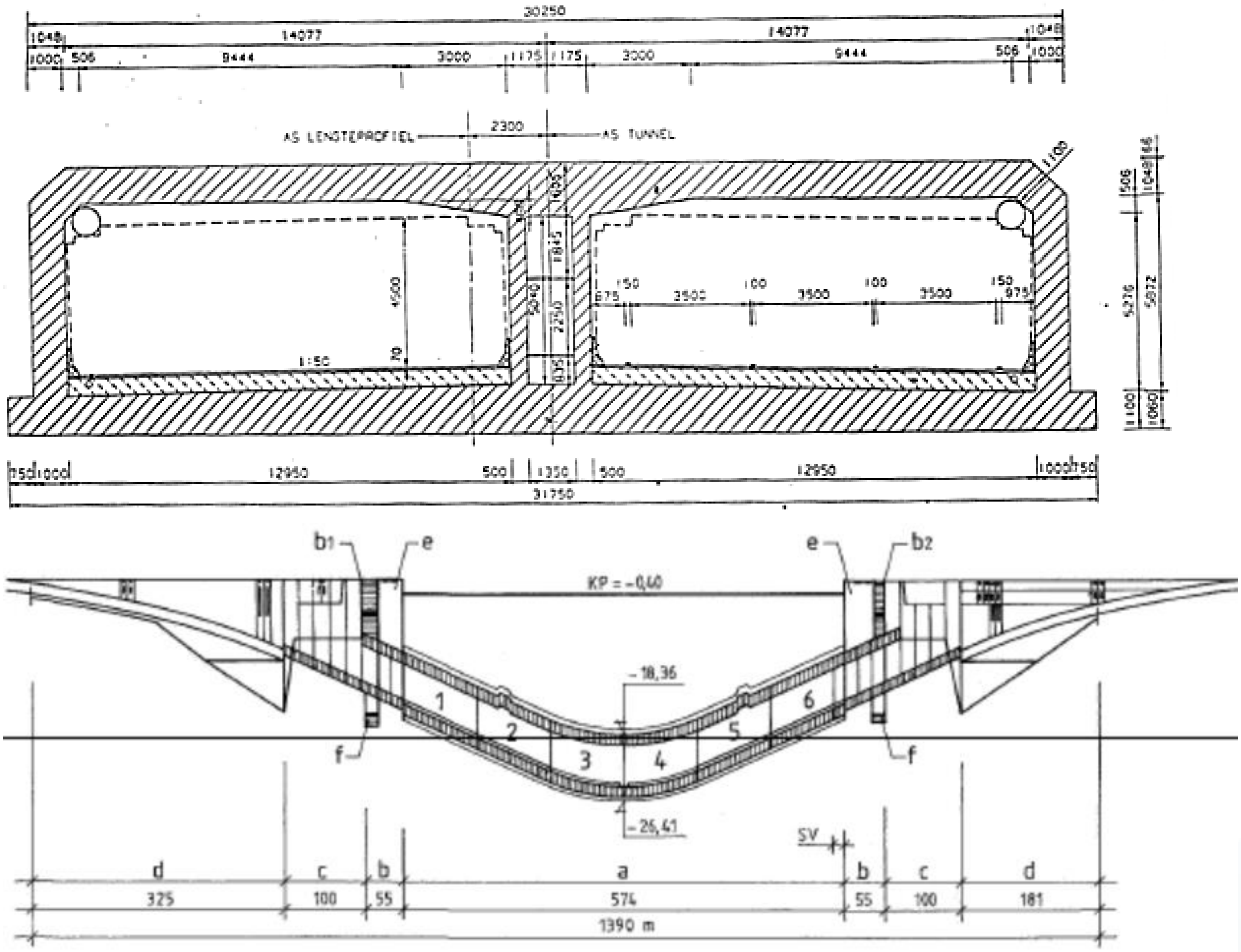


Figure 203 - Overview Wijkertunnel (second picture from (Cameriken & Leeuw, 1994))

Type of ships passing the tunnel

The ships which are passing the Wijkertunnel are mainly for the harbour of Amsterdam. The ships which are arriving in Amsterdam are smaller compared to the ships arriving in Rotterdam. The biggest ships fall in the category of 90.000 – 110.000 DWT. There is also a category of 110.000 – 150.000DWT, but there is only one ship which falls in this category for 2014. From this it can be concluded that the size of the ships is relatively small.

With respect to the amount of iron ore bulk carriers, it is known that in 2013 about 4% of the total bulk consisted of ores. The total throughput of bulk for that year was more than 78.000kton (Port of Amsterdam, 2015). Compare this with a total throughput of bulk of 296.000kton for the Port of Rotterdam in 2013 (Port of Rotterdam, 2015).

Spreading of the load

The cover on the Wijkertunnel is only 1m sand (Weger, 2001). This causes only little spreading of the load.

Probability of failure of ships

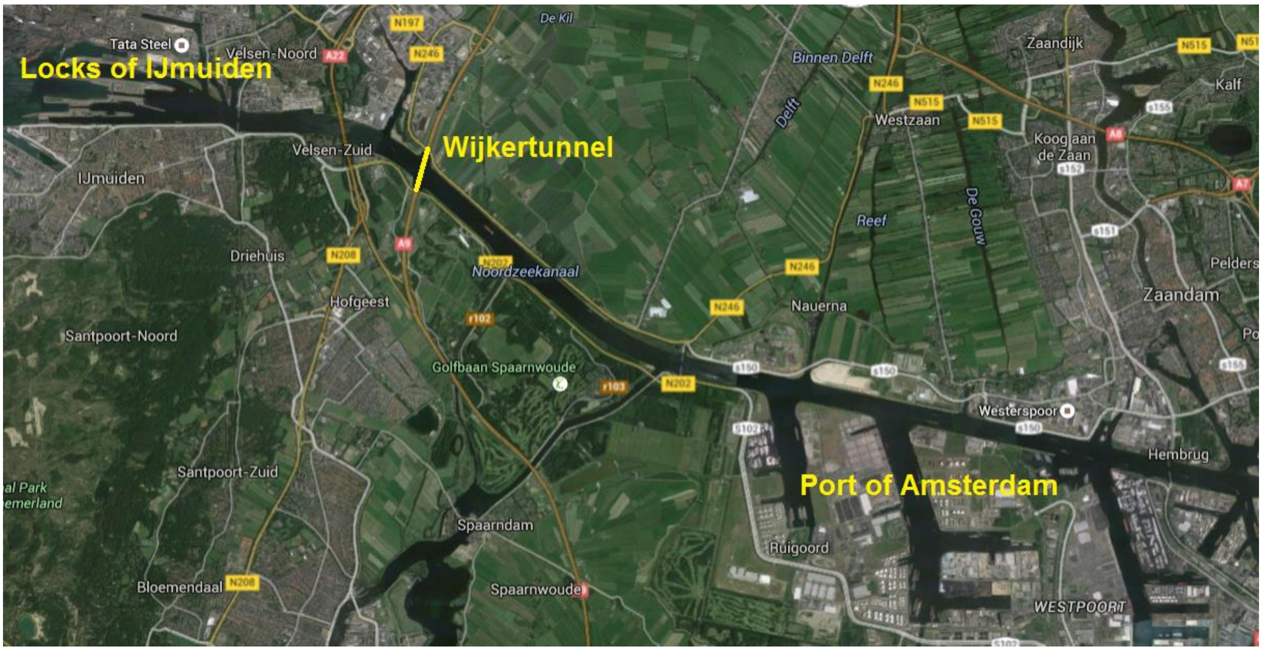


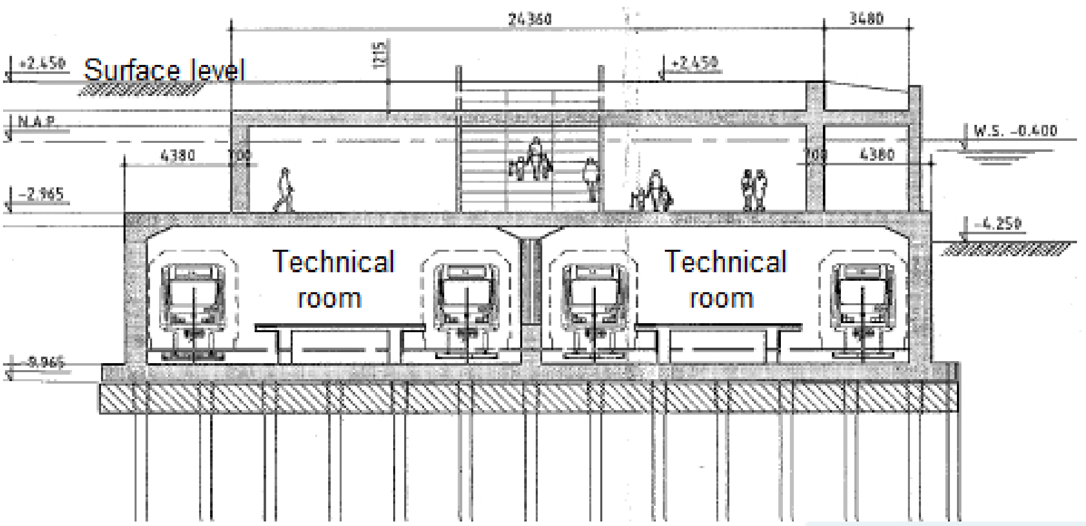
Figure 204 – Location Wijkertunnel

The Wijkertunnel lies in the main waterway, just a few kilometres beyond the locks of IJmuiden. There are no heavy naval activities required in that area, so the probability of failure is not that high.

Enough information available about shipping traffic

The tunnel lies just beyond the locks of IJmuiden. It is assumed that all shipping traffic which passes that locks do also pass the Wijkertunnel. It is reasonable to assume that all ships are registered when passing the locks of IJmuiden. This together with the fact that the locks lie in a Dutch area, so that it is assumed that it will be not that difficult to get the required data.

A4.1.2.3.2 North-South Line, the Netherlands



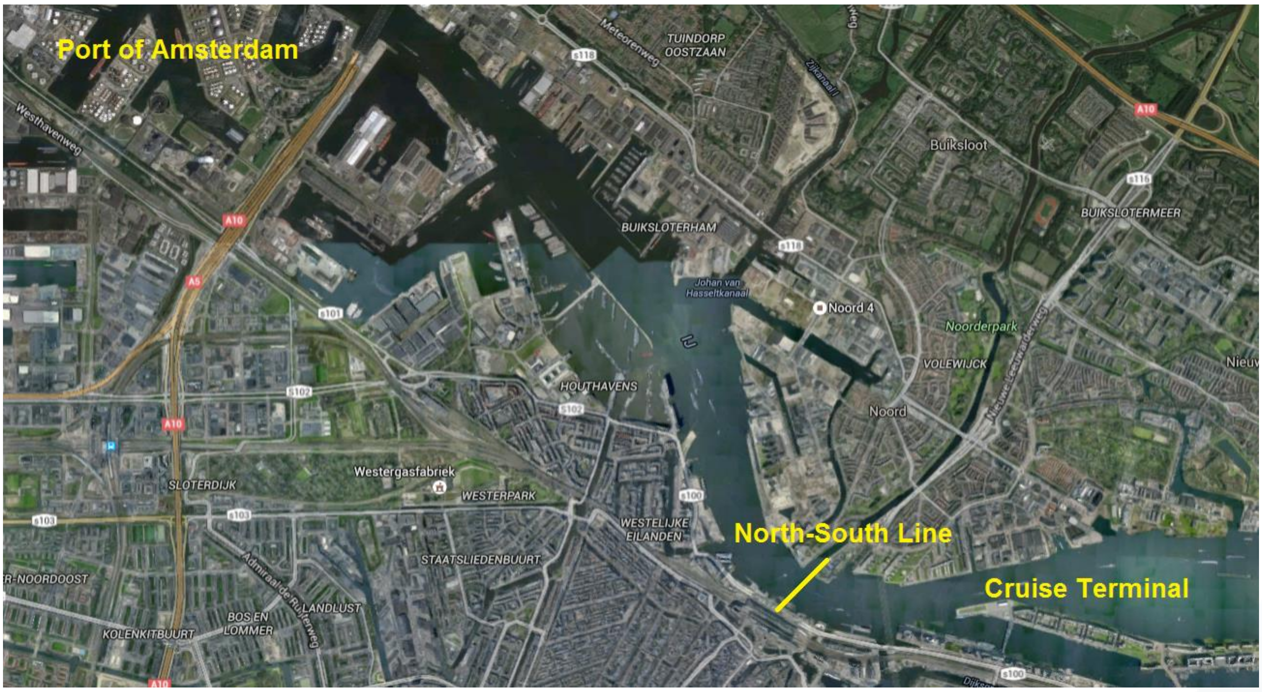
Type of ships passing the tunnel

The port of Amsterdam lies now before the tunnel, so all ships with the Port of Amsterdam as destination go not over the North-South line tunnel. There lies only a cruise terminal beyond the tunnel. So the biggest ships which pass the tunnel are large cruise ships. Iron ore bulk carriers do not pass that tunnel, so therefore with respect to this criterion, the tunnel scores bad.

Spreading of the load

About the cover on top of the tunnel is no information found. But it assumed that not much cover is present. Therefore the spreading of the load will be small. And hence gives a relatively good indication for this criterion.

Probability of failure of ships



The North South Line lies also in the in the main waterway. There are more ship quays in the neighbourhood of that tunnel. This causes a bit more naval activities. The tunnel scores therefore better with respect to this criterion.

Enough information available about shipping traffic

Because of the fact that the North South Line lies beyond the harbour of Amsterdam, that information cannot be used. Only the shipping traffic which does call the cruise terminal is maybe registered. Due to the fact that the tunnel lies in a Dutch area, it is assumed that the information needed will be available more easily (as compared to a tunnel located in a foreign country). Hence this criterion gets a good indication, but less compared to the Wijkertunnel.

A4.1.2.3.3 HZMB-Link

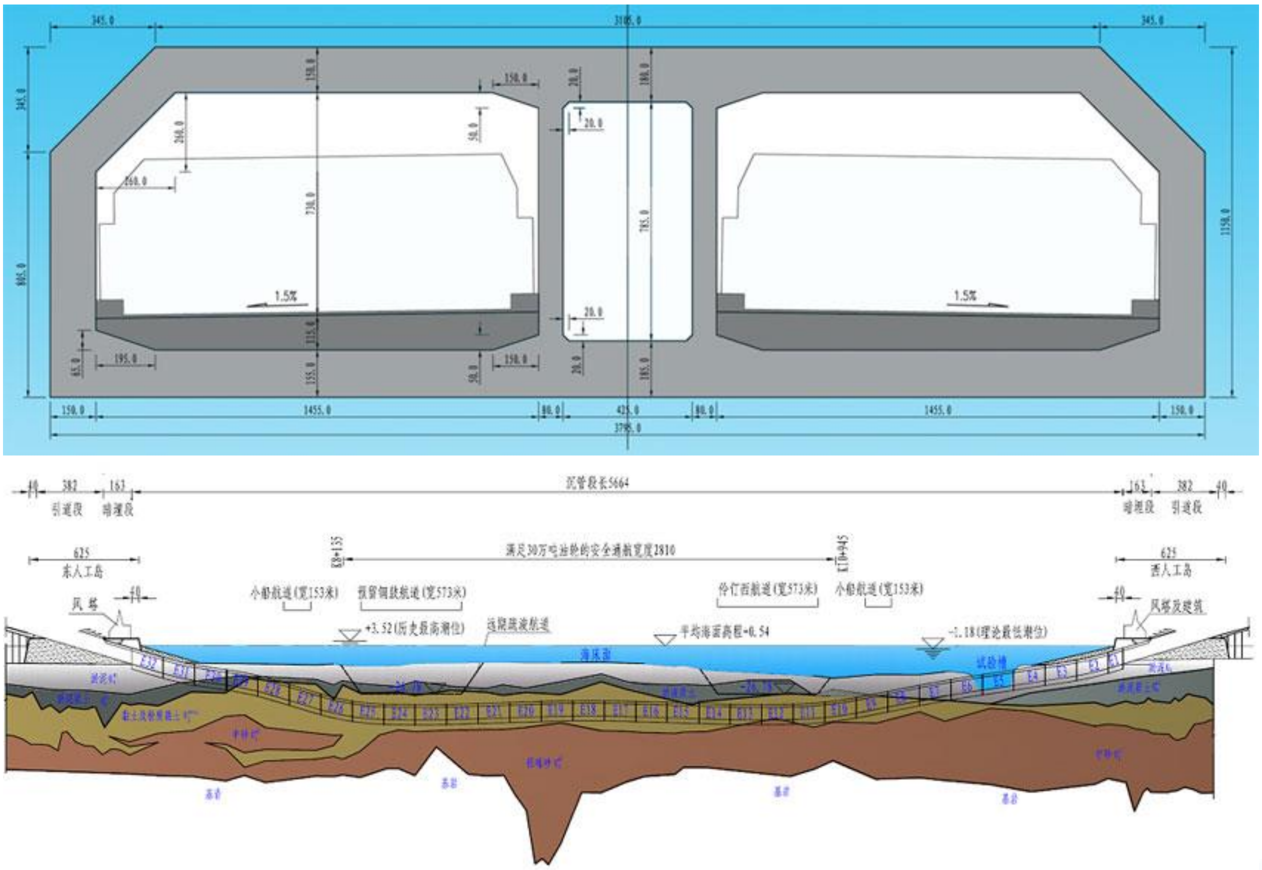


Figure 205 - Overview HZMB-tunnel[85]

Type of ships passing the tunnel

After this tunnel lie the Shenzen and the Guangzhou harbours. The Shenzen harbour has as its main activity the transhipment of goods. The Guangzhou harbour has a lot of activities with respect to cargo, but however not with respect to ore. The main waterway to this harbour has a water depth of 15.5m, which allows big, but not very big ships to enter that harbour[86]. The depth of the waterway above the tunnel however is deeper and allows bigger ships to pass.

Spreading of the load

There is much spreading of the load, because there is a huge amount of cover on top of the tunnel. There are also locations with only a small cover on the tunnel and at one point there is no cover present. But the chance that a ship sinks on that location is small, so this tunnel scores bad at this point.

Probability of failure of ships

[85] *http://www.tunneltalk.com/Hong-Kong-Zhuhai-Macao-Link-Jun11-Construction-starts.php*

[86] http://www.gzport.gov.cn/portal/site/site/portal/english/showContent.portal?contentId=558IX2SE5RZEOH0PN0NR0473ZJSPS0SH&categoryId=BDLR7Z20I7DJOQFSFXEK74FVON0UR137

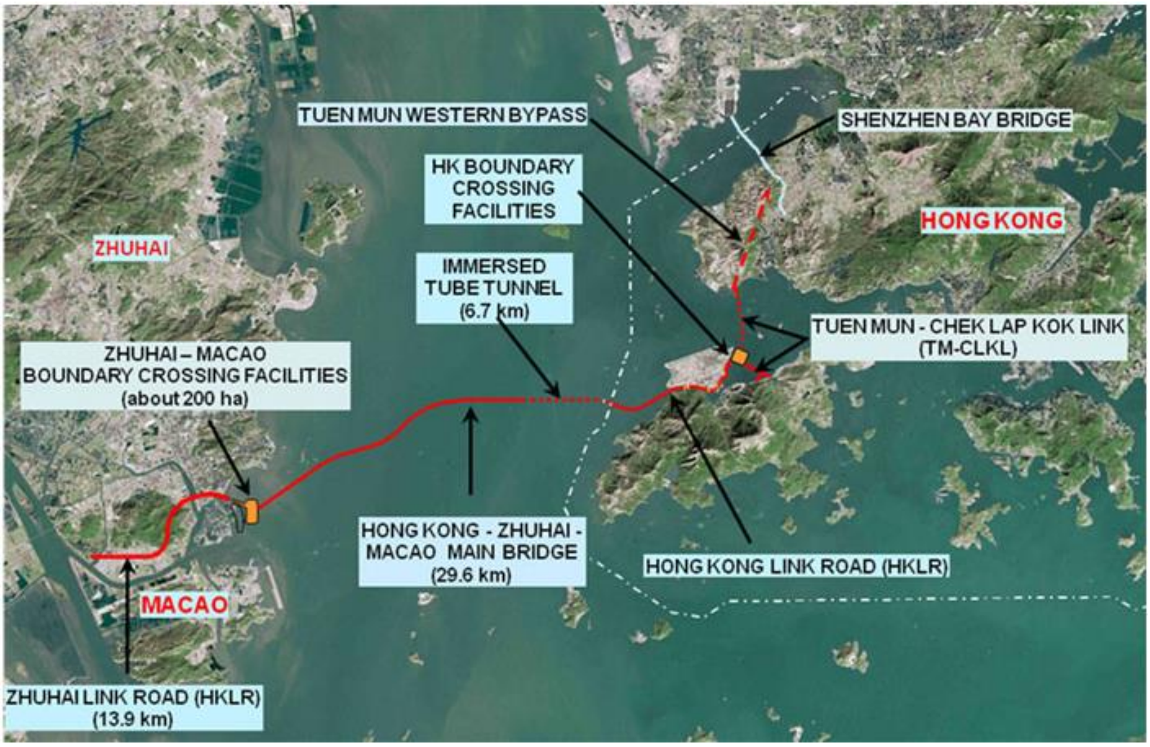


Figure 206 - Location HZMB-tunnel[87] (see box: immersed tube tunnel)

There are here a lot of naval activities, but the space which is available for the shipping traffic is also large. This decreases the probability of failure, because the main accidents of ships is assumed to be through colliding of ships (see Appendix 2, §A2.4 *How an iron ore tanker fails* on p.188)[88]. It can also be seen from the website which shows the current position of several ships that the tunnel is most used as passage route and not the bridge[89]. This increases the change of a sunken ship on the tunnel. There is further no harbour in the neighbourhood of the tunnel which should increase the probability of failure of a ship.

Enough information available about shipping traffic

It is the question if a lot of information can be found. Based on the previous considerations an estimate can be made and also some information can be asked by e-mail. For this situation it is assumed that there will be less information available.

[87] *http://www.tunneltalk.com/Hong-Kong-Zhuhai-Macao-Link-Jun11-Construction-starts.php*
[88] *This conclusion is based on shipping data from the Netherlands and is assumed to be true in general.*
[89] *https://www.marinetraffic.com/nl/ais/home/centerx:114/centery:22/zoom:10*

A4.1.2.3.4 Busan – Geoje Link

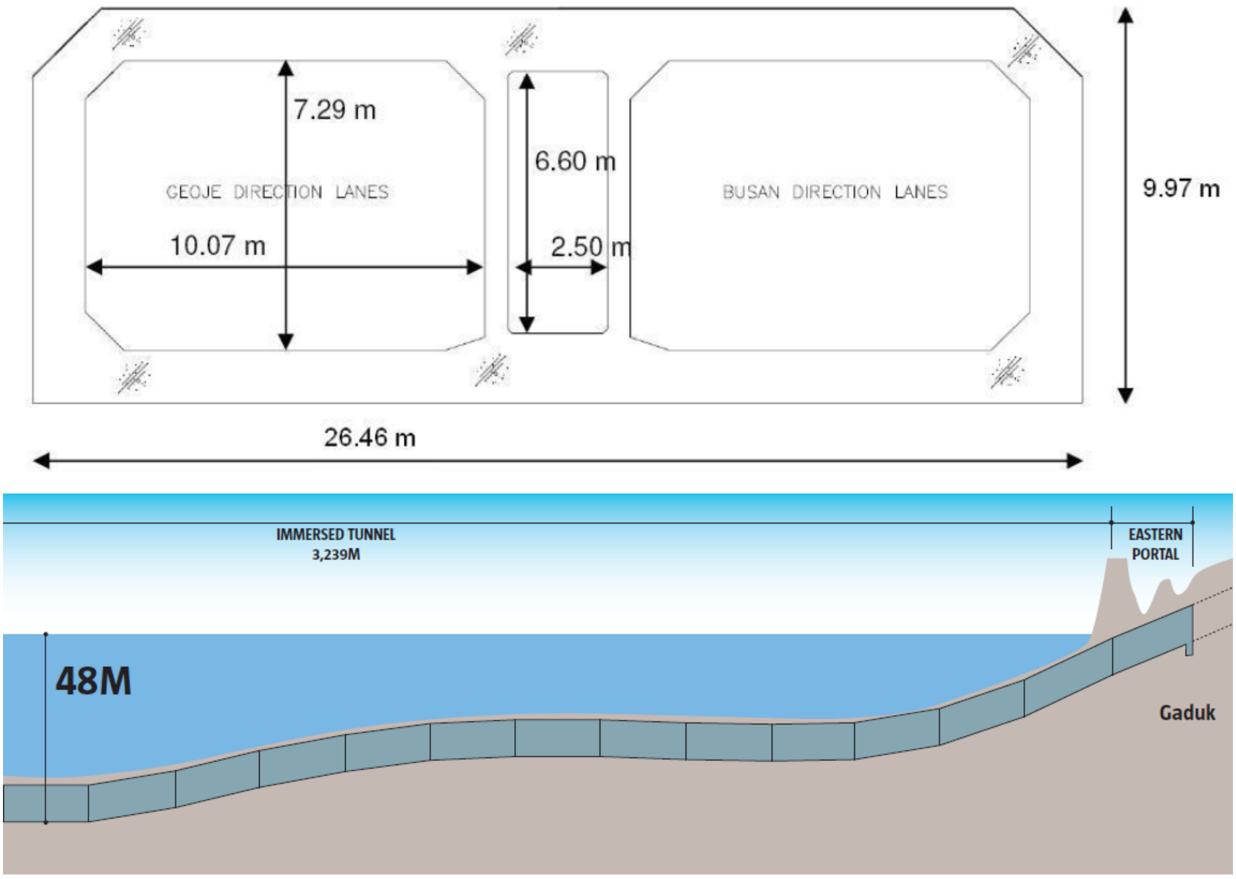


Figure 207 - Overview Busan-Geoje Link

Type of ships passing the tunnel

After the Busan – Geoje Link lies a big container terminal. Therefore there are a lot of ships passing that tunnel, but most of them will be a containership. Containerships can induce also large loads, but they will be less compared to (iron ore) bulk carriers[90].

Spreading of the load

There is only a small amount of cover on the top of the tunnel (Figure 207), therefore the spreading of the load will be small, so this gives a relatively high load on the tunnel.

Probability of failure of ships

[90] *For information about the shipping traffic over the Busan-Geoje Link, visit: http://portbusan.go.kr/eng/contents/port040201.jsp.*

Figure 208 - Busan - Geoje link (the red line is the immersed tunnel)[91]

There is enough space available for the ships to navigate. See Figure 208. This implies a relatively low probability of failure of the ships.

Enough information available about shipping traffic
There is some information available about the shipping traffic on internet. But because of the fact that the tunnel lies not in an area which is part of the Dutch government, it is likely that it will be difficult to get detailed information.

A4.1.2.4 Determining most relevant tunnel

For determining the most relevant tunnel each criterion is given a mark (for each tunnel). When multiplying those marks with the relative importance as stated in Table 72, a score is obtained for each tunnel. This is done in Table 73.

Table 73 - Determining most relevant tunnel

	Type of ships	Spreading of load	Probability of failure	Enough information	Score
Wijkertunnel	7	7	6	8	7.23
North - South line	5	7	8	7.5	6.31
HZMB-Link	8	4	6	7	6.92
Busan-Geoje Link	6	7	5	5	5.77

From the table it can be seen that the Wijkertunnel scores the best. Therefore that tunnel is used for evaluation of a sunken ship load.

[91] *http://www.dhigroup.com/global/news/2008/2/28/windandwaveforecastofthebusangeojesubmergedtunnellink*