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Navigation Locks in the Netherlands – Lock Chamber Typology and Failure Analysis

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Abstract

Navigation locks play a crucial role in the inland waterway network of the Netherlands. Although these structures typically have been designed with an intended service life of 100 years, their actual technical end of life is often unknown. Insight into the failure mechanisms and their triggers is required to better predict their technical condition and what demands they face. Only then is it possible to decide whether it is safe and economically beneficial to extend their lifetime. To determine the failure mechanisms and triggers for failure, it is required to know which type of structures are present. Five main types of lock chamber structures have been identified based on an archival investigation of locks of Rijkswaterstaat. For all these typologies common failure and degradation mechanisms have been investigated. The outcome of this research supports asset owners and engineers in their process of assessing the structural reliability of navigation locks.

Keywords: Navigation Lock; Lock Chamber; Gravity-based Structures; L-walls; Sheet Pile Walls; U-shaped Structures; Triggers; Events; Failure Mechanism; Degradation.

1 Introduction

About 25% of the Netherlands lies below sea level. Therefore, managing the inland water systems is of great importance. Higher sea water levels are expected in the coming decades, but also heavier rainfall and longer periods of draught should be anticipated for [1]. This means that the inland water systems need to be able to discharge water quickly or hold water for longer periods of time. Hydraulic structures, including navigation locks play an important role in these systems.

In the Netherlands there are over 6000 km of inland waterways [2]. The waterways for commercial navigation are classified according to the CEMT (Conférence Européenne des Ministres des Transports) classification [3]. About 4800 km of the Dutch waterways are suitable for commercial navigation (CEMT class 1 or higher). From a total of

2 billion tons of cargo that is being imported, exported or transported within the Netherlands, 15% is shipped via inland waterways [4]. The majority of this cargo will pass navigation locks to reach its destination. Inland navigation has a lower environmental impact compared to road transport [5]. Therefore, the availability and reliability of the navigation locks is of great economical and societal importance.

Many hydraulic structures, including navigation locks are nearing their technical end of life. Insight into the failure mechanisms and the degradation of the lock structures is required to better predict this. Only then is it possible to decide whether it is safe and economically beneficial to extend their lifetime, reducing the need for new structures and thus reducing investments and the consumption of labour and construction materials.

In this paper, an overview of the navigation lock chamber structures of Rijkswaterstaat is presented, focusing on lock chambers within lock complexes and not on gates and driving gear. The chambers are categorized in five main types and for all these typologies the most common failure mechanisms and triggers for failure have been identified.

2 Navigation Locks in the Netherlands

2.1 Historical overview

The Netherlands has a long history of navigation locks. The first navigation locks, which can be dated to around the early 13th century, were entirely made of timber. Around the 16th century, the use of stone in lock structures was introduced. In the centuries that followed, navigation locks have been developed in terms of size and material use [6], but the concept of navigation locks has not changed: two lock heads equipped with gates and a lock chamber in between, making it possible for vessels to pass differences in water levels. The main function of navigation locks is retaining differential water levels whilst facilitating shipping.

2.2 Locks for inland navigation

The total number of navigation locks in the Netherlands is estimated at around 2010 [7]. The majority are small locks which are only suited for recreational vessels. For commercial navigation 220 navigation locks (CEMT ≥ I) have been identified by combining data from open sources [8-10] and from Rijkswaterstaat. A summary is presented in Table 1, where also the asset managers of the locks are listed. The location of all these navigation locks, their CEMT classifications and the waterways are shown in Figure 1.



Figure 1. Waterways and navigation locks in the Netherlands

Rijkswaterstaat, which is part of the Dutch Ministry of Infrastructure and Water Management, manages most of the main inland waterways in the Netherlands. This is reflected in large number of locks in CEMT class V and VI, of which almost 90% are managed by Rijkswaterstaat. The other locks are owned by 10 (out of 12) provinces, 19 (out of 342) municipalities, 7 (out of 21) Water Boards and 3 different Port Authorities.

CEMT Class I vessels have a minimum length of 38,5 m, are over 5 m in width and have a maximum draft of 2,5 m. CEMT VI vessels can have a length of 270 m, a width of 34,2 m and a maximum draft of 4 m.

Table 1. Navigation Lock per Owner and CEMT-classification

CEMT	Rijkswaterstaat	Provinces	Municipalities	Waterboards	Port Authorities	Total
I	2	12	8	6	0	*28*
II	19	24	14	7	1	*65*
III	5	5	5	1	0	*16*
IV	10	7	2	1	0	*20*
V	61	3	2	2	1	*69*
VI	20	0	0	0	2	*22*
Total	*117*	*51*	*31*	*17*	*4*	*220*

2.3 Age

Aging of the infrastructure in the Netherlands is a challenge for the coming decades [11]. About a quarter of the navigation locks of Rijkswaterstaat have an estimated remaining lifetime of 0-33% of intended service life and half of the locks have an estimated service life of 33-67% [12], referring to the parts of the locks which are not easily replaceable such as lock walls and lock heads. The years of construction of the navigation locks of Rijkswaterstaat are plotted in Figure 2. Based on an average lifetime 100 years it can be concluded that 30 locks will reach their end of life before 2040 and another 34 locks in 2060. This assumption ignores the fact that life-extending maintenance can and has been done already; this action usually provides 30 years of extra service life.

3 Lock chambers

3.1 Lock inventory of Rijkswaterstaat

Rijkswaterstaat manages 127 locks, 117 of which are classified as CEMT class I or higher. For all these locks the structural elements have been identified, based on an inventory of the archives of Rijkswaterstaat.

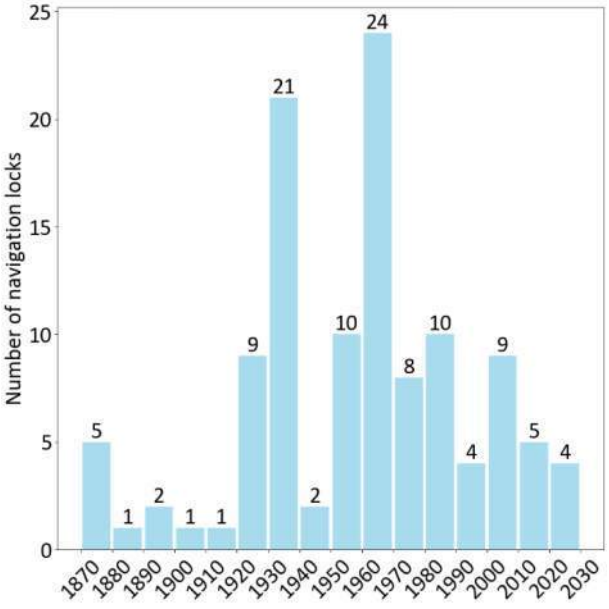


Figure 2. Histogram of year of construction for Rijkswaterstaat navigation locks (total of 117)

The components of the lock chambers are similar to those in quay wall structures. This is because their function is similar: to retain a difference in ground levels and water levels.

A main difference between lock chambers and quay walls is the presence of a floor at the water side of locks, which is not common in quay structures. The main function of this floor is usually to prevent scour, to prevent the vertical flow of water due to the water head differences outside the lock and inside the lock, but it can also have a structural function.

3.2 Lock Chamber Typologies

3.2.1 Introduction to typologies

Five main types of lock chamber structures have been identified:

a) Gravity-based structures
b) Sheet pile walls
c) L-walls
d) U-shaped structures
e) Green chambers

These types of structures will be explained in the next sections. Lock chamber floor structures are discussed in a separate section.

It must be noted that not all structures can obviously be assigned to certain typologies. Some literature bases their typology mainly on the geotechnical behaviour of quay walls [13]-[14], others [15][14] focus on the structural components of locks. In this research, a combination of these sources has been used.

3.2.2 Gravity-based structures (a)

Gravity-based lock chambers exist of large, massive soil retaining structures, combined with an isolated floor in between the opposite walls. The walls are mainly constructed of masonry or unreinforced concrete. On the top side of the walls, usually a reinforced concrete part is used to allow for installation of bollards. Bypass channels for levelling are often integrated into the structures.

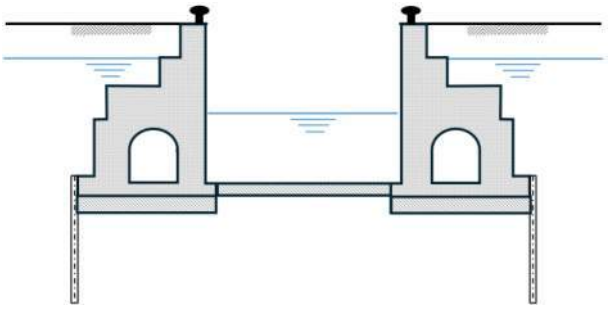


Figure 3. Cross section of Gravity-based structure

3.2.3 Sheet pile walls (b)

Sheet pile lock structures are constructed of sheet piles, combined with horizontal or inclined ground anchors. For locks with large retaining heights the application of steel combined walls or concrete diaphragm walls is common.

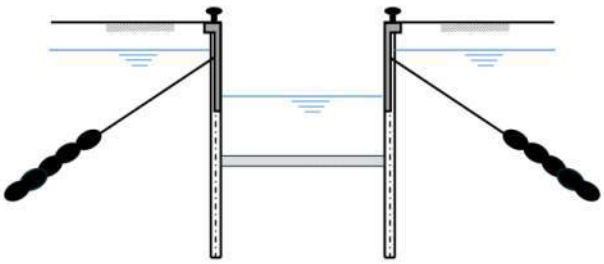


Figure 4. Cross section of Sheet pile wall

A concrete capping beam is placed on top of the walls, to allow for the application of bollards and for load distribution. At lower levels recessed bollards are either connected to the sheet piles or integrated into reinforced concrete elements. These structures do not allow for the integration of levelling systems.

3.2.4 L-walls (c)

L-walls are reinforced concrete walls connected to horizontal relieve platforms, which are founded on concrete or timber piles. A sheet pile wall is required to form the lock walls up to bottom level of the chamber.

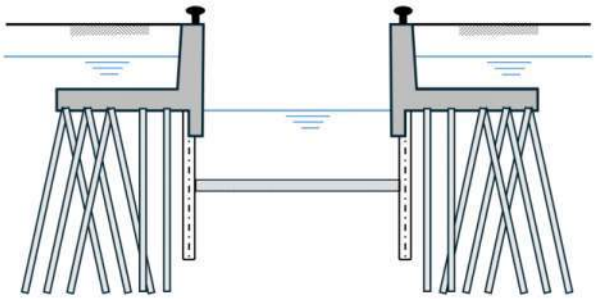


Figure 5. Cross section of L-walls

An alternative L-wall structure can be found in some locks where the L-walls are founded on grade, without piles. In this case the geotechnical mechanism is like those of gravity-based structures.

3.2.5 U-shaped structures (d)

U-shaped lock structures are made of reinforced concrete. Variation in shapes can be found in the presence of toe structures outside the walls, large chamfers at the inside corners of the wall-floor connection, inclination of the outside of the walls and the presence of platforms at top level of the walls.

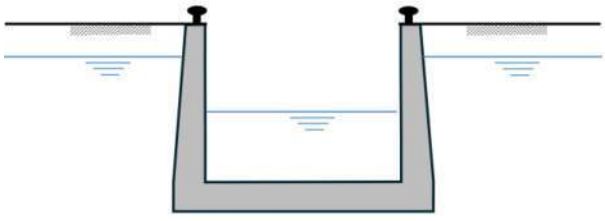


Figure 6. Cross section of U-shaped structure

The structure is usually directly founded on a firm sand layer or improved soil. Sometimes a piled foundation is required for the vertical stability of

the structure. Channels for levelling systems can be integrated at the outside of the structures.

3.2.6 Green chambers (e)

Green lock chambers are made of sloped embankments, without the use of any structural elements. The water height difference is overcome by impervious soils or by geotextiles. A scour protection is applied at the bottom level and on the slopes to prevent the development of holes which can influence the stability. Application of green chambers is only possible in locks with a limited water level difference. Separate structures are required for the temporary mooring of ships inside the lock chambers.

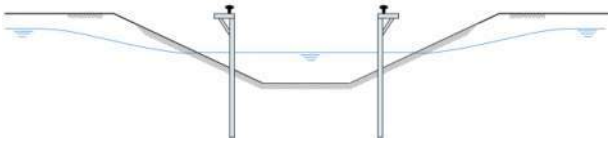


Figure 7. Cross section Green chamber

3.2.7 Lock chamber floors (f)

For structure types a to c, the lock floor is often constructed of reinforced or unreinforced concrete slabs, concrete tiles, basalt blocks or granular materials. A combination of the above is also possible, for example a reinforced concrete grid filled with concrete tiles. For hydraulically closed floor structures the application of vertical tension piles is sometimes required to prevent uplift of the floor. Other closed floors can be equipped with filter layers to prevent an overpressure.

In U-shape structures the floor is structurally integrated with the walls. Variants with a hinged connection in the middle of the floor or close the walls are also possible.

3.2.8 Longitudinal direction

In the longitudinal direction of the lock chamber, the structural elements of type a, c and d are usually segmented. This allows for thermal expansion and prevents damage to the structures caused by uneven settlements of the foundation. At the interface of the different sections, a joint must be formed. This joint must prevent the flow of water and soil, whilst providing some flexibility for small rotations and deformation between adjacent elements. Shear keys are often applied to maintain the alignment of elements in the longitudinal direction of the lock chamber.

3.3 Rijkswaterstaat Lock Chambers

An overview of all navigation lock structures of Rijkswaterstaat (CEMT-class ≥ I) is provided in Table 2. Gravity-based structures have been used in navigation lock chambers until the 2nd Word War. Afterwards, the use of steel, both for sheet piles and reinforced concrete became default. Sheet pile walls have been applied in locks constructed since the 1930s and mainly in the new locks that have been constructed in the 21st century.

Table 2. Overview of lock chamber types for Rijkswaterstaat locks

From	To	Gravity-based	Sheet piles	L-walls	U-shaped	Green chamber	Total
1860	1870					1	*1*
1870	1880	4					*4*
1880	1890	1					*1*
1890	1900	1				1	*2*
1900	1910	1					*1*
1910	1920	1					*1*
1920	1930	7				1	*9*
1930	1940	6	4	2	9		*21*
1940	1950			1		1	*2*
1950	1960		1		8	1	*10*
1960	1970			1	23		*24*
1970	1980				8		*8*
1980	1990			3	7		*10*
1990	2000		2	2	1		*5*
2000	2010		7		2		*9*
2010	2020		4			1	*5*
2020	2030		4				*4*
	Total	*21*	*22*	*10*	*58*	*6*	*117*

L-walls have been applied in a limited number of locks, whereas U-shaped structures can be found in about 50% of the Rijkswaterstaat locks, but not in recent ones. This can be explained by the fact that U-shaped structures need a large and dry construction pit. Most of the new locks that have been constructed in the last 30 years were replacements of old locks (Brantse kanalen, Terneuzen), or new locks in existing lock complexes (IJmuiden, Beatrix, Maxima, Eefde). In existing lock complexes, space is often limited and lowering of the ground water table is a risk for the existing locks or other structures. Therefore, the application of sheet pile (or combi-wall or diaphragm) wall structures was often the preferred option. For a limited number of locks, the application of a green chamber has been possible, of which the most recent one is the Meppelerdiepsluis (2016).

4 Failure Mechanisms, events and triggers

4.1 Definitions

A lock chamber structure has failed when it cannot fulfil its functions. Failure of the civil parts of lock structures is not something that has happened on a large scale so far, so learning from incidents does not provide sufficient insight. However, local failure or defects of parts of a lock chamber can give some insight in the state of the structure. For all lock chamber types an inventory has been made to identify possible failure mechanisms. Before a failure mechanism occurs, an event will likely have taken place, such as overloading or degradation. These events are initiated by triggers, which also can be categorized. The process from trigger to failure, presented in Figure 8, will be used to distinguish the various failure mechanisms of lock chambers. The different parts of the scheme are explained in the next sections.

4.2 Triggers

For lock chamber structures seven main triggers have been identified. Triggers are conditions or circumstances which lead to certain events. Appearance of one of these triggers, but most likely a combination of these can lead to unwanted events and eventually failure of (elements of) the structures. The triggers which have been identified for navigation locks are:

- Changing environmental conditions, e.g. lower or higher water levels, temperature changes or surface water composition.
- Past errors, construction or design errors.
- Aging of structures, caused by be the natural process of material degradation.
- Accidents, such as ship impacts.
- Insufficient maintenance, e.g. neglect of damage repair or renewal of coatings.
- Changed use, i.e. the allowance of larger vessels or operation under different water levels.
- Misuse, such as high surcharge loads on top of or close to the lock or overload of bollards.

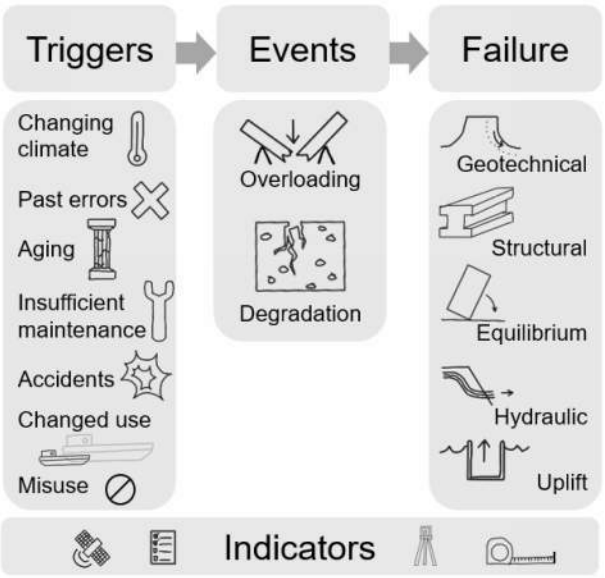


Figure 8. Failure path scheme

Within these categories some subcategories are listed as example. The triggers are listed in order in which the asset owner can influence these; the changing environment cannot be altered by the asset owner and past errors cannot been undone (but may be repaired), where maintenance can be restarted and misuse of the asset can be stopped.

4.3 Events

When one of the triggers or a combination of these occur, it can initiate unwanted events. These

events have been categorized into two main sets: overloading and degradation, following the main principle of Eurocode 1990 [16] where failure occurs when the load exceeds the resistance of a structural element.

Within the overloading category seven sub-sets can be found: water, soil, vessel or navigation, operational, erosion or external loads. For the degradation category seven sub-sets have been identified: concrete, masonry, steel, joints, scour protection, drainage and soil.

It must be noted that there are overlaps between overloading and degradation. When a concrete structure is overloaded, cracks can occur. These cracks will often not lead to direct failure but can initiate or worsen the corrosion process of the reinforcement and lead to failure on the long term. When drainage systems are not working properly, the water head difference on a retaining wall can increase and lead to failure of a sheet pile wall or anchorage.

4.4 Failure

Unwanted events can lead to failure of lock wall structures. Categorization of the different failure mechanisms has been based on the ultimate limit states in the Eurocode 1990:

- Loss of static equilibrium,
- Structural failure,
- Geotechnical failure,
- Uplift by water pressure,
- Failure of the soil by hydraulic heave, internal erosion of piping.

Other limit states like fatigue, vibrations and time-dependent effects are not considered separately but as part of either the structural or geotechnical failure mechanism.

For all the types of lock chamber structures listed in section 3.2 the main failure mechanisms have been identified. This is presented in Table 3. For the gravity-based structures and U-shaped structures distinctions has been made between piled and non-piled foundations. A separate column has been included for failure mechanism of the lock floor, which can be seen as separate structures for all types except for the U-shaped structure.

For most failure mechanisms separate subcategories have been identified. For example: the vertical bearing capacity can be exceeded in drained or undrained situations, or because of squeezing or punching. All types of lock chamber walls and floors have been assigned to multiple categories and subcategories.

4.5 Application

Assessing existing navigation locks can be a complex process. Knowledge of specific failure mechanisms of the structures, built in different periods of time using different types of materials requires unique experience. Next to that, experience that is gained on the analysis of a specific navigation lock is often not shared, making it hard for other asset owners to learn from this.

Based on the method as presented in this paper, a structured approach to the analysis of navigation lock chambers can be done. When selecting the relevant construction type(s), the common failure mechanisms and related events are provided. The relevance of each can be evaluated for the lock.

4.6 Indicators

Indicators can warn the asset owners that (partial) failure has occurred or is about to happen. Examples of indicators are:

- Excessive deformation of the walls, either vertically or horizontally in the direction of the chamber.
- Local holes in the surface or pavement next to the lock walls.
- Large cracks in concrete structures.
- Corrosion on sheet piles.

Indicators can be identified based on (visual) inspections or measurements.

4.7 Next steps

Filling a database with examples of specific triggers, events and failure mechanisms is the next step that will be undertaken to increase the value of future analyses.

Table 3. Failure Mechanism per Lock Chamber type

		Gravity-based*	Gravity-based**	Sheet piles	L-walls*	U-shaped*	U-shaped**	Green chamber	Floor*+**
Failure Mechanism	**Limit State**	a1	a2	b	c	d1	d2	e	f
Vertical bearing capacity soil	GEO		x				x		x
Horizontal bearing capacity soil	GEO	x	x	x	x				
Bearing capacity pile / anchor	GEO	x		x	x	x			x
Macro stability soil	GEO	x	x	x	x			x	
Overturning	EQU	x	x		x				
Uplift	UPL						x		x
Structural capacity wall	STR	x	x	x	x	x	x		
Structural capacity floor	STR				x	x	x		x
Structural capacity foundation elements	STR	x		x	x	x			x
Displacement induced failure	STR	x	x	x	x	x	x		x
Internal erosion	HYD	x	x	x	x	x	x	x	x
Heave, piping	HYD	x	x	x	x	x	x	x	x

* on piled foundation, ** without piled foundation

5 Discussion and conclusions

An overview of the navigation lock chambers which are managed by Rijkswaterstaat in the Netherlands is provided. For all lock chambers within these locks, the types of structures have been identified. These can be categorised into five different typologies.

In order to support the assessment of the structural state of the different lock types, an extensive list of possible failure mechanisms has been developed. These mechanisms can occur when unwanted events happen, either being an overload situation of material degradation. These events are preceded by triggers.

By linking the possible failure mechanisms to the different type of structures, asset owners and engineers are supported in their assessment of navigation lock structures.

Future developments such as the addition of indicators and adding past and future experiences of assessments are required to further improve the usability and quality of the method.

6 Acknowledgements

The authors would like to acknowledge the contributions of Rijkswaterstaat experts who participated in the brainstorm sessions about failure mechanisms of lock structures.

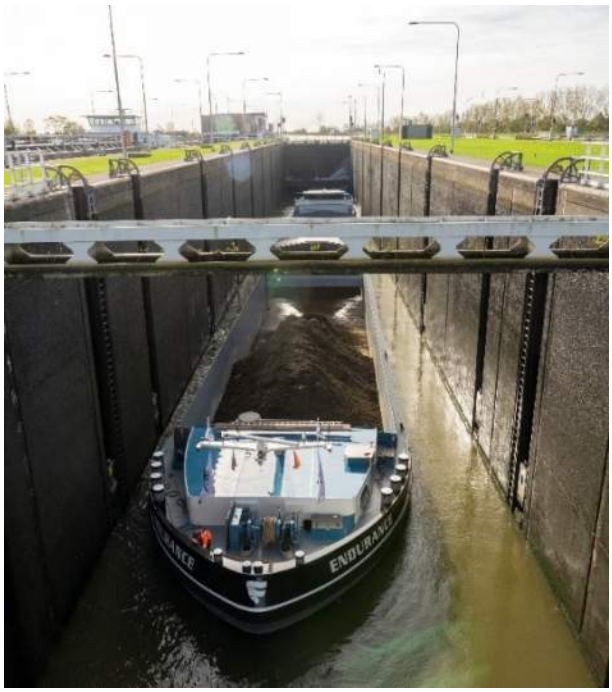


Figure 9. U-shape lock chamber in Lock Maasbracht (NL)

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