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HYDRAULIC DESIGN OF LOCK LEVELLING SYSTEMS: INVESTIGATION OF DIFFERENT SIMPLIFIED METHODS AND THEIR APPLICABILITY

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Aos meus Pais,

Aos meus irmãos

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RESUMO

As vias navegáveis oferecem enormes vantagens como modo de transporte quando comparadas a vias terrestres e aéreas. As eclusas são estruturas fundamentais para permitir a navegação nessas mesmas vias navegáveis. Juntamente com as mais recentes inovações no desenvolvimento de canais, como o Canal do Panamá, é requerido às eclusas que nivelem não só embarcações de maiores dimensões, mas também da forma mais economicamente viável possível.

O IMDC dispõe de conhecimento e ferramentas de medição com vista ao projecto de eclusas, desenvolvendo projectos referentes a navegabilidade. É, portanto, de elevada importância optimizar as ferramentas disponíveis, nomeadamente os *software* de simulação 1D geralmente utilizada numa fase preliminar do projecto de sistemas de nivelamento de eclusas. Consequentemente, é o principal objectivo da presente tese, desenvolvida em ambiente empresarial com o IMDC, investigar as potencialidades e limitações dos referidos *software* e propor soluções e recomendações quanto à sua abrangência de aplicabilidade.

Atualmente, existem dois *software* de simulação de sistemas de nivelamento de eclusas: LOCKFILL e LOCKSIM, que representam o foco principal da presente tese. Posteriormente, ao longo do presente trabalho, encontra-se uma descrição das suas actuais potencialidades e limitações, através do estudo dos manuais de utilizador. Com recurso à introdução dos vários parâmetros de projecto e requisitos inerentes a diferentes sistemas de nivelamento de eclusas, várias simulações sobre sistemas de nivelamento básicos são desenvolvidas. Através do conhecimento adquirido sobre tais sistemas de nivelamento existentes em conjunto com competências adquiridas na utilização do *software*, é elaborada uma abordagem a sistemas de nivelamento especiais, de modo a testar abordagens mais amplas e potencialmente inovadoras para o *software*.

Adicionalmente, relativamente ao *software* de simulação LOCKSIM, o cálculo das forças longitudinais que ocorrem durante o processo de nivelamento é optimizado, sendo introduzido no pós-processamento de resultados da simulação componentes adicionais das referidas forças, que não haviam sido considerados anteriormente, nomeadamente a componente relativa à diminuição de momento e a componente relativa a diferenças de densidade. No que diz respeito ao último, é desenvolvido um modelo numérico no presente trabalho. Esta abordagem é adequadamente descrita ao longo do presente trabalho.

PALAVRAS-CHAVE: Navegabilidade, Design hidráulico, Sistemas de nivelamento de eclusas, LOCKFILL, LOCKSIM

ABSTRACT

Waterways provide enormous advantages as a mode of transport compared to land and air. Locks are fundamental structures in order to enable navigation in said waterways. Along with the most recent innovations in the development of canals, such as the Panama Canal, locks are required to level not only larger vessels, but also to be as much economically viable as possible.

IMDC disposes of knowledge and measure tools to design locks and develops projects regarding waterways navigability. It is, therefore, very important to optimize the available tools, namely the 1D Simulation software generally used in preliminary design of lock levelling systems. Accordingly, it is the main objective of the present thesis, developed in a business environment with IMDC, to investigate the possibilities and limitations of said software and propose solutions and recommendations regarding its range of applicability.

There are, nowadays, two simulation software of lock levelling systems: LOCKFILL and LOCKSIM, which represent the main focus of the present thesis. Subsequently, along the present work there can be found a description of the actual potential and limitations, through the study of the user manuals. In addition to an introduction to the various design parameters and requirements inherent to different lock levelling systems, several simulations regarding basic levelling systems are developed. Following the acquired knowledge about the existent lock levelling systems and the gathered acquaintance to the software, special levelling systems are addressed, in order to test wider and innovative approaches to the software.

In addition, regarding the simulation software LOCKSIM, the computation of the longitudinal forces occurring during the levelling process is optimized, by introducing in the post processing of simulation results additional components of said forces, which were not taken into account before, namely the momentum decrease and density differences component. Regarding the latter, a numerical model is developed in this work. This approach is thoroughly described along the present work.

KEYWORDS: Navigability, Hydraulic design, Lock levelling systems, LOCKFILL, LOCKSIM

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SYMBOLS, ACRONYMS AND ABBREVIATIONS

Chapter 2

CEMT – Conférence Européenne des Ministres des Transports

CFD – Computational Fluid Dynamics

g – Gravitational acceleration [m/s^2]

S_k – Horizontal surface area of the lock chamber [m^2]

S_v – Horizontal surface area of the approach harbour [m^2]

L_r – Length of the culvert [m]

S_c – Cross sectional area of the culvert [m^2]

ξ_s – Loss coefficient of the valve [-]

ξ_r – Loss coefficient of the culvert [-]

F_t – Force on the ship without damping [N]

T_k – Wave period [s]

C_k – Velocity in the section where there is no vessel present [m/s]

C_s – Velocity in the section where the vessel is present [m/s]

h_{bow} – Water level at the bow [m]

h_{stern} – Water level at the stern [m]

l_s – Length of the vessel [m]

b_s – Width of the vessel [m]

d_s – Draft of the vessel [m]

C_b – Block coefficient of the vessel [-]

l_k – Hydraulic length of the lock chamber [m]

b_k – Width of the lock chamber [m]

z_k – Level of the lock chamber floor [m]

h_k – Water level in the lock chamber [m]

$h_{k,0}$ – Initial water level in the lock chamber [m]

x_b – Distance from the gate to the bow of the vessel [m]

Q – Discharge [m^3/s]

α – Vertical angle of the filling jet [º]

S_b – Measure of the filling jet momentum at the bow [-]

h_w – Modified water level in the case that the water level in the lock chamber is lower than the water level in the stilling chamber [m]

C – *Chézy* coefficient [m$_{1/2}$/2]

C_1 – Correction for the pressure build at the bow [-]

C_2 – Ratio of the surface area of the jet that hits the bow and the total surface area of the jet [-]

C_3 – Coefficient to correct for the flow profile immediately behind the stern [-]

β – Vertical angle of the bow [º]

γ – Horizontal angle of the bow [º]

k_I – Roughness of the lock chamber [-]

k_{II} – Roughness of the ship [-]

v_1 – Flow velocity in front of the bow [m/s]

Chapter 3

F'_p – Positive longitudinal force limit defined by the class of vessel [‰]

F'_n – Negative longitudinal force limit defined by the class of vessel [‰]

A_{ks0} – Wet cross section next to the vessel [m^2]

A_{ksm} – Wet cross section of the vessel at maximum discharge [m^2]

A_{str} – Jet cross section [m^2]

Chapter 4

l_{O1-O2} – Horizontal distance between centre axis of outlet 1 and outlet 2 [m]

h_{wk} – Level of the ceiling of the stilling chamber [m]

A_r – Cross sectional area of the culvert [m^2]

Chapter 5

L_{OA} – Vessel length overall [m]

L_{PP} – Vessel length between perpendiculars [m]

P_I – Momentum coefficient for deviations of the uniform flow profile [-]

ρ_1 – Density of the water of the lower layer [m^3/s]

ρ_2 – Density of the water of the upper layer [m^3/s]

ρ_b – Density of the water in the zone in front of the bow [m^3/s]

ρ_s – Density of the water in the zone behind the stern [m^3/s]

ε_b – Relative density difference in the zone in front of the bow [-]

ε_s – Relative density difference in the zone behind the stern [-]

c_{1b} – Front velocity of the intruding layer in the zone in front of the bow [m/s]

c_{1s} – Front velocity of the intruding layer in the zone behind the stern [m/s]

t_b – Moment the front of the intruding layer reaches the bow [s]

t_s – Moment the front of the intruding layer reaches the stern [s]

x_b – Distance from the gate to the bow of the vessel [m]

x_s – Distance from the gate to the stern of the vessel [m]

a_{1b} – Thickness of the salt layer in the bow of the vessel [m]

a_{1s} – Thickness of the salt layer in the stern of the vessel [m]

a_{2b} – Thickness of the fresh layer in the bow of the vessel [m]

a_{2s} – Thickness of the fresh layer in the stern of the vessel [m]

v_{1b} – Flow velocity of the salt layer in the bow of the vessel [m/s]

v_{1s} – Flow velocity of the salt layer in the stern of the vessel [m/s]

v_{2b} – Flow velocity of the fresh layer in the bow of the vessel [m/s]

v_{2s} – Flow velocity of the fresh layer in the stern of the vessel [m/s]

I_{dr} – Transport of momentum from the bow to the stern in a longitudinal direction [N]

1

INTRODUCTION

1.1. INTRODUCTION TO LOCKS

Mankind has been exploring river navigation since ancient times. It started to create primitive boats used for fishing, but the development of civilization led to vessels that grew in size and potential, evolving for expansion in trade and war.

In consequence of said development, problems of the limitations of river navigation started to arise. With the growth of vessels, ancient people realised rivers were often too shallow to carry anything but the smallest boats. The need to control the water level and provide more reliable navigation led to the development of dams, whose purpose was to deepen the water level behind the dam until it spilled over the top, creating a weir. However, the water level downstream of the dam would decrease, leading to the need to repeat the process along the river, creating a “Stairway of water”, consisted of “steps” of deep water. The first known dams to exist date back to around 2950-2750 B.C, built by the ancient Egyptians [1].

Once overcome the problems inherent in the water depth, another problem emerged: How to get the boats to get through said “steps” of water?

The answer to the latter question corresponds to the main object of the present dissertation – Locks.

Locks are devices used for raising and lowering boats, ships and other watercraft, enabling navigation in waterways where there are obstacles, such as weirs, that create differences in water heights of adjacent sections of said waterways. They are not only key structures for the development of canals and natural rivers navigation, but also strategic infrastructure for port development, especially if it is located in lower elevation regions. As an additional function, locks can also have an important task in flood defence, mainly in coastal areas [2].

The basic principle behind the lock operation is somewhat simple: consider an upward bound boat, that is, a boat moving upstream. After it enters the lock chamber, the lower doors are closed and the chamber is then flooded and filled with water from upstream to the level corresponding to the water level in the upstream part of the dam. The upper gates are then opened and the boat exits the lock. In case the boat is moving downstream, it is a similar process but in reverse, that is, the boat enters the lock chamber, the upper gates are closed and then the chamber is emptied by draining its water downstream until the water level corresponds to the downstream part of the dam water level. It works in a similar way to placing a boat in an empty bathtub and then filling it, enabling the boat to rise to a greater height. Emptying said bathtub would result in the reverse result, enabling the boat to decrease to a lower height [3].

However, the process of operation and use of locks entails specific necessities to be taken into account, such as limiting the delay for navigation – the operation of the navigation lock must progress smoothly and within a minimum time –; executing the lock levelling, that is, the filling and emptying of the lock chamber, at the highest possible pace; guarantee the safety from the shipping point of view – the hydraulic forces on the ships inside the lock chamber (in particular the longitudinal forces and the hawser forces, which will be described in more detail later in this document) must remain within specific limits during the operation, which means that the rise or drop of the water level in the chamber must occur at a moderate rate [4]. In other words, safety and comfort of the vessel must be ensured, while simultaneously assure the operation is carried out efficiently in the shortest time possible.

Furthermore, one of the main problems caused by locks is that its use implies a loss of water, proportional to the dimensions of the lock, from upstream to downstream. This loss of water can cause the waterway to dry, which can be critical during dry seasons – naturally, much more of a problem on an artificial canal than on river navigation. Therefore, a balance between the previously mentioned parameters and control of water lost. The latter can be achieved through water saving measures that guarantee the water supply to the channel at the rate that the water is being drained, such as double locks, pumping or water basins [5].

1.2. THESIS OBJECTIVES

The hydraulic design of lock levelling systems entails several steps. The focus of the present thesis is in the preliminary design phase, where software tools such as LOCKSIM and LOCKFILL are often used. This work aims, therefore, to investigate the limitations and possibilities of such software, by exploring the range of application to basic and special levelling systems. In order to do that, it is also the objective of the present work to acquire competences regarding the levelling process of a lock, as well as the different types of existing levelling systems.

Within said existent levelling systems, this thesis will focus on the analyse of the potentials and limitations of the above mentioned software when addressing:

- Levelling systems through openings in the gates;
- Levelling systems through short culverts;
- Levelling systems through long culverts;
- Levelling systems through non-conventional culverts.

Additionally, it is also the goal of this thesis to acquire competences regarding levelling situations where density differences between approach harbour and lock chamber are present.

Therefore, the present goal is to study the design of locks, with a special focus on the levelling processes, integral part of said design. Furtherly, develop an in-depth study of the specific software to be analysed and apply the competences gathered in the development of simulations of several considered scenarios, to finally be able to propose solutions, recommendations and/or improvement regarding the use of such software.

The future lock in *Melle*, the *Carrapatelo* lock in the Douro River and the future sea lock in Ijmuiden are used as case studies.

1.3. THESIS STRUCTURE

The present work is divided in six major chapters, with the present section covering a definition of the thesis objectives and structure, a brief and general introduction to locks and a brief mention of the history of locks and relevant examples in Portugal and the region of Flanders, in Belgium.

In the second chapter, a literature review regarding the study of lock levelling process and inherent levelling systems and design requirements is present, as well as the physical processes occurring in the lock chamber during said process.

This is followed by chapter three, where an in-depth study of the simulation software LOCKFILL and LOCKSIM manuals is developed.

In section four, it is introduced the first and second case studies considered in this work – the future lock in *Melle* and the existent lock of *Carrapatelo* in the Douro River. The approach to these case studies has the goal to apply the acquired competences in the previous chapter regarding basic levelling systems, in order to get acquainted to the software and make initial conclusions of its limitations and potentials.

Finally, in section five, after getting acquainted to the software, an approach to the future sea lock in Ijmuiden is made, in order to expand the range of applicability of the software to more complex levelling systems, namely through non-conventional culverts and levelling situations with a presence of density differences. Regarding the latter, in this section it is also introduced and developed a simplified numerical model intended to be included in 1D modelling of future preliminary design of this specific lock levelling systems.

The last chapter refers to final considerations of the developed work, in addition to partial conclusions found in each chapter, regarding the specific objectives defined for each of them, as well as the proposition of future developments to take into consideration.

1.4. HISTORY OF LOCKS

In order to respond to the previously mentioned problem regarding overtaking the “steps” of water created by the construction of dams, an early and rudimentary way of achieving that was by a flash lock. This system was used extensively in Ancient China and the earliest European references to what were clearly flash locks were in Roman times. It is the first known type of lock and it consists of a lock with a single gate, essentially a small opening in the dam, which could be quickly opened and closed [6]. As there was no lock chamber to be levelled, the process was not exactly the same as the one described in chapter 1.1. To make it possible for a boat to navigate downstream, the opening of the gate would result in a torrent of water spilling out, carrying the boat with it. On the other hand, in order for a boat to navigate upstream, after the opening of the gate it had to be man hauled or winched through against the flow without the paddles, which required considerable skill, both in the removal of the paddles as in the navigating the boat through the gate. The origin of the name results, therefore, of the “flash” that was released downstream by the opening of the gate.

Nonetheless, this method was dangerous. It resulted in many boats being sunk by the torrent of water. As the flash locks were commonly built into small dams where a head of water was used for powering a mill, it was not only dangerous, but also problematic, due to the lowering of the water level in the upstream part of the dam, which made the water level needed by the millers to operate their equipment insufficient.

This conflict of interests between navigation and milling led to the pursuit of other solutions, which in turn resulted in the more sophisticated devices, such as the pound lock. As the name suggests, the main innovation was to provide an upper gate to form an intermediate “pound”, making it possible to control the level of the water in said “pound”, resulting in a significant decrease of the quantity of water consumed by navigation. It was first adopted in medieval China in the 10th century (around 984, during the Song Dynasty). In Europe, the first true pound lock was built in the end of the 14th century at *Damme*, Belgium [7]. In the following decades it developed to other European countries, such as the Netherlands, Italy or Britain.

Although the pound lock had many significant advantages in comparison to the more elemental flash lock, a few of the latter remained. The pound lock is, therefore, the type of lock that is used almost exclusively nowadays, both in canals and rivers.

1.5. EXAMPLES OF LOCKS IN PORTUGAL

Ever since ancient times that river navigation is very important in Portugal, becoming the most important mean of transportation for several hundred years, with special incidence in the transport of commercial goods. More recently, due to the development of other means of transportation that reduced the influence of waterways, the navigability of rivers in Portugal focused more on tourism purposes.

The most notable case of navigability in Portugal is the Douro River. It is an international river, which rises in the hills of *Urbion*, in Spain, and covers about 850 km until his mouth in the city of Porto. Since immemorial times the Douro River established an important mean of transportation, exclusive in this region regarding transport of commercial goods until the beginning of the 20th century. Along its course, in an extension of about 210 km in Portugal, from the border with Spain delimited by the international part of Douro River until the river mouth, it is possible to navigate since 1990 due to the construction of 5 dams (*Crestuma-Lever, Carrapatelo, Bagaúste (Régua), Valeira and Pocinho*) equipped with navigation locks. It allows, consequently, the realization of cruises between the river mouth and the Spanish border [8].

The first lock to be built was Carrapatelo lock, built in 1971. The difference in the water level of this lock is about 35m, which makes it one of the highest dams in the world. It was followed by Régua (1973), Valeira (1976), Pocinho (1983) and finally Crestuma-Lever (1985), with differences of water level of, respectively, 28,5m, 33m, 22m and 13.9m and, as well as Carrapatelo lock, can handle ships with maximum dimensions of 83m in length, 11.4m on the beam, 3.8m load-draught and a cargo capacity of 2500 tons. Even though built with a time interval of more than a decade, and therefore with different technologies, the operation of the five locks is similar in principle [9].

Fig. 1.1 – Douro River navigation channel: 1 – *Crestuma/Lever*; 2 – *Carrapatelo*; 3 – *Régua*; 4 – *Valeira*; 5 – *Pocinho* [9]

1.6. EXAMPLES OF LOCKS IN FLANDERS

In order to introduce some examples of locks in the Flanders region, the focus falls naturally in the port of Antwerp. It is Europe’s second-largest seaport, after Rotterdam, and stand at the upper end of the tidal estuary of the Scheldt River.

A key element that led to the size and influence that characterize the port of Antwerp nowadays was the construction of the *Berendrecht* Lock, located in the right bank of the port. By the time of its inauguration, that dates back to 1989, it was the world's largest shipping lock, with a length of 500 m between the lock gates, a width of 68 m and an operational depth of 13.5 m [10]. It is nowadays the second largest shipping lock in the world, since its title was overtaken with the construction for a new lock on the left bank of the Antwerp port – *Kieldrecht* Lock. The construction of this remarkable lock began in November 2011, and completed in May 2016. Based on the design of the Berendrecht Lock, it has the same length and width, but with an operational depth of 17.8 metres [11]. Also, it entailed the use of twenty two thousand tonnes of steel, which correspond to three times as much as the Eiffel Tower. The necessity for its construction arose in order to ensure better access to the left bank of the port, since the existing *Kallo* Lock had reached its limits. It was very influent to Flanders, enabling the handling of increased size modern ships and reinforcing the leading position of the port of Antwerp in Europe. Within the many advantages the new lock offers, important to highlight the shorter waiting times for ships and faster routes for ships, consequently leading to more shipping traffic and greater added value. Additionally, the construction of the *Kieldrecht* lock also benefits in the European Union core transport network, since seaports such as the port of Antwerp play a crucial role as logistic centres and require efficient hinterland connections [12].

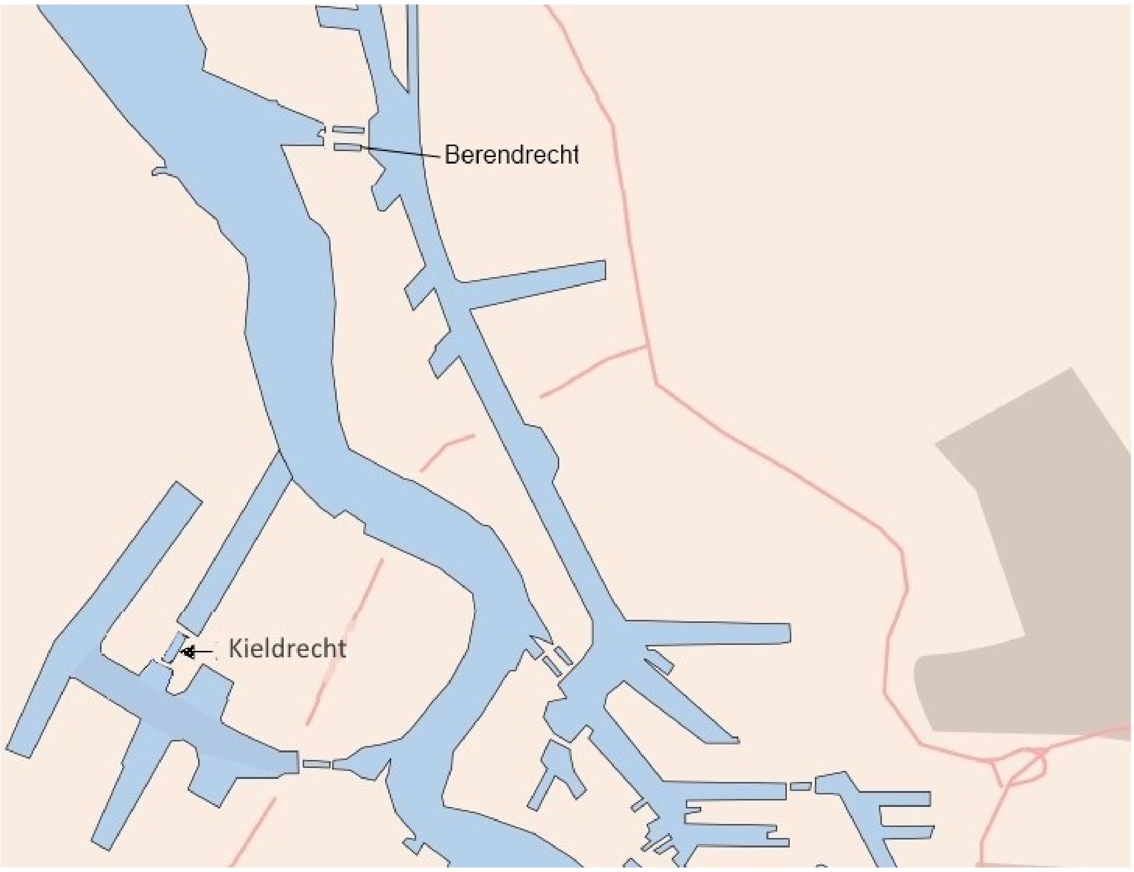


Fig. 1.2 – Location of Berendrecht and Kieldrecht locks within the port of Antwerp

2

LITERATURE REVIEW

2.1. DESIGN OF LOCK LEVELLING SYSTEMS

The planning and designing of locks entails a complex and extensive task, consisting of a large number of aspects. First of all, to the general project objectives are inherent, naturally, economic, financial and environmental objectives. Generally, the process initiates with the emergence of a problem or a necessity to be fulfilled, as is common in the engineering world. That is followed by addressing the problems to a range of possible solutions, which therefore must be accessed individually to confront the above mentioned economic, financial and environmental aspects inherent to each of the potential solutions and its respective impacts. This analysis is followed by a preliminary design process, addressing the requirements inherent to this structure in a specific situation and the design objectives, in order to achieve the more general goals, such as efficiency, safety (both with regard to the lock as to the ships) and reliable lock operations [2] [13].

Even though the author understands the crucial importance of these preliminary studies to the design of locks, the main goal of this paper is directed to the preliminary hydraulic design, with a particular focus on the detailed hydraulic design related to technical concerns and physical modelling in lock levelling systems, namely the intake and discharge systems inside the chamber, which constitutes a significant technical difficulty in the design of a lock.

The purpose of filling and emptying a lock chamber is to control the level of water inside it, ensuring the transportation of one or more vessels from downstream to upstream and vice-versa, respectively. This transportation is required to be executed in such a manner that it simultaneously guarantee the safety of the vessels inside the chamber and is time efficient, i.e., executed in the shortest time possible.

The filling of the chamber can be described as an intake of a certain water volume. The hydraulic phenomenon involved is characterized by a turbulent flow that results from the transformation of potential energy from the difference in the water level into kinetic energy. The non-permanent character of the levelling flow generates translatory waves, which result in horizontal hydraulic forces experienced by the vessels inside the chamber. That occurs, albeit with some differences, both for filling and emptying [13]. In both cases, the translatory waves are mainly significant in the direction of the longitudinal axis of the chamber. Nevertheless, in particular types of levelling systems, there can also be significant transverse translatory waves occurring. The vertical impulse of the water in the vessels is, naturally, also present. Although, due to the levelling occurring at limited velocities, that impulse is no more influent in the security and comfort of the vessels as if it was moored without vertical movement, simply floating. Therefore, the vertical impulse is neglected in lock levelling calculations.

Considering this, the hydraulic design objectives of a lock levelling system resides in simultaneously controlling and optimizing different dependent elements inherent to the hydraulic system. These elements are, as previously mentioned, reducing as much as possible the levelling time, to minimize the impact on the travelling time of the traffic, whilst reducing the forces acting on the vessels and the consequent forces on the mooring system as much as possible, in order to ensure a comfortable and safe rise/drop of the vessels inside the chamber. Also, there must be particular attention regarding the design of the inlets and outlets, since their influence in the intake and discharge flow, and hence the filling/emptying of the chamber, is very significant. The analysis of these elements and the interaction between them is, therefore, an integral part of this document.

The type of levelling system is usually dictated not only by the above mentioned parameters inherent to the lock purpose, but also by site conditions (geotechnical characteristics, environmental limitations) and by economic and financial considerations. Many types of levelling systems are possible to apply, in which the lockable openings play a major role in distinguishing them – The different types of filling and emptying systems are related to the way in which water is conveyed into or out of the chamber, from the basic and more simple cases to special cases, necessary for certain specific situations. A brief, yet more thorough, description of some of the said levelling systems can be found in chapter 2.3.

2.2. DESIGN REQUIREMENTS

2.2.1. LEVELLING TIME

The functionality of a lock resides mainly in enabling waterway navigation. For that reason, the time needed for a vessel to pass through a lock is of great importance. The total time, or passing time, of a vessel includes the time necessary for waiting, sailing in and out, mooring and unmooring and the operational time of the lock itself, i.e., the time in which is included the levelling time [13]. The need to optimize this passing time is due to possible safety and comfort problems as a consequence of very short times or, on the other hand, traffic problems as a consequence of longer passing times.

For this reason, the calculations inherent to the design of a levelling system are made as a function of time, and the objective to optimize the levelling time is an integral part of said design.

In some cases, a maximum allowable limit for the levelling time is stipulated, depending on, for instance, the amount of traffic expected to occur in a certain lock.

2.2.2. HAWSER/MOORING FORCES

Mooring refers to the fixation of a vessel to the bollards inside the lock chamber, to prevent displacements that would cause external damage to said vessel. That mooring is possible using hawsers, a nautical term for a thick cable or rope [14]. Therefore, the Hawser or Mooring forces are the forces exerted in the hawser during the levelling of a lock. These forces directly influence the safety and comfort of a vessel during lockage and constrain the minimization of the levelling time of said lockage. The study of these forces is, therefore, of great importance for the design and operation of the structure.

The Hawser force criterion [15] aims to guarantee a certain degree of safety and comfort to a moored vessel during lockage, by establishing a limit to the longitudinal force exerted on a vessel. In turn, this will affect other criteria such as the maximum levelling velocity and minimum levelling time. The mooring force criterion can be defined in terms of the maximum hydrodynamic force on the vessel and is, usually, expressed as a permillage (‰) of the vessel's displacement weight [16]. For practical reasons, the longitudinal force on a vessel and the consequent hawser force are considered as horizontal forces, which results in a conservative way to interpret these forces within the maximum limit verification.

The above mentioned upper limit has been changed throughout time. Originally, that value used to be constant and depended often on the country and somewhat on the vessel size. *Partenscky* (1986), *Vrijburcht* (1994) and later *De Mulder* (2007), developed a methodology to define that boundary to account for dynamic effects, focusing on inland navigation. CEMT (*Conférence Européenne des Ministres des Transports)* created, in 1992 [17], a set of class of vessels which define the type of lock and the allowable hawser/mooring forces.

Modelling the hawser forces in a physical model can lead to uncertain results, due to the difficulty to faithfully represent the real vessel-positioning system in the scale model. For that reason, numerous innovations have been trying to achieve a more accurate modelling of these forces. However, thanks to the significant increase of computational potential, more powerful, complex and diverse numerical models have been developed, being able to predict more accurately hydrodynamic forces, hence the hawser forces [15]. Important to mention is that, in general terms, numerical models are nowadays capable of predicting the longitudinal components of the hydrodynamic forces with sufficient accuracy, yet the same does not always apply to the transversal. This component requires special attention when modelling special cases such as asymmetrical filling. Despite the above mentioned innovation in numerical models, there is still a margin of error in regard to fully understand and quantify the mooring forces in navigation locks. Validation is required for a more accurate understanding, which can be obtained through in situ measurements, namely a direct measurement of the mooring forces and/or measuring the ship motion itself. Nonetheless, these are not practical to set-up without perturbing the lock operations, so a good path to follow would be to dedicate more efforts to improve in situ observations and measurements, in order to validate the ongoing progress in computational models.

2.2.3. LEVELLING VELOCITY

The mooring of a vessel inside a lock chamber can be executed in mooring bollards or floating bollards. When mooring to the former, during vertical movement the mooring needs to be moved to bollards situated higher or lower, during filling or emptying, respectively. That operation is performed manually, so it highly influences the maximum limit of the levelling velocity, because the boat crew need time to move the hawser to the next bollard.

Resorting to the use of floating bollards, the moving of the hawsers becomes unnecessary, since they rise and fall with the water level. They are usually applied in locks with high lift/drop. It is a more expensive resource, however it can result lower levelling time, which in turn results in a more cost-effective global lock operation [18]. Also, the levelling velocity is no longer a necessary requirement to take into consideration, because it is mainly a maximum limit that depends on the mooring operation during vertical movement.

2.3. TYPES OF LOCK LEVELLING SYSTEMS

2.3.1. OPENINGS IN THE LOCK GATE

Filling and emptying through openings located in the lock gate (almost always centered) are the most prevalent and simplest type of lock levelling. Besides, it is the least expensive system (except for levelling through opening of the gate itself, which will be addressed further in this paper), and has the most favourable maintenance aspects. It consists of a number of openings in the bottom of the gates with movable sluices, mostly on the upstream side [13]. The upper and lower gates are, for the most part, identical and therefore interchangeable. Energy dissipating barriers are usually placed on the downstream side of the lock with the purpose of, as the name indicates, dissipating the flow energy by enhancing the spreading of the filling jet and decreasing the flow velocity. This energy dissipation influences significantly the reduction of the hydrodynamic forces on the ships.

Its use is not recommended for initial lifts/drops bigger than 6m [13]. Nonetheless, with extra adjustments to the design of the openings, such as extra resistance grids or a large number of smaller openings, it may be applicable to initial lifts/drops up to 8m [13]. Said applicability can be even more accurate if the levelling time is considered unimportant. Taking into account these limits, this system is appropriate to inland navigation locks and small marine locks. In these contexts, the usual levelling time when this system is in effect is 8 to 10 minutes, and 12 minutes for higher lifts/drops. For significant smaller lifts/drops, it may be less than 8 minutes.

2.3.2. SHORT CULVERTS

Levelling through short culverts, when comparing to levelling through openings on the gates, can be more expensive, but on the other hand it prevents the lock gates to become weaker due to the existence of the openings. It is also a more adequate system for high lifts/drops, namely between 8 and 12,5m [13], hence making them less expensive. Due to the high construction costs, it is not recommended to empty the chamber through culverts, but with the above mentioned lock gate, unless this is impossible from a hydraulic point of view [13]. The culvert size is set by lift and desired and/or necessary filling time. There is a strong preference for two symmetric culverts in relation to the axis rather than a culvert on one side, due to the forces on vessels caused by the discharge inside the chamber and consequent influence in their manoeuvrability. An adequate flow distribution along the lock chamber is necessary to limit the longitudinal water surface forces, i.e., the translatory waves. Therefore, in order to dissipate energy from the discharge inside the chamber, the culverts are situated symmetrically in opposite walls so that the water jets collide with each other and lose their energy, in a similar phenomenon to the dissipation of flood flow discharges by jets in dams. Also, the outer corners of the lock culvert should always be rounded off, in order to counteract contraction of the flow in the culvert when passing through the outlet, dissipating energy. Jet energy dissipation reduces the chamber water surface roughness, leading to safer navigation for smaller boats [19]. Due to being more adequate for higher lifts, it is applicable to inland navigation locks, small and large marine docks, becoming a necessity in the latter when comparing to the opening in the gates system. Filling through short culverts must always ensure that the culverts remain under water. That precaution comes from the risk of transporting too much air though the culvert inlet when the water enters it. That air is unable to escape due to the short time it spends inside the culvert, resulting in a mixture of water and air entering the chamber, which can create undesired restless water.

2.3.3. LONG CULVERTS

For higher lifts/drops, levelling through short culverts may not be feasible, especially if a short levelling time is required. As the name indicates, long culverts are significantly longer than short culverts, and therefore known as longitudinal culverts in a sidewall filling system. Similar to short culverts, long culvert systems are also situated on both walls of the chamber, in order to dissipate energy by the collision of the jets coming from the layout of the discharge. A long culvert system is characterized by having multiple identical openings along the wall, which allows a more disperse outflow and, consequently, a smaller force on the ships inside the chamber, but the structure is more complex and significantly more expensive [20]. For said reason, it is not reasonable to use this system in lower lifts/drops, but it may be required for higher or, as mentioned above, for specific cases that require a short levelling time. Likewise to short culverts, it is avoided to empty the chamber through long culverts as well, due to the high cost of the construction. Important to mention that, for high lifts, a non-constant lift rate of the sluices is often applied to limit the filling time of the chamber.

2.3.4. LOCK SYSTEM IN THE PRESENCE OF A SALT GRADIENT

In locks located near the sea, there is also the problem of the presence of salt in the water, as a chamber that initially contains fresh water is filled with salt water. This entails consequent problems, namely the difference in water density between salt and fresh water and environmental problems arising from the water mixture. The latter problems can occur if water is used for human and/or animal consumption or to irrigate agricultural areas, as well as when the salt water penetrates the inland soil [2]. Salinity in the lock chamber and access channels may also become a problem in this case. Therefore, special levelling systems that take into consideration this presence of salt gradient must be designed for locks that face requirements to keep the salt penetration on the inland area and the loss of fresh water as low as possible.

The density differences between salt and fresh water create not only density currents that result in additional forces on the vessels and the lock gates, but also differences in draught. Basically, the boat vertical displacement is bigger in fresh water, resulting in a deeper sinking. The differences in water levels and water density between the bow and the stern contribute to the longitudinal force [13]. This contribution is one the components of the longitudinal forces that will be described in detail further in this thesis. The largest forces are generated when the gates are open and the lock chamber exchanges salt to fresh water, and vice versa. Instinctively, it is concluded that this component is more important in the particular levelling systems that are object of this chapter.

Naturally, as it is characteristic of special levelling systems, it results in extremely expensive lock systems, compared to the more basic cases mentioned above, and in consequences for the geometry of the lock (e.g. deepened bottoms, sufficiently wide for a salt lift trap and culverts) [13]. Lock systems with this intended purpose generally have a decelerating effect on locking, as the focus is on reducing as much as possible the salt intrusion in the fresh water, which requires a very calm water movement during filling and emptying. This results in even higher costs due to the increased levelling time.

Apart from the levelling systems specially designed to remove the salt layer during locking, other solutions to reduce salt water intrusion in locks include, e.g., an air-bubble-barrier in the lock head to avoid exchange of salt and fresh water as the gates are opened, movable sill on the lock's floor to reduce the water depth to a minimum for the ships to be locked, use of multiple lifts or salt water pump. In addition to this technical solution, reducing the opening time of the gates and/or the number of lock cycles may also reduce the salt intrusion in the chamber [2].

2.3.5. NON-CONVENTIONAL CULVERTS

Design of non-conventional culverts for a lock levelling system originates in the need to make adjustments in particular cases, due to, e.g., geotechnical, geographic or exploration peculiarities of the system. It results, naturally, in design changes of the already known culvert levelling systems, that can be related to a wide range of different approaches in intake of water, discharge of water (either in the chamber, e.g. asymmetrical filling, or outside of the chamber), levelling process and operation or even in the physical shape of the lock components, such as non-conventional shapes for gates, culverts and/or lock chamber.

The design and use of non-conventional culverts is always inherent to a more meticulous study, as its use is characteristic of a new approach and needs proper validation. It may also result in an over-expensive lock when compared to the basic cases, so a thorough economic evaluation most be executed to validate the viability of said design.

2.3.6. ALTERNATIVE LEVELLING SYSTEMS

2.3.6.1. Short Culverts with Stilling Chamber

This levelling system, although similar to the short culvert in the way the intake of water is executed into the culvert, discharges into a stilling chamber instead of directly in the lock chamber. The stilling chamber is fitted with energy dissipating barriers and baffle vanes in order to dissipate the energy of the discharge flow. That way, not only the vessels are not subjected to the direct impact of the jets but also the influence of said filling jets in the longitudinal force is lower, which results in lower mooring forces. Similarly to the short and long culvert systems, it is used in lifts/drops of 5 m or more [13]. Important to mention is that the emptying of the chamber is not done through the stilling chamber, but through gate opening or lock culverts installed at the lower head.

2.3.6.2. Bottom Filling

In a bottom, or floor, filling system, the water intake is done through one or more culverts in the floor (recommended to always place them symmetrically, to provide good water distribution throughout the chamber), and from them brought into the chamber via floor grids. These systems were developed for high lift/drop locks. They provide rapid levelling times but are also very expensive. Only a thorough economic evaluation can determine if it is beneficial to use this levelling system, weighing the extra structural costs with the operation costs saving due to the reducing of levelling times [13]. This levelling system is usually adopted for larger or higher-lift locks of modern commercial rank.

2.3.6.3. Slight Opening of Lock Gates

This a simple and inexpensive levelling system, as it doesn’t require special gates with openings in them or the construction of additional structures, e.g. culverts. Filling and emptying take place by means of slowly raising a gate or opening a sector gate. The area of discharge is, therefore, characterized by a gap opening corresponding to the total width of the lock and the height of the opening. However, special attention must be paid to its intake flow, possibly requiring it to discharge into a stilling chamber in order to dissipate its energy. The gate movement must also be very slow in order to prevent large translatory waves [13].

2.4. PHYSICAL PROCESSES

This section contains a more thorough and meticulous description of the phenomena happening inside the chamber during filling or emptying. A good understanding of these phenomena is crucial to choose and design a more efficient lock levelling system. A better understanding of previously mentioned concepts such as filling/emptying flow, flow energy, translatory waves, occurring longitudinal forces and computation of the mooring forces can be found in this chapter.

2.4.1. LEVELLING FLOW

The filling flow, i.e. the discharge into the chamber, is a function of the current lift (water level difference) over the opening through which the intake of water takes place, and the dimensions of said opening. Its evolution in time during the filling – flow rate –depends on the levelling system applied.

In the case of levelling through gate openings, the area of the openings increases gradually as the chamber is being filled. The discharge in the chamber is directly related to the water level and the water level during time is a function of the discharge. Therefore, said water level initially rises slowly and at maximum flow it rises the fastest. Notice that the maximum flow does not occur at the same time as the maximum opening, since it also depends on the upstream water level. The moment corresponding to the maximum discharge occurs before reaching the upstream water level, i.e. the end of the process. Therefore, the flow will start to decrease and the water level in the chamber will increase slowly near the end of the filling process, until the water level of the lock approach is reached. Emptying occurs in a similar way, differing in the water level falling instead of rising. Important to mention again that, in order to ensure proper mooring during the operation with fixed bollards, the rising velocity of the water level is limited to a maximum. Usually, the adopted limit is 1 m/min [13].

The particular moments in time of levelling that require more focus are, therefore, the moment of maximum discharge, the moment that the openings are completely open for the first time, and the moment that the chamber is completely levelled (opening discharge is zero and difference in water level between chamber and approach harbour is also zero). Also, from the designer point of view, the most important to consider is the moment when the difference in level between chamber and approach harbour is reduced to about 0.1 m, which corresponds to the moment when the gates may be opened, in order to reduce the operation time [13].

The software LOCKFILL, for levelling systems characterized by gate openings, calculates the discharge using *Bernoulli*, in function of the instantaneous water level difference (Δh) between upstream water level (h_u) and water level inside the lock (h_k), the surface area of the gate openings (A_h) and the discharge coefficient of the gate openings (μ). The latter is a very significant and important factor in numerical simulations, and will be therefore presented in more detail further in the present work. The discharge is as seen in expression (2.1) [21]. Important to mention that it is a generally used expression, and therefore not specific for LOCKFILL.

$$Q = \mu \, . A_h . \sqrt{2g|\Delta h|} \, . \frac{|\Delta h|}{\Delta h} \tag{2.1}$$

Where,

$$\varDelta h = h_v - h_k \tag{2.2}$$

$$h_k = h_{k,0} + \frac{Q \,.\, \varDelta t}{S_k} \tag{2.3}$$

Usually, the upstream water level, i.e. the water level in the approach harbour is not influenced by the filling process, because it is usually much larger than the lock chamber. Nonetheless, in the case that said water level is influenced by the filling process, it is given by:

$$h_v = h_{v,0} + \frac{Q \,.\, \varDelta t}{S_v} \tag{2.4}$$

If the levelling is executed through culverts, the filling and emptying flow and water level rising occurs in a similar way to the above mentioned, although with some differences, namely regarding the outlet of the culvert (inlet of water intake to the chamber) and filling jet, as it was described above. However at the end of the process for both filling and emptying, the discharge in the culverts reduces to zero to subsequently change direction and the water level is characterized by an oscillating vertical movement, rising and lowering around the upstream/downstream water level respectively, until it eventually stops at said level. The inertia of the culverts is. Therefore, important to take into account, as it has a significant influence on the levelling time and cause a damped oscillation of the water surface (overtravel phenomenon) [22]. Important to mention that, for this system, the discharge coefficient is replaced by the sum of the friction and local loss coefficients inherent to the various components of the culverts, namely the entrance (inlet section), changes of stream direction (curved segments such as bends or elbows), sudden changes in velocity and flow area (e.g. sudden expansion or sudden contraction of the culvert cross section), converging and diverting of flow streams (e.g. T-junctions, manifolds), existence of flow resistant barriers (e.g. grids or screens), valves and exit of the culvert (outlet section).

In LOCKFILL, the formulation for the culverts is based on continuity equations of the lock chamber and approach harbour, and the equation of motion of the culvert system [21]. The flow rate characteristic of these levelling systems can be determined by:

$$Q = \frac{\varDelta h - Q_0\left(f - \frac{L_r}{g\, S_C\, \varDelta_t}\right)}{\bar{\xi}\,|Q_0|\,.\,\frac{1}{2g\, {S_C}^2} + \frac{L_r}{g\, S_C\, \varDelta_t} + f} \tag{2.5}$$

Where,

$$\bar{\xi} = \frac{\xi_{s,0} + \xi_s}{2} + \xi_r \tag{2.6}$$

$$f = \frac{\varDelta t}{4}\left(\frac{1}{S_k}\right) \tag{2.7}$$

Δh is determined according to expression (2.2), following:

$$h_k = h_{k,0} + \frac{(Q + Q_0) \,.\, \Delta t}{2 \,.\, S_k} \tag{2.8}$$

If the upstream water level is not fixed:

$$h_v = h_{v,0} - \frac{(Q + Q_0)\Delta t}{2\, S_v} \tag{2.9}$$

2.4.2. PHENOMENA IN THE LOCK CHAMBER

As it was previously mentioned, the levelling process generates translatory waves in the lock chamber. In view of the discharge flow in or out of the chamber occurring in the upper/lower head, this phenomenon takes place mainly in a longitudinal direction. The generated translatory waves will then travel through the chamber, reflecting almost completely against the gates at both ends and partly against the bow and stern of the vessel. In the latter, the presence of the vessel actually decreases the speed of the translatory wave, increasing its height. Hence, the reflections are dependent on the blockage of the ship. Those reflections create an oscillating vertical movement in the water level. As a side note, notice that the oscillating period is the time that a disruption requires to travel up and down through the chamber. For calculation purposes, two wave velocities are defined in the lock chamber, one in the part where there is a presence of the ship and another in the part where there isn't. As made clear above, the latter will be higher than the former.

Another phenomenon that occurs in the levelling process is the high flow velocity provoked by the filling jets, which decrease in longitudinal direction of the chamber as it comes into contact with the surrounding water. That is mainly significant when filling through gate openings, once the flow energy through culverts dissipates as jets from both walls of the chamber collide with each other. Also, friction between the water and the chamber floor, the chamber walls and the vessel, as well as density differences throughout the chamber, must be considered. Regarding the latter presented parameter, notice that in the means that this thesis focus on the levelling systems of a lock, the characteristics of the lock chamber components, such as the floor and the walls, i.e. the general structure of the lock, will be based on pre-existing or pre-determined characteristics intrinsic to the case studies. Therefore, said characteristics will not be subjected to changes by the author, remaining fixed throughout the modelling.

These effects result in a flow impulse that decreases in longitudinal direction of the chamber and corresponds to the water level differences in the same direction, induced by the described phenomena.

2.4.3. OCCURRING LONGITUDINAL FORCES

The impulse described in the latter chapter represents the occurring longitudinal force exercised on a vessel, which must be calculated and considered in order to determine the active hawser, or mooring, forces and its respective limits. As previously mentioned, the longitudinal forces are usually expressed as a permillage (‰) of the weight of the water displacement of the vessel [21]. Henceforth, if a longitudinal force acts in the direction upstream to downstream, it will be considered positive, and vice-versa, i.e., considered negative if acting in the direction of downstream to upstream.

The components of such longitudinal force to be considered vary between filling and emptying, as described in the following chapters.

2.4.3.1. Filling

During the filling of the lock, the occurring longitudinal forces can be described as the set of actions of five components [13]:

a. Translatory waves

Component related to the wave phenomenon that occurs from filling the chamber. It is understood as two different contributions: average contribution, positive until the moment of maximum discharge and negative after said point, and the wave reflection mentioned in section 2.4.2, as a harmonic contribution. This component is larger at the beginning of the filling process because the water level is lower and, therefore, the relative blockage created by the vessel is larger. Important to mention that, in the eventuality of the maximum gate opening occurring before the maximum discharge time, this harmonic contribution is strengthened due to the discontinuities in the course of discharge [13]. It is therefore important to prevent this situation in order to provide a smooth filling.

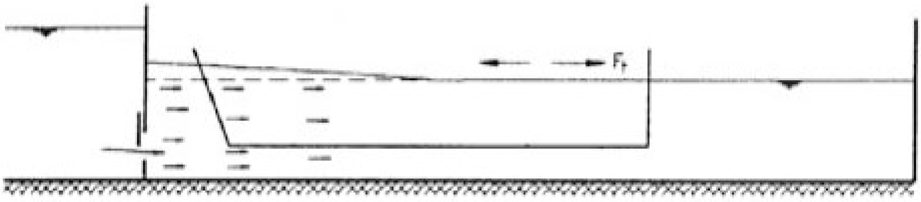


Fig. 2.1 – Translatory wave component of the longitudinal force during filling [13]

LOCKFILL calculates the translatory wave based on the flow rate at the inlet of the levelling system and taking into consideration the blockage of the vessel [21].
Also, in this software the force (in ‰) on the ship due to the translatory waves is compensated for damping by the inlet.
Hence, the final longitudinal force on the vessel due to translatory waves is given by
:

$$F_{tw} = F_t - (F_t - F_p) . \left(1 - e^{-C_e \frac{t}{T_k}} \right) \tag{2.10}$$

Where,

$$F_t = \frac{h_{bow} - h_{stern}}{I_s . C_b} \tag{2.11}$$

$$F_p = \frac{\left(l_k - x_b - \frac{l_s}{2}\right) . \frac{dQ}{dt}}{C_b . g . l_k \left((h_k - z_k) . b_k - t_s . b_s\right)} \tag{2.12}$$

$$C_e = 0{,}07 + 0{,}4 . \frac{t_s . b_s}{b_k \, (h_k - z_k)} \tag{2.13}$$

$$T_k = 2 . \left(\frac{l_k - l_s}{c_k} + \frac{l_s}{c_s}\right) \tag{2.14}$$

$$c_k = \sqrt{g \, (h_k - z_k)} \tag{2.15}$$

$$C_s = \sqrt{g * \frac{(h_k - z_k) * b_k - t_s * b_s}{b_k}} \tag{2.16}$$

b. Momentum decrease

As the momentum of the flow decreases in the longitudinal direction of the chamber, the water level differences resulting from it cause a negative contribution to the longitudinal force. Therefore, this component contribution is always negative, with the exception of locking short vessels that are not too close to the filling gate. This component peak occurs in the occasion of maximum momentum of the flow, which in turn corresponds to the moment just before the maximum discharge.

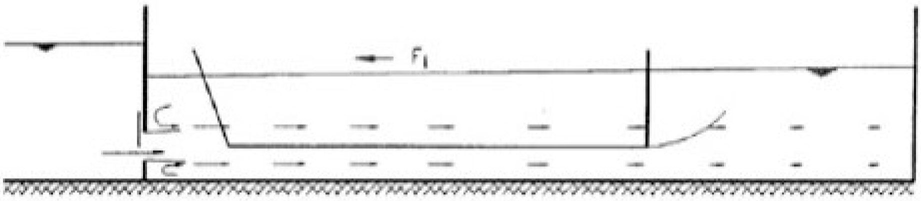


Fig. 2.2 – Momentum decrease component of the longitudinal force during filling [13]

In LOCKFILL, the force due to the decrease in momentum is distinguished between filling through gate openings and lock culverts, since in the latter there will be no filling jet present in the longitudinal direction [21].

Accordingly, the force resulting from this component in locks filled through gate openings is given by:

$$F_{si} = \frac{\rho t_s b_s}{h_k b_k - t_s b_s} \left(-\frac{l_k - x_s}{l_k} \, S_b \cos \alpha + \frac{Q^2}{h_k b_k - t_s b_s} \left(\frac{l_k - x_s - l_s}{l_k}\right)^2 \right) \tag{2.17}$$

When filling through culverts, on the other hand, is characterized by non-presence of the filling jet, and therefore the first term in brackets in the expression (2.17) is null. The resulting force from this component given by this levelling system is, therefore:

$$F_{si} = -Q\,|Q|\,\frac{\rho t_s b_s}{h_k b_k - t_s b_s}\left(\frac{\left(\frac{l_k - x_s}{l_k}\right)^2}{b_k h_w} - \frac{\left(\frac{l_k - x_s - l_s}{l_k}\right)^2}{h_k b_k - t_s b_s}\right) \tag{2.18}$$

Where,

$$h_w = \min\ (h_{woel} + \frac{0.1667}{2}\, x_s\ ;\ h_k) \tag{2.19}$$

c. Friction

The friction effects mentioned briefly in chapter 2.4.2 establish a positive contribution to the longitudinal force, with its peak taking place just before the maximum discharge. It is therefore similar in peak moment but opposite in force direction to component b, whilst their magnitudes also naturally differ, depending on the situation.

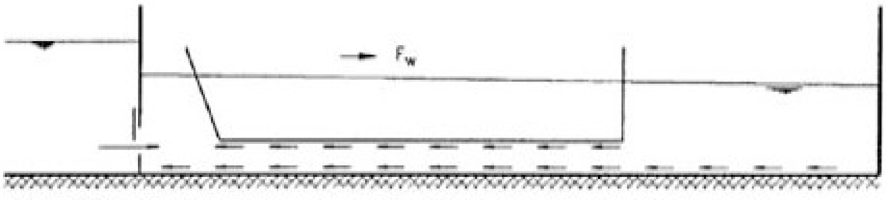


Fig. 2.3 – Friction component of the longitudinal force during filling [13]

In LOCKFILL, the resulting friction effect on the longitudinal force is calculated using the average flow velocity along the hull of the vessel, the *Chézy* formula and the formulas of *Strickler* and *Colebrook-White* [21], the result of which is shown by the following expression:

$$F_w = F_{bw}\left(\frac{t_s b_s}{h_k b_k - t_s b_s}\right) + F_{sw}\left(\frac{h_k b_k}{h_k b_k - t_s b_s}\right) \tag{2.20}$$

Where,

$$F_{bw} = C_3 \rho g \left(\frac{2l_k - 2x_s - l_s}{2l_k}\right)^2 \cdot \frac{Q|Q|}{(h_k b_k - t_s b_s)^2} \cdot \frac{(b_k + 2h_k) l_s}{C^2} \tag{2.21}$$

$$F_{sw} = C_3 \rho g \left(\frac{2l_k - 2x_s - l_s}{2l_k}\right)^2 \cdot \frac{Q|Q|}{(h_k b_k - t_s b_s)^2} \cdot \frac{(b_s + 2t_s) l_s}{C^2} \cdot \sqrt[4]{\frac{k_{II}}{k_I}} \tag{2.22}$$

$$C = 18^{10}\log\left(\frac{12R_I}{k_I}\right) \tag{2.23}$$

$$R_I = \frac{h_k b_k - t_s b_s}{\sqrt[4]{\frac{k_{II}}{k_I}} \cdot (b_s + 2t_s) + (b_k + 2h_k)} \tag{2.24}$$

d. Filling jet

The jet filling impact into the bow of the vessel, in the beginning of the process, where it is of higher significance, is also taken into account. It starts by providing a positive contribution to the longitudinal force in the chamber. The less contact with the vessel made, due to its rising during filling, the less the magnitude of this contribution will be. Accordingly, said contribution disappears when the jet is no longer in contact with the bow of the vessel.

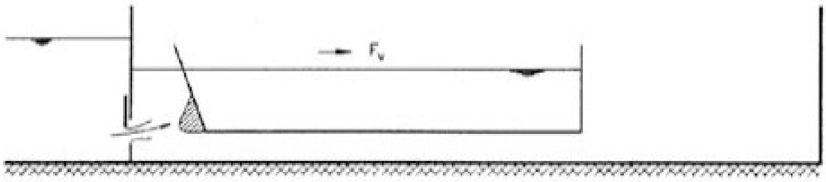


Fig. 2.4 – Filling jet component of the longitudinal force during filling [13]

LOCKFILL calculates this component using the following formulation [21]:

$$F_{SS} = \left(\frac{\rho h_k b_k}{h_k b_k - t_s b_s}\right)\left(C_1 C_2 Q\ \frac{l_k - x_s}{l_k} v_1 \sin\alpha + \ \beta \sin\beta \sin\gamma\right) \tag{2.25}$$

Note that, when filling through culverts, there is no jet filling impact, since the jets from both symmetrical outlets of the culverts collide against each other and not against the vessel, therefore $F_{SS} = 0$.

e. Density differences

Especially in the presence of a salt gradient mixing with fresh water, as described in section 2.3.4., the differences in density will induce the formation of a density current during the filling process. Consequently, the resultant differences in water levels become a significant component of the longitudinal force in the chamber. It results in a positive contribution when a chamber containing fresh water is filled with salt water and a negative contribution in the opposite situation. The processes involved when filling in the presented conditions, i.e. filling with water of different density than the water inside the chamber, are quite complex. According to LOCKFILL manual, it is not possible to capture all these effects in a one-dimensional model [21]. Thereupon, it is recommended to describe this phenomenon with physical model experiments.

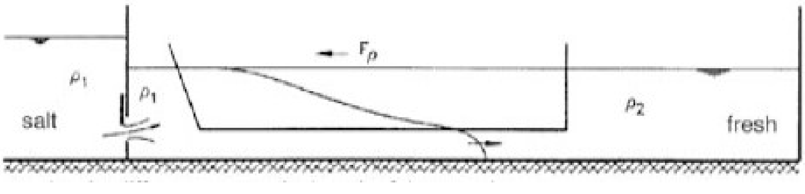


Fig. 2.5 – Density difference component of the longitudinal force during filling [13]

Naturally, the importance and impact of these different components depend on the levelling system applied. However, generally, components “a” and “b” provide the largest contribution to the sum of these components that compute the longitudinal force [13], as it will be possible to verify throughout this work.

2.4.3.2. Emptying

During the emptying of the lock, there are no additional components to consider. Nevertheless, the already mentioned components behave differently.

a. Translatory waves

It has a negative contribution until the maximum discharge moment and thereafter a mainly positive contribution, which peak occurs at the end of the emptying process when the water is at its lowest level and, consequently, the blockage provided by the vessel is bigger.

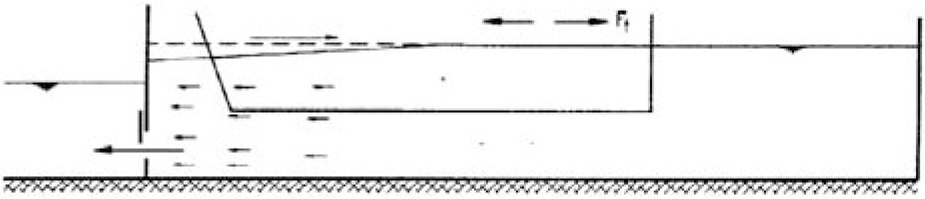


Fig. 2.6 – Translatory wave component of the longitudinal force during emptying [13]

b. Momentum decrease

Its contribution is, similarly to the filling of the chamber, negative, being that it is limited in the absence of concentrated flow.

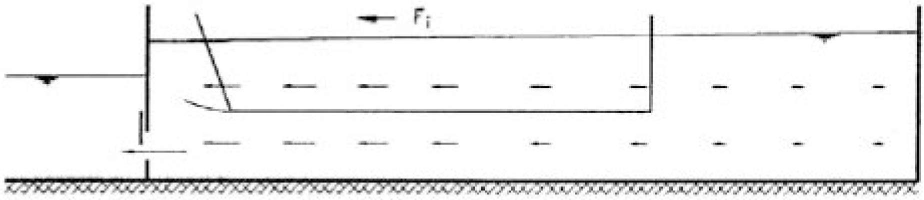


Fig. 2.7 – Momentum decrease component of the longitudinal force during emptying [13]

c. Friction

Limited and negative contribution, similar to the filling but in opposite direction.

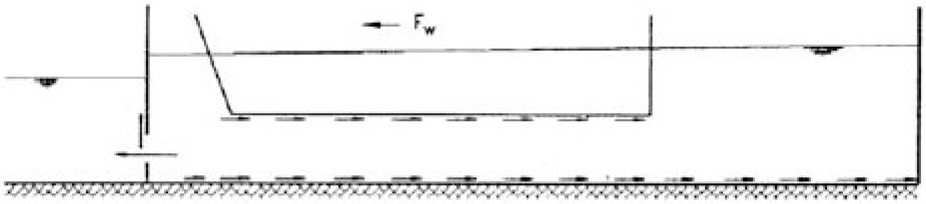


Fig. 2.8 – Friction component of the longitudinal force during emptying [13]

d. Filling jet

As there is not filling flow in emptying, this component is no longer examined in the emptying of the chamber – $F_{ss} = 0$

e. Density differences

As well as component “d”, this component is neglected once the density differences would only impact the longitudinal forces outside the chamber, and those do not respect the objective of this analysis.

In summary, once more component “a” is the dominant component in estimating the longitudinal force in the emptying of the chamber, component “b” is mostly used to check and can be ignored when deemed appropriated, component “c” is almost always ignored and components “d” and “e” no longer constitute a viable component of the occurring longitudinal force [13].

2.5. SOFTWARE TOOLS

2.5.1. LOCKFILL

LOCKFILL is a calculation program developed by *Deltares* (former WL|Delft Hydraulics), commissioned by the Dutch Ministry of Public Works. This program enables simulation of the locking process and it computes the hydraulic forces on a ship in the lock chamber [4].

The calculation method of LOCKFILL is based on scale model research, desk studies, and earlier developed calculation programs. Throughout the years, it has been improved. The first version of the software was developed by *Deltares* during 1989-1993, resulting in LOCKFILL 3.1. With the development of a new user-interface to make it available for the new operative systems in the market, at the end of 2002/beginning of 2003, *Deltares* upgraded it to LOCKFILL 4.1. In order to make it available to third parties, in 2012 another upgrade was developed, resulting in LOCKFILL 5.0. After applying it in several projects, around 2014 the actual version of LOCKFILL was developed – LOCKFILL 5.1. [21].

As demonstrated in the sections above, LOCKFILL computes the hydraulic conditions in the lock chamber (average water levels and levelling flow rate) and consequent longitudinal force on the ship as a function of time, considering the different components introduced in section 2.4.3. The hydraulic computations are based on a one-dimensional approach, in which cross-sectional averaged quantities are applied.

The software requires several input data, such as the discharge characteristics of the levelling system, the dimensions, draught and physical characteristics of the vessel in the lock chamber and the dimensions and characteristics of the lock structure. Optionally, there can be indicated a limit value for the longitudinal force, in order to conveniently and timely detect any problems regarding said limit.

Regarding the discharge characteristics, preliminary determination and establishment of these parameters is required, which can be accomplished either by analytical formulas, a scale model study or using CFD (Computational Fluid Dynamics) calculations.

The output that LOCKFILL provides include water levels, vertical velocity of the levelling, levelling discharge and components of the longitudinal force on the ship. That enables the determination of levelling time and the active mooring forces, which can then be compared to a limit value, if not introduced previously in the simulation.

The main application of LOCKFILL to this dissertation is that it simulates the levelling process of a lock. Even though it makes possible to simulate several options for levelling systems, such as through openings in the gates, through the lock gates and through short culverts in the walls with a stilling chamber, one of the main objectives of this work is to analyse if and how it can be applied to other levelling systems. Also, as this software has some significant limitations, they will be analysed as well to understand in which conditions the software can be applied and what improvements or modifications it would require to overcome said limitations.

2.5.2. LOCKSIM

LOCKSIM is a numerical model developed at the Tennessee Valley Authority's (TVA's) Engineering Laboratory for simulation of one-dimensional transient filling and emptying flow in navigation locks [23].

Similar to the above described software, LOCKSIM allows the simulation of lock levelling systems and will therefore be used in the modelling presented in this thesis, to understand and compare both software tools.

The origin of LOCKSIM is a BASIC computer code written by Gerald A. Schohl in the mid-1980s, primarily for water hammer applications in closed conduits. Its first application to a navigation lock dates back to 1989, in a study of a transient condition at TVA's Wheeler Main Lock. By 1992, the code (named at the time TFSIM) had been rewritten in C language and had the capability of modelling both open channels and closed conduits in the same network, making it possible to estimate longitudinal hawser forces as a lock goes through the levelling process. Ever since, the code has been used extensively, both for screening of potential innovative designs and for analysis of existing locks. LOCKSIM is a result of TFSIM without features unnecessary for simulation of lock levelling systems, making it a reliable tool for evaluating said systems [23].

In LOCKSIM, it is possible to arrange various components of a levelling system in any desired combination and, as it is operated interactively, allows the user to examine results and change parameters at any point during the simulation. It enables the simulation of a significant wider range of levelling systems, in comparison to LOCKFILL. Similarly to the latter, LOCKSIM also requires previously determined input data, namely regarding head loss coefficients. However, it provides more options for specifying components and boundary conditions, which may become very useful to the main purpose of this paper.

It provides, as an output, not only time series of the lock water level, essential for the design of a lock, but also information regarding other parameters, such as near velocities in lock approaches (upstream and downstream) and discharge and pressures in culverts. Hawser forces are not calculated directly but should be determined via post processing of the output data.

From the user point of view, LOCKSIM and LOCKFILL are significantly different to operate, as it will be described in detail further in this paper.

3

MODELLING

3.1. PRELIMINARY CALCULATIONS

In chapter 2.5.1, it was acknowledged that the presented simulation software LOCKFILL requires several inputs, regarding the discharge characteristics of the systems and the dimensions of both lock and vessel. To that effect, a calculation method can be used, namely through analytical formulations (found in the handbook *Design of Locks)* or using the LOCKDIM calculation programme (developed by *Deltares*). In this work, this preliminary task was performed resorting to the former, using the spreadsheet software *Microsoft Excel*.

The preliminary calculations allow the determination of essential data regarding the discharge characteristics, such as the opening height and the maximum lift velocity of the sluices, but also need input regarding the specific case study and the design objectives, such as initial water levels in both approach harbour and chamber, vessel and lock characteristics, width of the openings and adopted discharge coefficient. As mentioned before, this work will focus mainly on the hydraulic design and simulation of lock levelling systems, and therefore an explanation of the preliminary studies inherent to said hydraulic design will not be itemized. The result of those studies is information regarding a given case study, such as present initial water levels, dimensions of the lock chamber and class of vessel to consider for the simulations, hence the dimensions of said vessel, its block coefficient and the maximum permitted longitudinal force.

This is a particularly crucial stage of the design, on account of allowing the user to return to this software after executing the simulation, to change any parameters deemed adequate, as part of an iterative process. Although, there are some fixed values which are important to indicate, since, as the name implies, they will not be subjected to change throughout the simulations. The fact that they are considered fixed comes from several reasons, namely being natural phenomena, such as gravity, intrinsic characteristics of the lock and vessel, or parameters defined by specific objectives for a given case study. Regarding the characteristics of the lock, in a complete design of the lock structure those parameters could be subjected to change, or could even be the end result of the design and therefore effectively subjected to change. However, due to the nature of the study presented in this thesis, these parameters were considered fixed, depending on the specific case study. Concerning the specific objectives for a given case study, the particularities will be explained within its description. Accordingly, this result in a set of variables influencing the lock levelling operation, which can be managed in accordance to a specific case with a specific lock levelling system applied. In the following chapters regarding the modelling of the present case studies, a distinction and description can be found between fixed and variable values.

The *Microsoft Excel* sheet developed for this effect only takes into account th1e filling and emptying of the lock chamber with gate openings. Important to clarify is that this tool represents a pre-conceptual design tool, and therefore its main application is to estimate the dimensions of the gate openings, assumed rectangular, by taking into consideration four conditions [13]:

i. The contribution in the total longitudinal force of the component a (translatory waves – chapter 2.4.3.1) in the beginning of the filling process may not exceed the permitted longitudinal force. This condition results in an upper limit of the lift rate (v_{h0}).
ii. The contribution in the total longitudinal force of the component b (momentum decrease – chapter 2.4.3.1), just before the moment of maximum discharge may not exceed the permitted longitudinal force. This condition results in another maximum value of the lift rate (v_{hm}).
ii. The moment of maximum gate opening should occur slightly later than the moment of maximum discharge, in order to allow a smooth discharge and, consequently, a smooth levelling – lower mooring forces acting on the vessel.
iv. The total width of the gate openings (b_h) is limited by a lower value of 50% of the lock width and an upper value of 67% of the lock width.

Therefore, the maximum lift rate resulting from condition 1 is given by [13]:

$$v_{h0} = \frac{F'_p \, . \, g \, . \, A_{ks0}}{1000 \, . \, \mu \, . b_h \, . \, v_0} \tag{3.1}$$

Where,

$$A_{ks} \ = \big((h_{downstream} - \ z_k) \, . \ b_k - \ A_s\big) \tag{3.2}$$

$$v_0 = \ \sqrt{2 \, . g \, . \Delta h_0} \tag{3.3}$$

The upper limit to the lift rate resulting from condition 2 is given by [13]:

$$v_{hm} = \frac{- \, F'_n \, . \ \ A_{ksm} \, . \, C_b \, . \ g \, . l_s}{\left(\frac{16000}{27}\right) . \ \mu \, . \ b_h \, . \ v_0 \, . V \, . \left(\left(\frac{c_{l1}}{A_{str}}\right) - \left(\frac{c_{l2}}{A_{ksm}}\right)\right)} \tag{3.4}$$

Where,

$$A_{ksm} = \left(h_{downstream} + \frac{5}{9} . \ \Delta h_0 - \ z_k\right) . b_k - \ A_s \tag{3.5}$$

$$A_{str} = 1{,}5\ .\ b_h\ .\ d_2\ .(h_{downstream} - z_k) \tag{3.6}$$

$$c_{l1} = \left(\frac{l_k - x_b}{l_k}\right)^2 \tag{3.7}$$

$$c_{l2} = \left(\frac{l_k - l_s - x_b}{l_k}\right)^2 \tag{3.8}$$

Hence, the normative lift rate, corresponding to the maximum lift speed of the gate openings (v_h), is the minimum value between v_{h0} and v_{hm}.

The lifting time (t_h) [s], naturally depends on the lifting speed, and can be determined by [13]:

$$t_h = d_3\ .\sqrt{\frac{2\ .\ b_k\ .\ l_k\ .\ v_0}{3\ .g\ .\ \mu\ .b_h\ .\ v_h}} \tag{3.9}$$

Where:

d_3 = Relation between end of lift and maximum discharge. A value of 1.34 is recommended [13].

These two parameters allow the determination of the maximum lift height (h_h), represented in meters, which is the product of said parameters. The resulting area of the filling openings (A_h in m^2) is, following the initial premise that the opening has a rectangular shape, the product of the maximum lift height with the gate openings width that results from condition 4 [13]:

$$A_h = b_h\ .h_h \tag{3.10}$$

Nonetheless, providing input data for the subsequent simulation is not the only application of this calculation software. It also allows estimating the total filling time through an analytical formula for further comparison with the simulation output. A numerical analysis of the water level difference, the gate openings area and the filling velocity, all in function of time, is also possible to execute in this software, resulting in a graphical representation. In turn, said graphical representation allows the validation of condition 3, as well as an estimative of the total filling time for further comparison, the total filling volume, maximum filling flow and the validation of the maximum limit for the filling velocity, in order to allow a proper mooring of the vessel during the lock operation. The latter limit is, usually, 1 m/min, which was also admitted under this work.

3.2. LOCKFILL

The range of applicability of LOCKFILL to regular lock levelling systems is somewhat limited. It was developed with the objective of analysing average situations from a Dutch perspective, i.e., *Deltares* recommends to use it for low to moderate drops, as well as only for the levelling systems indicated in chapter 2.5.1. Its interface is very user friendly, as it is very practical to create a new input file, edit an existing one to match the case under investigation and accessing and analysing the software outputs.

However, that is mostly due to the lack of complexity of the range of applications of the software and its limitations. Nonetheless, for case studies inside its applicability range, it is very useful in estimating and predicting the levelling process, as well as computing the most important aspects resulting from it, as outputs of the simulations, such as the levelling time, levelling velocity and mooring forces.

The input file consists of data regarding the characteristics inherent to a specific case study of the approach harbour, the lock chamber, the chosen levelling system, the characteristics of the vessel and other simulation parameters [21]. All of these categories and its particular values adopted will be described in more detail for the case studies presented in this thesis. Even so, it is important to present a general introduction to the most important components of each category of the input file, regarding the more important aspects of this investigation, in order to understand the values adopted henceforth.

3.2.1. APPROACH HARBOUR

In this block, the components regarding the approach harbour are defined. The water density of the approach harbour is defined here, which requires particular care in case of a density difference between the approach harbour and the water inside the chamber, i.e., a salt water approach discharging inside a fresh water chamber or vice-versa. Also, here the user can choose if the water level of the approach harbour is calculated using the basin storage method or the time table method. The former is particularly useful in cases where the water level of the approach harbour will be subjected to changes due to the levelling process, e.g., in the calculation of a staircase lock. If there is a short distance between consecutive locks, the volume of water present in the intermediate basins is limited, and therefore requires special care regarding its water level during the filling and/or emptying process. However, in most cases, the approach harbour is a section of a river or a long canal, which has, in comparison to the lock chamber, a much larger surface area and volume, rendering negligible the effect that the levelling process has on the approach harbour water level. For these cases, the most appropriate approach would be the time table method, where the input consists of a table referring to the water levels as function of time. Naturally, the table is defined with equal water levels at the start of the calculation and at the end. This input section can be useful in particular situations where the water level in the approach harbour can be subjected to significant changes, e.g., in a marine lock, where the tidal range will influence the approach harbour water level at the sea side.

3.2.2. LOCK CHAMBER

In this block, the input parameters can be defined, regarding the initial water level in the lock chamber, the water density inside the lock chamber (ρ_k) and the dimensions of the lock chamber – length and width. The latter is assumed constant, so the lock chamber is schematised as a rectangular box. Notice that these dimensions refer to the hydraulic length and width, not the structural dimensions of the lock chamber. The length is very important for the calculation of the translatory waves component of the occurring longitudinal forces, and the water level changes. Consequently, it is a highly influential parameter in most calculations and results from this simulation. In turn, the width influences the momentum decrease, friction and filling jet, also components of the occurring longitudinal forces. A smaller width results in more flow concentrating in a longitudinal direction, which leads to larger forces and vice-versa, i.e. a larger width leads to lower forces. It also has direct influence in the width of the gate openings, resulting from the condition 4 described in chapter 3.1. The characteristics of the lock chamber bottom, namely the level and the roughness (defined by the *Nikuradse* roughness), also have to be defined in this input component. It refers also to the roughness of the walls, being therefore impossible to distinguish between different values for the roughness of lock floor and walls in the input file. The definition of this parameter has significant importance in the definition of the friction forces [21].

3.2.3. LEVELLING SYSTEM

This input component defines the lock levelling system to apply in a simulation. As mentioned above, there are only a few different possibilities available, due to the current limitations of the software. For the current work purposes, the available significant levelling systems are the levelling through gate openings and the levelling through culverts with stilling chamber. The latter, as it was presented in chapter 2.3.6.1, is a levelling system which will not be applied in the present simulations. Nonetheless, it was considered in order to analyse which existing template in the current LOCKFILL possibilities is best to represent a levelling system with short culverts, as addressed in chapter 4.1.5.

In the particular choice of levelling system through gate openings, LOCKFILL requires the input of several parameters:

- The maximum height of the openings and the lift speed of the gate opening slides as a function of time, both determined by analytical formulations inserted in *Microsoft Excel*;
- The total width of the gate openings (b_h), as function of relative lift height, ranging from 0 to 1, being 0 the indication the openings being totally closed and 1 the indication of the openings being totally opened. Assuming rectangular shaped gate openings, the width is constant throughout the slides lift, an assumption that must be introduced to the simulation through this parameter;
- The discharge coefficient as function of relative lift height. The software enables the input of the latter function in the form of a matrix. However, LOCKFILL manual does not clarify how the interpolation between the introduced matrix values is calculated. Accordingly, and also for calculation simplifications, the value for this discharge coefficient is an assumed value for a specific case study, as it will be further described, and remains constant throughout the slides lift. Under the circumstances where the assumption would be of a specific variance in time of this input parameter, it would imply significant changes in the inflow of the filling inside the chamber. It is, therefore, important to mention that the discharge coefficient is a highly influential parameter in the filling process, and should be subject of a in-depth study and design.

In this block, it is also required to input information regarding the filling jet, namely the angle that said jet makes with the horizontal plane (α), i.e., the vertical angle of the filling jet, the surface area of the filling jet behind breaking bars (A_{str}) and the level of the top of the filling jet behind breaking bars (z_G), i.e., the level of the top part of the gate openings. The surface area of the filling jet behind breaking bars can be determined through formulations introduced in the calculation programme and will influence the upper limit to the lift rate resulting from condition 2 presented in chapter 3.1. The vertical angle of the filling jet will mainly influence the force due to the decrease in momentum, introduced in chapter 2.4.3.1. Therefore, it might be adequate to consider it in cases where the mooring forces in the vessel are too high due to this particular component of the longitudinal forces. However, it is important to keep in mind that a positive angle will create a stronger impact on the bow of the vessel and possibly unwanted turbulence in the water surface, and a negative angle could have negative impact on the bottom of the chamber, which can be particularly drastic depending on the bottom material. This angle will be assumed has 0º, i.e. parallel to the lock chamber bottom. Nonetheless, it is a variable to keep in mind for theoretical approaches. As for the level of the top of the filling jet behind breaking bars, i.e. the position of the openings within the gate, there was no specific information in any of the given case studies about this parameter. Therefore, a value is assumed. These assumptions will be further explained in detail, in the modelling of the case studies.

When addressing short culverts levelling system through the culvert with stilling chamber template available in the software, this block is naturally subjected to changes when compared to the gate openings template. It requires the input of:

- Number of culverts
- Level of the ceiling of the stilling chamber
- Characteristics inherent to the culvert itself, such as:
- Length
- Cross sectional area
- Residual resistance coefficient (summation of all resistance coefficients inherent to the culvert, such as inlet, outlet and bends, with the exception of the sluice gate)
- Maximum sluice gate height and the lift speed of the sluice gate as a function of time, obtainable through calculation software similar to gate openings slides
- Loss coefficient of the sluice gate variation as function of relative lift height, which for this situation is considered not to be constant throughout the openings of the slides. Its variation is presented further in this document, regarding the specific case studies approached.

3.2.4. VESSEL

The vessel characteristics to input in the simulation depend, naturally, on the case study. For European inland vessels, it is common to define those characteristics through the class of vessels introduced in the set created by CEMT [17]. It is therefore necessary to define the class of vessel to be incorporated in the simulation, and consequently introduce in the input its characteristics, such as ship mass (M_S) and ship dimensions - length (l_S), breadth (b_S) and draft (d_S). For simplicity, and in line with the general shape of many inland cargo ships for which the software was designed and the calculation method validated, the ship is schematised as a rectangular box. However, for the calculation of the force due to the filling jet, the shape of the vessel is of high significance, so in this component the bow is schematised as two plates under an angle. For that purpose, LOCKFILL requires an input of the vertical and horizontal angles of the bow. In case there is no given information regarding said angles for a case study characterized by a specific class of vessel, in this work are assumed the standard values of 63º and 30º for the bow angle in the vertical (angle the bow makes with the waterline) and the horizontal (angle the bow makes with the ship axis), respectively. These values are adopted from examples presented in the LOCKFILL manual [21].

The mass and dimensions of the ship, together with the water density in the lock chamber, define the block coefficient, which in turn is used in the calculation of the force due to translatory waves, as it can be found in chapter 2.4.3. The LOCKDIM formulations also require the input of this block coefficient, so it is necessary to ensure that this value conforms to the value calculated by LOCKFILL, otherwise the results from the analytical and numerical calculations in the preliminary calculations will differ from the ones resulting from the LOCKFILL simulation. The block coefficient is, therefore, determined by:

$$C_b = \frac{M_s}{\rho_k \, l_s \, b_s t_s} \tag{3.11}$$

In addition to the information given by the class of vessels table and the assumed parameters mentioned above, LOCKFILL also requires the input of the *Nikuradse* roughness of the ship hull, for the friction force calculation.

Finally, another important parameter to input in this block is the distance between bow and lock gate (x_s). This selectable distance defines the stop line, and depends on the space needed in order to limit the risk of the vessel crashing into the gate. Usually, the closest distance is the most conservative case for the design, as it often results in the largest forces. As well as other parameters presented here, the values assumed for this distance will be explained in detail for each case study. Simulation of a scenario generally takes no more than a few seconds, so using a too long end time is not too much of an obstacle.

3.2.5. SIMULATION PARAMETERS

This block defines the calculation time and time step. These input values will be constant throughout all the simulations for a given case study, in order to more accurately perform comparisons between said simulations. By recommendation of the LOCKFILL manual [21], the time step value adopted was 1s. The end time of calculation depends on the case study, considering how much time is predictable for the levelling process to take place.

3.3. LOCKSIM

Despite also being a one-dimensional numerical model such as LOCKFILL, LOCKSIM has significant differences when compared to the former software, namely related to the input data, output data and overall interface and operation. Nonetheless, both software's have the same objective, which is to provide a preliminary design of the levelling systems. Similar to LOCKFILL, it requires physical modelling as a supplement, in order to validate the 1D calculations. If sufficient confidence is gained in the numerical results, it should be possible to replace the traditional detailed lock model with a simpler model.

The software presented in this chapter consists of a somewhat more complex lock levelling simulator, being able to approach more complex lock levelling systems than LOCKFILL, such as the levelling through short or long culverts. That complexity entails a less friendly interface from the user point of view when compared to LOCKFILL. It requires more input data, described as a collection of interconnected components and nodes with imposed initial elevation and boundary conditions. It also requires the user to previously develop a schematic representation of the hydraulic network, in which the different components and nodes are defined and labelled, making it possible to observe how said nodes and components are connected together to represent the flow paths inherent to the levelling process. Each component is, therefore, bounded by nodes. This schematic representation can be as simple or as detailed as necessary.

In summary, the steps for applying LOCKSIM in the design of a new or existing lock levelling system are:

i. Prepare a schematic representation of the hydraulic network.

ii. Gather necessary input data, similarly to the above described in LOCKFILL. However, important to mention is that the calculation method provided by LOCKDIM is not adapted for this software. When modelling in the present software, this calculation method will be used to estimate certain input values, while other input values will be either assumed by the author or adopted from literature.
iii. Create LOCKSIM input file.
iv. Perform simulation – Simulation is done selecting the *Run Unsteady* command. LOCKSIM assumes that the correct initial condition is steady-state, i.e., the initial node heads and demands specified in the input file define a steady-state condition. This makes it so that the software will perform a preparation stage to indicate progress in processing the input file. If one or more nodes and/or components fail said processing, the respective errors are listed. If no errors occur, the user can continue the simulation until the desired stopping time. After stopping the simulation, the output plot file is provided.
v. Process output results, through spreadsheet software such as *Microsoft Excel*.

Regarding step iii, the input file consists of data regarding the specified nodes elevation and boundary conditions, and the specified components lengths, areas, loss coefficients and boundary conditions, therefore describing the information depicted in the schematic representation. Also, the input file contains sections on constants, functions, cross sections and plot variables, as described further in the present chapter. Similarly to LOCKFILL, the input data is introduced in a text format, divided into the indicated sections, in the following order:

i. Constants
ii. Components
iii. Nodes
iv. Functions
v. Cross Sections
vi. Post processing

3.3.1. CONSTANTS

This section includes specifications for all of the constants, which are, in fact, mostly simulation parameters. As recommended by Schohl [23], the constants *wf_time* (implicit weighting factor), *dQ_max* (solution discharge tolerance), *dH_max* (solution head tolerance), *dX_max* (tolerance for tee and manifold coefficients), *plot_line* (maximum length of a line in the plot file), *plot_field* (width for each value in the plot file) and *plot_labels* (specifies the format, either *column* or *row*, used to write the plot variable labels into the plot file) are adopted from the values usually applicable to any navigation lock simulation and therefore remain unaltered throughout this work. The described parameters values are, respectively, *wf_time* = 0.55, *dQ_max* = 0.001, *dH_max* = 0.0001, *dX_max* = 0.0001, *plot_line* = 300, *plot_field* = 11 and *plot_labels* = row. The values of *dQ_max, dH_max* and *dX_max* should be reasonable, but not too large, as it's better to get an occasional “Maximum convergence achieved” message, which still allows the simulation to proceed, than to set tolerances too high and, therefore, lose accuracy of the iteration process.

Also included in this section is the input parameter *time_step* (simulation time step). Its value is usually a constant, but a data cluster may be used to specify a time step that varies with simulation time. To ensure stability and accuracy, the time step is limited by the Courant criterion, meaning that it should be small enough to accurately resolve the boundary conditions of the components. Scholl [23] recommends, for simulations of filling and emptying systems, a constant time step of 5 seconds, which was adopted for all the present simulations. Scholl [23] also recommends using the same time step for every simulation so that all are affected by similar numerical damping.

3.3.2. COMPONENTS

As mentioned before, this section includes specifications for all of the components included in the schematic representation. For the simulations presented in this work, the components were divided in different groups in order to compute the energy losses present in the levelling process. The common specification of those groups is that each component is introduced by the respective upstream and downstream node, as mentioned before. Those groups are, therefore, distinguished as:

- **Segments** – represented by *imp_pipe* components in the present software, this group considers friction losses in the straight sections of the culvert. The input parameters consist of length, hydraulic diameter, roughness coefficient and wave velocity. Length and hydraulic diameter depend on the specific case and scenario considered, and will be therefore explained in more detail throughout chapters 4 and 5. As for the wave velocity, or wave speed, as presented in the LOCKSIM user's manual [23], the value recommended by said manual as a representative value of concrete conduits is 3500 ft/s, which can be converted to SI units as 1065 m/s.
- **Inlets and outlets** – introduced to the software as a *pipe_loss* component, it defines the local losses inherent to the entrance and exit of the filling flow into and from the culvert. This group requires the input of upstream and downstream section hydraulic diameters, used for the calculation of the speed in both heads of the component. Usually, in the case of a filling process (emptying would be directly inverse), the upstream area of the inlet (water body) and the downstream area of the outlet (lock chamber) are significantly higher than the culvert area, resulting in essentially zero speed for these sections. Therefore, there is no need to input the correct section of the inlet upstream and outlet downstream, since these are hard to correctly define, as long as the assigned value is large enough to result in a negligible upstream/downstream velocity head, in order for the software to assume zero speed. Naturally, the values adopted for these input parameters are a function of the specific modelling case and will be described further in this work. This components also require the loss coefficient (K) associated with the equation of the head loss:

  $$\Delta h = K * \frac{U^2}{2\,g} \tag{3.12}$$

  A distinction of these values as function of the flow direction is made. Regarding a specific defined culvert, in simulating the filling of the chamber through said culvert, the flow direction is considered to be positive. Accordingly, for the emptying of the chamber through that same culvert, the flow direction is considered to be negative. Therefore, for filling the loss coefficient is represented as K+ and for emptying as K-. Naturally, both these values were determined and distinguished for each inlet/outlet. These parameters depend on the geometry of the inlet and outlet, and can be modified with resource to various approaches, in order to either minimize or maximize energy loss in the entrance and/or exit of the culvert. These values are of high importance to the levelling process, as it highly influences the discharge flow and, consequently, the mooring forces acting on the vessel and the levelling time. Similarly to other parameters described here, an in-depth analysis of the values assumed can be found in the chapter relative to the simulations.

- **Bends** – Similarly to the inlet/outlet components, also the local loss due to the change of the stream direction in curved segments of the culvert, translated as bends, is introduced to the software as a *pipe_loss* component. It is required to input the bend hydraulic diameter, which corresponds to the adopted culvert hydraulic diameter, and a loss coefficient K, such as the one described for the inlet/outlet. However, it is considered that in the bend the loss of energy is equal in both directions of the flow, as long as the considered bend is symmetric, so there is no need to distinguish between positive and negative directions. This coefficient will depend on the format of the bend, and is as well of high importance to the levelling process, being able to significantly influence a levelling system by adopting different formats for the bends.
- **Valves** – Valves and respective inherent slides can be modelled in LOCKSIM by means of the *valve* component, in order to introduce the local loss inherent to the opening of the filling/emptying valves. This is one of the most important parameters to take into consideration for the design of a levelling system, as not only the size, shape and operation characteristics of the adopted valve influence the levelling process, but also its position, i.e. opening state, as a function of time and corresponding discharge coefficient as a function of its position. This is influenced by the choice of lifting function, and correspondent lifting velocities.

  Accordingly, both the valve position as a function of time and the "K" value variation as a function of the position are defined in the input file with the aid of functions, as presented in chapter 3.3.4. Also, another input parameter required by LOCKSIM is the valve hydraulic diameter. Important to mention is that the *valve* component refers to a filling through culverts that incorporate a valve with slides. Other mechanisms, i.e., types of valves, could be adopted, since LOCKSIM enables other options for the simulation, such as reverse tainter valves (*rev_tainter*) or a simple non-return valve that remains fully open for positive flow and closes instantaneously to prevent negative flow (*check_valve*) [23]. These options require similar, however with small differences, input as the sliding valve.
- **T-junctions:** Due to the need to compute the local losses derived from the combining or dividing the filling flow into flow streams, an input component, *converging_tee* and *diverging_tee,* respectively, are introduced in the input file. The former is bounded upstream by two nodes and downstream by one, and vice-versa for the latter. It represents a fundamental parameters to characterize for the particular case of levelling through long culverts, where the tee diverges into two separate flow paths, one directed to the chamber and other continuously in the long culvert, directed to the following tee, and repeating the process. For this group, the required input parameters regarding the tee are characterized by three nodes mentioned above, depending whether it is a converging tee or a diverging tee, as well as an input hydraulic diameter (similar to the diameter adopted for the other components of the culvert and constant for every "leg" of the tee) and the angles between said "legs" of the adopted tee configuration, for a given case. The definition of said angles is very important and influent, since LOCKSIM calculates the head loss coefficients based on specified configurations.
- **Chamber** – The lock chamber is modelled with components introduced to the software as *open_channel* components, divided in segments of the free-surface channel (lock chamber). The length of each segment is an integral part of the input requirements and is divided into computational reaches. For the *open_channel* component, the reaches are all the same length (Δ_x), according to LOCKSIM manual [23]. Said reaches are also specified by the user in the input file. It is desirable for accuracy, although not necessary for stability, to specify enough reaches to ensure that the solution's Courant number (C_r), remains near, or greater than, 1.0 during most of a simulation. The Courant number is given by [23]:

$$C_r = \frac{\Delta t}{\Delta x} * \sqrt{\frac{g\,A}{T}} \tag{3.13}$$

The distance Δ_x (quotient between the chamber segment length and corresponding number of reaches) is defined and set for each scenario accordingly.

Along with this information, LOCKSIM also enables to describe the cross section present in each segment of the lock chamber. Said cross sections, which will depend on the presence of the vessel inside the chamber, are defined in the "CROSS_SECTIONS" section (chapter 3.3.5),. A correct definition of these components is of vital importance for the simulation, since the presence of the vessel, even though it does not affect the filling flow rate and the filling time, will majorly influence the translatory wave component of the longitudinal forces acting on the vessel, and consequently the mooring forces, as its presence in the chamber results in an increased wave height, and thus a bigger hawser force.

Similarly to other components, LOCKSIM allows the user to specify other non-required parameters. For this work, the optional parameters introduced were the bottom level of the chamber, upstream and downstream of the chamber, in order to fix the chamber structure as having a constant bottom level throughout its length, by giving both parameters the same value, depending on the case study. This is an important parameter for case studies where upstream and downstream sections of the chamber don't share the same bottom level, which will influence the mooring forces present. Also, another optional parameter available to introduce in this section of the input file is iq, an estimate of initial, steady-state discharge. According to LOCKSIM manual [23], this specification is sometimes necessary to avoid and incorrect component discharge initial condition. In order to avoid said situation, these value is fixed at zero for any lock chamber, as the discharge before levelling is always zero.

3.3.3. NODES

This input file section introduces the specifications of the nodes designated in the schematic representation and introduced as an input requirement for the components section described above, as connection points for different components. It allows the user to define the elevation of the node (required input) and other parameters, such as, e.g., the initial water level, initial demand and/or fixed demand. Notice that LOCKSIM allows the definition of a significant number of other parameters, which are not expected to be necessary for the present work. Naturally, the simulation can only be executed if all nodes introduced in the components section are defined in this section as well.

The distribution of the nodes in smaller distinct groups is not a software requirement, as they can be specified in any order the user finds appropriate, as long as each node is specified in a different text row. However, based on available literature and inherent recommendations, the author found useful to divide the nodes in distinct groups associated with its position in the schematic representation, to define a convenient order that allows for a simpler analysis and consequent necessary modifications throughout the simulations. Therefore, the nodes were distinguished by groups such as:

- **Water body** – The approach harbours next to each of the heads, henceforth named upstream and downstream head, for every given case study and scenario. Notice that the upstream and downstream are not fixed positions in the lock, as they can vary when the levelling changes direction. Therefore, the upstream is always the head with the highest water level and downstream the head with the lowest water level.

- **Gates** – As the nomenclature implies, in this group the specifications for the upstream and downstream gates can be found. Notice that the distinction between up and downstream follows the same premise as the water body group.
- **Upstream and downstream head culverts** – In a short culvert levelling system, there must be culverts present in both heads. This necessity becomes even more significant for levelling systems that require filling and emptying in both directions. The symmetry between up and down stream culverts is not a mandatory requirement, i.e. they are not necessarily identical. Also, this distinction is predicted to be particularly useful for analysing and simulating asymmetrical levelling.
- **Chamber** – The chamber nodes that define the chamber components are introduced in this group. Notice that, despite the case study, scenario or number of chamber components present, the chamber nodes have the same elevation and initial water level (for each simulation). Said initial water level matches the downstream level when filling the chamber and the upstream level when emptying.

3.3.4. FUNCTIONS

This section includes all the functions to be introduced to the non-fixed components and/or nodes of the simulation. That is, if it is desired to have a specific parameter change as a function of other specific parameters throughout the simulation, this is the section where said functions can be found. LOCKSIM functions can define variations in node demand or head with time, valve position with time, valve loss coefficient with position, storage surface area with elevation and other required functional relationships [23]. As indicated in chapter 3.3.4., valve size, shape and operation characteristics are of great influence to the levelling process. Therefore, for this work, the deemed important functions to introduce in this section regard the valve position as a function of time, as well as the loss coefficient variation as a function of the valve position.

The former is introduced as a relative height as a function of time. In this input parameter it can be introduced, in addition to the necessary input parameters to define the linearity of the opening, the initial opening time (*xshift*), i.e., the moment in simulation time where the valve begins to open, and the total lifting time (*xscale*), i.e., the total time it takes for a given valve to fully open. These two input parameters will be subjected to previous study and changes throughout the simulations as deemed necessary, since they depend on the lifting velocity of the present valve, the present scenario to be considered and consequent dependency and interaction between different elements of said scenario, which will be described and deepened appropriately at a later stage of this work, in relation to each considered simulation scenario.

3.3.5. CROSS SECTIONS

As mentioned in the previous chapter, this section of the input file describes the cross sections used by the *open_channel* component. LOCKSIM allows the definition of three types of cross section: trapezoidal, circular or riverine. Further, the input parameters of the cross section depend on the element to which the cross section belongs. In this work, both chamber and vessel dimensions are determined based on the premise that they are both rectangular shaped, following the same premise for LOCKFILL as presented in chapter 3.2.4. For that reason, the cross sections will be defined as trapezoidal, with both side slopes equal to zero, to correspond to a rectangular section. For the chamber cross section, the required inputs are *bed_width*, which defines the width of the chamber and *MN_n*, which defines the roughness of the chamber bottom and walls, expressed as a *Manning* coefficient. With this input parameters and the length of the chamber defined in the chamber components, the chamber dimensions are all introduced in the input file. The vessel cross section dimensions are defined, similarly to the LOCKFILL input, by the class of vessels introduced in the set created by CEMT [17]. After defining the class of vessel to be incorporated in the simulation, it is possible to input the cross section parameters *bed_*width (width of the chamber where the vessel is located), float*_beam* (breadth of the vessel – b_s) and *float_draft* (draft of the vessel – t_s). It is also required to define the roughness coefficient of the vessel. Along with the length of the vessel introduced in the chamber components, resulting from the sum of the length of all the segments defined with *cross_section=vessel*, the total dimensions of the vessel are introduced in the input file. Also, the mass of the ship, which constitutes a required input in LOCKFILL for the vessel characteristics, only influences the mooring forces on the vessel. For that reason, it is not a required input in LOCKSIM, since the mooring forces are calculated in the post-processing, after the simulation.

3.3.6. POST PROCESSING

This section specifies the variables to be saved during a simulation for later plotting, i.e., the output data provided by the simulation that the user deems necessary for analysis and post processing, integral part of step 5 for applying LOCKSIM to the design of lock levelling systems.

According to Schohl [23], the mooring forces on a vessel are estimated based on the water level difference between two points in the chamber, i.e., the hydraulic gradient, which can in turn estimate the translatory waves component of the longitudinal forces occurring in the chamber. The referred two points correspond, in order to compute the mooring forces, to where the bow and the stern (upstream and downstream points) of the vessel are positioned during the levelling process. It is therefore necessary to introduce these two points of the chamber as nodes in the schematic representation and subsequent input file, in order for the software to provide the water level in said nodes. By defining said nodes water levels as a plot variable, they become available in the output file for subsequent data treatment. The forces due to the translatory waves are, therefore, calculated with the aid of the following formula:

$$F_H = W * \frac{(d_u - d_d) + (z_{bu} - z_{bd})}{L_{ud}} \tag{3.14}$$

In section 2.4.3., it is explained that the normative limit imposed to the mooring forces by the class of vessel is expressed as a permillage (‰) of the weight of the water displacement of the vessel (W). In order to compare the resulting mooring forces from a specific simulation to its respective normative limit, the formulation introduced in the post processing spreadsheet in *Microsoft Excel* relates to the relative hawser force $\left(\frac{F_H}{W}\right)$. In case the chamber floor elevation is constant throughout the chamber, $z_{bu} = z_{bd}$, enabling an additional simplification of the above expression. The relative hawser force can, therefore, be described as follows:

$$\left(\frac{F_H}{W}\right) = \frac{(d_u - d_d)}{L_{ud}} * 1000 \tag{3.15}$$

In previous chapters it has already been introduced how and how much the translatory waves component influences the total occurring longitudinal forces when compared to other components. When levelling through short culverts, that influence is even more significant, which justifies the approach by LOCKSIM of only taking that component into consideration. However, as the mooring forces calculation is done in a post-simulation phase in *Microsoft Excel*, it was explored in this work how to expand said calculations to include the momentum decrease component. While its influence in levelling through short culverts is naturally lower than in levelling through gate openings, due to the non-existence of a filling jet parallel to the lock walls and colliding in the bow of the vessel, it can still influence to the mooring forces of the former levelling system.

Due to LOCKSIM neglecting this component, it was introduced in the calculation software the momentum decrease formulation provided by LOCKFILL manual [21], which can be found in chapter 2.4.3.1. There are, however, important details inherent to this formulation that should be addressed. The present variable is "Q", which represents the filling flow from the gate openings. As mentioned before, said flow has a direction parallel to the lock walls, i.e., longitudinal direction. However, to compute the momentum decrease component in short culverts levelling system, the filling flow is perpendicular to the lock walls, i.e., perpendicular to the flow introduced in the formulation. This means that, in order to estimate a viable result for the momentum decrease, it is necessary to estimate how much of the filling flow from the culverts, on both walls, influences the momentum decrease after their collision, i.e. how much percentage of the intake filling flow diverges into a longitudinal direction after the collision between opposite culverts inflow. Accordingly, the solution addressed in this work for this purpose was to define the outlet flow as a function of time in the plot variables of the input file on LOCKSIM, so the simulation provides it as an output value. Subsequently, assumptions of the above mentioned percentage were made in order to analyse which resulting values are more viable. These assumptions were based on the premise that, if the intake flow occurred in the exact middle axis of the chamber, it would diverge equally in both longitudinal directions, as the chamber area on both directions is similar. Accordingly, when using short culverts for filling a lock, the downstream area of the culvert is bigger than the upstream. That led to the assumption of values higher than 50%, as the downstream direction is the flow direction corresponding to the momentum decrease formulation given by LOCKFILL. For higher accuracy in these assumptions, a relation between upstream and downstream chamber areas of the culvert could be determined. The problem in addressing these areas is that, in the study cases presented further in this work, the shape and size of the gates is unknown. However, by addressing the premise introduced in the cross section block in this chapter, an assumption of a rectangular shape of the lock can lead to an assumption that the gates are also rectangular and perpendicular to the lock walls, which in turn enables approximate estimative of the relation between upstream and downstream chamber areas of the culvert.

The relative hawser force $\left(\frac{F_{si}}{W}\right)$ resulting from this component can be, therefore, described as the following [21]:

$$\left(\frac{F_{si}}{W}\right) = \frac{-Q\,|Q| \frac{\rho t_s b_s}{h_k b_k - t_s b_s} \left(\frac{\left(\frac{l_k - x_s}{l_k}\right)^2}{b_k h_w} - \frac{\left(\frac{l_k - x_s - l_s}{l_k}\right)^2}{h_k b_k - t_s b_s} \right)}{W} * 1000 \qquad (3.16)$$

Notice that, for the particular case of levelling through long culverts, the momentum decrease component, whilst not null, has little significance in the total mooring forces. The culvert outlets located in the downstream part of the wall resulting filling flow will collide with the upstream outlets filling flow, resulting in a momentum decrease total force of approximately zero, even assuming it has lower intake flow in the former than in the latter. For this reason, this component influence in the mooring forces will not be addressed for levelling systems through long culverts. Important to mention is that, outside the range and goals of the present work, a viable way to compute the above mentioned percentage of intake flow diverging into the longitudinal direction would be through two-dimensional CFD modelling.

In the post-simulation calculations in *Microsoft Excel* software, also the levelling velocity will be addressed, in order to control this parameter, to allow a proper mooring of the vessel during the lock operation. The limit of 1 m/min, adopted in chapter 3.1. for LOCKFILL simulation, was also admitted here. That levelling velocity can be obtained through the following formula:

$$v_i = 60 * \frac{h_i - h_{i-1}}{t_i - t_{i-1}} \tag{3.17}$$

LOCKSIM does not set a limit to the number of plot variables that may be defined and saved during a simulation.

3.4. CONCLUSIONS

The input format of LOCKSIM makes it possible to distinguish between a significant number of different scenarios, but also makes it more time consuming to re-write the input parameters for each given scenario, when comparing to the practical approach provided by LOCKFILL. However, its usefulness in optimizing a levelling system by simulating a vast number of scenarios balances the negative factors inherent to the software use, making these factors less important when comparing software, in view of the necessity to optimize solutions. LOCKSIM is, therefore, significantly more useful when trying to achieve more efficient and economical solutions, as there are almost infinite number of scenarios and options the user may adopt for a given situation, even if not applicable to every type of levelling system. LOCKFILL is more user friendly, providing a faster and more intuitive interaction with the software, but its applicability range is still very limited, making it obsolete when the need for levelling through different systems occurs. Nonetheless, both LOCKSIM and LOCKFILL require preliminary knowledge of navigation locks and their design, as well as preliminary calculations. Regarding the latter, LOCKFILL uses a calculation method which can be incorporated easily in *Microsoft Excel*. Notice that, however, that is only due to both the calculation method and the simulation software association with levelling through gate openings, which once again demonstrates the lack of designing options available in LOCKFILL. On the other hand, LOCKSIM preliminary design comprises a significant number of assumed, adopted or extrapolated values, which can be risky for the accuracy of the simulation results, relying on the user's correct approach to the given situation and experience.

Emphasizing on a certain desired applicability of a levelling system for a given situation, there can be observed a very significant difference between both software. LOCKFILL was developed from a Dutch perspective, and is therefore focused on a certain type of locks, namely for small lifts/drops, which justifies the approach to levelling through gate openings. It is, for the most part, a good approach for said types of locks and usually the most economical option. LOCKSIM, on the other hand, regardless of having a wide range of simulation parameters that can be addressed, is incapable of simulating a lock levelling system through gate openings. Both these limitations are related to the one-dimensional approach inherent to each software, since levelling systems through gate openings imply a different jet direction entering the chamber than the levelling systems through short or long culverts.

Regarding output format, while LOCKFILL simulation provides a table and graphical plot of the most important results inherent to a levelling process, such as the levelling time, levelling velocity and mooring forces, LOCKSIM requires further analysis and post-processing in, e.g. *Microsoft Excel*, which again results in a more time consuming process. In other words, while LOCKFILL can perform automatically the determination of velocities, flows and, subsequently, forces after the hydraulic calculations inherent to the simulation, LOCKSIM only performs and provides outputs related to said hydraulic calculations, without any further automatic calculations. Regarding specifically the mooring forces that result from the occurring longitudinal forces in the chamber, while LOCKFILL provide information regarding the five components inherent to said longitudinal forces, the post-processing of LOCKSIM computes the mooring forces regarding only the translatory waves component, as it is the main component for levelling systems through short and long culverts. Within this work, it was estimated how to also calculate the momentum decrease component.

A similar negative aspect of both software falls on its one-dimensional approach of the levelling process. This narrows the possibilities of approaching different scenarios, in which, e.g. the angle of the filling jets, both for gate openings and culverts, could be explored. Even though the one-dimensional approach assures a faster calculation, it also introduces uncertainties, which emphasizes the necessity of physical modelling in addition to numerical modelling in a later stage of the design process, because in comparison to a real situation, the point of view from a one-dimensional approach of the levelling process is limited and does not provide all data inherent to the process. This establishes an even bigger concern when using the software in cases outside its original range of validation. Another possible solution to this negative aspect could be the use of CFD modelling, as it provides two-dimensional simulations.

In summary, the one-dimensional characteristics of each software makes it adequate for levelling systems through gate openings, in LOCKFILL, and levelling systems through short or long culvert, in LOCKSIM. LOCKFILL enables a more intuitive, user friendly and faster overall simulation process, including the preliminary calculations, while LOCKSIM enables a wider range of possibilities for both the levelling system choice and its inherent components. In order to research the unknown possibilities of these software, the following chapters provide an exploration of the applicability of LOCKFILL for short culverts levelling system, and the applicability of LOCKSIM for other special levelling systems.

4

BASIC LEVELLING SYSTEMS

The main objective of this thesis is directed to the preliminary hydraulic design of lock structure, focusing on the choice, analysis and simulation of lock levelling systems, in particular the investigation of the possibilities and limitations of the software generally used in this specific subject, applied to special levelling systems. In order to do that, the need to understand both the knowledge inherent to the design of lock levelling systems and the presented software arose. This chapter will, therefore, emphasize in understanding and modelling basic levelling systems for specific case studies in which such levelling systems are, or are likely to be, present. That is expected to allow an acquaintance to the software and analysis limitations and potential inherent to it, so the acquired knowledge can further be used in developing recommendations, solutions and/or improvements in which such software can be used in special levelling cases (chapter 5).

Considering that, in this chapter there can be found the introduction, modelling in both LOCKFILL and LOCKSIM software and respective analysis and significant conclusions of two case studies: *Melle* lock and *Carrapatelo* lock.

4.1. MELLE LOCK

4.1.1. CASE STUDY INTRODUCTION

This case study was, as above mentioned, considered in order to analyse the applicability of the simulation software to basic lock levelling systems. It regards a future lock in *Melle*, which design is executed by IMDC together with Tractebel. Notice that the design considerations adopted and assumed throughout this chapter are not necessarily the final design solution, but said considerations are based on a hydraulic design characterized by the specifications and needs of the case study.

This lock is to be located in the Scheldt River, in the region of Flanders in Belgium, more particularly in a reach southeast of Ghent. The construction of this lock was considered due to the Scheldt being heavily silted in that reach, making it hardly accessible for recreational navigation. Therefore, in order for recreational vessels to sail in and around Ghent, they are forced to use the "Ringvaart" south of Ghent, which in turn lowers the capacity available for commercial shipping. The objective of this lock is, accordingly, to enable recreation navigation in this specific Scheldt reach, to be used instead of the "Ringvaart", freeing commercial capacity. Additionally, it also has the goal to limit maintenance dredging of the Scheldt, since by constructing a lock, the 5 km upstream of the lock need much less maintenance dredging, and to provide safety against flooding due to extreme high water levels in the Scheldt, limiting the necessary flooding protection works to the downstream section of the river instead of the full length along the river.

Fig. 4.1 – Location of the future Melle Lock

The dimensions of the lock were pre-defined and taken into consideration for this look according to the data that was granted to the author. Said dimensions were not subjected to changes throughout this work due to its objective resting on levelling systems analysis, and not lock structure analysis. Therefore, the following lock dimensions were taken into consideration (notice that all dimensions refer to the hydraulic dimensions, and not the structural dimensions, as the former is more significant for the succeeding hydraulic calculations):

- Lock length: 78 m
- Lock width: 7.5 m

The class of vessel considered for this case study, also according to data granted to the author, was CEMT Class-II, which characteristics are expressed in the following table 4.1:

Table 4.1 – Vessel characteristics

Normative vessel	**Dimensions**			**Mass (ton)**	**Maximum mooring force (‰)**
	Length (m)	Breath (m)	Draught (m)		
CEMT Class-II	55.0	6.6	2.5	650	1.50

Two levelling situations were considered to be the more critical for this case study, regarding the upstream and downstream levels. As the lock is located on a river, namely river Scheldt (*Schelde* in Dutch), the sea tide influences the downstream level, making it switch between a lower value 1.9 m and a higher value of 7.5 mTAW (Belgium level datum). The upstream level, on the other hand, will be under the influence of only the river tide, which makes it switch between 4.5 m and 4.7 m. Therefore, the two most critical situations are:

i. The filling of the chamber when the upstream level is 4.7 mTAW and the downstream level is 1.9 mTAW, resulting in a lift of 2.8 m.
ii. The filling of the chamber when the upstream level is 4.5 mTAW and the downstream level is 7.5 mTAW, resulting in a lift/drop of 3 m.

These scenarios will henceforth be referred to as V1 and V2, respectively.

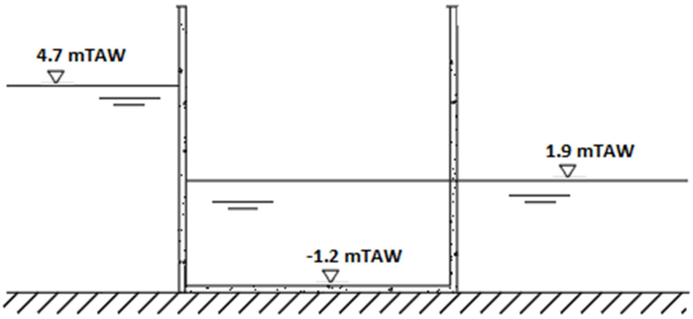


Fig. 4.2 – Initial water levels correspondent to scenario V1

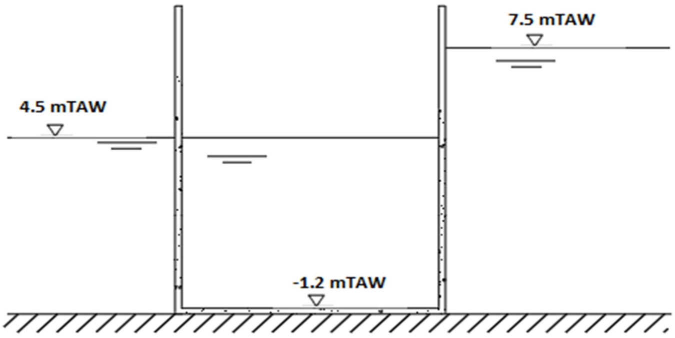


Fig. 4.3 – Initial water levels correspondent to scenario V2

As is common practice in engineering, these critical levels are a conservative approach to real existing water levels. Said water levels presented here are predictably very rare to occur, as the probability of said occurrence would have to be result of a highly improbable storm. Therefore, the subsequent analysis will be a positively guarantee of safety to both the structure and the vessel, regarding the mooring forces. In consequence, the levelling times resulting from said analysis will be higher than the expected times of real succeeding situations. However, important to keep in mind that, within adequate range, the assumed critical levels could be lowered, in order to try to achieve a more economically viable option for the lock levelling system. This conservative approach is considered to be useful for the purpose of getting acquainted to the software, as it is predicted that it leads to the need to explore more software options in order to achieve the desired results.

The fact that the downstream level can shift to both higher and lower levels than the upstream level, results in the need to fill and empty the chamber in each direction, according to the situation that presents at the time of the lock use. For that purpose, the lock must have similar levelling systems in both directions.

For this case study, the levelling system considered for the preliminary design of the lock was through openings in the gate. However, due to the fact that the levelling can be done in two directions, levelling through short or long culverts might be more appropriate. For that reason, in this work there were considered three types of basic levelling systems for this case study: through openings in the gate, through short culverts and through long culverts.

Important to mention that both filling and emptying are done through the same system. Also, as this are basic levelling systems, the levelling is done symmetrically, i.e., either the openings of the gates are symmetrically positioned in relation to the chamber longitudinal axis or, in the case of culverts, same number of culverts are used on both sides of the chamber.

4.1.2. LOCKFILL – LEVELLING THROUGH OPENINGS IN THE GATES

The modelling of a levelling system through gate openings was performed based on the *Melle* lock case study. Therefore, it was performed taking into account two different scenarios: V1 and V2. As presented in chapter 3, to the modelling phase in LOCKFILL, it is inherent a preliminary design phase in which some of the inputs required by the software are calculated.

Notice that the *Nikuradse* roughness values, both for the lock chamber as for the vessel, necessary to introduced in LOCKFILL input file, were adopted from recommendations given by the LOCKFILL manual [21]. These are, naturally, fixed parameters to consider throughout this chapter, for the reasons presented in chapter 3.1.

In order to determine the maximum lift rate of the gate openings and consequently the discharge flow, it is necessary to estimate a discharge coefficient, both for filling and emptying through said gate openings. That implies an extensive and complex preliminary study in order to compute the exact value. Ideally, this discharge coefficient can best be determined in a physical scale model. Due to lack of time and resources, the discharge coefficient was estimated as an average value from existing measurements with similar openings, as recommended by the handbook “Design of Locks – Part 1”

[13]. In said literature, the recommendation is to adopt a value between 0.65 and 0.75, for this type of levelling system. A higher adopted value would mean smaller discharge flow, leading to smaller acting mooring forces and higher levelling time. On the other hand, the effect of an adoption of a lower value on the outcome are higher mooring forces, higher levelling velocities and smaller levelling times. The adopted fixed value for all the following simulations present in this chapter is, therefore, 0.65, as it represents the most conservative case for the present situation. With a view on the design of a lock and intrinsic need to find better designing solutions, instead of the present focus of this work, one particular influent and common approach to increase the discharge coefficient in order to lower the mooring forces would be to incorporate energy dissipating barriers. This is important to mention for this are commonly included in this types of systems, but will not however be considered for this particular simulation. The resulting over conservative approach is predicted to allow for a bigger need to find solutions within the software, which in turn is predicted to allow for a more deep and significant understanding of said software, which is considered to be more useful for this work objectives.

The coefficient for cross section jet (d_2), used to compute the maximum lift rate regarding the longitudinal force due to the momentum increase is, as recommended by the Design of Locks Handbook, 0.25[13]. For the same purpose, the value adopted for the distance between the gate and the vessel of the bow (x_b) is 3 m, as it represents a reasonable value according to the lock and vessel sizes in this case study.

The block coefficient of the vessel is also a required input parameter for the preliminary calculations. As described in chapter 3.2, this value is used in the calculation of the force due to the translatory waves in LOCKFILL. It is therefore necessary to ensure the conformity between the input parameter in the *Microsoft Excel* calculation sheet and the value calculated by LOCKFILL. This results in a block coefficient of 0.72.

Additional assumptions were made regarding this type of levelling system:

- The gate openings have a rectangular cross section, characterized by a width and a height.
- The openings are considered to be symmetrical with respect to the longitudinal axis of the chamber, in order to perform symmetrical filling and emptying.
- The gate openings slides work simultaneously. The lift height and lift velocities are considered constant throughout the openings width. This reflects that, despite the number of openings incorporated in the gate, they will either have a common slide or have different slides that work simultaneously and similarly to one another. In a practical approach, this difference would reflect in the discharge coefficient. As it is, in this case, a fixed value, the number of openings is neglected.
- The width of the openings considered in the calculations is a total width, not accounting for the number of openings incorporated in the gates. It can be described, if you will, as a big large rectangular opening. As that is not a common final design solution, for the reasons mentioned above regarding the discharge coefficient, this assumption also results in a conservative approach.
- The lift height is equal to the openings height, i.e., the relative lift height can change between 0, meaning it is fully closed, and 1, reflecting the openings being fully open.
- The lock is designed for levelling in both directions. For that reason, while it is at first assumed that the scenarios are independent from each other, it will be taken into account in further conclusions.

The total width of the discharge openings is, as described in chapter 3.1., limited between 0.5 and 0.67 times the lock width. According to the design of locks handbook [13], a value closer to the latter limit is recommended for inland navigation locks on the application of rectangular openings, such as the present case. A lock width of 7.5 m, results, therefore, on an openings width of 5m, according to the referred recommended limit.

4.1.2.1. Scenario V1

The preliminary calculations concluded that, to the conditions presented above and the scenario V1 corresponded the following results:

Table 4.2 – Preliminary calculations results for scenario V1

Scenario	b_h (m)	v_h (m/s)	t_h (s)	h_h (m)	A_h (m^2)
V1	5	0.0029	238.7	0.69	3.46

For the LOCKFILL simulation for this scenario, it is still necessary to define some other variables, which can subsequently be subjected to change, if deemed appropriate and/or necessary, namely regarding the filling jet angle (α) and level of its top part (z_G). For a first hypothesis, the filling jet angle was admitted to have a horizontal projection, i.e., parallel to the lock chamber bottom and the water surface and was therefore fixed at 0 º. On the other hand, z_G has to meet some requirements, as it is mandatory that the gate openings are permanently drowned. Also, if the gate openings and its consequent flow are positioned too low on the gate, it might damage the chamber bottom, if additional procedure to protect it isn't placed. If they are positioned too high on the gates, it increases the force of the jet on the vessel, which might be harmful for said vessel, and it creates undesired turbulence in the water surface. Important to mention that, as mentioned before, one problem inherent to levelling systems through openings in the gates is that said openings lower the structural resistance of the gates, in the same way a window or a door lower the structural resistance of a wall, i.e., their position represents the weakest structural part of the gate. The resulting impulse of the water force acting and being sustained by the gates increases with depth, which means that the lower the gate openings are positioned within the gate, the less safety it will be, in principle. This premise is taken into account from a theoretical point of view, for the structural resistance of the gates and the chamber is not a subject of study for this work.

Accordingly, the level of the gate openings was determined considering a gap between the lock chamber bottom and the bottom of the openings equal to the lift height, i.e., the openings height. Notice that this represents a hypothetical approach for a first iteration, and can be subjected to change to analyse its influence on the simulation results. The top level of the filling jet can, therefore, be determined by:

$$z_G = z_k + 2 * h_h \tag{4.1}$$

This resulted, for a first hypothesis, in $z_G = 0.18\, m$.

As it was mentioned in chapter 3.1, the calculation software also allows the calculation of important output results through analytical formula and numerical analysis, which can be used for further comparison with the simulation results. This comparison is useful to validate the simulation results when deemed necessary.

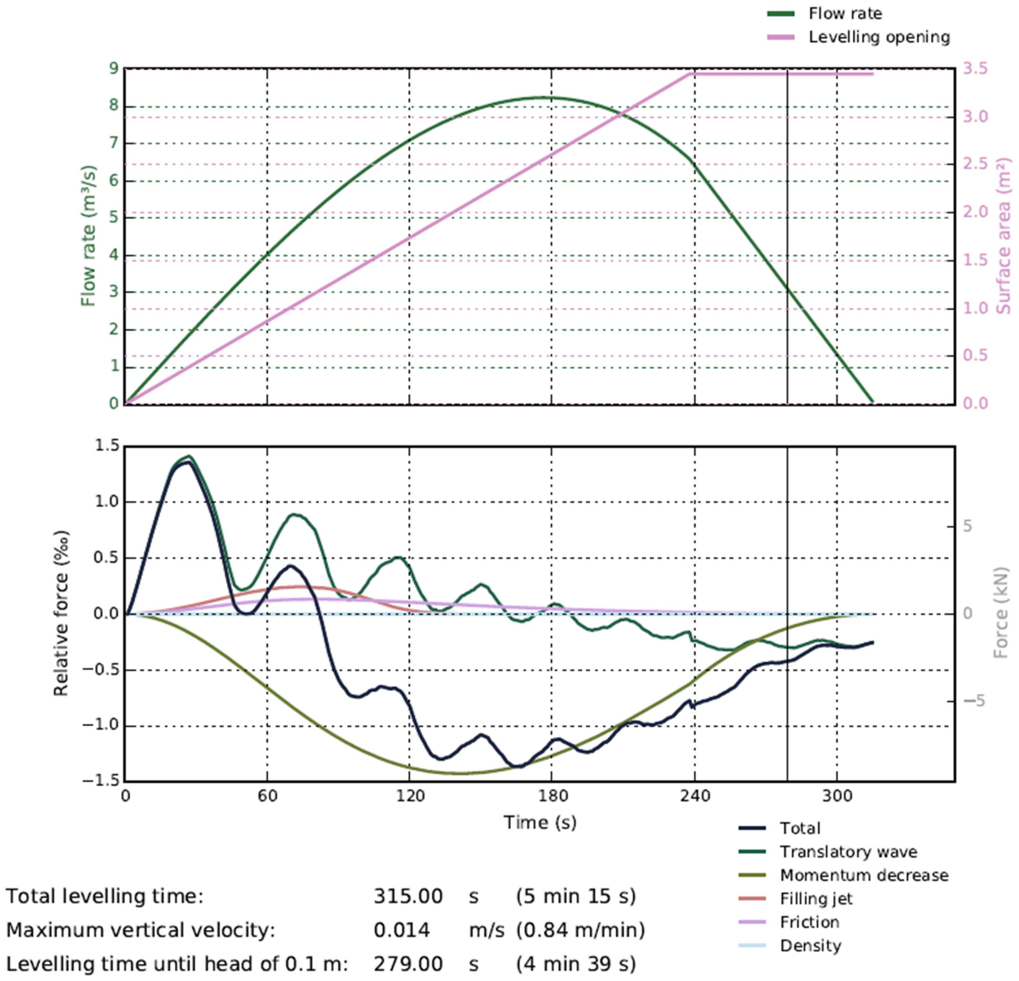
The simulation results and subsequent results comparison with LOCKDIM calculations are as follows:

Table 4.3 – LOCKFILL simulation results comparison with LOCKDIM (Scenario V1)

	Flow rate		**Levelling velocity**		**Levelling time**	
	Maximum (m^3/s)	t (s)	Maximum (m/min)	t (s)	(s)	(min)
LOCKDIM	8.251	177	0.85	177	313	5.2
LOCKFILL	8.234	177	0.84	177	315	5.3

Table 4.4 – Longitudinal forces results from LOCKFILL simulation (Scenario V1)

	Longitudinal forces				
	Translatory waves	Momentum decrease	Friction	Filling jet	TOTAL
Max (‰)	1.414	-	0.133	0.245	**1.359**
t (s)	27	-	81	72	27
Min (‰)	-0.322	-1.428	-	-	**-1.365**
t (s)	253	142	-	-	167



```
Total levelling time:                 315.00   s    (5 min 15 s)
Maximum vertical velocity:            0.014    m/s  (0.84 m/min)
Levelling time until head of 0.1 m:   279.00   s    (4 min 39 s)
```

Fig. 4.4 – Graphical overview of LOCKFILL simulation results (Scenario V1)

As it can be observed, not only the mooring forces remained within the limit of ± 1.5‰, also the levelling velocity maximum limit of 1 m/min is respected. There is, in these conditions, no need to lower the lifting velocity of the gate opening slides. Due to the mooring forces maximum and minimum values being close to their respective limits, for this particular case there is no need to project solutions in order to lower the levelling time, for it is predictable that would result in above the limit longitudinal forces.

Notice that LOCKFILL also displays the moment that the difference in level over the gate is reduced to about 0.1 m, which is of most importance for the designer. It is usually that parameter that the designer takes into account in order to compare design options with a view of optimizing a solution.

4.1.2.2. Scenario V2

Initially, scenario V2 was addressed has if independent from scenario V1, i.e. initially it was not taken into account the design objective for the lock to level in two directions. Therefore, the preliminary calculations resulted in:

Table 4.5 – Preliminary calculations results for scenario V2 (Hypothesis 1)

Scenario	b_h (m)	v_h (m/s)	t_h (s)	h_h (m)	A_h (m^2)	z_G (m)
V2	5	0.0102	129.5	1.32	6.6	1.44

The simulation concluded that this hypothesis resulted in mooring forces higher than the imposed maximum limit. That led to the need to lower the normative lift speed of the slides, which constitutes a viable solution, since the velocity given by the preliminary calculations establishes a maximum value, which in reality can be controlled, i.e., lowered, by the lock operator. As a result of an iterative process, the parameters that achieved mooring forces within the limits were:

Table 4.6 – Preliminary calculations results for scenario V2 (Hypothesis 2)

Scenario	b_h (m)	v_h (m/s)	t_h (s)	h_h (m)	A_h (m^2)	z_G (m)
V2	5	0.009	137.9	1.24	6.2	1.28

However, analysis of the simulation results concluded that the filling velocity, whose limit was fixed at 1 m/min, was approximately 1.56 m/min. In order to respect said limit, using a feature founded in *Microsoft Excel* that performs an iterative process to achieve a specific objective, it was possible to determine a maximum lift speed of the slides that resulted in a filling velocity of the lock chamber equal to 1 m/min. This process resulted in:

Table 4.7 – Preliminary calculations results for scenario V2 (Hypothesis 3)

Scenario	b_h (m)	v_h (m/s)	t_h (s)	h_h (m)	A_h (m^2)	z_G (m)
V2	5	0.0037	216.4	0.79	3.95	0.38

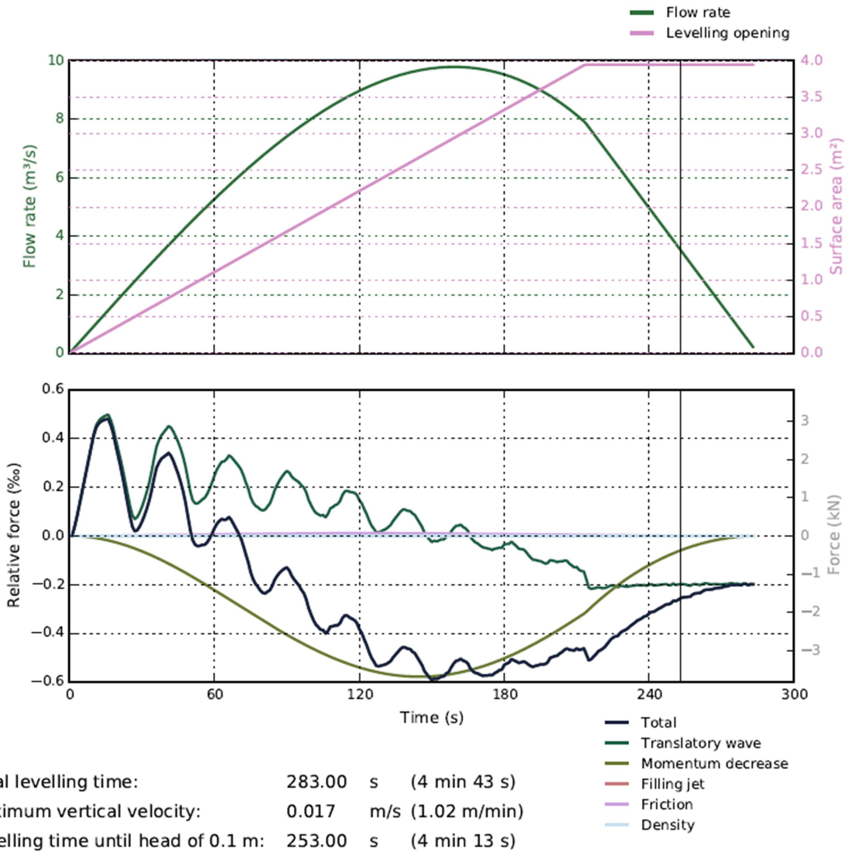
The simulation results and subsequent results comparison with LOCKDIM calculations are as follows:

Table 4.8 – LOCKFILL simulation results comparison with LOCKDIM (Scenario V2)

	Flow rate		Levelling velocity		Levelling time	
	Maximum (m^3/s)	t (s)	Maximum (m/min)	t (s)	(s)	(min)
LOCKDIM	9.754	160	1	159	283	4.7
LOCKFILL	9.795	159	1.02	160	283	4.7

Table 4.9 – Longitudinal forces results from LOCKFILL simulation (Scenario V2)

Longitudinal forces					
	Translatory waves	Momentum decrease	Friction	Filling jet	TOTAL
Max (‰)	0.498	-	0.011	0	**0.48**
t (s)	16	-	120	0	16
Min (‰)	-0.217	-0.578	-	-	**-0.592**
t (s)	216	145	-	-	150



Total levelling time: 283.00 s (4 min 43 s)
Maximum vertical velocity: 0.017 m/s (1.02 m/min)
Levelling time until head of 0.1 m: 253.00 s (4 min 13 s)

Fig. 4.5 – Graphical overview of LOCKFILL simulation results (Scenario V2)

As it can be observed in fig. 4.5 even though the initial water level difference is bigger, in scenario two the levelling time is shorter as the mooring forces are significantly below the limit, illustrating a safe levelling process. The comparison between scenarios demonstrates, therefore, that scenario V1 is the worst case scenario for this specific situation, for the low volume of water present initially in the chamber results in an even bigger presence of the vessel, resulting in a bigger influence of the latter in the mooring forces.

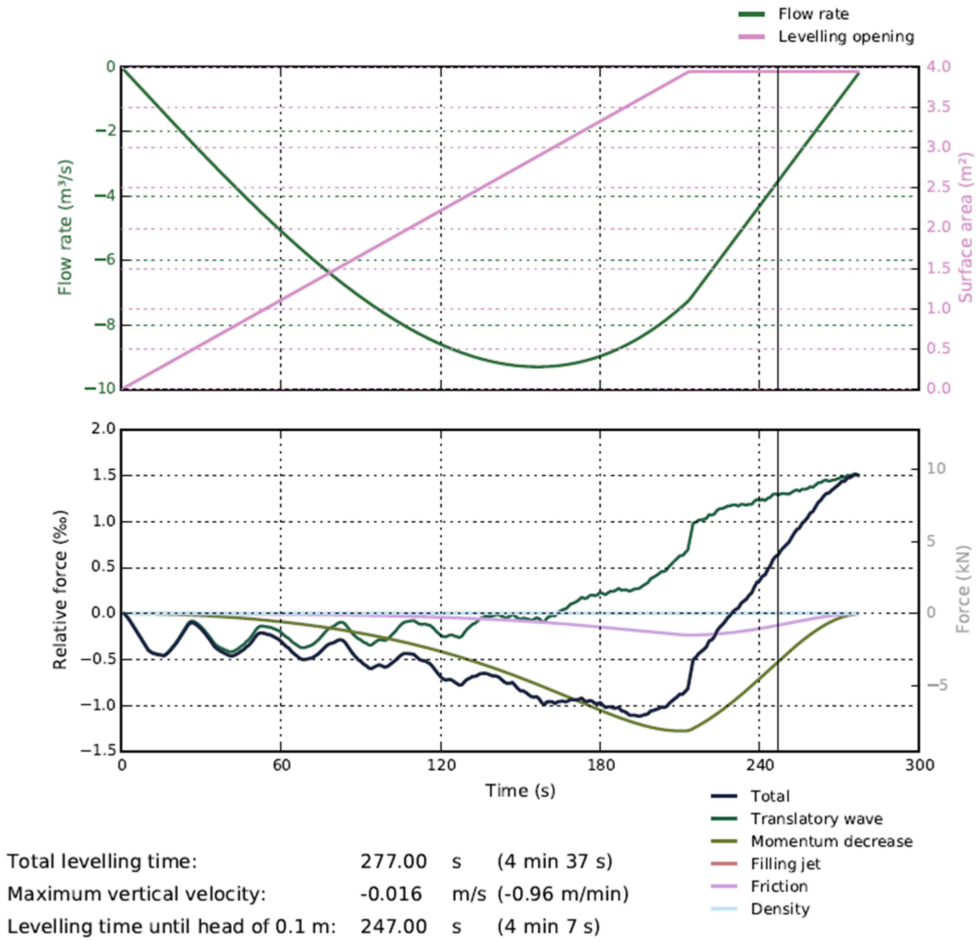
However, it must be taken into account that the present lock is designed with a view to level in both directions. This means that, at some point, it will need to empty the chamber through the downstream head, when the water level in the approach harbour is at the minimum expected value of 1.9 m, resulting once again in a low volume of water to sustain the vessel inside the chamber. For this reason, an analysis of the emptying situation for scenario V1 was developed. For the initial conditions, the parameters correspondent to the optimal design of the gate openings for filling in scenario V2 were adopted (table 4.7). Notice that the position of the openings within the gate no longer follows the adopted relation in previous simulations, which might result in turbulence problems in the water surface, to occur predictably in the end of the emptying process, when the water level in the chamber is at its lower level. Nonetheless, in these conditions, is it assured that the gate openings will remain permanently drowned – $z_G \leq h_k$

The results for said simulation are as follows:

Table 4.10 – Longitudinal forces results from LOCKFILL simulation of an emptying process

Longitudinal forces					
	Translatory waves	Momentum decrease	Friction	Filling jet	TOTAL
Max (‰)	1.518	-	-	-	**1.512**
t (s)	276	-	-	-	276
Min (‰)	-0.453	-1.277	-0.236	-	**-1.117**
t (s)	16	210	214	-	195

Fig. 4.10 shows that, as predicted, the maximum mooring force applied to the vessel occurs approximately simultaneously as the end of the levelling process. Its value is slightly over the maximum limit, which could be easily lowered by decreasing the lift speed of the slides during the operation, whilst the levelling velocity is within the respective limit. Also, the moment that the difference in level over the gate is reduced to about 0.1 m occurs before the mooring forces reach the limit value. Assuming the operator starts opening the gates at this moment, the interaction between chamber and downstream approach harbour is predictable to sustain the translatory waves, making so that said limit of the mooring forces is never reached.



Total levelling time:	277.00	s	(4 min 37 s)
Maximum vertical velocity:	-0.016	m/s	(-0.96 m/min)
Levelling time until head of 0.1 m:	247.00	s	(4 min 7 s)

Fig. 4.6 – Graphical overview of LOCKFILL simulation of an emptying process

Some designs similar to this one require gate openings on both gates similar to each other, i.e., the premise of approaching both scenarios as if independent from each other in order to achieve an optimal design solution, would not be a viable option. If that is the case for this situation, it would be necessary to design the downstream openings with the characteristics of the upstream openings. No simulation was performed under these conditions, as it represents a less conservative case for filling of scenario V2 and emptying of scenario V1.

4.1.3. LOCKSIM – LEVELLING THROUGH SHORT CULVERTS

The levelling system through gate openings has the possibility to distinguish between the shape and size of the openings, as well as other variables mentioned above. However, a levelling system through short culverts can have an even greater diversification of the characteristics intrinsic to the system, i.e. to the culverts themselves.

Three different scenarios (C1, C2 and C3) were developed and considered for the levelling system characteristics. The side and top view of each scenario can be found in the respective section. The lock and vessel were addressed with the characteristics introduced in section 4.1.1. In agreement, the necessity of levelling in both directions remains, as well the levelling situations V1 and V2. This results in a total of six scenarios addressed in this section. The adoption of said scenarios was made in order to estimate the range of potentiality of the software when different designs are considered.

While the configurations for the different scenarios were distinguished, the method used for each simulation was similar:

i. Develop a schematic representation of the present scenario hydraulic network.
ii. Adopt hydraulic diameter "D" and loss coefficients "K_i" for "i" components of the culvert.
iii. Preliminary calculations.
iv. Determination of nodes elevation.
v. Development of LOCKSIM input file.
vi. Simulation with LOCKSIM software.
vii. Post-processing of the output results from the simulation.

This method entails the following assumptions and adoptions:

- Initially, the considered scenarios and respective simulations only considered the filling of the chamber, as it is considered to be a more critical levelling situation than emptying. The filling is done symmetrically.
- The lock gates characteristics, such as shape and height, were not determined. Only its position within the lock is relevant.
- The lock chamber and the vessel are both characterized by having a rectangular cross section.
- Assuming concrete culverts, the value of roughness coefficient adopted was the extreme value for plain concrete (0.017 $s.m^{-1/3}$), according to Berlamont (1998) [24]. This proved to be, throughout the following modelling of different scenarios, an acceptable value, since it is the most critical situation regarding levelling time. Same value was adopted for the roughness of the lock walls and bottom.
- The lengths of "i" components of the culverts were initially adopted from the case study literature provided. An increase of the culvert length implies higher costs, so they were only subjected to changes if necessary due to the configuration of the culverts in some scenarios.
- A value of 60 m was adopted for the length of the vessel, even though the considered vessel for the simulation is characterized by having a length of 55. Also, a value of 3 m given by the case study literature was adopted for the distance between bow and lock gate (x_s). These adoptions were made in order to give the desirable accuracy to the computational reaches, as presented in section 3.3.2 .
- **Preliminary calculations** – Despite the calculation programme used for the preliminary calculations having been developed for levelling systems through openings on the gate, it proved to be also beneficial for the present levelling system. It enables estimation, according to the formulations presented in section 3.1.., of the slides lifting speed and lifting time for that situation. The latter corresponds to the input parameter for LOCKSIM *xscale* (section 3.3.4.). As introduced in section 3.1, the maximum limits for the lift rate result from two conditions, namely guaranteeing that the translatory wave generated from the discharge into the chamber does not exceed the longitudinal force limit in the beginning of the filling process, and assure the momentum decrease contribution in the total longitudinal force does not exceed the limit just before the moment of maximum discharge. In the interest of adapting the preliminary calculations to levelling systems through culverts, the second condition was overlooked, since in these systems the momentum decrease contribution in the total longitudinal force is not significant. Nonetheless, condition 3 introduced in section 3.1 is still valid for this levelling system, so the lifting time (t_h) is determined based on the same formulation. However, said formulation determines the lifting time as a function of several parameters, from which its

included the filling openings width (b_h). Since the openings, for this particular case, have no longer a rectangular opening, the value of b_h to include in the formulation is given by assuming that the maximum lift height (h_h), i.e., the maximum vertical distance the slide has to through, corresponds to the hydraulic diameter of the culvert, resulting in the following assumption:

$$b_h = \frac{A_h}{h_h} = \frac{\frac{\pi . D^2}{4}}{D} = \frac{\pi . D}{4} \tag{4.2}$$

In order to adapt the preliminary calculations as close as possible to a culvert levelling system, an important step was to relate the discharge coefficient (μ), inherent to both gate openings levelling systems and the developed calculation programme, with the loss coefficients (ζ) that characterize the flow resistance of the culverts.
The following formulation [25] was adopted for this relation:

$$\mu = \frac{1}{\sqrt{\Sigma \zeta_i}} \tag{4.3}$$

Where:

$\Sigma \zeta_i$ – Sum of the local loss coefficients of “i” components of the culvert. Important to mention that this parameter is not including the culvert friction losses, since these are calculated by the simulation software, based on the introduced values for component lengths and roughness coefficient. This entails a not so rigorous adoption of the correspondent discharge coefficient. However, it is not predictable that it will significantly influence the results.

The preliminary calculations described here will be repeated when deemed necessary to adopt different values for the hydraulic diameter of the culvert and/or the adopted local loss coefficients.
Notice that, the preliminary calculations being adopted from a calculation programme designed for levelling systems through openings on the gates implies a margin of error, whose magnitude would have to be verified by physical modelling.

- **Culvert Nodes** – Even though, as an initial premise for the simulations, it will be considered that the culverts, in both upstream and downstream heads, are identical, the possibility of having a different culvert system in each head of the lock will be approached. Accordingly, in the nodes section of the input file a distinction between up and down stream culvert nodes is present. Also, for each head, the nodes were divided in sub-groups related to left and right culverts, referring to the left and right of the filling flow direction, i.e., if the observer is positioned in the upstream head looking at the downstream head, his left and right define the left and right described here. However, unlike the distinction between up and down stream nodes, the levelling of a lock through short culverts requires left and right culverts to be symmetrical, to enable a symmetrical levelling. Therefore, it is required that said symmetricity of culverts in respect of the longitudinal axis of the chamber is fixed. Even so, the distinction between left and right culverts in the script is still useful, as it enables a more organized labelling and analysis of the general nodes described. If deemed appropriate, it could also be useful in order to analyse an anti-symmetrical levelling of a lock.

A required input in LOCKSIM is the nodes elevation, as presented in chapter 3.3.3. This represents, for the culverts, the elevation of its central longitudinal axis. Due to lack of data regarding the vertical initial position of the culverts present in this case study, an assumption was made, characterized by determining said initial position as function of the culverts hydraulic diameter. The latter corresponds, for circular culverts, to the circular cross section diameter. The nodes elevation is, therefore, calculated according to the following adopted formulation:

$$z_i = z_{bottom} + \frac{D}{4} + \frac{D}{2} \tag{4.4}$$

As it can be seen in the previous expression, the outside wall of the culvert is assumed to be positioned at a distance of D/4 from the lock bottom.

- **Slide opening function** – Despite being a versatile parameter, as in practice the lifting mechanism can be programmed to open the valve in a wide range of ways, for this work there was permanently assumed a linearity of the opening as a function of time, i.e, a constant lifting velocity. The latter is determined in the preliminary calculations. It is also possible to define the slides opening in the software as a fixed position, if necessary. The adoption of a constant lift velocity is justified for representing the simplest and less expensive lifting function, characteristics which were deemed adequate for the present analysis, since the case study represents a basic levelling system.
- **Slide loss coeffient** – The loss coefficient (K) for the slide is given as a function of the valve relative position. It depends, naturally, on the type of valve. Due to lack of information of the type of valve used in the present case study, a general function was adopted from *Berlamont* (1998), pg. 361, (*Simon*, *Carlier*, *Degrémont*) [24],which can be found in table 4.11. The respective function is shown graphically in fig. 4.7.

Table 4.11 – Adoption for the loss coefficient (K) as a function of the valve relative position (d/D)

(d/D)	0	0.125	0.25	0.375	0.5	0.625	0.75	0.875	1
K	1000	98	17	5.52	2	0.81	0.26	0.15	0.12

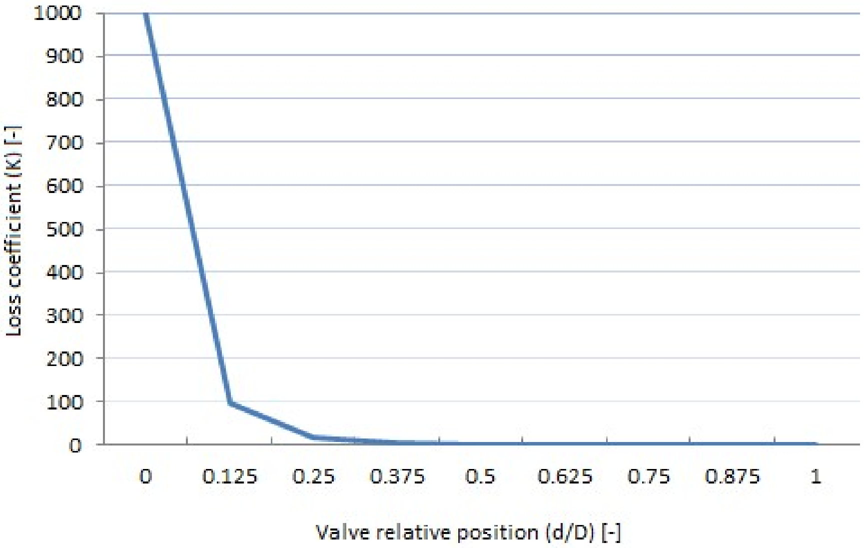


Fig. 4.7 – Graphical display of the loss coefficient (K) as a function of the valve relative position (d/D).

This approach entails a margin of error, as it is possible the general case adopted is not viable for a lock with these characteristics, and therefore not reflecting with complete accuracy the reality of the present situation, which can be achieved with resource to physical modelling.

- As previously introduced in chapter 3.3.6, in order to determine the mooring forces component due to the momentum decrease, it is necessary to estimate the percentage of the intake filling flow diverges into a longitudinal direction. Accordingly, by addressing an estimative of the upstream and downstream areas of the culvert, it was assumed that around 90% of the filling flow diverges into a longitudinal direction after the collision between opposite culverts flow.

4.1.3.1. Scenario C1-V1

Scenario C1 is characterized by filling the lock chamber through a single culvert on each side of the head. Is this case, as it is also present the levelling situation V1, the filling is done through the south head of the lock.

The schematic representation for scenario C1 can be found in annex A.1.

As for the top and side views, they are as follows:

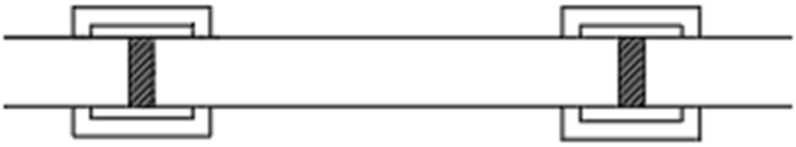


Fig. 4.8 – Top view correspondent to scenario C1

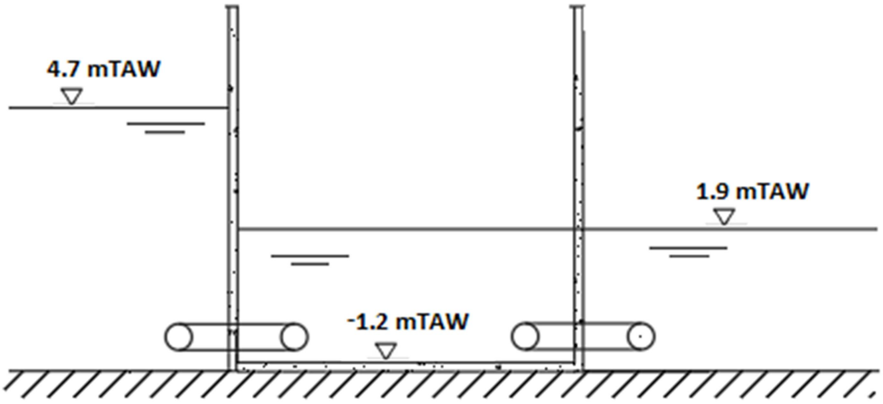


Fig. 4.9 – Side view correspondent to scenario C1-V1

Several simulations were performed. In order to analyse the influence of the hydraulic diameter of the culvert on the results, it was varied between 0.8 and 1.0. Smaller diameters than these are not predicted to be economic viable, since it results in significantly higher levelling times, and would only be a viable option if the mooring forces on the vessel remained too high after the previous hypothesis. The culvert components assumed to induce a significant resistance in the filling flow can be distinguished as: inlet section, bend 1, bend 2 and outlet section. The local loss coefficients (K) adopted for this components were, initially, based on given literature from this case study, and correspond to a rounded entrance, round bends and a round exit into the chamber, i.e. an overall round culvert. This represents a reasonable choice of culverts design, since for a small lock such as the one present here, the culverts can be pre-fabricated, which makes it easier to implement round culverts. However, it was also studied the influence of the culverts configuration, considering a culvert with significantly higher "K" values, characterized by a straight entrance, elbow bends with sharp corners and a straight exit into the chamber. The adopted "K" values, found in table 4.12, were determined according to *Idelchick* [26].

Table 4.12 – Adopted "K" values for each component of the culvert

K	Inlet	Bend 1	Bend 2	Outlet	Σ K
Round	0.2	0.36	0.36	0.9	1.82
Straight	0.5	1.15	1.15	1	3.8

This resulted in 4 different hypothesis considered for the simulations. The preliminary calculations results are as follows:

Table 4.13 – Preliminary calculations results for scenario C1-V1

Preliminary calculations				
D (m)	Culvert	μ (-)	v_h (m/s)	t_h (s)
0.8	Round	0.741	0.029	199.97
0.8	Straight	0.513	0.042	199.35
1	Round	0.741	0.023	199.39
1	Straight	0.513	0.034	198.86

The simulation results, after post-processing the output from LOCKSIM, can be found in annex B.1 to B.4 and in table 4.14.

Table 4.14 – LOCKSIM simulation results for scenario C1-V1

D (m)	Configuration	Discharge		Levelling Velocity		Levelling time		Longitudinal forces	
		Max (m^3/s)	t (s)	Max (m/min)	t (s)	(s)	(min)	Max (‰)	t (s)
0.8	Round	3.972	155	0.454	150	750	12.5	0.321	70
0.8	Straight	3.096	150	0.356	150	970	16.2	0.449	10
1	Round	5.949	150	0.687	145	485	8.1	0.438	70
1	Straight	4.639	150	0.538	145	625	10.4	-0.618	175

As it can be observed in the previous table, the selected hydraulic diameters are conservative hypothesis, since the maximum levelling velocity and longitudinal forces are significantly below the respective limits.

The simulation results reveal that the hydraulic diameter is more influent to the filling time than the resistant coefficients within the culvert. When changing from straight to round culvert and keeping a hydraulic diameter of 0.8 m, the levelling time decreases about 3 minutes and 42 seconds. On the other hand, when increasing a round culvert diameter from 0.8 m to 1.0 m, the levelling time decreases almost than 4 and a half minutes. Nonetheless, this premise needs further validation, since it is, so far, only true for the present case study, characterized by a small chamber and small culverts.

Throughout the different simulations and tests performed, it was noticeable the major influence of the valve characteristics in the filling process. It was observed that the slide lift velocity and the loss coefficient (K) as a function of the valve relative position, when subjected to changes, were significantly influent to the filling process. However, this entails the possibility that the results might not be as accurate as desired. The slide lifting time is determined in the preliminary calculations, which, as mentioned above, imply a certain margin of error when applied to levelling systems through culverts. Also, the function of the loss coefficient (K) of the valve is adopted from a general case, which is not validated to be applicable to this specific levelling system. Even though the inaccuracy of results creates a problem to the designer, within this work it is important to verify the influence of the valve characteristics in the levelling process and, therefore, the importance of supplementing the simulations with physical modelling, in order to achieve a more accurate definition of said characteristics.

Another important observation was the influence of the culvert configuration in the filling process – Even though the straight culvert induces higher resistance to flow, which results in a lower discharge, its resistance to flow also enables a higher maximum limit for the lift speed and consequently a lower lifting time of the valve when compared to round culverts. Nonetheless, the present simulations results demonstrate that the culvert configuration has a higher influence in the former than the latter – When changing from round to straight culvert, it only very slightly lowered the lifting time of the slides but significantly decreased the discharge and increased the levelling time. Therefore, the use of straight culverts, even if not necessary for the design of the present scenario, manifested an important influence in the levelling process. It demonstrates that increasing the flow resistance in the culvert could be an interesting approach to the levelling system design in other conditions, such as the necessity to lower the mooring forces in a specific case.

Predictably, the designers approach to the present situation would be to use a round culvert and adopt a higher diameter, while respecting the levelling velocity and maximum mooring force limits, in order to achieve a minimum permitted levelling time. However, an increase of diameter entails more costs and might not be economically viable. For that reason, it is necessary to approach different configurations in the design process.

4.1.3.2. Scenario C1-V2

The filling of the lock in situation V2 is done through the north head, since it corresponds to a situation where the high river tide and low sea tide occur simultaneously. The major difference in the levelling process between V1 and V2 is the initial water level in the chamber, since it corresponds to 3.1 m and 5.7 m, respectively.

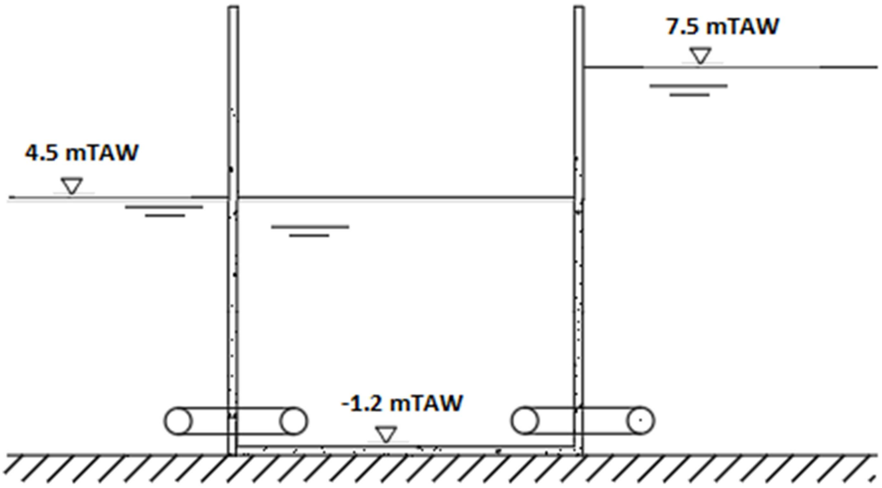


Fig. 4.10 – Side view correspondent to scenario C1-V2

Initially, this scenario followed the premise that the north and south head culvert systems are designed to be identical. Accordingly, a simulation was executed based on the most optimal hypothesis from the previous scenario, i.e. round culverts with a hydraulic diameter of 1 m.

The preliminary calculations results are as follows:

Table 4.15 – Preliminary calculations results for scenario C1-V2

Preliminary calculations				
D (m)	Culvert	μ (-)	v_h (m/s)	t_h (s)
1	Round	0.741	0.0866	102.98

As it can be observed in table 4.15, the initial water level in the chamber influences the maximum lifting velocity, enabling a faster lift of the valve slides.

The simulation results, after post-processing the output from LOCKSIM, can be found in annex B.5 and in table 4.16.

Table 4.16 – LOCKSIM simulation results for scenario C1-V2

D (m)	Configuration	Discharge		Levelling Velocity		Levelling time		Longitudinal forces	
		Max (m^3/s)	t (s)	Max (m/min)	t (s)	(s)	(min)	Max (‰)	t (s)
1	Round	6.807	80	0.703	85	465	7.8	0.287	15

Notice that, with the same levelling system and a higher initial water level difference, i.e. a higher volume of water necessary to fill when compared to V1, the levelling time is lower, as well as the mooring forces. The higher initial water level inside the chamber allows not only, as mentioned above, a faster lift of the valve slides, but also a reduced presence of the vessel in contact with the translatory waves generated by the discharge. In these conditions, the relative blockage created by the vessel is lower, which allows the translatory waves to travel through the chamber without reflecting against the vessel as much as in the previous situation. Therefore, the wave velocity does not decrease as much and the wave height is lower, reducing the oscillating vertical movement in the water surface, and consequently the longitudinal forces.

Naturally, once again the simulated hypothesis does not represent the optimal situation, since the mooring forces on the vessel, as well as the levelling velocity, are significantly lower than the normative limits. However, it was useful in order to understand the influence of the initial water level in the chamber in the levelling process.

In conclusion, this results show that the initial premise that both heads systems are identical might not lead to the most efficient solution, urging the need for the designer to explore other configurations and its economic impacts when comparing to this one.

4.1.3.3. Scenario C2-V1

Scenario C2 consists on a levelling system with two culverts on each side of the head, with similar lengths but different elevation, as it can be observed in fig. 4.12. Once again, the levelling situation V1 is present, so the filling is done through the south head of the lock.

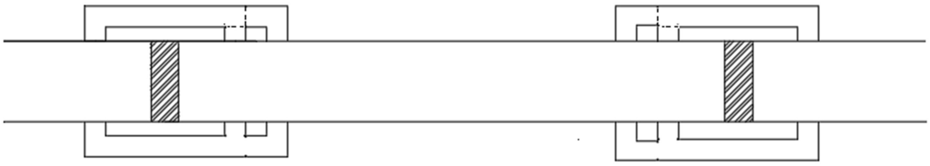


Fig. 4.11 – Top view correspondent to scenario C2

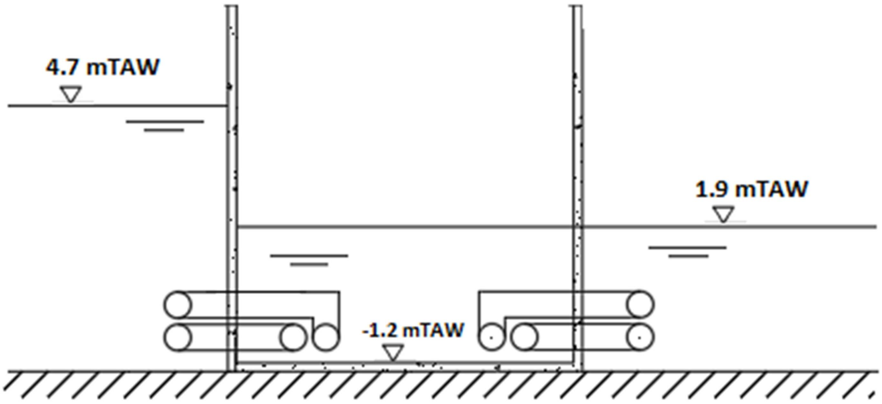


Fig. 4.12 – Side view correspondent to scenario C2-V1

The schematic representation for scenario C2-V1 can be found in annex A.2.

In conformity with the initial assumptions and adoptions presented in this chapter, additional ones were made for this specific scenario, as follows:

- The lower elevation culvert will henceforth by referred to as culvert number 1 and the upper culvert as culvert number 2.
- Both culverts have identical hydraulic diameters, i.e. $D_1 = D_2$
- The initial idea for this scenario was to configure the system so both culverts could converge in the same outlet, by introducing a T-junction component before the outlet in the input file, and therefore reduce the costs inherent to a longer second culvert. However, a simulation error of "maximum convergence achieved" occurred in LOCKSIM. According to *Schohl* [23], this message indicates that the solution tolerances have not been met for this iteration. *Schohl* [23] also indicates that this issue can be resolved by opening the valves more slowly. However, that would not only result in a low performance system but also negatively interfere with the comparisons with the other considered scenarios. It was also weighted the possibility of a bigger diameter outlet, in which both culverts would converge. This hypothesis was dismissed due to not being very adequate for comparison with other scenarios. However, it is an interesting approach for situations where it is desired and/or necessary that the outlet is as close to the gate as possible.

  It can be observed in fig. 4.12 that both culverts have different inlets and outlets, notwithstanding having identical characteristics. Culvert number 2 configuration is characterized by being slightly longer than culvert 1, and having a vertical bend before outlet 2, so the latter has the same elevation as outlet 1. This is necessary because the software did not allow a simulation with outlets at different elevations.
- In accordance with the latter assumption, while outlet 1 is located in a distance "x_s" to the gate (identical to scenario C1), outlet 2 is located slightly further in the lock wall. The distance between outlets is determined assuming a distance between culverts exterior walls of D/2. The distance between outlets concerns the distance between the center of the circular cross section of each culvert. Therefore, the horizontal distance between the outlets, as function of the hydraulic diameter, is given by:

$$l_{O1-O2} = \frac{D}{2} + \frac{D}{2} + \frac{D}{2} = \frac{3}{2}D \tag{4.5}$$

- The nodes elevation of culvert 1 are calculated according to expression (4.4). The vertical distance between culverts, also a function of the adopted hydraulic diameter is assumed to be $D/2$.

  Therefore, the nodes elevation of culvert 2 is calculated as follows:

$$z_2 = z_1 + \frac{D}{2} + \frac{D}{2} + \frac{D}{2} = z_1 + \frac{3}{2}D \tag{4.6}$$

- The valve slide is opened vertically, hence both valves have a similar slide. The second culvert can, therefore, only start to fill the chamber after the first is fully opened. This can be introduced in the input file by defining a different initial opening time (*xshift*), presented in section 3.3.4., to the second valve function. That parameter will be, therefore, the sum of the total lifting time with the time the slide takes to go through the gap between culverts. The latter only depends on how the operator programmes the lifting during the gap, since there are no limits to its lifting velocity. For that reason, and since the gap was defined as $D/2$, the time the slide takes to go through the gap between culverts was assumed to be $t_h/2$, where t_h corresponds to the faster lifting time between the culverts. In other words, it is an estimation based on the premise that the slide is being lifted at an approximately constant rate. Notice that the lifting time is not necessarily the same for both culverts just because they have identical hydraulic diameters, since it also depends on the discharge coefficient, which is different due to the above mentioned extra bend and higher length in culvert 2.

This scenario entails a larger cost than scenario C1, on account of its system having one more culvert on each side of the head. The objective of simulating and analysing this scenario is to understand how much an extra pair of culverts influences the levelling process. Following the previous simulations, it was established that, at this point, is redundant to consider straight culverts, since the influence of the culvert configuration was already analysed. The goal now is to understand how much cost efficient is this scenario for the levelling process, to contrast with the additional cost inherent to having one more pair of culverts in each head.

Therefore, two different hypotheses were simulated, to contrast the influence of changing the hydraulic diameter for this particular case. Accordingly, the preliminary calculations results are as follows:

Table 4.17 – Preliminary calculations results for scenario C2-V1

Preliminary Calculations					
D (m)	Configuration		μ (-)	v_h (m/s)	t_h (s)
0.8	Round	Lower culvert	0.741	0.023	199.39
		Upper culvert	0.677	0.025	199.59
1	Round	Lower culvert	0.741	0.029	199.83
		Upper culvert	0.677	0.032	199.91

As it is shown in table 4.17, once again the hydraulic diameter changes don't induce a very significant change in the lifting time. Since the lower culvert is the first to open, until the opening of the upper culvert, the system behaves identically to scenario C1. The simulations results are expressed in table 4.18.

Table 4.18 – LOCKSIM simulation results for scenario C2-V1

D (m)	Configuration	Discharge		Levelling Velocity		Levelling time		Longitudinal forces	
		Max (m^3/s)	t (s)	Max (m/min)	t (s)	(s)	(min)	Max (‰)	t (s)
0.8	Round	3.972	155	0.437	160	560	9.3	0.366	25
1	Round	5.949	150	0.656	135	425	7.1	0.558	25

Examining the contrast between the present scenario with C1, by including a second pair of culverts it was possible to reduce the levelling time whilst only slightly increasing the longitudinal forces, demonstrating the benefits of this solution. However, culvert number 2, in either hypothesis, does not reach the maximum discharge (annex B.6 and B.7), i.e. it does not take part in the filling of the lock as much as possible, not maximizing its usefulness. Even though this mostly occurs because it is a small lock, this is not a desirable situation. It is predictable that the cost saving inherent to reducing the levelling time in about 3 minutes and 1 minute, for hydraulic diameters of 0.8 m and 1 m, respectively, will not counterbalance the higher costs inherent to including a second pair of culverts.

Even though it is not the present thesis goal, important to notice that the present results, similarly to scenario C1, show that there is a significant margin to optimize the design solution. In this case, the solution would be to reduce the diameter, which would lower the costs of the culverts, until culvert 2 maximizes its usefulness, as opposed to the case in scenario C1, where the solution would be to increase the diameter in order to lower as much as possible the levelling time. In addition, a posterior economic analysis would have to be done to compare if it is more beneficial to use two smaller diameter culverts, with a given levelling time, or one larger diameter culvert. Nonetheless, the importance of these simulations for the present work is to observe and understand how this software can benefit a preliminary phase of the design of levelling systems, to be furtherly validated with physical modelling and/or 2D or 3D simulation software and subjected to an economic analysis. Accordingly, it is concluded that the software allows for a wide range of possibilities, while still within certain limitations, e.g. the impossibility of discharging in outputs of different elevations in the chamber, which could be an interesting design option.

4.1.3.4. Scenario C2-V2

This scenario aims to both analyse how the present levelling system performs in the presence of a higher initial water level in the chamber and a higher water level difference to fill, but also to compare with scenario C1-V2 and possibly consider different systems for different heads.

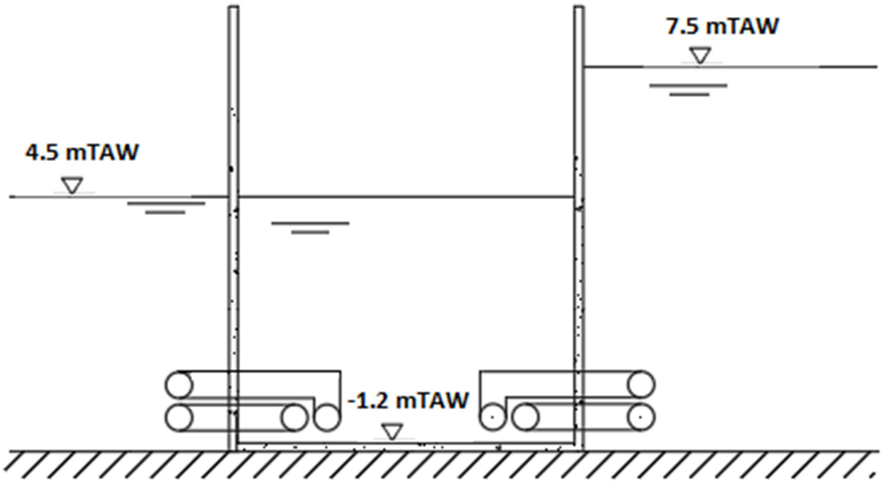


Fig. 4.13 – Side view correspondent to scenario C2-V2

In this case, opposite to C1-V2, it was considered important to perform simulations with both 0.8 m and 1 m of hydraulic diameter of the culverts. While for scenario C1-V2 only the previously achieved best hypothesis for the design was simulated, in order to compare and analyse the differences between V1 and V2, in the present situation both previously considered scenarios have pros and cons vis-à-vis the optimization of the design: while the 1 m diameter allows for a faster levelling time, the 0.8 m diameter enables a larger contribution of culvert 2 in the levelling process while saving the cost inherent to a larger culvert.

Subsequently, the preliminary calculations resulted in:

Table 4.19 – Preliminary calculations results for scenario C2-V2

Preliminary Calculations					
D (m)	Configuration		μ (-)	v_h (m/s)	t_h (s)
0.8	Round	Lower culvert	0.741	0.108	103.15
		Upper culvert	0.677	0.118	103.11
1	Round	Lower culvert	0.741	0.087	102.97
		Upper culvert	0.677	0.095	102.96

As expected, following the conclusions in section 4.1.3.2, the initial water level in the chamber enables a faster lift of the valve slides.

Table 4.20 exhibit the simulation results.

Table 4.20 – LOCKSIM simulation results for scenario C2-V2

D (m)	Configuration	Discharge		Levelling Velocity		Levelling time		Longitudinal forces	
		Max (m^3/s)	t (s)	Max (m/min)	t (s)	(s)	(min)	Max (‰)	t (s)
0.8	Round	6.223	220	0.64	220	470	7.8	0.185	15
1	Round	7.764	210	0.80	210	330	5.5	0.287	15

Notice that the maximum discharge time occurs later than in scenario C2-V1. This is due to, for the present scenario, a stronger contribution to the filling process of culvert 2, resulting in a total maximum discharge value superior to the maximum discharge value of culvert 1, which does not reflect the situation for the previous scenario. The major parameter that allowed this is the shorter lifting times of the slides, due to the larger initial water level. This, however, doesn't atone for the fact that culvert 2 is still not being used to its full potential. Several options could be addressed in order to rectify this situation and optimize the solution, such as, for instance, introducing a smaller hydraulic diameter to culvert 2 while maintaining the same in culvert 1. Nonetheless, the choice between D=0.8 m, D=1.0 m, other considered diameter or using different diameters for both culverts, entails, once again, an economic study, namely verifying if the decreasing of diameter compensates for the increasing of levelling time, and vice-versa.

One important observation is that the initial water level inside the chamber has a major impact in the levelling process, as above mentioned in chapter 4.1.3.2., enabling the conclusion that, for this case, it is predictable that the most efficient design solution would not be identical systems on both heads. Among a wide range of different options for designs, differing the systems on both heads may include differences in, for instance, culvert configuration, number of culverts, hydraulic diameters or vertical position, i.e. elevation, of the culverts.

However, any of this or other options entails another necessary verification: the choice of culvert system for filling in, for instance, scenario V1, must be able to empty the lock for scenario V2, since both those processes occur in the south head, in this case. This was considered to be interesting for the present thesis, not on behalf of validating the design but to analyse how the software applies to emptying. With that in mind, based on the premise that the culvert system corresponding to scenario C2-V1 is the final design for filling through the south head, it must now be validated for emptying the lock in the levelling situation correspondent to V2. Since the culverts have identical characteristics, and the upstream and downstream levels for the emptying through the south head and filling through the north head are the same, for scenario V2, the preliminary calculations results are the same as in table 4.19.

In order to simulate the emptying of the chamber, some alterations had to be introduced in the input file for LOCKSIM. While maintaining the same schematic representation, it was necessary to change between each other the upstream and downstream nodes of the components, in the interest of changing the flow direction within the culvert. The latter was, for the simulations performed so far regarding filling, from outside to inside the chamber, whilst with this changes in flow direction, the flow direction within the culvert is programmed to be from the chamber to the approach harbour. In accordance, the nodes which represented the outlets of the culvert are now inlets, and vice-versa, and therefore were subjected to changes of the resistance coefficient values. For simplification, the same coefficients were considered for inlets and outlets, 0.2 and 0.9, respectively. The resistance coefficients of the bends are the same for each direction and were, therefore, not subjected to changes.

Regarding the post-processing, in accordance with chapter 2.4.3.2, the component of momentum decrease is neglected, since the presented values for the culvert discharge indicate the discharge to the approach harbour and not the chamber. Notice that said values are not, in this case, important for the post-processing calculations of the mooring forces. However, they were still included in the output in order to have an idea of the behaviour of the culvert in the opposite direction.

The simulation results for the emptying of the chamber in this scenario are as follows:

Table 4.21 – LOCKSIM simulation results for scenario C2-V2 (Emptying)

D (m)	Configuration	Discharge		Levelling Velocity		Levelling time		Longitudinal forces	
		Max (m^3/s)	t (s)	Max (m/min)	t (s)	(s)	(min)	Max (‰)	t (s)
0.8	Round	6.218	220	0.64	220	465	7.8	-0.142	30
1	Round	7.769	210	0.80	210	325	5.4	-0.225	30

By comparing this results with the results from table 4.20, as predictable the discharges and levelling velocities (which still have to respect a maximum limit, since the crew still has to operate the mooring of the vessel during the emptying process) are similar, since the culvert system is identical. The small changes of these values are due to the fact that the flow from culvert 2 had an increase of speed when changing elevations and, in this case where the flow direction changed, it had a decrease of speed on the same culvert section. The levelling times are, as well, similar in value. In annex B.10 and B.11, it is also possible to observe that the longitudinal forces in the lock chamber behaved as expected, having a negative contribution until the maximum discharge moment and thereafter a mainly positive contribution, with its peak occurring at the end of the emptying process, as introduced in chapter 2.4.3.2. These results validate the possibility to simulate the emptying process with the same accuracy as the filling.

4.1.3.5. Scenario C3-V1

Similarly to previous addressed scenario, C3 is also characterized by a levelling system consisted by a pair of culverts on each side of the head. However, on this case, the elevations of both culverts are identical and the lengths differ, resulting in a short culvert with intrinsic characteristics similar to the one found in scenario C1 and in a slightly longer culvert that goes around the first (fig. 4.14 and fig.4.15). Firstly, the applicability of this scenario within the software will be analysed for levelling situation V1.

Fig. 4.14 – Top view correspondent to scenario C3

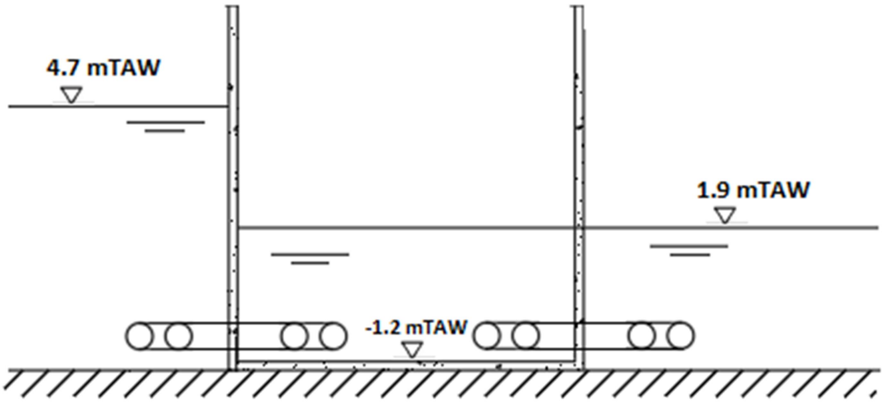


Fig. 4.15 – Side view correspondent to scenario C3-V1

Following the results from the previous scenarios, it was considered interesting to see the influence of a difference in length in the culverts, in contrast to the differences in configuration and elevation observed before. For that reason, the considered hypothesis did not include changes in said parameters. Round culverts, with intrinsic characteristics introduced in table 4.12, are considered for all simulations, as it is not expected that the mooring forces become so high that they warrant a configuration that induces greater head losses. Initially, to focus on this parameters influence and to validate the introducing of this scenario to the software, similar diameters were assumed for both culverts. However, it was also deemed interesting to explore if and how the software executes a simulation with culverts with different diameters, which was included in the hypothesis inherent to this section.

Whilst the assumptions and adoptions introduced for scenario C2 are no longer applicable, notice that the initial assumptions and adoptions presented in 4.3.1 are still considered for the present scenario. Naturally, as the configuration of the levelling system is subjected to changes, it becomes necessary to make additional assumptions:

- Henceforth, the shorter culvert will be referred as culvert number 1, and accordingly the longest culvert as culvert number 2.
- The distances between culverts, in both longitudinal and transverse direction, is assumed to be a function of the adopted hydraulic diameter, with a value of D/2. Notice that this distance is not mandatory or even desirable. It is usual to have both culverts adjacent to each other, in order to avoid increasing the expropriation area and, consequently, the construction costs for the lock. It is however considered the above introduced distance for this analysis to increase the differences in length of the culverts, and therefore understand said differences influence when levelling. For the same reason, when different hydraulic diameters have been adopted for each culvert, the distances between them are determined as function of the highest diameter.
- As culvert number 2 goes around culvert number 1 and it was concluded in the previous chapters that converging both culverts into one outlet with the same hydraulic diameter was not viable, once again two different outlets were considered. Since the distance between culverts is the same as in the previous scenario, the horizontal distance between outlets follows expression (4.5)
- The nodes elevations of both culverts are calculated according to expression (4.4), following the same premise as previous scenarios, i.e. determining said elevations as function of the hydraulic diameter of the culvert. Important to mention that, when addressing the hypothesis based on different hydraulic diameters between culverts, the nodes elevations will be considered identical for both culverts and as a function of the highest diameter culvert. This adoption follows the premise that not only the difference in elevations is not predictable to be significant to the results, but also applying different elevations to adjacent culverts is not a viable construction option, especially for a small lock.
- One major difference between scenarios C3 and C2 is that, while in the latter the vertical opening of the valve resulted in a single slide being lifted, in the former that no longer occurs. Subsequently, each culvert will have an independent lift of the valve slides, which enables both culverts to discharge at the same time. This is predictable to significantly increase the discharge, which results in higher mooring forces in the beginning of the levelling process but lower levelling times.

In summary, the goal for this scenario is to simultaneously analyse the efficiency of the present culvert configuration, in contrast to the increase of costs said configuration entails, and also analyse the influence for the levelling process induced by filling through two culverts with differences in length and/or hydraulic diameter.

Therefore, four hypotheses (distinguished by the letters A, B, C and D) were considered and simulated. The hydraulic diameters considered for each hypothesis, as well as the respective preliminary calculations results, are given by table 4.22.

Table 4.22 – Preliminary calculations results for scenario C3-V1

Preliminary calculations					
Scenario	Culvert nº	**D (m)**	μ (-)	v_h (m/s)	t_h (s)
A	1	0.8	0.741	0.029	199.83
	2				
B	1	1	0.741	0.023	199.39
	2				
C	1	1	0.741	0.029	199.83
	2	0.8		0.023	199.39
D	1	0.8	0.741	0.023	199.39
	2	1		0.029	199.83

The results of the performed simulation can be found in table 4.23. Firstly, it is visible once again the influence of the change in hydraulic diameter, with an even greater difference compared to previous simulations due to the simultaneous discharge by both culverts. Notice that the longitudinal forces maximum value is negative and occurs later during the filling process in hypothesis B and D. However, for both those cases, said negative maximum value is very close to the positive maximum value, that occurs at similar times as other hypothesis, as it can be observed in annex B.13 and B.15, respectively. As above mentioned, hypothesis A and B were considered mainly to observe and understand how much influence the difference in length of two culverts can have on the filling process, while other characteristics are identical for both culverts. In annex B.12 and B.13, the difference in discharge is visible but, nonetheless, small. The resistance to the flow inherent to a longer culvert is, on this particular case, not very relevant to the filling process. Notice that this occurred for an already conservative approach, with the considered distances between culverts being higher than usual, allied with an adoption of an already conservative *Manning* coefficient value. Notwithstanding, this results demonstrate that the simulation software can simulate this type of levelling system and configuration, whilst its predictable that for situations where the above mentioned differences in length are higher, the simulation might be helpful.

Approaching hypothesis C and D, the difference in length is once again not very influent in the levelling process. As it can be observed, defining the shortest culvert with a higher or lower diameter than the longest, results in similar discharges, levelling times and longitudinal forces. However, it proved to be a viable approach for the design of the levelling process itself: Hypothesis B is not be viable, since it does not respect the levelling velocity maximum limit, while reducing only one of the culverts diameters (hypothesis C and D) results in a significantly better solution than decreasing the diameter on both culverts (hypothesis A). On the other hand, the higher levelling velocity from hypothesis B could be contradicted by lowering the lifting velocity or even start one of the slides lift later than the other, which would result in a lower maximum discharge value. As the latter occurs at a similar moment as the maximum levelling velocity, it is likely that only by approaching the slide lift parameters, it should enable this hypothesis to respect every normative limit. Also, this is a case where applying the straight culvert introduced above instead of a round culvert could be a viable option. Once again, an economic analysis is necessary to reach the optimal solution, since without said analysis it is impossible to know if it is more economical efficient to save about 1 and a half minutes of levelling time (hypothesis C and D), have a smaller diameter culvert (hypothesis A) or levelling with the conditions for hypothesis B mentioned above.

Table 4.23 – LOCKSIM simulation results for scenario C3-V1

Scenario	Discharge		Levelling Velocity		Levelling time		Longitudinal forces	
	Max (m^3/s)	t (s)	Max (m/min)	t (s)	(s)	(min)	Max (‰)	t (s)
A	6.861	150	0.76	135	405	6.8	0.673	25
B	9.791	125	1.10	130	275	4.6	-1.018	95
C	8.432	130	0.947	130	325	5.4	0.848	25
D	8.397	130	0.943	130	325	5.4	-0.841	130

In order to contrast the adopted configuration in C3 to the one in C2, results from simulations of hypothesis A were compared with the hypothesis in section 4.1.3.3 that also consists on levelling through two culverts with a hydraulic diameter of 0.8 m. Even though the differences in length and elevation are evident, assuming both scenarios as equally economically viable, the conclusion is that the most important parameter between said scenarios is the number of slides. The fact that in C2 both culverts share the same slide, delays significantly the levelling process since the second culvert can only start discharging after the first is fully opened, while, on the other hand, in C3 both culverts work simultaneously. This results in a difference of about 2 and a half minutes in levelling time, which can be economically significant for small locks. However, notice that the present configuration needs two different slides, as well as the energy to lift them simultaneously, which by itself entails higher costs.

4.1.3.6. Scenario C3-V2

In this section, initially a hypothesis similar to hypothesis B in last chapter was simulated, with the difference residing naturally in the initial water level in the chamber inherent to scenario V2.

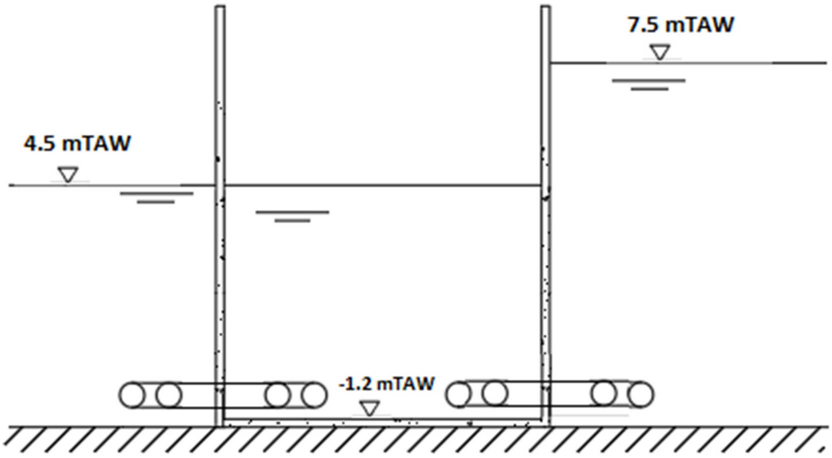


Fig. 4.16 – Side view correspondent to scenario C3-V2

As predictable according to the previous simulation results, the higher initial water level in the chamber allows for a faster lift of the valves, which by itself increases the discharge flow and, consequently, the levelling velocity. Therefore, this simulation was developed in order to observe the balance between a positive factor for lowering the levelling velocity – higher initial water level in the chamber, and a negative factor – decrease of lifting time. The preliminary calculations results are expressed in table 4.24, while the simulation results are expressed in table 4.25.

Table 4.24 – Preliminary calculations results for scenario C3-V2

Preliminary calculations				
D (m)	Culvert	μ (-)	v_h (m/s)	$t_h\ (s)$
1	Round	0.741	0.087	102.98

Table 4.25 – LOCKSIM simulation results for scenario C3-V2

D (m)	Configuration	Discharge		Levelling Velocity		Levelling time		Longitudinal forces	
		Max (m^3/s)	t (s)	Max (m/min)	t (s)	(s)	(min)	Max (‰)	t (s)
1	Round	12.084	80	1.245	80	250	4.2	0.541	15

As it is possible to observe, in this scenario, the application of a levelling system with the present conditions exceeds the maximum permitted levelling velocity. Even though the lowering of the culvert diameter would be the more feasible option for this design, due to having already included its influence in the present work in several simulations, two hypotheses for the optimization of this scenario were considered:

- **A** – Change the round culverts with straight culverts, with the characteristics presented in table 4.12.
- **B** – Open one of the slide lifts later than the other, instead of opening both simultaneously. Due to the results from previous simulations for scenario C3 showing that culvert 1 discharges slightly more than culvert 2, the latter was considered to open later than the former in this simulation.

In section 4.1.3.1 it was determined that a change from round to straight culvert induces not only higher head loss in the culvert flow but also allows for a faster lift of the valve. These two phenomena have, respectively, a positive and negative influence when the goal is to lower the filling velocity. When approaching hypothesis B, initially the culvert 2 slide was adopted to begin lifting when culvert 1 was halfway opened, i.e. $t_{i2} = \frac{t_{h1}}{2}$. However, in these conditions, the levelling velocity was still superior than the normative limit. Therefore, another simulation was developed where $t_{i2} = t_{h1}$, meaning the second slide starts opening at the moment where the first slide is fully opened, similar to what occurred in scenario C2.

The preliminary calculations inherent to the above mentioned hypothesis are displayed in table 4.26, while the consequent simulation results can be found in table 4.27.

Table 4.26 – Preliminary calculations results for scenario C3-V2 (Hypothesis 2)

Preliminary calculations					
Scenario	D (m)	Culvert	μ (-)	v_h (m/s)	t_h (s)
A	1	Straight	0.513	0.125	102.95
B	1	Round	0.741	0.087	102.98

Table 4.27 – LOCKSIM simulation results for scenario C3-V2 (Hypothesis 2)

Scenario	Discharge		Levelling Velocity		Levelling time		Longitudinal forces	
	Max (m^3/s)	t (s)	Max (m/min)	t (s)	(s)	(min)	Max (‰)	t (s)
A	9.502	75	0.983	70	320	5.3	0.534	15
B	9.403	160	0.965	170	300	5	0.287	15

Scenario B resulted is a more viable solution, even though the second culvert is not being used to its full potential, since it does not reach its maximum discharge before the filling of the chamber. Nonetheless, not only has it resulted in lower levelling time, but also in lower longitudinal forces. It is also not predictable that it should induce any higher costs in comparison to the initially considered hypothesis for this scenario, since the total time of both slides operation is identical. The only, but significant difference is that the slides are operated one after the other, instead of operating two slides simultaneously. Once again it is demonstrated the influence the valves have in the filling process and how important it is to accurately introduce its characteristics in the simulation software.

4.1.4. LOCKSIM – LEVELLING THROUGH LONG CULVERTS

In chapter 2.3.3, it was introduced the levelling system through long culverts. Accordingly, for the *Melle* Case study it was developed the simulation of levelling through a longitudinal culvert on each wall of the lock. Since this case study is characterized by small drop, of 2.8 m in scenario V1 and 3.0 m in scenario V2, it is anticipated that it might not be a very feasible option from the designer point of view, especially due to the more expensive costs inherent to this levelling system. Nonetheless, it was deemed interesting to apply it to this case study, in order to analyse the behaviour of the software when computing this type of levelling system.

Unlike levelling system through short culverts, the previously denominated North and South heads now share a common culvert. Once again, there is still a need of levelling in both directions, since it is present the same case study. However, the difference is that, for either V1 or V2, the filling and emptying has to be done through the same system but by opening different head valves. It is therefore not possible to adopt different levelling systems for each head depending on the levelling situation.

The method used for this chapter's simulations differs from the one presented in chapter 4.1.3, related to short culverts: while the software still requires the development of a schematic representation of the present scenario hydraulic network, the preliminary calculations were not considered to be viable for this case. So far, the preliminary calculations were based on an adopted hydraulic diameter for the culvert and a discharge coefficient as function of the loss coefficients. The latter is much more difficult to accurately estimate before the simulations. While the resistance coefficients from the inlets, bends and outlets can be estimated in the same fashion, the T-junctions loss coefficients are calculated by LOCKSIM during the simulation and not an input value, as it was introduced in chapter 3.3.2. Besides, the length of the long culvert is much higher than the length of the short culverts, and consequently the intrinsic head losses, neglected in the previous preliminary calculations.

Regarding the present scenario and inherent levelling system, the following assumptions and adoptions were made:

- The scenarios characterized by a levelling system through long culverts will be henceforth denominated L1.
- Due to the reasons above mentioned regarding the non-applicability of the preliminary calculations to this case, the lifting time was assumed a variable.
- The levelling is done symmetrically.
- The lock gates characteristics, such as shape and height, were not determined. Only its position within the lock is relevant.
- The lock chamber and the vessel are both characterized by having a rectangular cross section.
- Similarly to the adoption in chapter 4.1.3, it was assumed the presence of concrete culverts, with an adopted value of roughness coefficient of 0.017 s.m$^{-1/3}$. Same value was adopted for the roughness of the lock walls and bottom.
- Once again, a value of 60 m was adopted for the length of the vessel (l_S) and 3 m for the distance between bow and lock gate (x_S), in order to give the desirable accuracy to the computational reaches.
- As introduced in chapter 3.3.2, for the particular case of simulating levelling through long culverts in LOCKSIM, T-junctions are introduced in the input file in order to compute the division of flow inherent to the present levelling system. The angles between “legs” of the T-junction, responsible for the internal calculation of the head losses in this component by LOCKSIM, were adopt based on the following possible configuration for division of flow at a T-junction, as given by Schohl [23] (fig. 4.17). Notice that the arrows indicate flow directions.

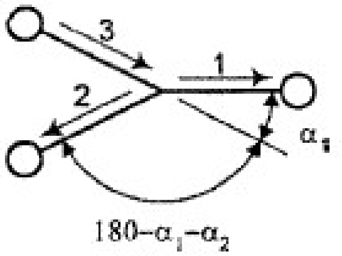


Fig. 4.17 – Configuration for division of flow at a T-junction, as given by Schohl [23]

Accordingly, the adopted angles were $\alpha_1 = 0^o$ and $\alpha_2 = 90^o$.

- The lengths of the long culvert components until the first T-Junction and after the last one, were adopted from the case study literature provided.
- The culvert nodes are determined as function of the culvert hydraulic diameter, following the same adoption presented in chapter 4.1.3,
- Idem for the slide opening function and slide loss coefficient adopted. For the former, the difference is that the lifting characteristics are no longer determined by preliminary calculations, as above mentioned.
- Initially, there were considered 7 outlets from the long culvert correspondent to the seven chamber nodes considered, with distances between them identical to the distances between the chamber nodes – 12 m. However, it was noticed that when filling the chamber, the three outlets further away from the culvert inlet didn’t discharge any flow. That enabled the conclusion that, for this specific case, seven outlets was excessive. Another adoption was made in light of this conclusion, which considered 4 outlets, discharging into the chamber nodes C1, C3, C5 and C7. Therefore, the distances between outlets were fixed at 24 m.

- In a levelling system through long culverts, the inflow during the filling is not constant throughout the chamber, but it is assumed that the contrast of the flow from the southern outlets (Discharge into nodes C5 and C7) with the flow from the northern outlets (Discharge into nodes C1 and C3) guarantees an extremely low longitudinal force due to the momentum decrease component, since the momentum of each referred flow decreases in a contrary longitudinal directions, balancing each other. Therefore, this component is neglected in the post-processing of the simulations output.

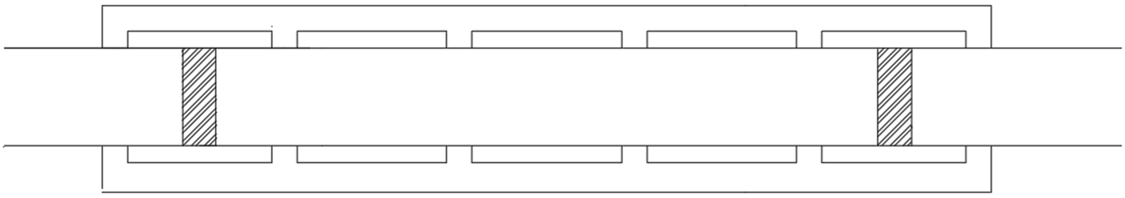


Fig. 4.18 – Top view correspondent to scenario L1

4.1.4.1. Scenario L1-V1

A hydraulic diameter of 1.0m was adopted. The present levelling situation is V1. Three hypotheses were simulated, with differences in the lifting time, in order to explore the influence of this parameter in the levelling process when its value is undetermined preliminary. The adopted lifting times were 400 s, 300 s and 200 s, for hypotheses A, B and C respectively.

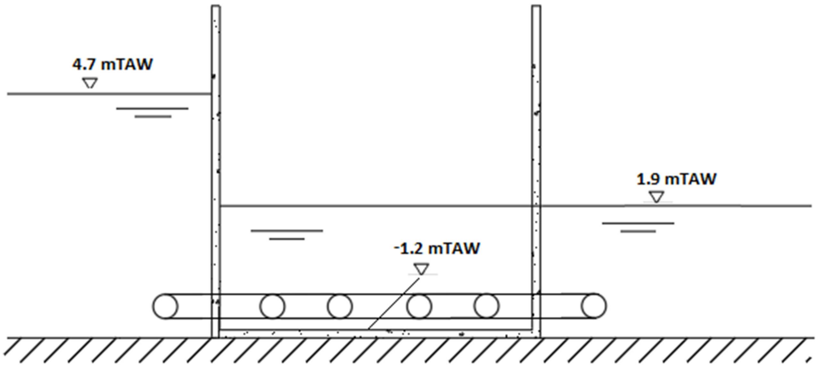


Fig. 4.19 – Side view correspondent to scenario L1-V1

The simulations results are as follows:

Table 4.28 – LOCKSIM simulation results for scenario L1-V1

Scenario	t_h (s)	Discharge		Levelling Velocity		Levelling time		Longitudinal forces	
		Max (m^3/s)	t (s)	Max (m/min)	t (s)	(s)	(min)	Max (‰)	t (s)
A	400	4.696	250	0.485	250	585	9.8	-0.482	125
B	300	5.056	195	0.521	200	550	9.2	0.274	10
C	200	5.567	150	0.596	155	515	8.6	0.389	25

These levelling system simulations had some odd results, namely regarding the discharge values after the levelling process finishes, as seen in annex B.19, B.20 and B.21. According to Schohl [23], "The presence of tee and manifold components in a network sometimes leads to solution difficulties resulting in one of the following messages: 'Maximum convergence achieved'; 'Maximum number of iterations reached without convergence' (…) these messages indicate that the solution tolerances have not been met for this iteration." This is believed to be the cause for the odd results post-filling of the chamber. Schohl additionally says: "May have convergence problems when specifying very fast valve openings. Can 'workaround' this issue, but solution obtained with such fast valve openings will usually indicate very poor lock performance." Accordingly, it can be observed that the lower the adoption of lifting time, the odder the results are. It is deemed possible that the simulation of this leveling system, characterized by the introducing of T-junctions in the input file, may not induce accurate results, since it also shows odd differences in the translator waves for the different hypothesis. Once again, these simulations require physical modeling in order to validate the results.

Nonetheless, it is assumed said convergence errors only occur after the filling of the chamber is complete, since no errors occurred in the software during the simulation, and it is therefore assumed the results are viable, in order to enable comparison with previous scenarios. However, significant doubts remain due to the odd nature of the results.

Accordingly, the results found in table 4.28 demonstrate that, for this specific case where the lock is relatively small, the investment inherent to the application of a long culvert system does not constitute a viable option, since, compared to previous scenarios, it results in higher levelling times. Notice that these hypotheses do not reflect an optimal design of the long culvert system, since there is still a significant gap between the mooring forces acting on the vessel and their respective limits, as well as a significant gap between the levelling velocity and its respective limit. On the other hand, in order to optimize this hypothesis, it would be necessary to lower the lifting time, which is predictable to result in an inaccurate display of the filling process, due to the simulation problems described above.

As an additional note, a deeper look was taken into the input parameters of the T-junctions, namely the angles between the "legs" of that component. One important limitation of the software is its one-dimensional approach, i.e. it is assumed by the software that the discharge from *pipe* components (culvert) into the *open_channel* components (chamber) is always perpendicular. It was therefore explored if by changing the value of α_2 from 90º to, for instance, 45º or 135º, it would imply a non-perpendicular discharge into the chamber. For α_2 = 135º, an error occurred within LOCKSIM, which does not allow α_2 to be higher than 90º. For α_2 = 45º, it was therefore concluded that the software accurately determines the head losses in the T-junction for that situation, but is does not automatically assume a non-perpendicular discharge into the chamber, since the results only barely changed. Either way, considering α_2 = 45º would be an unfeasible option for the overall filling process, since, considering it would actually be the discharge angle into the chamber, it would result in higher translatory waves for the same filling flow, due to the filling jets from both walls no longer dissipate as much energy by colliding against each other. Following the same consideration, changing α_2 could, however, be a feasible option if it was somehow possible to define it as 45 and 135 in consecutive outlet, making it so that the filling jets from each culvert would collide between them in pairs. Due to lack of time and the above mentioned limitations of the software, this theory was not deeply explored, since it would require 2D or 3D simulation software, as well as physical modelling for further validation.

4.1.4.2. Scenario L1-V2

In the conditions of levelling situation V2 within scenario L1, two hypothesis were considered for simulations: filling (A) and emptying (B), through the north head and south head respectively, through a long culvert with the same characteristics of hypothesis B from chapter 4.1.4.1.: hydraulic diameter of 1.0 m, lifting time of 300 s. These hypotheses were chosen because it was considered interesting to complement the results from the previous scenario with analysis of how the software can model the emptying through long culverts. Similar to what was executed in section 4.1.3.4, in order to simulate the emptying of the chamber, some alterations were introduced in the input file, namely changing between each other the upstream and downstream nodes of the T-junction components and interchange the inlets with the outlets.

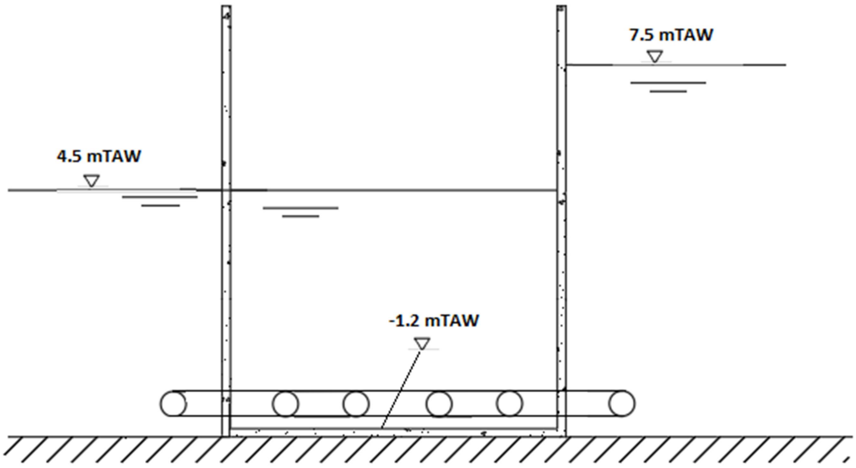


Fig. 4.20 – Side view correspondent to scenario L1-V2

The results from the simulations are displayed in table 4.29 and annex B.22 and B.23.

Table 4.29 – LOCKSIM simulation results for scenario L1-V2

Scenario	Discharge		Levelling Velocity		Levelling time		Longitudinal forces	
	Max (m^3/s)	t (s)	Max (m/min)	t (s)	(s)	(min)	Max (‰)	t (s)
A	5.278	195	0.542	205	565	9.4	0.192	40
B	5.301	195	0.544	205	560	9.3	-0.087	100

Regarding the filling (A), the simulation resulted similarly to the ones found in the previous chapter.

The results from the emptying situation (B) are not considered to be viable, since not only the same odd values for the discharges are visible, but also the translatory waves results are inaccurate. As mentioned before, when emptying the translatory wave has a negative contribution until the maximum discharge moment and thereafter a mainly positive contribution, which peak occurs at the end of the emptying process. Such phenomena occurred in the previous emptying simulations, but not on the present one. Not considering any possible mistakes from the author, it is possible that inaccuracy is caused by the lack of capability of LOCKSIM to adequately simulate emptying through long culverts. This is possibly due to miss-calculations of the converging inflowing from the chamber into the culvert. Further exploration of this problem was not executed in this thesis, for lack of time

4.1.5. LOCKFILL – LEVELLING THROUGH SHORT CULVERTS

Initially, it was considered the possibility of modifying the LOCKFILL template of levelling systems through openings in the gates in order to represent in the same software, a levelling system through short culverts. As mentioned before in this work, one significant difference between levelling systems through the gate openings and short culverts is that in the former the filling jet is entering the chamber in a direction parallel to the lock wall, and in the latter the filling jets discharge into the chamber in a direction perpendicular to the lock wall. Therefore, a step towards an accurate introduction of a levelling system through short culverts in the gate opening would be to add 90º to the filling jet horizontal angle. However, chapter 4.1.2, where said template was studied, enables the conclusion that within its input parameters, none of them allowed a change of horizontal direction of the jet. The only angle of the filling jet through gate openings which it is possible to modify is the vertical angle, which is useless for this particular purpose.

Therefore, this was considered an inaccurate option, due to the one-dimensional characteristic of the template contradicting the one-dimensional characteristic of a levelling system through culverts.

Accordingly, also as introduced in chapter 3.2.3, in order to best represent a levelling system with short culverts, the more adequate LOCKFILL available levelling system template is through culverts within a stilling chamber. The method applied in order to execute that representation as accurately as possible was to relate the input parameters of LOCKFILL with the ones from LOCKSIM, with the following assumptions and adoptions, addressed to the input file component “Levelling system” (section 3.2.3):

- **Number of culverts**: LOCKFILL allows simulations using 1 to 16 culverts. Notice that this is the number of culverts on each side of the wall, so for the previous scenario C1 it would be one and two for scenario C2 and C3. It is possible to distinguish the input parameters for each culvert. However, a deeper exploration is needed in order to understand the limit of distinction that can be achieved, namely to eventually contrast scenario C2 with scenario C3.
- **Level of the ceiling of the stilling chamber (h_{wk}):** As it is possible to observe in figure 4.21, one problem inherent to this template is the additional volume of water that needs to be filled, analogous to the stilling chamber volume, which does not exist in a short culvert levelling system. Accordingly, it is believed that introducing the lowest possible value for h_{wk} results in the lowest volume of the stilling chamber, and therefore in a more approximate estimation of the volume of water that need to be filled. Hence, it was considered that between the lock bottom and the level of the ceiling of the stilling chamber there was a distance equivalent to the culvert height or, for this case study, the culvert diameter. In summary, this parameter is given by:

$$h_{wk} = z_k + D \tag{4.7}$$

- **Culvert characteristics**: While in LOCKSIM input file, the segment components were introduced separately, in LOCKFILL the culvert length (L_r) is not defined as a set of different components together, but as a whole. For that reason, the culvert length is adopted from the summation of all culvert components addressed for this case study in LOCKSIM. Naturally, this will be subjected to change depending on the considered scenario. The same premise is followed for the input of resistance coefficients – since there is, in LOCKFILL, no individual input of each component, this parameter will be given as a summation of each components resistance coefficient considered for this case study in LOCKSIM, with the exception of the valve. As for the cross sectional area of the culvert (A_r), it is determined as a function of the considered hydraulic diameter, as follows:

$$A_r = \frac{\pi \, .D^2}{4} \tag{4.8}$$

- **Maximum sluice gate height**: As the name demonstrates, this parameter is the maximum opening height of the sluice. Subsequently to the considerations in LOCKSIM, this parameter is considered equivalent to the considered hydraulic diameter.
- **Lift speed of the sluice gate as a function of time**: Similar to the approach in LOCKSIM, in order to determine the lift speed, or lift velocity, of the sluice gate, it is necessary to execute preliminary calculations in LOCKDIM, following the same method for adapting said calculations to a levelling system through short culverts, introduced in chapter 4.1.3. It is assumed, in accordance to the simulations executed in LOCKSIM, the lift velocity of the slides is constant throughout the lifting. This is, furtherly, introduced in LOCKFILL input file as a function of time
- **Loss coefficient of the sluice gate variation as function of relative lift height**: This parameter, as explored before, is highly influential to the filling process and cannot, therefore, be considered constant throughout said process. Since this parameter is inputted in LOCKFILL as a function of the relative lift height, it can be directly related to the same

parameter inputted previously in LOCKSIM. Therefore, the function presented in table 4.11 of section 4.1.3, is introduced in the present input file.

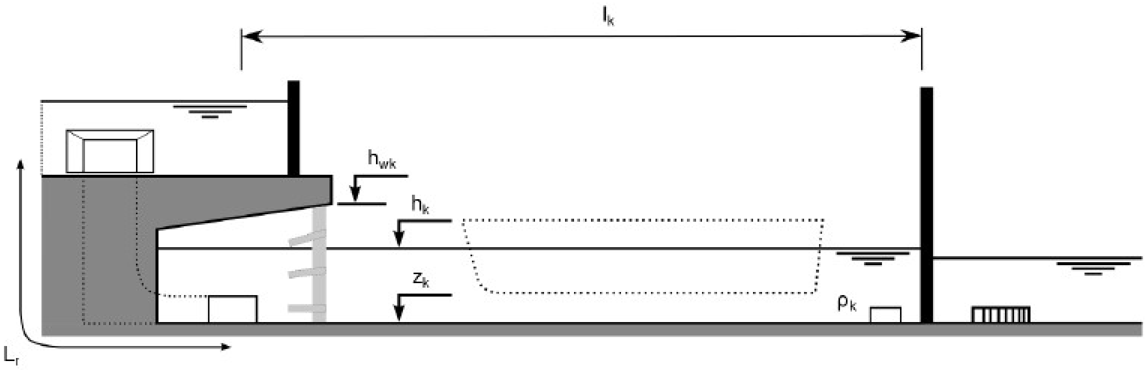


Fig. 4.21 – Schematic of a lock with culverts and stilling chamber, as given by LOCKFILL user manual [21]

Regarding the other input file components, namely "Approach Harbour", "Lock Chamber" and "Ship", the approach was identical to the one found in section 4.1.2, since these components are independent from the levelling system and only depend on the case study characteristics, which necessary data for input can be found in section 4.1.1.

However, a major problem occurred. As it is possible to observe in figure 4.21, this levelling system in LOCKFILL implies that the culverts are positioned before the gate. This does not represent either the reality of a levelling system through short culverts or its representation in LOCKSIM, since in both cases it is positioned after the gate. The adoption for the culverts position in LOCKSIM was to assume initially, for a system with a single culvert, that the outlet is discharging in the same point as the beginning of the moored vessel, i.e. with a horizontal distance equal to x_s from the gate. Therefore, in LOCKFILL, not only is the culvert not positioned in the same point as the beginning of the moored vessel, but it distances it more than x_s. In order to lower this difference, some hypotheses were considered, as follows:

- A lower value of x_s results in a more critical situation for the mooring forces acting on the vessel, and therefore a more conservative design option. Accordingly, reducing it does not represent a correct design, but it also leads to a viable approach to the preliminary design from a safety point of view. Ideally, reducing its value to 0 m, i.e. assuming the vessel was in contact with the gate, represents the closest distance between culvert outlet and vessel, for this levelling system. However, this results in a simulation error in LOCKFILL that reads:

$$x_s \geq 0{,}15 \,.\, b_k \tag{4.9}$$

  Since the width of the lock (b_k) is a fixed value for the study case, a value of x_s = 1.125 m was adopted. This represents the minimum value that enables a simulation, and is predictable to result in higher mooring forces and lower levelling times than the initially adoption of x_s = 3 m. In summary, this adoption means the vessel is too close to the gate, which can be harmful for both the vessel and the lock gate, but it results in a shorter distance between bow and culvert, which is good for a more accurate representation of the levelling system within the software. Notice that this parameter is also inherent to the preliminary calculations, and therefore this adoption must be considered for it.

- In figure 4.21, and therefore in this particular template in LOCKFILL, instead of the distances between gates, the lock length (l_k) defines the distance between the culvert outlet and the downstream gate, since the filling also occurs in the stilling chamber. Therefore, it is believed that by inputting this parameter value equal to 78 m, corresponding to the distance between gates, it considers the culvert to be positioned in the same place as the gate. Nonetheless, this is just a hypothesis, since there could not be found any information in the software Manual regarding this parameters. In order to achieve a more accurate representation of the above mentioned distance between vessel and culvert, another option could be reducing a distance of 3 m (correspondent to x_s) to the lock length (l_k), for a total of 75 m, corresponding to the distance between bow and downstream gate also considered in previous simulations. However, this is also believed to negatively influence the levelling process, since it assumes a smaller length to the lock, which results in smaller volumes of water needed to fill it. Accordingly, this hypothesis was not considered for the simulations.

Additionally, important to mention that according to LOCKFILL Manual, while it is possible to adjust this template to give a good estimate in case there is no stilling chamber, “this option is not suited for longitudinal filling systems which have culvert outlets over the entire length of the lock chamber” [21], i.e. it is not a suitable to simulate long culvert based systems. Also, the asymmetry in the inflow in the lock chamber when filling with only one side culvert is not taken into account within the software, making it impossible to execute said levelling situation.

With that in mind, and since LOCKFILL is significantly more user friendly and less time consuming, a total of ten scenarios were considered, displayed in table 4.30. The choice of these scenarios focused on the final objective of validating the applicability of a levelling system through short culverts in LOCKFILL, by comparing its simulation results with the results from LOCKSIM simulations. Accordingly, with these scenarios, it is possible to execute simulations for both levelling situations inherent to the case study, V1 and V2. Also, in order to compare to previous considered scenarios, simulations with different number of culverts were considered, similar to the difference between previous scenarios C1 and C3. Notice that C2 was not considered, since LOCKFILL does not consider differences in elevation between culverts. Within these scenarios, it was also varied the hydraulic diameter, between 0.8 m and 1.0 m, in accordance to previous scenarios, and the configuration of the culvert, between round and straight, which is introduced through the resistant coefficient.

Table 4.30 – Considered scenarios for LOCKFILL simulation of levelling through short culverts

Scenario	Levelling situation	Nº of culverts	D (m)	h_{wk} (m)	L_r (m)	A_r (m^2)	K (-)
A	V1	1	0.8	-0.4	14.38	0.503	1.82
B	V1	1	1	-0.2	14.38	0.785	1.82
C	V1	1	1	-0.2	14.38	0.785	3.8
D	V1	2	0.8	-0.4	14.38/19.18	0.503	1.82
E	V1	2	1	-0.2	14.38/20.38	0.785	1.82
F	V2	1	0.8	-0.4	14.38	0.503	1.82
G	V2	1	1	-0.2	14.38	0.785	1.82
H	V2	1	1	-0.2	14.38	0.785	3.8
I	V2	2	0.8	-0.4	14.38/19.18	0.503	1.82
J	V2	2	1	-0.2	14.38/20.38	0.785	1.82

Table 4.31 – Preliminary calculations results for levelling through short culverts in LOCKFILL

Preliminary Calculations			
Scenario	D	μ (-)	v_h (mm/s)
A	0.8	0.741	2.41
B	1	0.741	2.41
C	1	0.513	3.48
D	0.8	0.741	2.41
E	1	0.741	2.41
F	0.8	0.741	2.41
G	1	0.741	2.41
H	1	0.513	3.48
I	0.8	0.741	2.41
J	1	0.741	2.41

In order to validate the adopted approach to simulate a levelling system through short culverts in LOCKFILL, it is necessary to verify the viability of its results with the results obtained in LOCKSIM simulations with similar parameters. Notice that the input parameters given to each software differ, namely in the preliminary calculations. This is due to requirements inherent to the approach, such as the adopted distance between bow and lock gate, which has been assumed 3 m and 1.125 m, in LOCKSIM and LOCKFILL respectively, as above mentioned. Also, the vessel length (l_s) was assumed 60 m in LOCKSIM simulations, as presented in 4.1.3, while for LOCKFILL the value of 55 m was adopted, in respect to the case study considered vessel characteristics. The preliminary calculations resulted in table 4.31, where it is possible to observe that, once again, the discharge coefficient influences the lifting velocity much more significantly than a change in hydraulic diameter.

The simulations parameters introduced in LOCKFILL were defined as a simulation time of 1200 s, in accordance with the LOCKSIM simulations, and a time step of 1 s, in conformity to the recommended value introduced in section 3.2.5. The results can be found in table 4.32.

Table 4.32 – LOCKFILL simulation results for levelling through short culverts

Scenario	Discharge		Levelling Velocity		Total Levelling time		Levelling time until head of 0.1 m		Longitudinal forces	
	Max (m^3/s)	t (s)	Max (m/min)	t (s)	(s)	(min)	(s)	(min)	Max (‰)	t (s)
A	2.32	253	0.24	253	>1200	>20	1112	18.5	0.221	73
B	3.33	308	0.36	307	941	15.7	787	13.1	0.277	65
C	2.56	215	0.24	215	>1200	>20	990	16.5	0.357	72
D	4.12	246	0.42	245	737	12.3	615	10.3	-0.43	255
E	5.18	254	0.54	255	549	9.2	468	7.8	0.539	19
F	2.41	253	0.24	253	>1200	>20	1155	19.3	0.085	36
G	3.37	309	0.36	308	968	16.1	814	13.6	0.121	10
H	2.66	216	0.3	216	>1200	>20	1029	17.2	0.144	36
I	4.29	247	0.2	247	758	12.6	636	10.6	-0.212	36
J	5.44	268	0.54	269	562	9.4	481	8	-0.257	248

The differences in diameter between, for instance, scenarios A and B, and scenarios D and E, can be compared to LOCKSIM simulations of similar scenarios, found in sections 4.1.3.1 and 4.1.3.5, respectively.

Table 4.33 – Comparison of LOCKFILL simulation results with respective LOCKSIM simulation results for levelling through short culverts

Scenario		Discharge		Levelling Velocity		Levelling time		Longitudinal Forces	
		Max (m^3/s)	t (s)	Max (m/min)	t (s)	(s)	(min)	Max (‰)	t (s)
LOCKFILL	**A**	2.32	253	0.24	253	>1200	>20	0.221	73
	B	3.33	308	0.36	307	941	15.7	0.277	65
LOCKSIM	**A**	3.97	155	0.45	150	750	12.5	0.321	70
	B	5.95	150	0.69	145	485	8.1	0.438	70
LOCKFILL	**D**	4.12	246	0.42	245	737	12.3	-0.43	255
	E	5.18	254	0.54	255	549	9.2	0.539	19
LOCKSIM	**D**	6.86	150	0.76	135	405	6.8	0.673	25
	E	9.79	125	1.10	130	275	4.6	-1.018	95

It is possible to conclude from table 4.33 that, for identical levelling systems with very similar characteristics, the results are significantly different. Assuming the LOCKSIM simulations are more accurate, since the software was developed for the present levelling system, the adopted approach in LOCKFILL is still not optimal. It represents a less conservative approach, in light that the computed longitudinal forces maximum values are lower than in LOCKSIM, resulting consequently in higher levelling times. The fact that the inherent inaccuracy of the approach results in a less conservative approach is not expected, from a design point of view, to be useful.

However, notice that, whilst the magnitude of the results is inaccurate, it might still represent a valid tool for comparing different hypothesis within the specified levelling system. In order to explore the influence of the hydraulic diameter through this approach in LOCKFILL, it can be observed that the differences between scenarios A and B are similar in both software results, such as, for instance, about 1 m^3/s in discharge and about 300 seconds in levelling time. On the other hand, for scenarios D and E, said similarity in differences did not present itself. That is believed to be due to the inherent complexity to the latter scenarios, characterized by an extra culvert in comparison to A and B.

Table 4.34 – Comparison of LOCKFILL simulation results with respective LOCKSIM simulation results for levelling through short culverts (2)

Scenario		Discharge		Levelling Velocity		Levelling time		Longitudinal Forces	
		Max (m^3/s)	t (s)	Max (m/min)	t (s)	(s)	(min)	Max (‰)	t (s)
LOCKFILL	**B**	3.33	308	0.36	307	941	15.7	0.277	65
	C	2.56	215	0.24	215	>1200	>20	0.357	72
LOCKSIM	**B**	5.95	150	0.69	145	485	8.1	0.438	70
	C	4.639	150	0.54	145	625	10.4	-0.618	175

The differences in culvert configuration, presented in table 4.34, do not represent a similarity in differences between scenarios within each software as narrow as when addressing the differences in hydraulic diameter. This comparison between software demonstrates, however, the same conclusion given by table 4.33: the approach to levelling through short culverts represents not only an inaccurate in magnitude, but also incautious for a safe design. Nonetheless, for a basic preliminary design, it correctly displays the influence the configuration, i.e. the resistance coefficient of the culvert, has in the results: higher resistance coefficient leads to lower discharge and lower levelling time. Also, the important conclusion given by the LOCKSIM simulations that the longitudinal force is not necessarily lower when the resistance coefficient is higher, as introduced in section 4.1.3.1, is also registered in the present approach. It demonstrates that the simulation in LOCKFILL, while generating inaccurate results due to the limitations of input characteristics of the levelling system in the software, may not incorrectly simulate the levelling process.

Regarding the differences between software when addressing levelling through a single or two culverts, it can be observed in the results presented in table x that the approach in LOCKFILL is not very suited for multiple culverts. Notice that scenarios G and F in LOCKFILL simulations correspond, respectively, to scenarios C1-V2 and C3-V2 in LOCKSIM simulations.

Table 4.35 – Comparison of LOCKFILL simulation results with respective LOCKSIM simulation results for levelling through short culverts (3)

Scenario		Discharge		Levelling Velocity		Levelling time		Longitudinal Forces	
		Max (m^3/s)	t (s)	Max (m/min)	t (s)	(s)	(min)	Max (‰)	t (s)
LOCKFILL	**A**	2.32	253	0.24	253	>1200	>20	0.221	73
	D	4.12	246	0.42	245	737	12.3	-0.43	255
LOCKSIM	**A**	3.97	155	0.45	150	750	12.5	0.321	70
	D	6.861	150	0.76	135	405	6.8	0.673	25
LOCKFILL	**B**	3.33	308	0.36	307	941	15.7	0.277	65
	E	5.18	254	0.54	255	549	9.2	0.539	19
LOCKSIM	**B**	5.95	150	0.69	145	485	8.1	0.438	70
	E	9.79	125	1.10	130	275	4.6	-1.018	95
LOCKFILL	**G**	3.37	309	0.36	308	968	16.1	0.121	10
	J	5.44	268	0.54	269	562	9.4	-0.257	248
LOCKSIM	**G**	6.81	80	0.703	85	465	7.8	0.287	15
	J	12.08	80	1.245	80	250	4.2	0.541	15

It is believed, once again, the more complexity inherent to a specific levelling system, the more inaccurate the results from LOCKFILL will be. Whilst the magnitude of the values is significantly different from the results in LOCKSIM, the comparisons between hypotheses modelled in the same software continue to exhibit viable relations. The extra culvert introduced in the levelling system resulted, for scenarios A and D, in comparison to filling through a single culvert, added an additional 77% and 73% of maximum discharge, in LOCKFILL and LOCKSIM, respectively. These results follow the logic expectations, since it is not expected that a second culvert results in a total maximum discharge equivalent to twice the maximum discharge with a single culvert. The same comparison for scenarios B and E, i.e. for culverts with higher diameter, resulted in an increase of maximum discharge value of 56% and 65% for LOCKFILL and LOCKSIM simulations, respectively. On the other hand, when levelling through the north head, i.e. in situation V2, LOCKSIM concluded that with an additional culvert it would be discharged about 78% as much as with a single culvert, which follows the logic expectations, while in LOCKFILL the difference when adding an extra culvert to the filling system resulted in only about 61% more discharge. Possible justifications for this difference between software results, in addition to the margin of error inherent to the adaptation of the LOCKFILL template and respective assumptions (for instance, the presence of the stilling chamber adds more volume necessary to fill, resulting in higher levelling times), may be the input of resistance coefficients. In LOCKSIM it is possible to define a resistance coefficient to each culvert component deemed necessary, while in LOCKFILL it is introduced a total value for K correspondent to the sum of all the resistance coefficients. It is believed that would reduce the total flow energy, instead of gradually reducing the flow that goes through each component. It justifies why the differences in additional discharge induced by the extra culvert are more dominant when the filling flow has higher values throughout the simulations, inherent to the characteristics of the V2 levelling situation or to the increase in hydraulic diameter.

In an additional note, it is also compared the momentum decrease component to the longitudinal force. As it was introduced in chapter 3.3.6, this component was integrated in the post processing of LOCKSIM simulations through a formulation provided by LOCKFILL manual. Analysing the longitudinal forces graphical output the variation of this component throughout time is similar for simulations in both software. Disregarding the inaccuracy in magnitude of values, said similarity is a positive validation of the incorporation of the formulation in LOCKSIM post processing.

4.2. CARRAPATELO LOCK

4.2.1. CASE STUDY INTRODUCTION

In order to deepen the knowledge about the range of applicability of LOCKSIM, it was deemed interesting to simulate a case study characterized by a high drop, which does not reflect the characteristics of the *Melle* lock and the Ijmuiden lock. Accordingly, the *Carrapatelo* Lock was considered as a viable case study to achieve that goal.

The *Carrapatelo* lock is one of the five locks that enable inland navigability in the Douro river, located in the north of Portugal, as introduced in chapter 1.3. This lock was the responsibility of HED (*Hidro Eléctrica do Douro*), one of the companies that originated EDP (*Energias de Portugal*) and it was built by SOREFAME (*Sociedades Reunidas de Fabricações Metálicas*), under guidance of some French based companies, such as *STRIM – Génie Civil* [27].

Fig. 4.22 – Aerial photograph of the *Carrapatelo* Lock

Unlike the previous addressed *Melle* lock case study, where different scenarios with different hypothetical designs were considered, in order to analyse the influence of said differences in design in the levelling process, the main objective in this section is to attempt to introduce the present case study in the simulation software as accurately as possible, in order to validate the applicability of LOCKSIM to high drop locks, as mentioned above. Therefore, the lock and the respective levelling system are adopted from the data provided, subjected to the necessary assumptions in order to adjust said data to the simulation software, without considering other hypothetical scenarios.

Accordingly, the lock dimensions are introduced in table 4.36 [27].

Table 4.36 – *Carrapatelo* lock characteristics

Length [m]	Width [m]	Bottom level [mZH]
95	12.10	7.2

Regarding the considered vessel characteristics, the lock was developed previously to the CEMT classification, and therefore said classification was not the basis for the design of the present lock. It is considered, regarding the navigability of the Douro River in all locks, that each lock must enable a lift/drop of a vessel with the following characteristics [27]:

Table 4.37 – Considered vessel characteristics

Length [m]	Breath [m]	Draft [m]	Weight [ton]
83	11.4	3.7	1400

Similar to *Melle*, this lock is located far away from the sea, and therefore it is considered that there is no density difference between lock chamber and approach harbour. However, since between *Carrapatelo* lock and the sea there is the *Crestuma* dam, the downstream side of the present lock is not affected by the sea tide, in contrast with the situation in the *Melle* lock. Since this lock is located in a dam, the upstream approach harbour always has a significant higher water level than the downstream, and therefore the levelling is done in only one direction. The considered water level difference between upstream and downstream is 34.5 m, with an initial water level in the chamber of + 12.0 mZH and 46.5 mZH in the approaching harbour.

The mooring of the vessel is executed in floating bollards, as is common of high drop locks. Since the floating bollards rise and fall with the water level, the operation of moving the hawsers in unnecessary, and therefore the levelling velocity is no longer limited.

Despite the levelling being done in only one direction, the filling and emptying of the lock is executed through the same system, characterized by a long culvert on each side of the lock chamber. The emptying of the lock will not be considered for this case study.

The filling is done, therefore, through a concrete long culvert, with a section of 3x3 meters. The intake of water is done through gravity, i.e. following the inlet there is a decrease in elevation, from the initial 19.0 mZH to -0.5 mZH (under the lock chamber bottom). Then, the culvert divides in two smaller culverts (1.5x3 meters), each leading to a valve. The existence of two valves in the system is due to enabling the filling of the chamber through only one of them, in the eventuality of the other needing repairing or replacement. After passing through the regulating valves, there is an increase of elevation leading to the middle of the long culvert situated in the lock wall. The filling flow is then divided into opposite longitudinal directions, leading to four outlets.

Notice that the levelling is done symmetrically, i.e., the left and right part of the levelling system is identical.

4.2.2. LOCKSIM – LEVELLING THROUGH LONG CULVERTS

The method used for introducing and simulating this case study in LOCKSIM follows the previous approaches. The development of a schematic representation of the respective hydraulic network is required, while, for this case, the preliminary calculations are not necessary, since the lift velocities are include in the provided information regarding the levelling system [27]. The schematic representation adopted can be found in annex A.5.

Nonetheless, in order to approach the levelling system in LOCKSIM, several assumptions were made, as follows:

- The lock gates characteristics are neglected, only its position within the lock is relevant for the present study.
- The lock chamber and the vessel are both characterized by having a rectangular cross section.
- The present culvert, as well as the lock walls and bottom, consists of concrete. However, no specific value for the roughness coefficient is known. Since the goal of this section is not to

analyse the most critical situation in order to achieve an optimized design, the maximum value for plain concrete adopted in previous case studies does not represent a plausible adoption. Therefore, a weighted average value for the *Manning* coefficient of 0.015 $s.m^{-1/3}$ is adopted for both culverts and lock bottom.

- The lengths of the different components were adopted from provided schematic drawings.
- There are four different types of T-Junctions present in this levelling system:
  i. A diverging T-Junction splitting the culvert into two smaller culverts, precedent to reaching the valves. Its input is based in the configuration in figure 4.17. Since this T-Junction does not entail a change of direction, but instead a splitting of the culvert, the angles between "legs" of the T-junction are assumed equal to 0º.
  ii. A converging T-junction after the valves, converging the two smaller culverts into a larger culvert again. Its input is based in figure 4.23, as given by Schohl [23]. The required input is identical to the case of diverging T-junctions, and in this case, since it does not represent a change of direction, the angles between "legs" of the T-junction are also assumed equal to 0º.

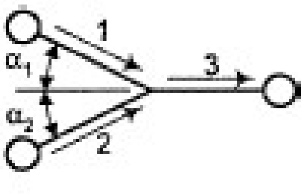
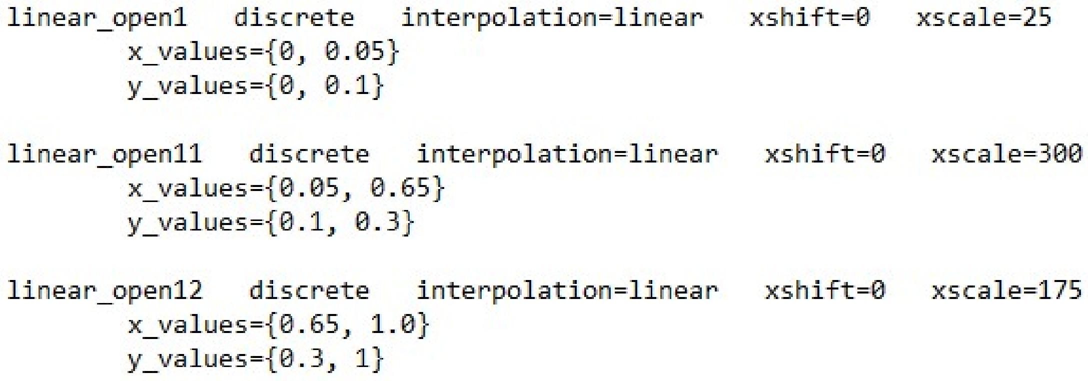


Fig. 4.23 – Configuration for convergence of flow at a T-junction, as given by Schohl [23]

  iii. As above mentioned, eventually the culvert leads to the filling long culvert, parallel to the lock wall. It reaches it in the middle of the lock chamber, where a T-junctions is present in order to diverge the flow into both upstream and downstream direction, leading to the four outlets. Accordingly, the angles between "legs" of the T-junction are assumed equal to 90º.
  iv. Finally, T-Junctions are introduced precedent to outlets 2 and 3, i.e. the middle outlets, in order to discharge through said outlets and simultaneously enable flow to be directed to outlets 1 and 4. Accordingly, the angles between "legs" of the T-junction are assumed 90º and 0º, respectively.
- It was assumed the valve follows the same type of valve adopted for the previous study case. Accordingly, the values for the adopted loss coefficient (K) for the slide as a function of the valve relative position can be found in table 4.11.
- As mentioned above, the provided literature regarding the present case study included the lift velocity of the valves inherent to the filling process. The slide functions are considered to be linear for both valves, however the lift rate is not constant. Two situations are distinct: filling through both valves simultaneously and filling through just one of the valves (since they are identical, it is not relevant which one). In the former, the lift speed is set at 0.012 m/s after the beginning of the lifting, during 25 seconds, traveling for 10% of the total lift height. It then decreases to 0.002 m/s, during 300 s, traveling for another 20% of the total height. The lift speed is finally set once again at 0.012 m/s, travelling the remaining 70% of the total lift

height in a total of 175 s. As for the latter situation, it starts with a lifting speed of 0.006 m/s, travelling 20% of the total height in a total of 100 s, stops for 660 s, and then proceeds with the same lifting same, for a total time of 400 s until the end of the lift.

Initially, it was attempted to introduce the different variation of the valves function in the input file for the operation of both valves simultaneously, as follows:



```
linear_open1   discrete   interpolation=linear   xshift=0   xscale=25
        x_values={0, 0.05}
        y_values={0, 0.1}

linear_open11   discrete   interpolation=linear   xshift=0   xscale=300
        x_values={0.05, 0.65}
        y_values={0.1, 0.3}

linear_open12   discrete   interpolation=linear   xshift=0   xscale=175
        x_values={0.65, 1.0}
        y_values={0.3, 1}
```

Fig. 4.24 – Visual representation of the initially considered valves function in LOCKSIM input file

Since LOCKSIM does not allow for a valve between two nodes to have more than one function, the valve input is not consisted of three consecutive and adjacent pairs of nodes.

However, this approach did not achieve viable results. Therefore, it was finally assumed a constant lift rate for a total lifting time of 500 s for the present situation.

Regarding the situation characterized by the operation of only one of the valves, a similar approach was adopted, after applying the specific changes, although the results were not viable as well. A constant lifting time correspondent to 1160 s was, therefore, adopted.

- Due to lack of information regarding the desired or necessary distance between gate and the bow of the vessel (x_s) , a value of 6 m was adopted.
- The length of the long culvert was assumed equal to the length of the vessel, and consequently the outlet 1 is situated next to the bow of the vessel, and outlet 4 next to the stern of the vessel.

This assumptions and adoptions were made in order to simplify as much as possible the present levelling system, to enable an accurate simulation in LOCKSIM. Consequently, it does not correspond identically to the levelling system inherent to the existent Carrapatelo lock. Nonetheless, regarding the goal of this section, this simplification is not considered harmful for the intended analysis. If necessary, a more detailed and meticulous approach to LOCKSIM could have been made, specifying several components to more accurately resemble the real levelling process. This would be helpful in order to optimize the design, although that is not the present goal.

Following the presented assumptions, two scenarios were considered and analysed, for a situation where the filling is characterized by two valves operating simultaneously – Scenario A, and a filling operation with only one valve – Scenario B, whose results can be found in table 4.38 and in a graphical display in annex B.24 and B.25, respectively.

Table 4.38 – LOCKSIM simulation results relative to the approach to *Carrapatelo* lock

Scenario	Discharge		Levelling Velocity		Levelling time	
	Max (m^3/s)	t (s)	Max (m/min)	t (s)	(s)	(min)
A	151.08	255	4.02	255	420	7
B	77.19	580	7.88	585	850	14.2

As expected, scenario B resulted in about half the maximum discharge observed in scenario A, as well as about twice the levelling time. Since this levelling system is characterized by discharging symmetrically, not only in relation to the longitudinal axis of the chamber but also to the transverse axis, the levelling process results in null longitudinal forces. Even though this is not believed to reflect the veracity of the levelling process results, it demonstrates that this specific levelling system leads to very low mooring forces. Together with the existence of floating bollards, it enables the attempt to lower as much as possible the levelling time without taking into account the levelling velocities and mooring forces normative limits.

Since the approached scenarios simulations present viable results, it demonstrates that LOCKSIM can be applied to levelling situations characterized by a high drop.

4.3. CONCLUSIONS

This chapter conclusions can be divided into two groups: Analysis of the characteristics inherent to the design of different levelling systems and comparison between the applicability and limitations of the simulation software considered in this work: LOCKFILL and LOCKSIM.

Regarding the former, by analysing the influence of several different parameters inherent to the levelling process it was possible to conclude that the most influent between them is the valves, and respective slides, characteristics, such as the lifting rate and the loss coefficient as a function of the position. Restrictions applied to the slides operation greatly confine the optimization of a levelling process, and therefore a focus on this component enables a significant tool in order to achieve a better design option. Furthermore, the initial water volume present in the chamber is significantly influential to the process, since even when a need to fill a bigger volume of water arises, correspondent to levelling situation V2, it can result in lower mooring forces and levelling time when compared to a scenario that requires a lower filling volume but is simultaneously characterized by a lower initial water volume in the chamber, due to the increase of the blockage of the filling discharge induced by the vessel. Also directly related to the blockage of the vessel, the distance between the upstream gate and the bow of the ship can be more influent to the filling process when compared to other parameters. Additionally, an important conclusion regarding the optimization of the preliminary design of a lock is that, in a lock that is required to level in both directions, considering identical levelling systems in both heads may not lead to an optimal design, and consequently may not constitute the most economically viable option.

Concerning the simulation software approach in the present work, the advantages and limitations of using each software are presented in table x and y, regarding LOCKFILL and LOCKSIM, respectively.

Table 4.39 – Advantages and limitations of LOCKFILL

LOCKFILL	
Advantages	**Limitations**
• User friendly interface	• Narrow range of applicability to different levelling systems
• Less time consuming process	• Not suitable for high drops
• Enables the computation of different longitudinal force components, with the exception of density differences	• Does not enable the input of more complex characteristics of a specific levelling system
• Graphical output	• One-dimensional approach

Table 4.40 – Advantages and limitations of LOCKSIM

LOCKSIM	
Advantages	**Limitations**
• Wider range of applicability to different levelling systems	• Less user friendly interface
• Enables the approach to more complex levelling systems	• More time consuming process
• Allows the user to “play” with a larger number of variables, which is deemed very useful for optimizing the preliminary design of a levelling system	• Does not take into account other longitudinal force components besides the translatory waves component
	• Outputs only provided in text files, which requires post-processing of the results
	• Does not enable the introduction of more than one lifting function to a valve
	• Does not allow outputs into the open channel, i.e. the lock chamber, at different elevations
	• One-dimensional approach

Additionally, important to mention that the comparison of LOCKFILL simulation results with the analytical results provided by LOCKDIM enables validation of the applicability of LOCKFILL to levelling systems through openings in the gates, which is helpful from a design point of view, since said validation can result in a less time consuming process.

Furthermore, it was concluded that both software can equally simulate, with accuracy within their specific range of applicability, both filling and emptying processes.

5

SPECIAL LEVELLING SYSTEMS

5.1. IJMUIDEN LOCK

5.1.1. CASE STUDY INTRODUCTION

The future sea lock in Ijmuiden represents the considered case study for the present chapter, relative to special levelling systems. It is located in the river mouth of the north sea canal, separating it from the north sea (figure 5.1).

Fig. 5.1 – Location of the future sea lock in Ijmuiden

It is projected to be an integrant part of the lock complex of Ijmuiden, currently made up of four locks. This lock complex is the entrance to the economically very important port area along the North Sea Canal, serving as gatekeeper to around 80% of Europe's cargo by sea, leading to the port of Amsterdam [28]. Hence, this future lock is characterized by great dimensions, in order to be suitable for the levelling of some of the world's largest ship.

Independent institute *Deltares* has carried out extensive hydraulic research on a scale model of the sea lock [29]. The results from this physical modelling will be used for further validation of the present work approaches and respective results.

Notice that the design considerations introduced furtherly in this section does not represent the final design solutions inherent to this future sea lock, but a design approach considered in the preliminary design stage. This approach to the specific design present in this work was made due to its inherent characteristics being appropriate to the interest of the present thesis study, namely the presence of a levelling system through a non-conventional culvert.

Therefore, the main objective of this chapter is to apply the knowledge gathered in the previous chapter about the simulation software LOCKSIM and attempt to introduce the present case study levelling systems as accurately as possible, for further comparison of the simulation results with provided physical modelling results, and thus verify the applicability and limitations of LOCKSIM. Hence, the case study data necessary for the software input is based on adopted data from the physical modelling. Accordingly, if the simulation results are similar to the physical modelling results provided (it is not expected to be identical, since there are assumptions and adoptions present in order to adapt the data to the software input), it validates the software potential to model special levelling systems.

Accordingly, the lock dimensions considered for the simulations are introduced in table 5.1.

Table 5.1 – Ijmuiden lock characteristics

Length [m]	Width [m]	Bottom level [mNAP]
545	70	-17.75

The considered vessel characteristics are as follows:

Table 5.2 – Considered vessel characteristics

Type	L_{OA} [m]	L_{PP} [m]	Breath [m]	Draft [m]*	Weight [N]	Block coefficient [-] **
Bulk Carrier	330	320.75	52	14.05	$1.8695\text{x}10^9$	0.836

*In fresh water ($\rho = 1000$ kg/m^3)

** Calculated as a function of the water displacement, provided by the given literature, according to the expression (3.11) in chapter 3.2.3.

The adopted length for the calculations and simulations input is the length between perpendiculars (L_{PP}), since it is the vessel length in the surface of the water. However, from a designer point of view, it is necessary to consider L_{OA}, in order to verify if the lock is big enough for the vessel, while also considering a specific distance from bow to gate. Despite representing, in this work, only an indicative value, it was deemed interesting to introduce it, in order to understand the difference between the normative lengths of a vessel.

The draft of the vessel depends on the density of the water in the chamber. The approach to this particular parameter will be addressed further in this work, when introducing the salt gradient component.

Notice that the vessel length considered for the determination of this parameter is L_{PP}.

The mooring forces limit, for this specific type of vessel, is defined as ± 0.2‰.

To the western and eastern heads of the lock are inherent different levelling systems, dimensions and characteristics. The western head represents the seaside head of the lock, while the eastern head represents the inland head of the lock. Therefore, the approach harbour adjacent to the western head can be defined by salt water and its water level is influenced by the sea tide. On the other hand, the approach harbour in the eastern head is considered consists of fresh water and is influenced by the river tide. The considered water levels are introduced for each considered scenario, accordingly, as well as the difference in densities. Regarding the levelling systems applied to each head, whilst levelling through both heads is done through short culverts, their dimensions and configurations are different (fig. 5.3 and fig. 5.4). Both western and eastern gates are considered to be similar, and consist on rolling gates, which entails the necessity of having a small chamber adjacent perpendicularly to the lock that guarantees enough space for the gate to roll on when it opens.

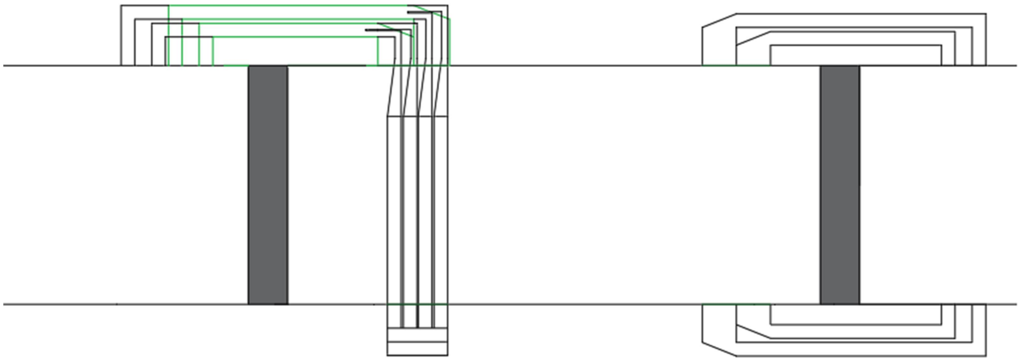


Fig. 5.2 – Top view of the considered levelling system for the Ijmuiden lock

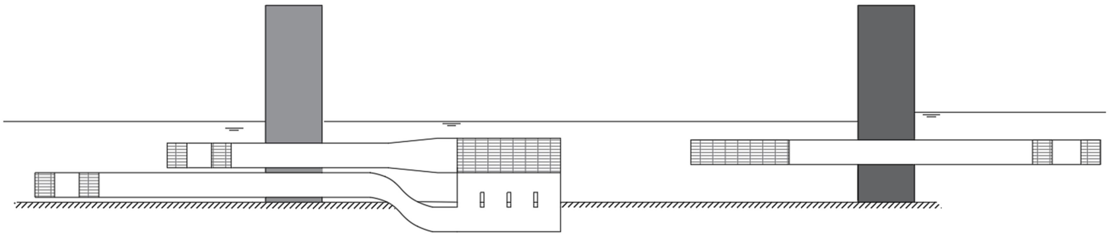


Fig. 5.3 – Side view of the considered levelling system for the Ijmuiden lock

The filling through the western head is done by two culverts, in different elevations. The upper culvert is a short culvert with two different pipes converging into one outlet with a larger diameter, located in the left side of the lock. The lower culvert, on the other hand, has its inlet in the left side of the lock and its outlet in the right side of the lock, to enable symmetrical filling. The fact that its inlet is in the left side is due to the above mentioned extra chamber for the gate to roll on being positioned on the right side of the lock. Accordingly, the culvert goes under the chamber in order to enable a symmetrical discharge into the lock during its levelling, which entails a longer convert. This solution was adopted due to the possibility of the culvert passing below the extra chamber being regarded as not feasible, because of the soil conditions. Therefore, the one challenging goal in this section is too introduce as accurately as possible this non-conventional filling system in LOCKSIM, in order to reflect the above mention symmetrical filling that is expected to occur, i.e. reflect identical or very similar discharges from both western head outlets.

The eastern head levelling system is also characterized as having a short culvert with two different pipes converging into one outlet with a larger diameter located, in this case, in the right side of the lock and a non-conventional culvert system in the left side. However, in this case, the latter is characterized by integrating the small chamber where the gate rolls when opening into the levelling system. Due to lack of information regarding the dimensions of said chamber, it was considered that the left culvert system was identical to the right. Even though the adopted levelling system reflects a conventional case for levelling through short culverts, it is deemed interesting to address in order to not only verify the approach to a more complex short culvert levelling system, in comparison to the one introduced in chapter 4, but also to validate the common assumptions and adoptions between the levelling systems on both heads.

In addition to analysing the suitability of the software when addressing non-conventional converts regarding their configuration, in the present chapter is it also analysed the influence of the presence of a salt gradient in the levelling process, since the western head approach harbour corresponds to the north sea, and it is expected the need to fill an initial fresh water chamber with salt water, and vice-versa.

5.1.2. LOCKSIM – LEVELLING THROUGH NON-CONVENTIONAL CULVERTS

The approach to this case study is different to the approach to *Melle* lock, in chapter 4.1. Instead of approaching different design possibilities in order to validate the software applicability, the present case will be based on a given design for the Ijmuiden Lock, similar to the approach to *Carrapatelo* lock in chapter 4.2. Therefore, not only the vessel and lock dimensions will remain constant throughout the considered hypotheses, but also the levelling system dimensions and characteristics as presented in the previous chapter. This enables a different goal for this chapter – validate the applicability and potentiality of approaching non-conventional culverts with LOCKSIM software. For that purpose, it is necessary to study the given data about the levelling system, and adapt it as accurately as possible into a schematic representation, and consequently an input file, inherent to LOCKSIM.

The lock levelling system design approach was based, therefore, in a provided preliminary design from the existent physical modelling, which can be found in figures 5.4 and 5.5 for the western and eastern heads, respectively.

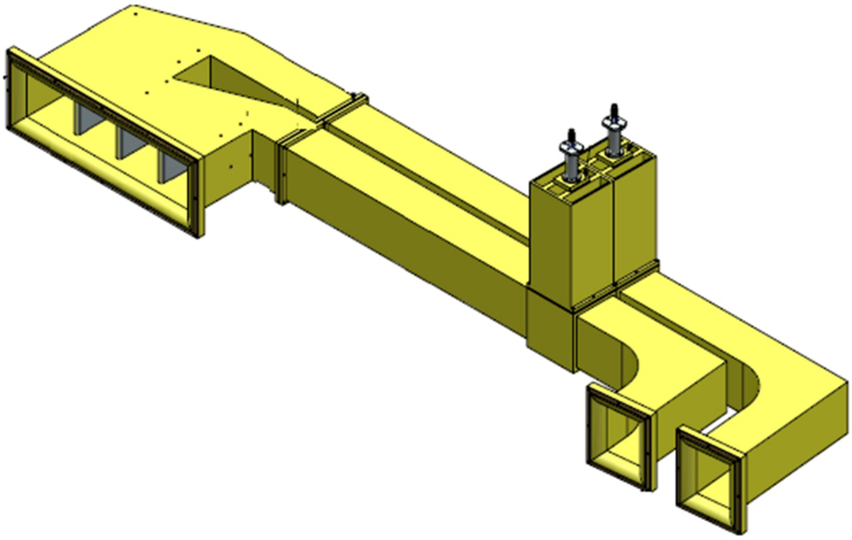


Fig. 5.4 – Levelling system configuration in the eastern head

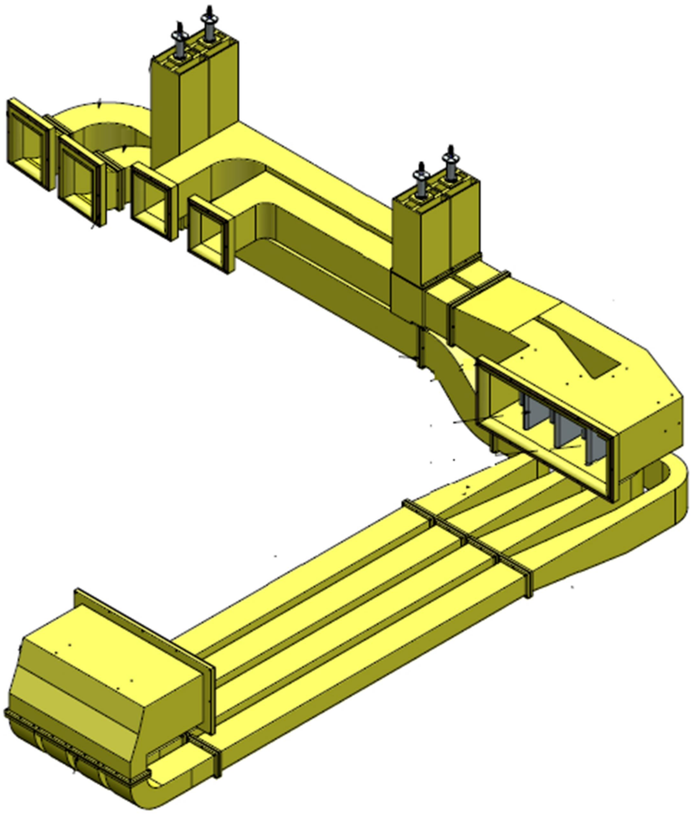


Fig. 5.5 – Levelling system configuration in the western head

Notice that there are four different culvert systems in total: identical short culvert systems on both sides of the eastern lock, correspondent to figure x, a short culvert system on the left side of the western lock and a non-conventional culvert whose inlet is located on the left side of the western head and outlet on the right side, as the culvert goes under the lock chamber. Accordingly, the western and eastern heads levelling system correspondent schematic representation can be found, respectively, in annex A.6 and A.7, respectively.

Due to the complexity inherent to these special levelling systems, LOCKSIM is considered to be the most appropriate simulation software to approach. In chapter 4 it was possible to understand that the limitations inherent to LOCKFILL would not allow for an accurate approach to this situation, not only because it does not accurately approach basic levelling systems through short culverts, but also because its incapable of specifying certain critical characteristics of the present levelling systems, such as, e.g. differences in the inlet and outlet positions, the converging of two pipes into a single outlet, different cross sections throughout the length of the culvert, different elevations between culverts and within the same culvert and differences in water density between approach harbour and lock chamber.

In order to address the main objects of study in this chapter, the following scenarios were defined and analysed:

- **Scenario A**: Filling through the eastern head, in the absence of salt gradient, i.e. filling a fresh water chamber with fresh water from the approach harbour. This scenario was defined in order to validate the approach and adaptation of the eastern head levelling system into the software.
- **Scenario B:** Identical to scenario A, but the filling is done through the western head. As well as the previous introduced scenario, also scenario B aims to validate the adaptation of its respective levelling system into LOCKSIM.

The water densities considered throughout this section were fixed as 1000 kg/m^3 and 1020 kg/m^3 for fresh and salt water, respectively. As well as said density difference, the initial water levels inherent to each scenario were based on similar scenarios considered in the physical modelling provided to the author.

The approach to simulate the levelling process relative to this case study in LOCKSIM involved a series of assumptions with the aim of simulating the intrinsic characteristics of said case study as accurately as possible, so that is as feasible as possible to compare with the results of physical modelling provided:

- According to the provided literature, the culverts are constituted of concrete. Similar to the situation with the *Carrapatelo* lock, no information about the roughness coefficient is specified and the maximum value for plain concrete adopted in previous case studies does not represent a plausible adoption. Therefore, a similar value for the *Manning* coefficient of 0.015 s.m$^{-1/3}$ is adopted for both culverts and lock bottom.
- A sensitive subject to address was the attempt to properly represent and introduce the different culvert configurations in LOCKSIM. Therefore, here follows a description of the adoptions and assumptions made regarding the different culvert components:
  i. **Inlet** – There are several types of water inlets, which can be distinguished mainly by their entry edges. In the present case, all three culvert configurations addressed comprehend similar inlet sections, characterized by having a round entrance with a 1 m radius. The rounding of the edges considerably reduces the head losses. The adopted value for the resistance coefficient *K* for this component was based on an overview of different literature. Idelchick [26] indicates that, for rounded entrance, *K*

has a value between 0.04 and 0.28. It is expected that, for the present case, the resistance coefficient is closer to the lower value, since it is relative to a large culvert. To validate that assumption, additional research was made, where, for this case of round entrances, *K* was considered 0.042 [30] and 0.04 [31]. Since the latter source referred to circular culvert, and it is expected that a non-circular section induces slightly bigger resistance to the flow than a circular one, a final adoption of K_{inlet} = 0.042 was established.

ii. **Bends** – Opposite to the adoption to the inlet component, the bends resistance coefficient was distinguished between three different types of bends:

   a. **Round inner corner, sharp outer corner** – This type of bend is present in the eastern culvert systems, as well as the culvert system in the left side of the western head.

   According to Idelchick [26], it is possible to estimate the resistance coefficient of this type of bend as function of a relation between the width of the culvert cross section (b_o) and the bend inner radius (r), assuming a 90° turn. Table 5.3 displays the considered K for different relations b_o/r.

Table 5.3 – Considered K values for the bends according to *Idelchick* [26] – Round inner corner, sharp outer corner

r (m)	b_0 (m)	r/ b_0 (-)	K (-)
2	4	0.5	0.48
5	4	1.25	0.4

   b. **Round inner and outer corner** – This type of bend is present throughout the length of the long culvert on the right side of the western head. Idelchick [26] enables the estimation of the different K values for this type of bend as function of the turn angle (δ), the relation between the culvert width (b_o) and the bend radius (R), which is the sum of the inner radius (r) with half the culvert width (b_o/2), and the relation between culvert height (a_o) and width. The considered K for the simulations are as follows:

Table 5.4 – Considered K values for the bends according to Idelchick [26] – Round inner and outer corner

r (m)	b_0 (m)	a_0 (m)	R (m)	R/ b_0 (-)	a_0 / b_0 (-)	δ	K (-)
2	4	5	4	1	1.25	90	0.2
3	4	2.5	5	1.25	0.63	90	0.21
3.2	1.8	5	4.1	2.28	2.78	90	0.125
5	4	5	7	1.75	1.25	90	0.152

   c. **Special bend** – This bend represents a non-conventional bend, and therefore its inherent resistance coefficient is not directly displayed by any available literature. It can be found in the last bend of the culverts before the outlet. Two significant factors define this bend: the type of turn, since there is no outer corner, and the change of cross section width from upstream to downstream of the bend. Idelchick [26] provides an approximate bend example, characterized by outer and inner sharp corners and change of section. Addressing this example, it is expected to estimate a resistance coefficient capable of establishing the influence of the cross section. Regarding the example bend, it is predictable that when the flow goes through it, the shape of the bend induces a dead zone, which is expected to have a slight head loss. The assumption is that said non-existent head loss in the present case, is balanced by the friction of the existing wall, resulting in similar bends. Therefore, the resistance coefficients were based in this example given by Idelchick, where they are defined as function of the relation between lower (b_o) and larger (b_1) culvert width and the relation between culvert height (a_0) and b_o. Notice that the values presented in table 5.5 represent the bend at the end of the long culvert in the right side of the western head, and the special bend located in all other culvert systems, respectively.

Table 5.5 – Considered K values for the bends according to Idelchick [26] – Special bend

b_1 (m)	b_0 (m)	a_0 (m)	b_1/ b_0 (-)	a_0 / b_0 (-)	K (-)
7	2.5	21	2.8	8.4	0.45
10	4	5	2.5	1.25	0.8

The estimated values for *K* follow the pre-conceived understanding that a sharper corner results in a higher head loss, and consequently round corners result in a lower head loss.

iii. **T-Junctions** – For the three short culvert systems, in the eastern head and in the left side of the western head, T-junctions are introduced in the input in order to compute the converging of two smaller culverts into one larger culvert, before the outlet. The angles between "legs" of the T-junction were adopted based on the configuration for converging of flow at a T-junction, presented in fig. 4.23.

Since the direction of flow does not change with the converging, both angles were assumed equal to 0º.

Regarding the non-conventional culvert system in the western head, it is inherent a diverging of flow, from two culverts into four, followed by a further converging of the latter into a single culvert, before the last bend. Similar to the above mentioned, since the direction of flow does not change, the angles were assumed equal to 0º for both the diverging situation (following the configuration given by Schohl, presented in fig. 4.17) and the converging. In the latter, important to mention that LOCKSIM does not allow a converging of four culverts into one. Therefore, as it is possible to verify in the schematic representation (annex A.7), this situation was addressed by converging two sets of smaller culverts into an intermediate fictional culvert, introduced with an area equal to the sum of both areas from the smaller culverts, and then converging the two resulting intermediate fictional culverts into one single culvert.

iv. **Barriers/Grids** – The goal of including grids in a culvert is too not only avoid materials of significant size entering the chamber, but also to reduce the head losses. In this case study, while differing in its dimensions, all present systems contain grids located after the last bend and before the converging of the two culverts that characterize said systems, with the exception of the non-conventional longer culvert, where the grid is located before the outlet and after the converging of the four smaller diameter culverts. Nonetheless, it is also located after the last bend. The fact it is positioned after a bend results in a flow colliding with the grids in an oblique direction, which increases the head loss generated by the grids. By approaching the current grids through adequate literature [30], it was possible to estimate a value of $K = 3.15$, identical for all culvert systems presented here. This component was introduced in LOCKSIM input file as a *pipe_loss* component, similar to the inlet and the bends.

v. **Change of cross section** – In the western head, each culvert system, left and right, include a section that induces a cross sectional area change. Initially, this component was introduced in the segments group of the LOCKSIM input file, specifying the different areas upstream and downstream. However, that leads to a simulation error. In order to introduce this change of cross section as accurately as possible, it was assumed that, instead of a progressive expansion throughout the length of the segment, it occurs a sudden expansion/reduction of the cross section in the middle point of the segment. Said sudden expansion/reduction is then defined as a local head loss, i.e. introduced as a *pipe_loss* component in the input file, which is expected to approximately represent the continuous head loss that occurs throughout the section due to the change of cross section. The resistance coefficients inherent to it were estimated according to Idelchick [26], as a function of the relation between upstream and downstream area. The two sections addressed correspond to section 1, located in the left culvert system of the western head, and section 2, located in the right culvert system of the same head.

The correspondent K values estimated are as follows:

Table 5.6 – Considered K values for the local head loss due to expansion/reduction of a cross section, according to Idelchick [26]

Culvert system	US Area (m^2)	DS Area (m^2)	K (-)
Left	20	28	0.082
Right	9	10	0.01

vi. **Change of elevation** – In the non-conventional culvert, there is a section that induces a change of elevation, to enable the culvert to reach an elevation lower than the lock bottom, in order to pass below it. The assumption regarding this component was to separate it into three sub-parts: two vertical bends, separated by a segment. The former are considered as round bends, with a correspondent **$K = 0.152$**. The latter is introduced to assure the length of this component, which is significate, is not neglected.

vii. **Outlet** – Similar to the inlet sections, all three culvert configurations addressed comprehend similar outlet sections, characterized by a round exit. According to Schohl (20), it is possible to estimate the loss coefficient for the outlet as a function of the relation between the area of the culvert (A_c) and the area after the rounding, i.e. the exit area (A_e), as follows [32]:

$$\left(\frac{A_c}{A_e}\right)^2 \leq K_{outlet} \leq 1 \tag{5.1}$$

Since the outlets inherent to the culvert systems for this case study are very large, it is expected that $\left(\frac{A_c}{A_e}\right)^2$ is close to 1. Therefore, it was adopted for all culvert systems $K_{outlet} = 1$.

- In the previous simulations referent to chapter 4 of the present work, the culvert were characterized with a circular cross section, therefore only requiring the input of the hydraulic diameter, since LOCKSIM automatically assumes a circular cross section and determines its area according to said hydraulic diameter. However, in the case study inherent to this chapter, the culverts are characterized with a rectangular cross section. Hence, it is required to input both the cross sectional area and the correspondent hydraulic diameter (D_h). The latter was determined as a function of the height (a) and width (b) of each culvert cross section, as follows:

$$D_h = \frac{2\,.\,a\,.\,b}{a+b} \tag{5.2}$$

- LOCKSIM assumes the different components as nodes, i.e. points, in a schematic representation, with the exception of the *imp_pipe* components (segments). Hence, the adopted lengths for each specific culvert were considered between said points, in order to avoid neglecting significant head loss throughout, for instance, the length of the bends. Therefore, for instance, the bend node is considered to be the middle point of the bend cross section, which entails an increase of length to the adjacent segments.
- The length of the non-conventional culvert section located below the lock bottom, not described by the case study given literature, was determined based on the given dimensions of adjacent components and the considered lock width.
- The nodes elevations were determined based on the given literature regarding the case study.
- In the physical modelling, the distance between bow and gate (x_s) was considered 35 m and 50 m. A value of 50 m was adopted for the present simulations in LOCKSIM.
- In the modelling regarding *Melle* case study, in chapter 4, it was assumed that the culvert outlet position coincided with beginning of the vessel. However, such assumption is no longer required, since for this case study it can be found in the given case study information the exact distance from the gate to each of the outlets. Notice that said distance is different between west and east head. This results in the filling flow discharging in the chamber before the beginning of the vessel, while when assuming for the previous case study the filling flow collided immediately with the bow. It is considered important to have this information, for it is predictable that the outlet and the vessel position in the chamber while filling can be influent to the levelling process, and therefore an accurate input of these longitudinal positions is important for the overall accuracy of the introduction of the case study in LOCKSIM.

- While the slides lifting function varies according to the specific scenario and culvert system, the slides loss coefficient as a function of its position was adopted from the case study literature and it is common for all scenarios. The adopted function is, therefore, defined as follows:

Table 5.7 – Adoption for the loss coefficient (K) as a function of the valve relative position (d/D)

(d/D)	0.01	0.05	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	0.95	1
K	12124	886.21	221.21	49.91	18.41	8.1	3.94	2	1.02	0.51	0.2	0.06	0

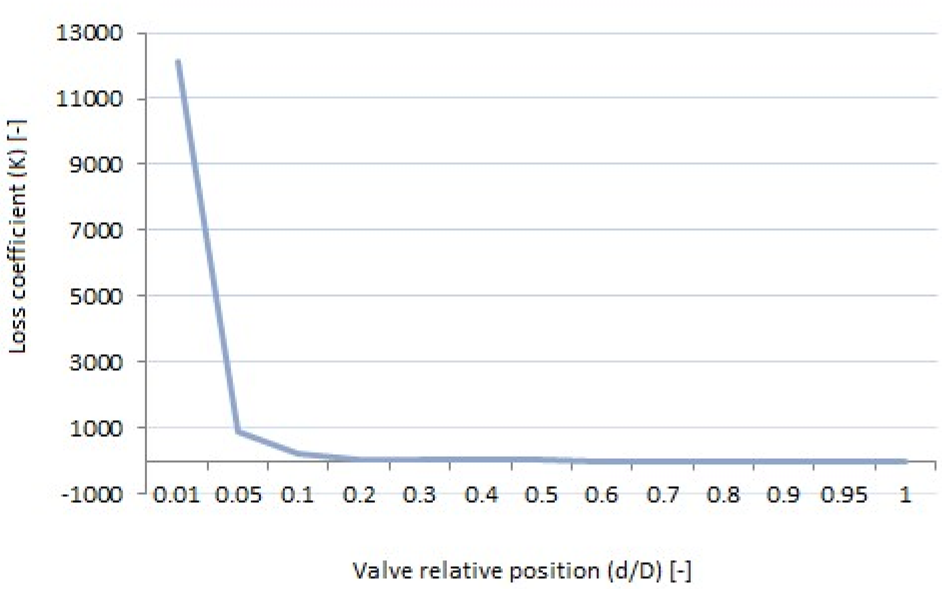


Fig. 5.6 – Graphical display of the loss coefficient (K) as a function of the valve relative position (d/D).

- The post-processing of the output results from the simulations is executed as introduced in chapter 3.3.6.

5.1.2.1. Scenario A

Scenario A, as introduced in the previous chapter, reflects the filling through the eastern head, in the absence of a density difference between chamber and approach harbour water. The water levels were adopted from a similar scenario in the physical modelling, for further comparison. Accordingly, it was considered a levelling situation with an initial water level of +0.11 mNAP in the approach harbour and -1.74 mNAP in the lock chamber, for a total drop of 1.85 m. The slide lift function was also adopted from the physical modelling for identical purpose. It consists of a linear opening of the valve slide, naturally similar to both left and right side culvert systems, since in the eastern head, these are identical. The slide lift function parameters adopted can be found in table 5.8.

Table 5.8 – Adopted slide lift function parameters (Scenario A)

Scenario	v_h (mm/s)	h_h (m)	t_h (s)
A	7.5	5	666.667

The lift height (h_h) corresponds to the culvert height, while the lifting time (t_h), to be introduced in the input file as the *xscale* parameter of the function, is determined as follows:

$$t_h = \frac{h_h}{v_h} \tag{5.3}$$

Table 5.9 provides a comparison between the results from the present simulation in LOCKSIM (LS) and the provided physical modelling results (PM), for a similar scenario. A more graphical overview of the LOCKSIM simulations after the post-processing of the output results can be found in annex B.26.

Table 5.9 – Comparison of LOCKSIM simulation results with respective physical modelling results (Scenario A)

Scenario A	Discharge		Levelling Velocity		Levelling time		Longitudinal Forces			
	Max (m^3/s)	t (s)	Max (m/min)	t (s)	(s)	(min)	Max (‰)	t (s)	Min (‰)	t (s)
LOCKSIM	156.75	410	0.286	415	690	11.5	**0.136**	205	**-0.093**	540
PM	144	398	-	-	673	11.2	**0.11**	-	**-0.16**	-

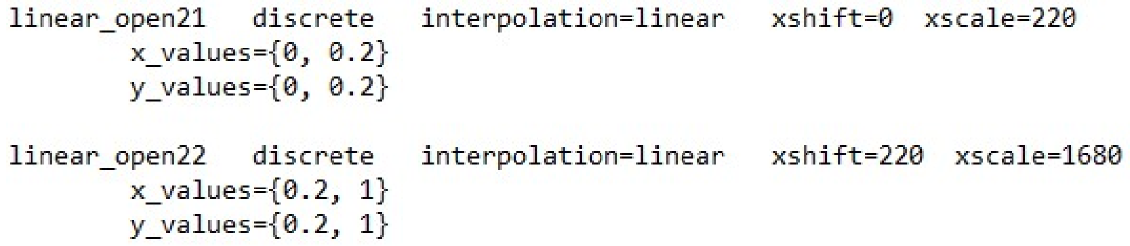
For the levelling through the eastern head levelling system, the results from the LOCKSIM simulation are very similar to the results from the physical modelling, even though in the LOCKSIM approach there was a specific significant assumption, namely neglecting the small chamber for the gate to roll on, and considering identical culvert systems on both sides of the head. This assumption might, however, justify the higher maximum discharge observed in LOCKSIM, since it is presumed the gate recess chamber induces a higher head loss to the filling flow. Nonetheless, both the levelling time and longitudinal forces having very similar values, which validate the assumptions made for this scenario and particular levelling system applied. Notice that only the minimum value for the mooring force has a more significant difference between LS and the PM results. One possible cause for said difference is the contribution of the momentum decrease component. As it was presented and furtherly concluded in this work in chapter 4.1.5, the approach to the determination of this longitudinal force component in the post-processing of LOCKSIM resulted in a logical and expected variation throughout time, although with some inaccuracy in the magnitude of values. Since the momentum decrease component is characterized as having a mainly negative influence in the mooring forces, the inaccuracy of computing the magnitude of this component in the post-processing adopted approach might have resulted in a slight inaccuracy in computing the minimum mooring force value. Notwithstanding the magnitude difference of the latter between LS and PM, the LS simulation resulted in a smaller value, which is harmful from a design point of view, since it reflects an incautious approach from a safety perspective.

5.1.2.2. Scenario B

The present scenario is, as above mentioned, characterized similarly to scenario A, considering the presence of a vessel inside the chamber during the filling process and a constant water density from the approach harbour to the chamber, namely correspondent to fresh water (ρ = 1000 kg/m^3). The filling is, however, done through the western head, defined by the previously presented inherent culvert systems. Since the approach harbour corresponds, in this case, to the sea side, its water level is affected by the sea tide. Similar to scenario A, the water levels were adopted from an accordant scenario addressed in the physical modelling provided. The initial water level in the approach harbour is fixed at +4.00 mNAP and in the chamber at -0.73 mNAP, for a total drop of 4.73 m.

There are, however, very significant differences between scenarios A and B, mainly due to the higher complexity inherent to the culvert systems in scenario B. In this case, two very different culvert systems are applied, which is predictable to result in different discharges. That difference must remain as low as possible, to avoid asymmetrical filling of the chamber, which in turn would create transverse forces occurring in the chamber, resulting in possible harmful damage for the vessel. Notice that, the higher the above mentioned increased complexity of the culvert systems is, mainly the non-conventional longer culvert in this case, the more difficult it is to introduced it accurately in LOCKSIM, for it entails a large number of assumptions for the different components and filling process parameters, such as the slides function. The slide lift function is considered to be linear for the right culvert (non-conventional culvert) with a constant lift velocity of 3.5 mm/s and also linear for the left culvert (short culvert system with converging of culverts). In the latter, however, the lift velocity is not considered constant throughout the total lift, being set at 4.4 mm/s until 220 s after the beginning of the lifting and 2.4 mm/s during 1680 s after that, fixing the lifting time at 1900 seconds (approximately 32 min).

Initially, this function was introduced in the input file functions in order to distinguish the two lifting functions for the left culvert, following a similar process as the approach to the Carrapatelo lock, as follows:

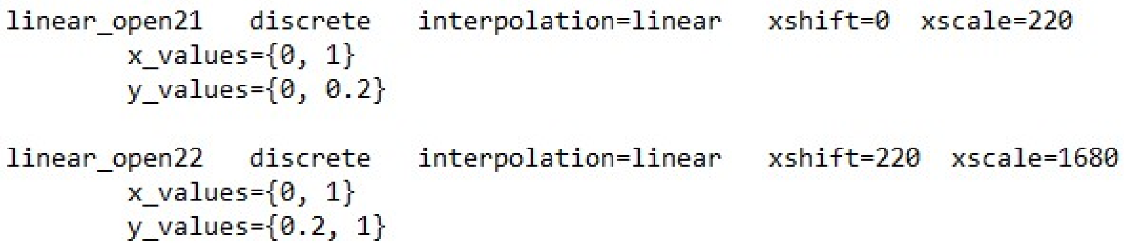


```
linear_open21   discrete   interpolation=linear   xshift=0   xscale=220
        x_values={0, 0.2}
        y_values={0, 0.2}

linear_open22   discrete   interpolation=linear   xshift=220   xscale=1680
        x_values={0.2, 1}
        y_values={0.2, 1}
```

Fig. 5.7 – Visual representation of the initially considered valves function in LOCKSIM input file

As it can be observed in the above figure, the premise would be that for the first 20% of the lifting, it would follow the first function parameters, and for the remaining 80%, the second function. These intervals were adopted from the PM by analysing the graphical representation of the lifting functions, where it was possible to observe that the lift function changed after lifting 1 m. Since the total lift height corresponds to 5 m, it was concluded that the functions changed after lifting 20% of the total height. However, with this input, LOCKSIM considered only the first function for the valve. It was, therefore, necessary to change the valves input. To attempt to solve this problem, an intermediate node was created for the valve to distinguish the functions. However, once again, the results were not as expected. While still applying the latter change, another attempt to solve the problem was approached, as follows:



```
linear_open21   discrete   interpolation=linear   xshift=0  xscale=220
        x_values={0, 1}
        y_values={0, 0.2}

linear_open22   discrete   interpolation=linear   xshift=220  xscale=1680
        x_values={0, 1}
        y_values={0.2, 1}
```

Fig. 5.8 – Visual representation of the secondly considered valves function in LOCKSIM input file

Although resulting in more viable results, it still did not correspond to the expected, based on the physical modelling. Therefore, it was finally assumed a lifting of the left culvert characterized by a single linear function, with a total lifting time correspondent to the same 1900 s, and a consequent constant lifting velocity according to expression 5.3. This proved to be the most accurate approach in order to achieve an adequate simulation of this levelling system. The slide lift function parameters adopted can be found in table 5.10.

Table 5.10 – Adopted slide lift function parameters (Scenario B)

Scenario	Side	v_h (mm/s)	h_h (m)	t_h (s)
B	Left	2.632	5	1900
	Right	3.5	5	1428.57

Similar to scenario A, a comparison between the results from the present simulation in LS and the provided PM results can be found in table 5.11, with the correspondent graphical representation in annex B.27.

Table 5.11 – Comparison of LOCKSIM simulation results with respective physical modelling results (Scenario B)

Scenario B	**Discharge**		**Levelling Velocity**		**Levelling time**		**Longitudinal Forces**			
	Max (m^3/s)	t (s)	Max (m/min)	t (s)	(s)	(min)	Max (‰)	t (s)	Min (‰)	t (s)
LOCKSIM	166.18	950	0.264	795	1615	26.9	**0.058**	140	**-0.044**	830
PM	186	850	-	-	1398	23.3	**0.08**	-	**-0.11**	-

One of the major problems encountered in this simulation was the difference in discharge throughout the filling process from the two systems. As it can be observed in annex B.27, the discharge from the left culvert is significantly higher than the one from the right culvert. Since there is no information regarding each systems individual discharge variation in time, it is uncertain if the same situation occurred in the PM. However, as mentioned above, this is a situation needed to avoid, for it is predictable to cause harmful transverse forces in the chamber, due to the asymmetrical filling. Nonetheless, since LOCKSIM does not take that phenomenon into account, it did not display any errors. A possible explanation for the lower values of discharge from the right culvert system is that the head loss induced by the various components inherent to this system, plus the head loss resultant from the increase in length when compared to the left system, significantly reduce the discharge. As above mentioned, this culvert system complexity implied a high number of assumptions, such as adopted lengths, resistance coefficients and valve functions, to which is inherent a certain margin of error, and therefore may result in a less accurate simulation from LOCKSIM.

Notice that, in the longitudinal forces graphical representation (annex x), the translatory waves component function over time has an odd shape. Since the previous simulations performed in this work validate the formula used to compute this component in the post-processing phase, it is believed this odd shape is caused by the asymmetrical filling caused by the difference in discharge from the two culvert systems. Although this conclusion needs validation, it is believed this to be a viable tool for future studies, since it shows that the post-processing of the LOCKSIM simulation outputs can exhibit the symmetry or asymmetry of a filling process, by analysing not only the discharges but also the resultant longitudinal forces variation during said process. Adding this incapability of distinguishing more than one function for the same valve to the same observed in chapter 4.2., it leads to the conclusion of a significate limitation of LOCKSIM. This limitation can be harmful when attempting to achieve an optimal design for a given case study, since, as observed before, the valves functions are highly influential in the filling process, and the ability to manage and address different lifting rates becomes a very useful tool in order to achieve that goal.

As for the overall results from the simulation found in table x, there are some significant differences in the order of magnitude. The justification for the lower discharge in the LOCKSIM simulation follows the observed lower discharge by the right culvert system, as well as the higher levelling time follows said lower discharge. Regarding the longitudinal forces, not only are the differences between LS approach and PM due to, once again, the lower discharge, but it once again displays a more significant difference in the minimum values, enabling the conclusion that the approach to the momentum decrease component calculation by the post-processing in LS, while once again with a logical and expected variation in time, lacks accuracy in the magnitude of the forces.

5.1.3. PRESENCE OF A SALT GRADIENT

Differences in salinity, hence in water densities, are a common and current problem for locks in vicinity of the sea, as presented in chapter 2.3.4. A navigation lock prone to be affected by density differences during the levelling process is usually the link between the sea and a canal, river, basin or harbour – sea lock. The differences in density between the salt water from the sea and the fresh water from the inland side of the lock influence the flow patterns and therefore the longitudinal forces present in the lock chamber during the filling or emptying process, since if density differences are present in the water, gravity will cause stratified flows in the lock [33].

Two distinct situations can be distinguished: filling an initial fresh water lock chamber with salt water (fig. 5.9), and filling an initial salt water lock chamber with fresh water (fig. 5.10), each generating an intruding layer in the lock. After the salt or fresh layer intrusion, the flow changes into a two-layer flow. Since the salt water is heavier, i.e. more dense, than the fresh water, in the former the intruding layer propagates along the bottom of the lock in the downstream direction during the filling time with a certain velocity of propagation, passes the stern, reflects against the downstream gate, changing direction, and reflects at the stern. After the end of the filling, the intruding layer continues to propagate in the lock. On the other hand, when filling a salt water chamber with fresh water, the opposite occurs, as the layer rises to the free surface, propagating mainly beside the vessel. After filling, salt water flows along the bottom in the direction of the filling gate, since the filling discharge has decreased [33]. Notice that the intruding layer, despite the relative differences between salt and fresh water being small, induces a considerable extra force on the vessel, since, as mentioned above, after being generated it propagates in the lock and reflect against the vessel and the gates.

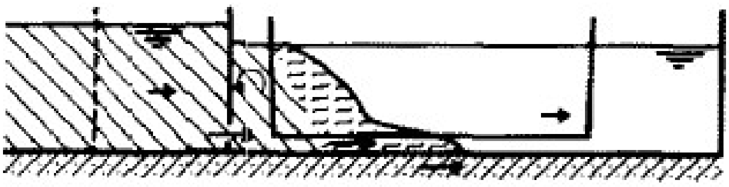


Fig. 5.9 – Filling a initially fresh water lock with salt water

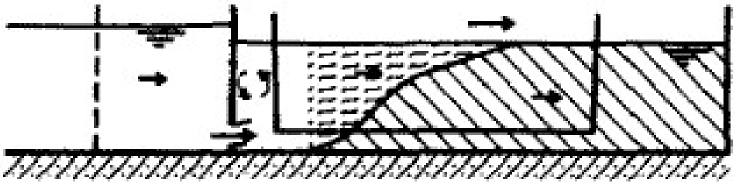


Fig. 5.10 – Filling a initially salt water lock with fresh water

Additionally, another important phenomenon occurs after the filling process, when the lock gate is opened to enable the vessel to exit: an exchange process between the water of the lock with the water of the approach harbour. Albeit this phenomenon is very important for a complete design of a sea lock, this thesis is focused on the levelling process of a lock, and will therefore, in this chapter, focus on the influence of differences in density on the mooring forces of a vessel during the filling process. The emptying process is not considered in this section since, in this case, the density differences do not contribute to the longitudinal forces occurring in the lock chamber.

In the case of filling an initially fresh water lock with salt water, the relative longitudinal forced caused by the differences in density is negative during the filling process, becoming positive after the filling process is completed, while the amplitude of the force decreases quickly. The most critical situation to the mooring forces of the vessel occurs when the difference in density between bow and stern is maximum. This occurs a short time after the beginning of the filling, when the density of the water in the bow of the vessel is almost similar to a salt water density, i.e. the bow is surrounded by salt water, but the water in the stern remains with the initial water density, i.e. fresh water density [33]. After that, the intruding salt layer will continue to propagate, eventually appearing in the stern.

When filling and initially salt water lock with fresh water, the process is similar and simultaneously opposite, since the longitudinal force component caused by the density differences are now positive during the filling process and negative thereafter [33].

The simulation software addressed in this section, LOCKSIM, cannot currently measure accurately the influence of this component. Therefore, in order to determine the longitudinal forces on the chamber due to the influence of the density differences component, a numerical model was developed, based on the formulations presented by Vrijburcht [33]. The goal is to determine the relative longitudinal force as a function of time, in permillage, due to the density differences during the filling process, and then include it in the post-processing of LOCKSIM simulations.

5.1.3.1. Numerical Model

The development of the present numerical model in order to compute the relative longitudinal forces due to the density differences during the filling process is, as above mentioned, based on the formulations presented by Vrijburcht [33]. These entail some assumptions, which are also valid for the numerical model and define its range of applicability:

- The present numerical model is considered for a filling an initially fresh water chamber with salt water from the approach harbour, due to the lack of necessary information regarding the filling of a salt water lock with fresh water.
- The water in the lock, as well as in the approach harbour, has a homogeneous density before the filling process.
- The current model and inherent formulations are only applied to levelling systems through short culverts, such as the present case study, and levelling systems through openings in the gate. Levelling systems with openings over the length of the lock, i.e. long culvert systems are not applicable, since it does not follow the premise of the intruding layer entering the chamber through one of its heads. Locks with devices to reduce salt intrusion are also not taken into consideration.
- Following the assumption from Vrijburcht [33], the mooring forces on the vessel caused by differences in density can be determined with the help of a hydrostatic pressure distribution around the vessel.
- Within several input required for the model, namely regarding the case study characteristics, the filling process data are fundamental. It is necessary, in order to determine the longitudinal force due to the density difference component, to be acquainted with the discharge variation in time during the filling process, as well as the water depth variation in time, in both the bow and the stern of the moored vessel. According to Vrijburcht [33], the flow and density patterns in the lock during the filling process are complex, and cannot be derived in a simple way using mathematical models. However, as above mentioned, it is not currently possible to simulate a filling process that accounts for the density differences between chamber and approach harbour in LOCKSIM. Despite the fact that said density differences influence the filling process, namely the discharge and mainly the water depths throughout the chamber, the input required for the model presented here is adopted from the simulation in the same exact conditions, but without a density difference present. It is taken into account that this assumption might entail some inaccuracy in the results. It is, however, expected that it is still possible to achieve a viable estimative of the longitudinal forces due to density differences.

Vrijburcht [33], provides a method to determine the longitudinal force caused by density difference for two distinct situations: a limited blockage induced by the vessel and a situation with a vessel inducing a large blockage. As the name implies, the main contrast between situations is the increased blockage of the cross-section. Initially, both situations were considered. However, when applied to the present case study, the results from the calculations inherent to the limited blockage case were not plausible. It is believed that is justified by the considerable blockage of the vessel inherent to the present case study. Accordingly, a model regarding a situation with a large blockage induced by the vessel was considered and developed.

The larger blockage of the vessel inhibits the entrainment of the fresh water layer, i.e., the upper layer, by the filling jets. Notice that said entrainment was the source of the miss-calculations verified in the model for a vessel with a limited blockage when applied to the present case study. The phenomena that occurs in this situation is that the large blockage enables a mix of the water originally present in the zone between the culvert outlet and the bow of the vessel with the water coming from the filling jets. Accordingly, the density of the mixed water in this zone increases in time, with a rate dependent on the filling discharge, the volume of water present in the zone and the initial density difference, eventually reaching the same density as the approach harbour. As above mentioned, the salt water intrusion layer propagates in the longitudinal direction adjacent to the bottom of the lock, eventually passing the stern of the vessel, reflecting against the downstream gate and reaching the stern for the second time. Additionally, the most critical situation for the longitudinal force occurring in the lock chamber is defined by the higher difference in density of the surrounding fluids in the bow and stern of the vessel. Therefore, in this case, due to the inhibition of entrainment of fresh water by the filling jets, it is highly expected that, at a certain moment of the filling process, the density of the water in front of the bow corresponds to the density of salt water, while the water behind the stern remains with the density of fresh water. This moment would then define, predictably, the highest mooring force occurring in the vessel.

The input required for the model is, in addition to the discharge variation in time during the filling process, as well as the water depth variation in time mentioned above, relative to the parameters inherent to the problem to be addressed, such as:

- **Initial water levels in the chamber and in the approach harbour:**
    1. Initial water depth in the approach harbour – h_u [m]
    2. Initial water depth in the lock chamber – h_d [m]
- **Lock characteristics**:
    1. Length – l_k [m];
    2. Width – b_k [m];
    3. Bottom level – z_{bottom} [mNAP]
- **Vessel characteristics**:
    1. Mass – M_s [kg];
    2. Length – l_s [m];
    3. Width – b_s [m];
    4. Draft – d_s [m];
    5. Block coefficient –C_b, determined following expression (3.11) [-]
- **Water densities:**
    1. ρ_1 – Density of the water of the lower layer, i.e. density of the heaviest fluid (Usually, salt water)
    2. ρ_2 – Density of the water of the upper layer, i.e. density of the lightest fluid (Fresh water)
- **Horizontal distance between the upstream gate and the bow of the vessel** – x_b [m]
- **Horizontal distance between the upstream gate and the stern of the vessel** – x_s [m]
- **Coefficients**:
    1. g –Acceleration of gravity [m/s^2]
    2. P_I - Momentum coefficient for deviations of the uniform flow profile [-]

This coefficient concerns the influence of the transport of momentum on the longitudinal force. A coefficient P_l= 1 relates to a one-dimensional flow situation, while a higher coefficient comprises flow velocities which deviate from the mean flow velocities. According to Vrijburcht [33], the variation of this coefficient has a small influence in the longitudinal forces on the vessel.

The methodology inherent to the present model entails a need to determine the variation of the density during the filling process in the zone between the culvert outlet and the bow. Said variation is determined as a function of the filling discharge, as follows:

$$\rho_{b_i} = \frac{\rho_1 . Q_i + \rho_{b_{i-1}} . \left(\frac{h_{b_{i-1}} . x_b . b_k}{\Delta t}\right)}{\left(\frac{h_{b_i} . x_b . b_k}{\Delta t}\right) + Q_i . \left(\frac{l_k - b_k}{l_k}\right)} \tag{5.4}$$

Where,

$$\Delta t = t_i - t_{i-1} \tag{5.5}$$

It is a considered, for t_i = 0, a density equivalent to the initially considered density in the lock chamber, i.e. fresh water, in this case.

Regarding the zone behind the stern, a similar formulation was adapted to compute the density variation in said zone, after the intruding layer reaches it ($t > t_s$), which can be found in expression (5.6).

$$\rho_{s_i} = \frac{\rho_1 . Q_i + \rho_{s_{i-1}} . \left(\frac{h_{s_{i-1}} . x_s . b_k}{\Delta t}\right)}{\left(\frac{h_{s_i} . x_s . b_k}{\Delta t}\right) + Q_i . \left(\frac{l_k - b_k}{l_k}\right)} \tag{5.6}$$

Accordingly, it is a considered, for $t_i \leq t_s$, the density in this zone (ρ_{s_i}) is equivalent to the initial density in the lock chamber (ρ_2).

This parameter variation entails the variation of parameters dependent on it, such as the relative density difference (ε_i) and the front velocity of the intruding layer (c_{1_i}). The variation of these parameters during the filling process is introduced by expression (5.7) and (5.8), respectively.

$$\varepsilon_i = \frac{\rho_i - \rho_2}{\rho_2} \tag{5.7}$$

$$c_{1_i} = c_1' . \sqrt{\frac{\varepsilon_i . g . (h_u + h_d)}{2}} \tag{5.8}$$

Vrijburcht [33] recommends values for the coefficient for the front velocity (c_1') between 0.42 and 0.48, for a salt intrusion layer, and 0.48 and 0.52, for a fresh intrusion layer.

In accordance to the distinction between the zone in front of the bow and the zone behind the stern introduced for the variation in density, also these two parameters are distinguished, resulting in ε_b and c_{1_b}, for the former zone, and ε_s and c_{1_s}, for the latter, as a function of ρ_b and ρ_s, respectively.

In order to determine the moment the front of the intruding layer reaches the bow (t_b) and the stern (t_s) for the first time, it was introduced in the model the calculation of the horizontal distance between the gate and the front of the intruding layer in each time-step –x_i. Accordingly, for each time step:

$$x_i = x_{i-1} + \left(\frac{c_{1b_i} + c_{1b_{i-1}}}{2}\right) . \Delta t \tag{5.9}$$

It is now possible to determine t_b, corresponding to the moment where $x_i = x_b$, and t_s being the moment when $x_i = x_s$.

Vrijburcht [33] defines the longitudinal force due to the density difference component through a simplified equation, which determines the force as function of the water levels of the free surface and the interface between different density fluids, the cross-section of the vessel and the densities of the fluids, i.e. salt water and fresh water. Furtherly, the resulting force is made dimensionless by the weight of the ship and expressed in per mil (‰), correspondent to the relative longitudinal force, which is then added to the previous determined components to compute the total longitudinal force variation in time during the filling process.

Three situations were distinguished in order to compute the relative longitudinal force due to density differences, which depend on the intruding layer progression during the filling process:

A. The bow and the stern of the vessel are both immersed in the upper layer, i.e. the fresh water layer
B. Only the bow is immersed in the lower layer (Salt layer)
C. Both bow and stern are immersed in the salt water layer.

When filling a fresh water lock with salt water from the approach harbour, the initial situation corresponds to A. The intruding layer, with a higher density, will gradually mix with the fresh water and propagate through the lock chamber, eventually reaching situation B. Finally, when the stern becomes immersed in salt water, situation C arises and remains present until the end of the process.

Since to this situations are inherent different bow and stern water depths, which highly influence the relative longitudinal forces, it is reasonable to address them with different formulations, as given by Vrijburcht [33]. The formulations and respective boundary conditions, as function of the thickness of the fresh layer at the bow (a_{2b}) and the stern (a_{2s}), are as follows:

A. Bow and stern immersed in the fresh water layer

$$F_r' = \frac{\Delta h_{bs}}{l_s . C_b} . 1000 \tag{5.10}$$

With,

- $a_{2b} > d_s$
- $a_{2s} > d_s$

B. Bow immersed in the salt water layer

$$F_r' = \frac{d_s \,.\, \Delta h_{bs} + {}^1\!/_2 \,.\, \varepsilon_b \,.(d_s - a_{2b})^2}{l_s \,.d_s \,.C_b} \,.\,1000 \tag{5.11}$$

With,

- $a_{2b} < d_s$
- $a_{2s} > d_s$

C. Both bow and stern immersed in the salt water layer

$$F_r' = \frac{d_s \,.\, \Delta h_{bs} + {}^1\!/_2 \,.\varepsilon_b \,.(d_s - a_{2b})^2 - {}^1\!/_2 \,.\, \varepsilon_s \,.(d_s - a_{2s})^2}{l_s \,.d_s \,.C_b} \,.\,1000 \tag{5.12}$$

With,

$a_{2b} < d_s$
$a_{2s} < d_s$

The difference in water level between bow and stern (Δh_{bs}) also depends on the situation presented during the filling of the lock. The formulations and respective boundary conditions, also as function of the thickness of the fresh layer at the bow and the stern, adopted from Vrijburcht [33], yet slightly modified, are as follows:

A. Bow and stern immersed in the fresh water layer

$$\Delta h_{bs} = \frac{({}^1\!/_2 \,.\, \varepsilon_b .(\,(h_b - a_{2b})^2 \,.b_k\,) - {}^1\!/_2 \,.\, \varepsilon_s \,.(\,(h_s - a_{2s})^2 \,.b_k\,)\,) + \left(\frac{I_{dr}}{\rho_2 \,.g}\right)}{(h_k \,.b_k - d_s \,.b_s)} \tag{5.13}$$

With,

$a_{2b} > d_s$
$a_{2s} > d_s$

The modifications to the formulations from Vrijburcht [33] regarding the present model refer to the adopted water level, by enabling a distinction between water level in the bow (h_b)and in the stern(h_s), given, as mentioned above, by the simulations without density differences from LOCKSIM. On the other hand, these parameters were presented in the formulations as given by Vrijburcht as an average water level in the lock– h_k. This adoption is made in order to attempt to optimize the model as much as possible. The premise followed by the author is that, even if it is not possible to include the density difference in the LOCKSIM simulations, by including the effects of the other components have in the filling process in the present model, namely in the water level in the bow and stern of the vessel, it allows to determine the longitudinal forces during the filling time due to the density differences component while taking into consideration the influence of other components. Hence, for instance, in a time-step of the simulation where it was registered a high difference in water levels between bow and stern, when compared to a time-step that registered a short difference in said water levels, it will provide a more accurate display of the density differences influence, rather than adopting an average water level in the chamber, assuming that during the filling there are no more causes to differences in water depth between bow and stern except for the density differences.

Notice that the output given by LOCKSIM is the water elevation in the bow and stern. To include it in the present formulations, h_b and h_s must reflect the water level in the chamber, and are, therefore, the result of the subtraction of z_{bottom} to the respective extracted values from the simulation.

B. Bow immersed in the salt water layer

$$\Delta h_{bs} = \frac{\left({}^{1}/_{2} \cdot \varepsilon_b . \left((h_b - a_{2b})^2 .b_k - (d_s - a_{2b})^2 .b_s \right) - {}^{1}/_{2} \cdot \varepsilon_s . \left((h_s - a_{2s})^2 .b_k \right) \right) + \left(\frac{I_{dr}}{\rho_2 .g} \right)}{(h_k .b_k - d_s .b_s)} \tag{5.13}$$

With,
$a_{2b} < d_s$
$a_{2s} > d_s$

C. Both bow and stern immersed in the salt water layer

$$\Delta h_{bs} = \frac{\left({}^{1}/_{2} \cdot \varepsilon_b . \left((h_b - a_{2b})^2 .b_k - (d_s - a_{2b})^2 .b_s \right) - {}^{1}/_{2} \cdot \varepsilon_s . \left((h_s - a_{2s})^2 .b_k - (d_s - a_{2s})^2 .b_s \right) \right) + \left(\frac{I_{dr}}{\rho_2 .g} \right)}{(h_k .b_k - d_s .b_s)} \tag{5.14}$$

With,
$a_{2b} < d_s$
$a_{2s} < d_s$

As presented by these formulations, the longitudinal force due to differences in density depends not only of parameters inherent to the problem to be addressed, but also of the water level difference between bow and stern (Δh_{bs}) and the thickness of the salt layer in front of the bow (a_{1b}) and behind the stern (a_{1s}), which reflects the importance to accurately define them.

Since the fresh layer is absent in the zone in front of the bow, the thickness of the salt layer (a_{1b}) corresponds to the water depth (h_b). Consequently, there is no flow velocity of the fresh layer in the said zone ($v_{2b} = 0$). The flow velocity of the salt layer (v_{1b}) is, on the other hand, given by the continuity equation given by expression (5.15).

$$v_{1b} = \frac{\left(\frac{Q\,.(l_k - x_b)}{l_k}\right)}{h_b\,.b_k} \tag{5.15}$$

The previous determination of the moment when the front of the intruding layer reaches the stern (t_s) is fundamental in order to compute the thickness of the salt layer behind the stern (a_{1s}), since it defines the boundary conditions – before that moment there is no presence of salt water in the zone behind the stern, resulting in $a_{1s} = 0$ and $v_{1s} = 0$. Due to the nonexistence of density differences in that zone, $a_{2s} = h_s$ and v_{2s} follows expression (5.16), for $t < t_s$.

$$v_{2s} = -\frac{\left(\frac{Q_i\cdot\,(l_k - x_s)}{l_k}\right)}{h_s\,.b_k} \tag{5.16}$$

With,

$t < t_s$

After the intruding layer reaches the stern ($t > t_s$), the flow velocity of the salt layer is considered to be equivalent to c_{1s} and the thickness of the salt layer is computed according to the following formulation:

$$a_{1s} = \frac{Q\,(t - t_s\,)\,.\,\left(\frac{(l_k - x_b)}{l_k}\right)}{c_{1b}\,.b_k} \tag{5.17}$$

With,

$t > t_s$

As for the flow velocity of the fresh layer (v_{2s}), with $t > t_s$, it can be determined according to expression (5.18).

$$v_{2s} = \frac{a_{1s}\,.v_{1s}\,.b_k - \left(\frac{Q_i\cdot(l_k - x_s)}{l_k}\right)}{(h_s - a_{1s})\,.\,b_k} \tag{5.18}$$

With,

$t > t_s$

The computation of the transport of momentum from the bow to the stern in a longitudinal direction is, for all situations, given by:

$$I_{dr} = \left(\rho_b\,.\,h_b\,.\,v_{1b}{}^2 - \rho_s\,.\,a_{1s}\,.\,v_{1s}{}^2 - \rho_2\,(h_s - a_{1s})\,.\,v_{2s}{}^2\right).\,b_k\,.\,P_I \tag{5.19}$$

A graphical display of the introduced calculation parameters can be found in figure 5.11.

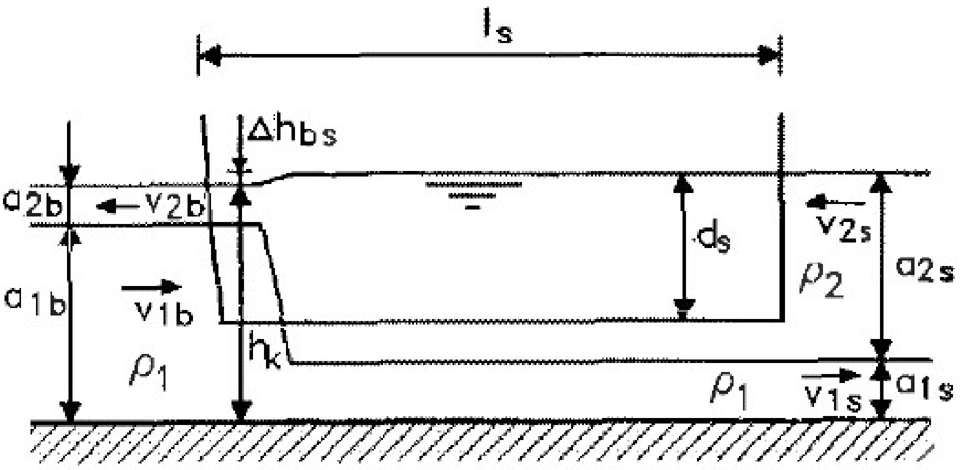


Fig. 5.11 – Graphical display of the parameters inherent to the numerical model calculations

Notice that, for the situation referring to a large blockage induced by the vessel, inherent to this case study, the situation in the zone in front of the bow is, in accordance to the above mentioned, as observed in the figure 5.12.

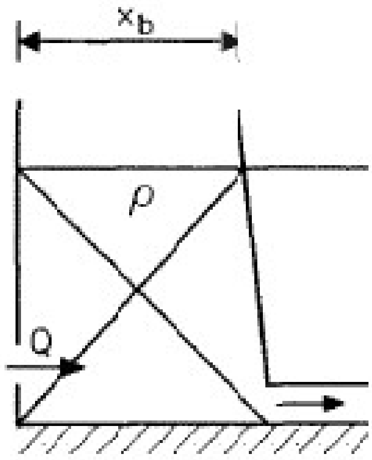


Fig. 5.12 – Situation in the zone in front of the bow referent to a large blockage induced by the vessel

5.1.3.2. Validation of the Numerical Model

In order to validate the numerical model introduced in the previous chapter, an example from Vrijburcht [33] was addressed. The example was chosen for the present validation taking into account the model applicability and it is characterized by a levelling system through openings in the gates. Therefore, in order to acquire the necessary input regarding the discharge and water depth variation throughout the filling process, it was simulated in LOCKFILL. The results from the simulation, i.e. the water depth and discharge variation as a function of time, found in fig. 5.13, were furtherly compared with the example results (fig. 5.14), in order to validate the simulation and, consequently, the viability of the input values required by the numerical model.

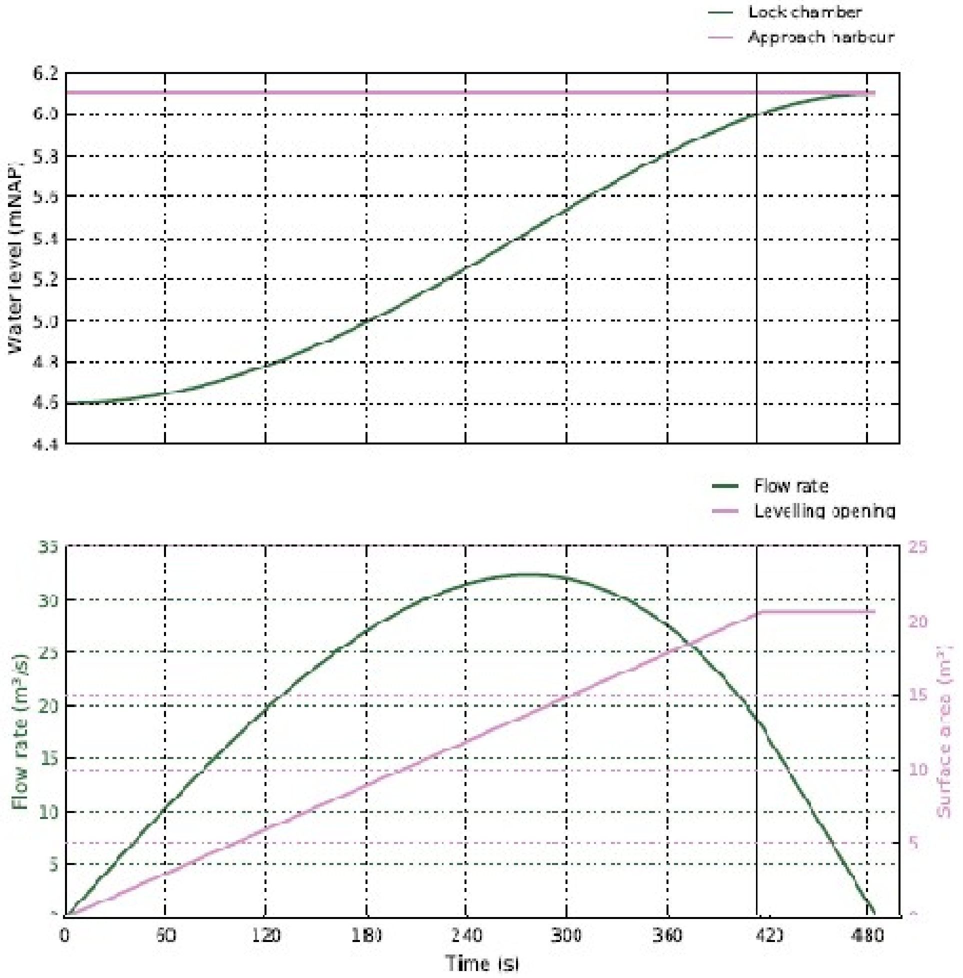


Fig. 5.13 – Water depth and discharge variation as a function of time from LOCKFILL simulation

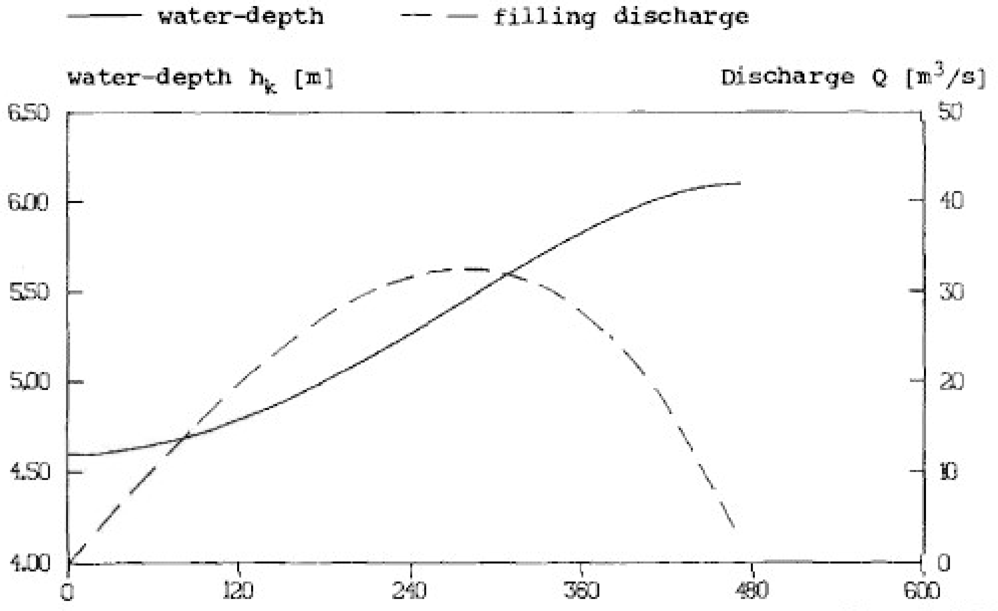


Fig. 5.14 – Water depth and discharge variation as a function of time from Vrijburcht example [33]

Even though the approach for the simulation of this example in LOCKFILL entailed some assumptions, the simulation results were viable, as it is possible to conclude by comparing the levelling time and maximum discharge values, as well as the water depth variation during the filling process. Notice that LOCKFILL does not provide a distinction in the water depth in the bow and the stern, but instead an average water depth in the chamber. Nonetheless, this is not considered to imply a problem regarding the validation of the model, since this distinction represents an added value to the model results, and not an applicability limitation.

Finally, in order to validate the developed numerical model, its results (fig. 5.15) are compared with the results from the example (fig. 5), as given by Vrijburcht [33], namely comparing the thickness of the salt layer variation as a function of time in front of the bow and behind the stern (a_{1b} and a_{1s}, respectively) and the density of the water variation, also in front of the bow and behind the stern (ρ_b and ρ_s, respectively).

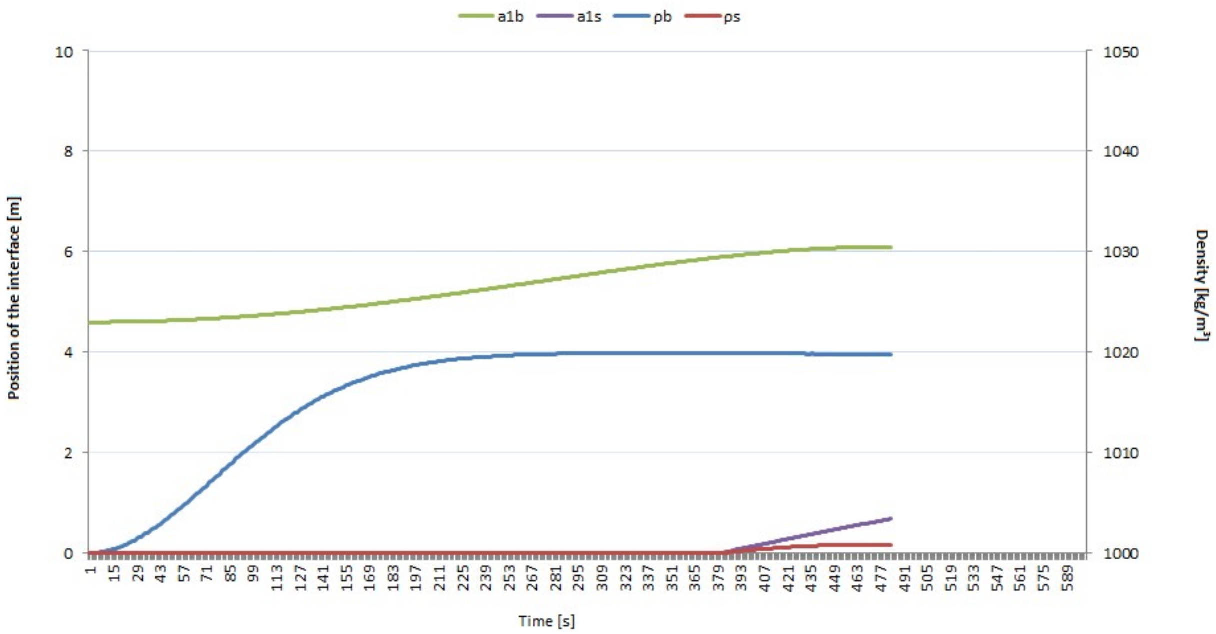


Fig. 5.15 – Thickness of salt layer and water density in the bow and stern results from the numerical model

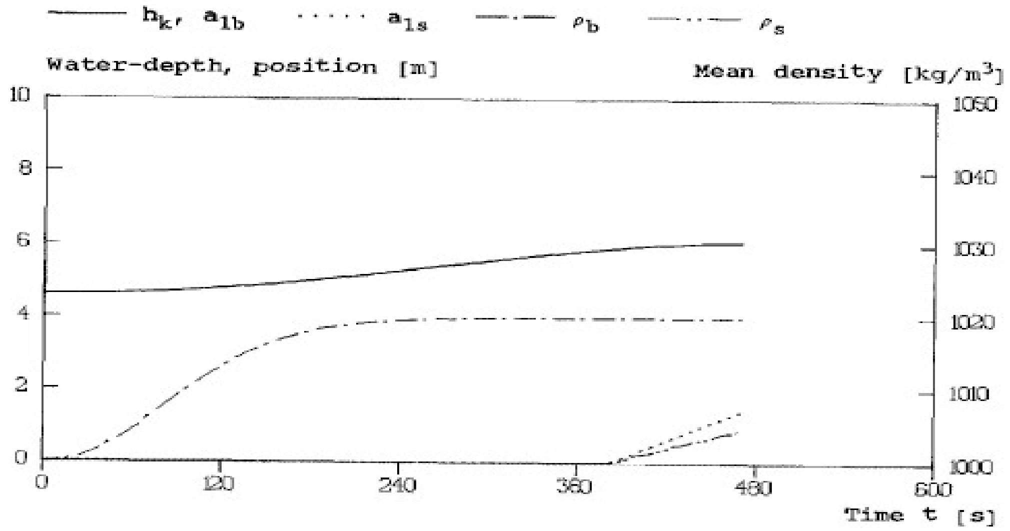


Fig. 5.16 – Thickness of salt layer and water density in the bow and stern results from Vrijburcht [33].

As it is possible to observe, the calculation parameters determined by the developed numerical model resulted in similar values as the calculation parameters given by Vrijburcht. Also, the transport of momentum (I_{dr}) demonstrates a viable variation, following the expectation of increasing progressively with the propagation of the intruding layer, and decreasing after the latter reaches and passes the stern cross-section (figure 5.17).

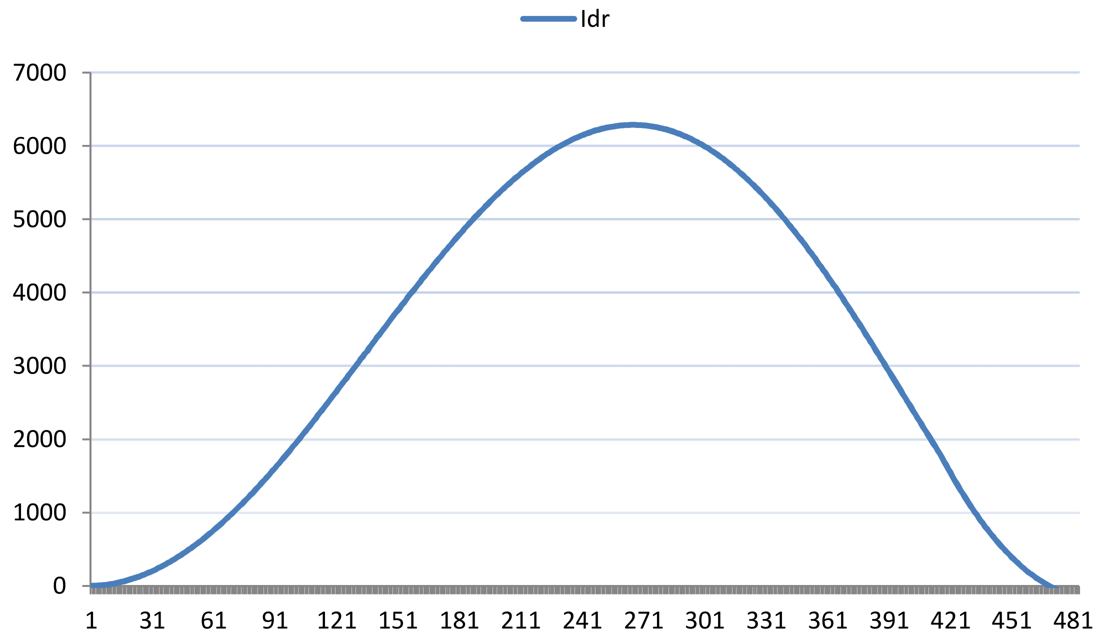


Fig. 5.17 – Transport of momentum variation as a function of time from the numerical model

On the other hand, such similarity was not verified when comparing the resulting mooring forces. The variation in time follows the preconceived logic, that is the increase of the longitudinal force in a negative direction, when only the bow of the vessel is immersed in the more dense fluid, and a decrease of the longitudinal force after the intruding layer reaches and passes the stern of the vessel, reflecting the above mentioned most critical situation regarding the mooring forces, that occurs when the bow and the stern are immersed in fluids with different densities. However, the increase of the longitudinal force occurs at a very strong and fast rate, resulting in a higher magnitude of values than expected. By comparing the results found in fig. 5.18 and 5.19, referring to the numerical model results and the example results from the given literature, respective, it is possible to observe that, while the maximum water level difference between bow and stern (Δh_{bs}) differed in about 7% to 12%, the mooring forces disagree in about 22% to 32%, which constitutes a considerable inaccuracy, since both the simulation and the calculation parameters resulted in very similar values to the ones provided by Vrijburcht. It was also expected that Δh_{bs}, and consequently F_r', eventually lowered to 0, which is not observed. These parameters stabilize in a positive value after the filling time, which is believed to be due to that phase of the filling process being characterized by phenomena, such as the above mentioned exchange process when opening the downstream gate, that is not considered and computed by the numerical model.

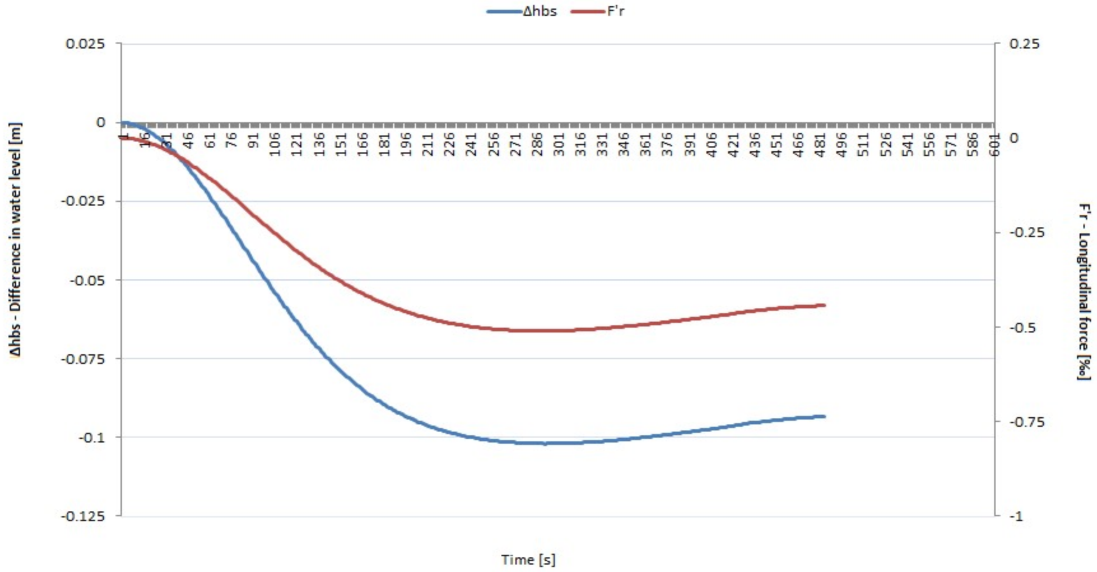


Fig. 5.18 – Longitudinal force and difference in water level as a function of time from the numerical model

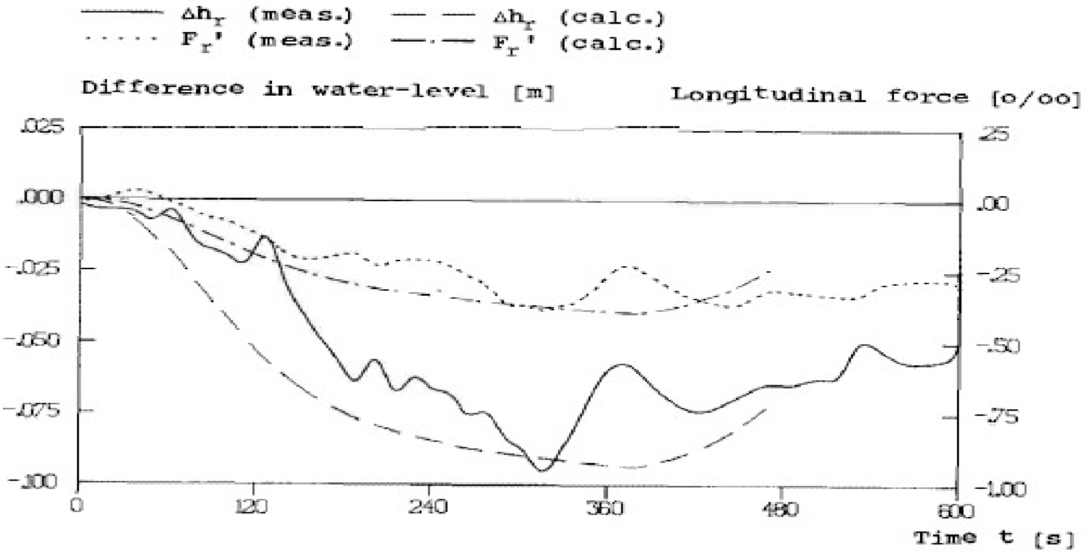


Fig. 5.19 – Longitudinal force and difference in water level as a function of time from Vrijburcht [33].

In light of said inaccuracy, a process to test the influence of Δh_{bs} in the longitudinal force due to density differences (F_r') was executed, by gradually decreasing the former at a constant rate.

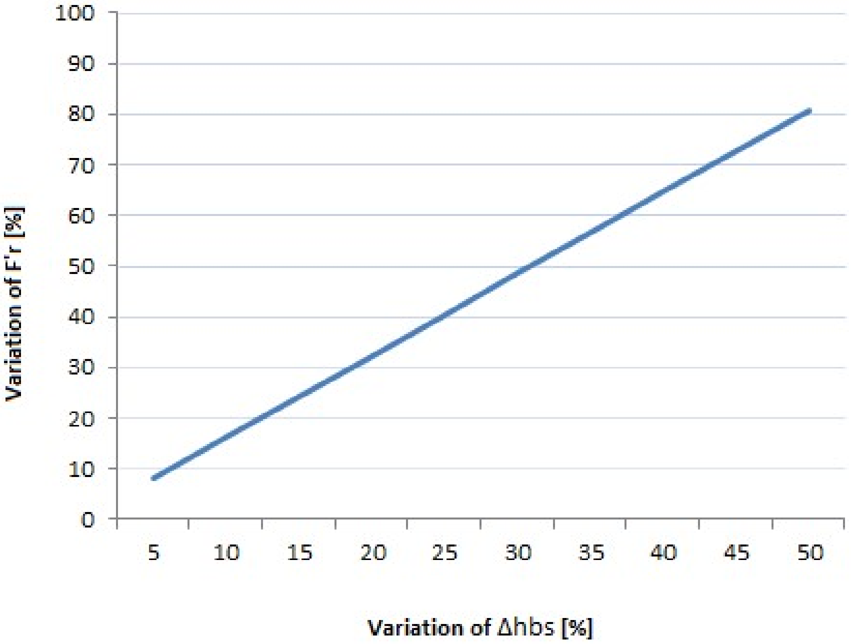


Fig. 5.20 – Influence of the water level difference variation in the longitudinal force due to density differences

As observed in figure 5.20, a decrease of Δh_{bs} correspondent to 5%, resulted in a decrease of $F_r{}'$ of about 8%. This means that, if an inaccuracy of the input values of the numerical model leads to, for instance, an inaccuracy in the determination of Δh_{bs} correspondent to 20%, the longitudinal force due to density difference would be inaccurate by a margin of about 32%. Therefore, F_r' is more susceptible to inaccuracies in the input values or due to incorrect assumptions and adoptions when addressing a specific case study. In conclusion, in order to atone for the susceptibility inherent to the computation of F_r', more examples would have to be addressed to attempt to improve and completely validate the viability of the developed numerical model, since currently a slight margin of error inherent to the input values may lead to a significant inaccuracy in the value of the longitudinal force result in the numerical model.

5.2. CONCLUSIONS

The approach to special levelling systems enabled some important conclusions regarding the applicability and limitations of LOCKSIM. The non-conventional culvert constitutes a design solution which proved to be too complex for a viable simulation with 1D software, leading to inaccurate results. Also, LOCKSIM did not take into account the situation of asymmetrical filling that occurred as an error, but on the other hand the post-processing of results enabled the verification of such situation occurring in the filling process, which can be useful for the user.

Additionally, it was concluded that it is possible to estimate the influence of density differences in a filling process through a simplified numerical 1D model, to further include in the post processing of LOCKSIM results. However, it requires a very accurate input of the discharge and water depth as a function of time, given that the resultant longitudinal force component is very susceptible to inaccuracies. For that reason, taking into account the present case study, it was not possible to correctly apply the developed numerical model in order to determine the longitudinal force due to density differences, since it is only applicable to the considered scenario B, correspondent to the levelling process characterized by an approach harbour with salt water. On account of said scenario being also characterized by a levelling system through non-conventional culvert, the simulation results were not considered viable, and therefore the input required by the numerical model, i.e. the discharge and water depth as a function of time, are highly inaccurate, which would lead to a defective determination of the longitudinal force component due to density differences in this case study.

6

CONCLUSIONS

6.1. FINAL CONSIDERATIONS

In addition to the conclusions presented in chapter 4.3. and chapter 5.2., it is possible to draw significant supplemental final considerations, summarizing the most important conclusions to be extracted from the present thesis, with a view to making possible future developments, as follows.

- The more complexity inherent to a levelling system, the more assumptions are required in the approach to the simulation software, and consequently the more inaccurate the results from the 1D simulation are.
- The approach to the momentum decrease in the post processing of LOCKSIM results proved to be useful, although not as accurate as desired. It displays a viable variation in accordance to what is expected, while consisting on a conservative approach from a design point of view. Therefore, it is deemed useful for the preliminary design of a lock levelling system.
- The one-dimensional characteristic inherent to both software not only restricts possible design options to take into account, but also makes it necessary to complement the simulation results with physical modelling for validation and an economic analysis in order to achieve the optimal design solution.

6.2. FUTURE DEVELOPMENTS

The improvements to the post-processing of LOCKSIM results developed within this thesis, such as the introduction of additional approaches to the momentum decrease and density differences components of the longitudinal force occurring in the lock chamber during the filling process, constitute a viable and useful approach from a design point of view. It enables a more detailed computation of the mooring forces, which is, as above mentioned, a critical design requirement of the preliminary hydraulic design of lock levelling systems. Although, there is still a significant margin of error inherent to this approaches. Therefore, the author suggests the following, in order to improve said approaches:

- Regarding the momentum decrease component determination, notice that it was based on a formulation adopted from LOCKFILL. This entailed an important and susceptible assumption of the discharge in the longitudinal direction of the chamber. It is believed, therefore, that a more accurate computation of this discharge will lead to a more precise determination of this longitudinal force component.

- As for the density differences component, it was based on the developed numerical model introduced in chapter 5.1.3.1. This numerical model may, as well, be subjected to improvements, namely attempting to reduce the susceptibility inherent to the longitudinal force calculation, which can be improved by approaching more precise formulations, possibly adopted from physical models. Also, the range of applicability of the model is still very narrow. The extension of this range of applicability was considered within this thesis, but unfortunately due to lack of time it was impossible to perform further developments. It is, therefore, recommended to extend said range of applicability, in order to enable the approach to different levelling situations.
- A sensitivity analysis regarding the estimated, assumed and adopted parameters influence in the diverse calculations throughout the present work could be useful in order to optimize the developments made.

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ANNEX A

LOCKSIM SCHEMATIC REPRESENTATIONS

In the present annex there are introduced the schematic representation required for the LOCKSIM simulations of the various scenarios approached throughout this work.

Table A.1 – Schematic representation of Scenario C1 (Melle case study)

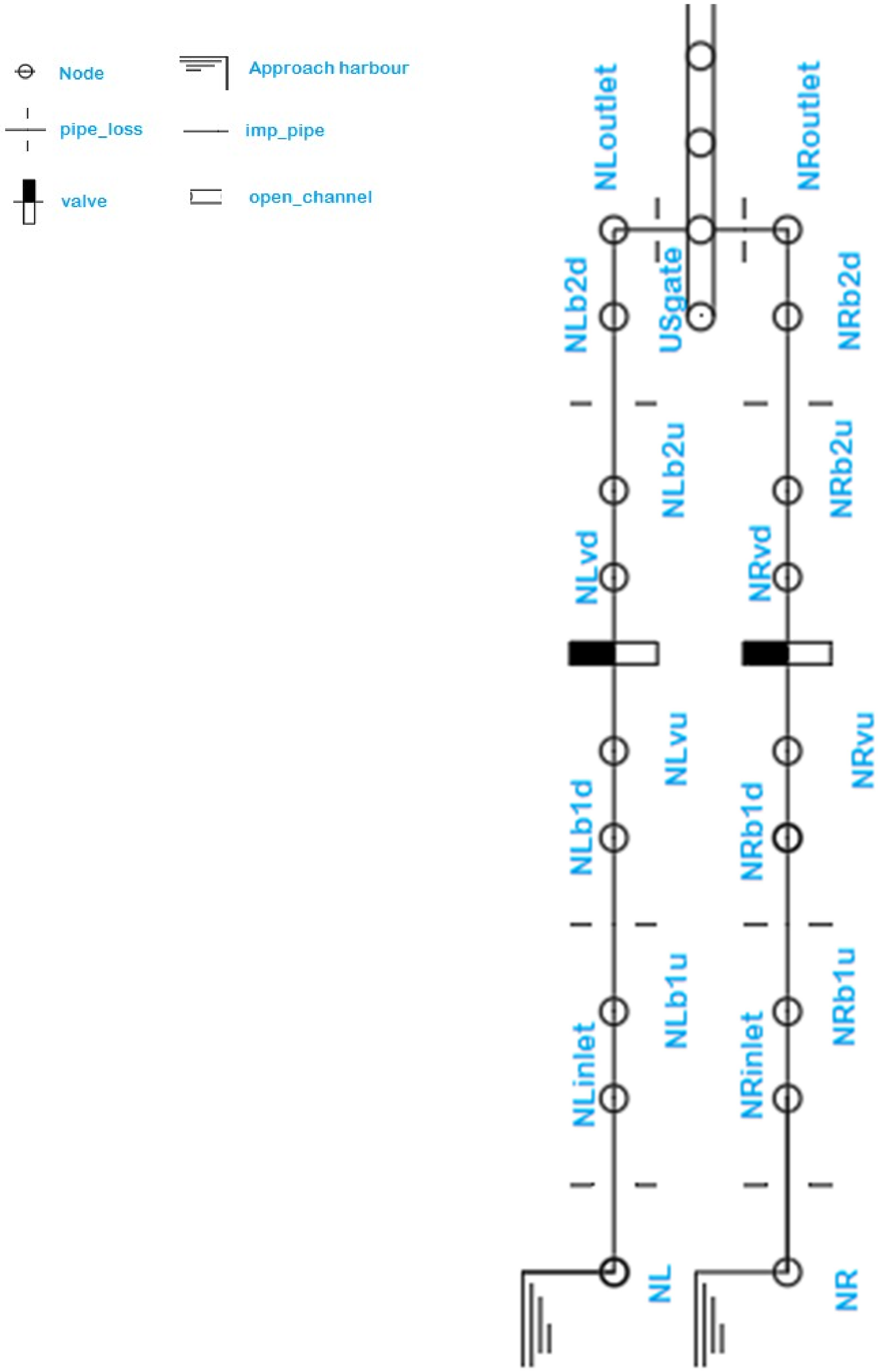


Table A.2 – Schematic representation of Scenario C2 (Melle case study)

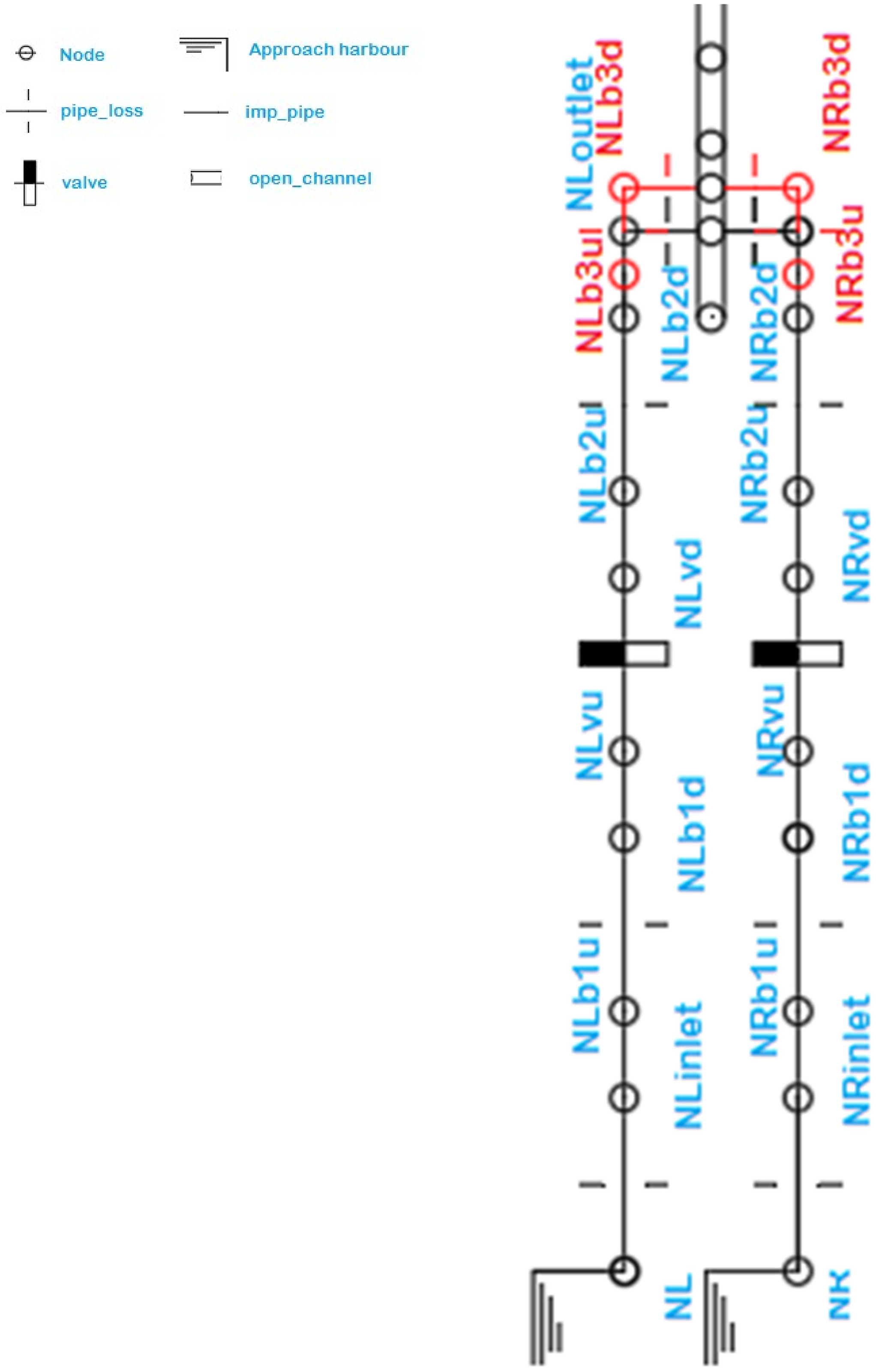


Table A.3 – Schematic representation of Scenario C3 (Melle case study)

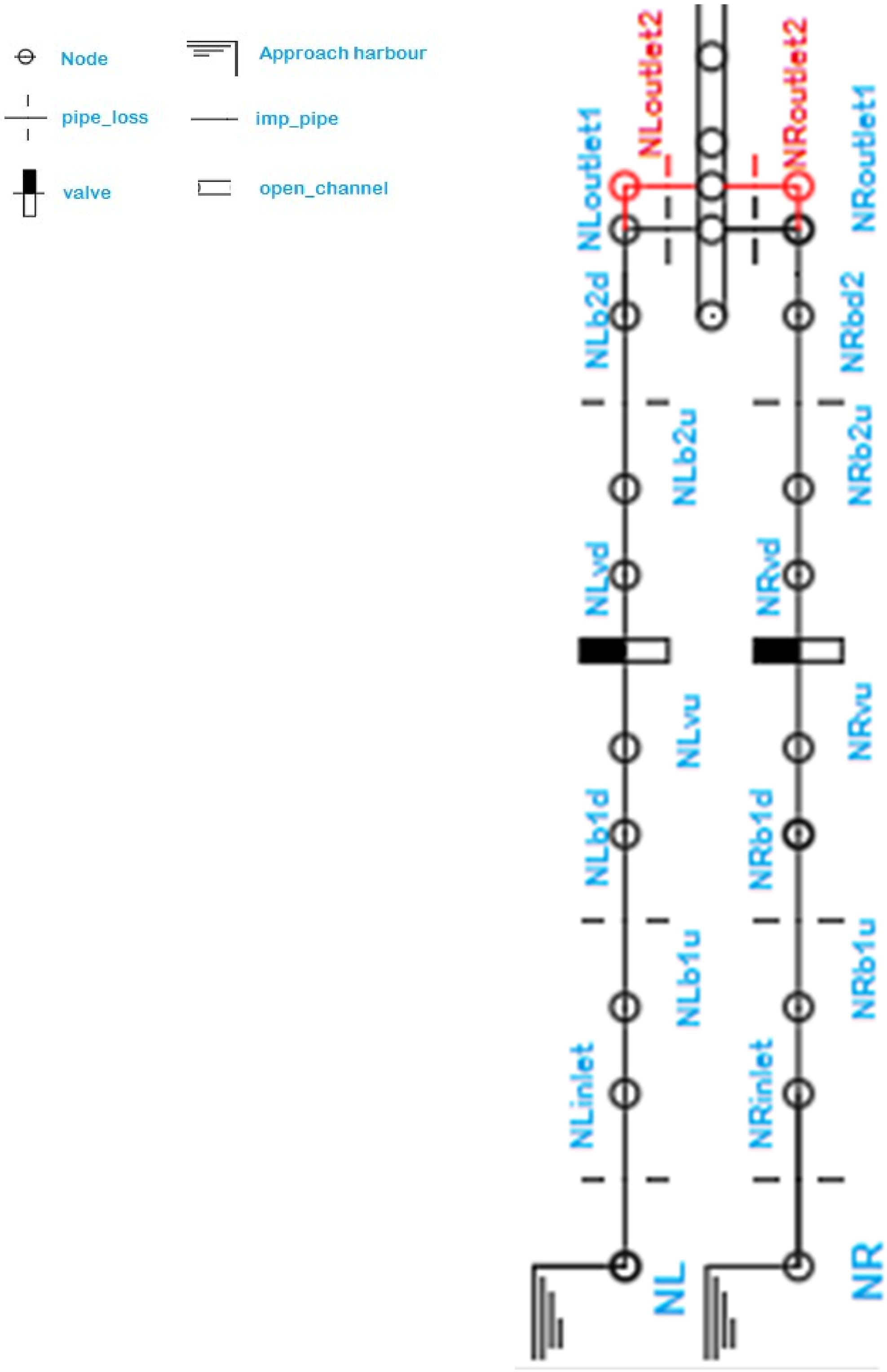


Table A.4 – Schematic representation of Scenario L1 (Melle case study)

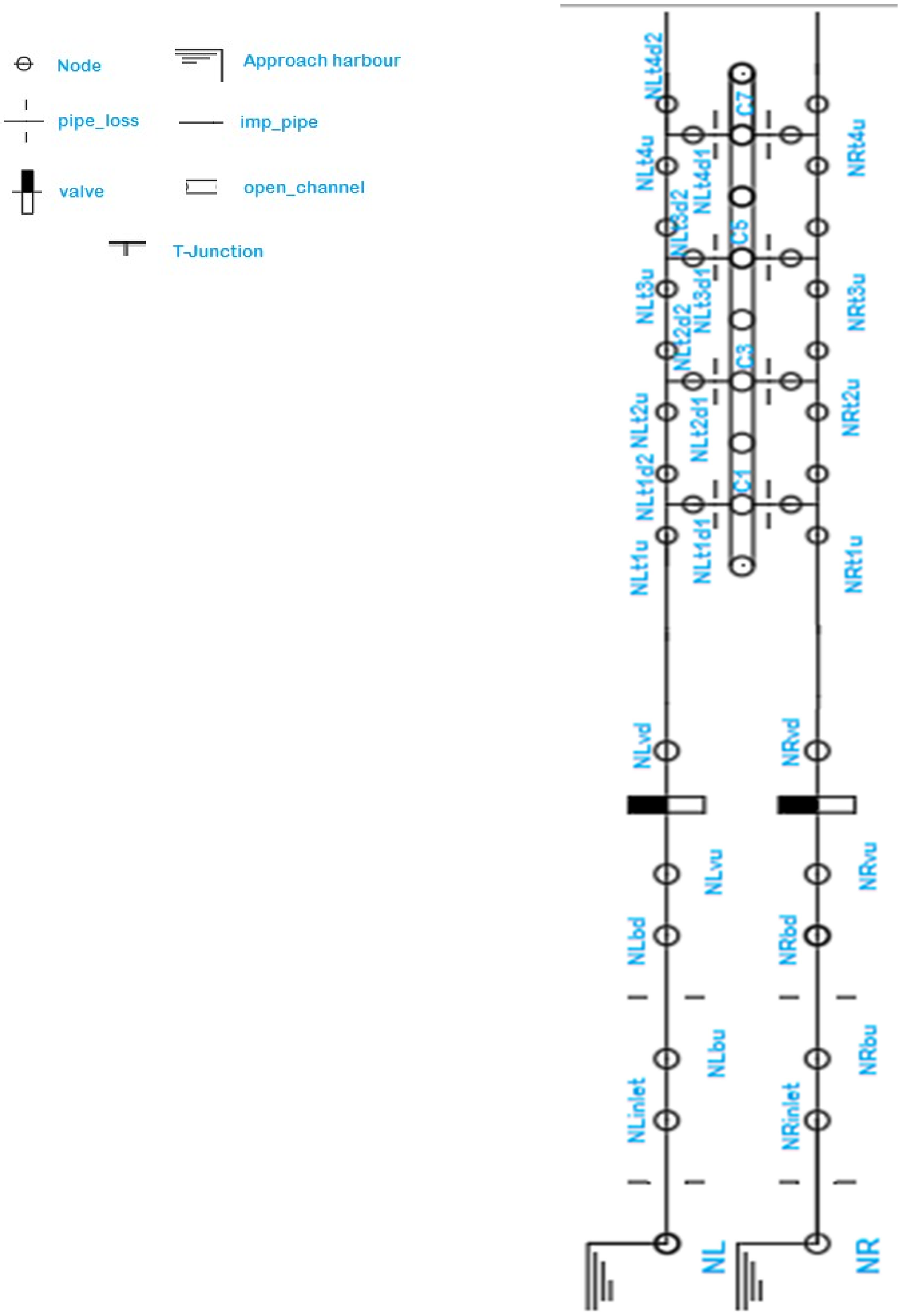


Table A.5 – Schematic representation of Carrapatelo case study

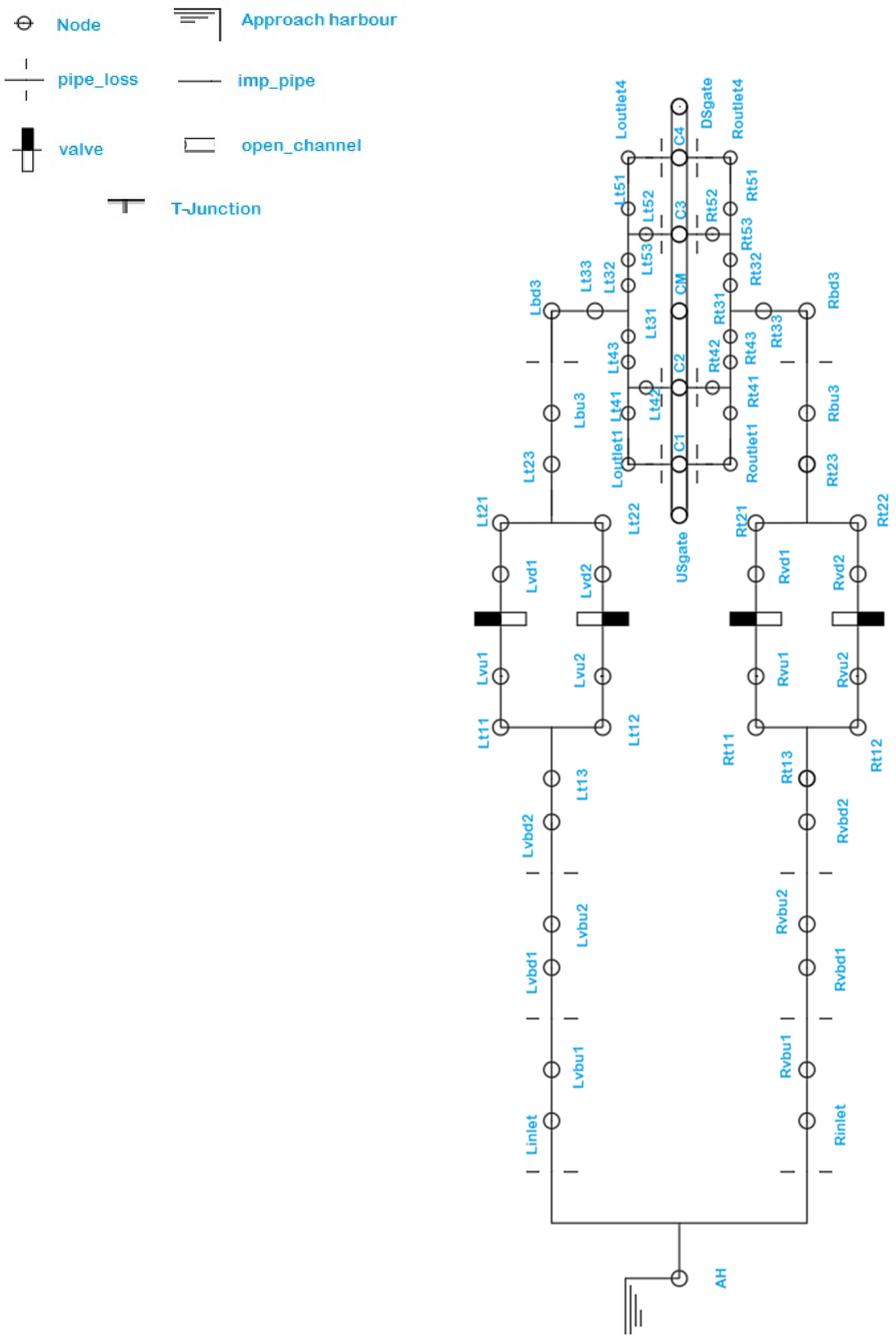


Table A.6 – Schematic representation of Scenario A (Ijmuiden case study)

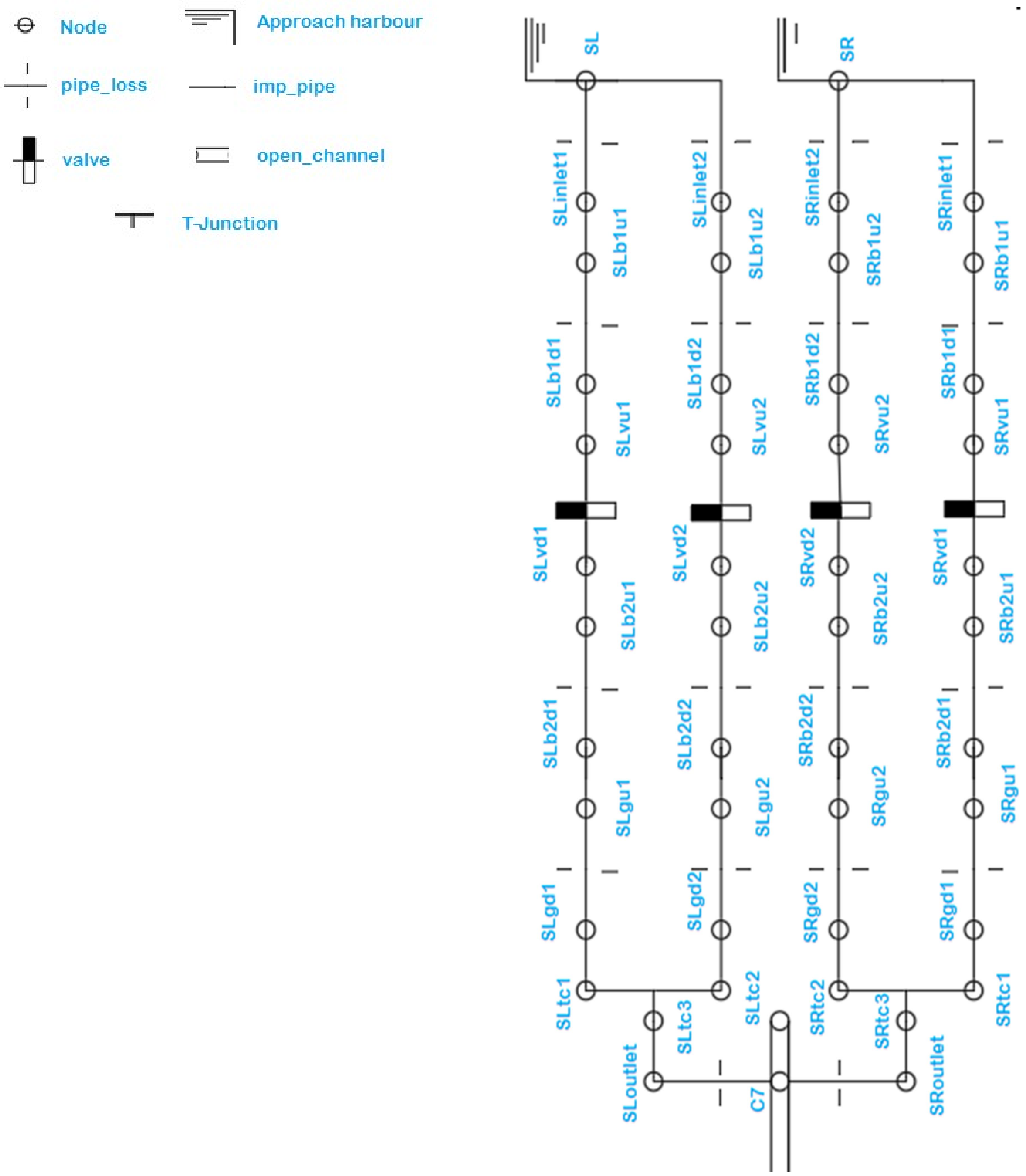
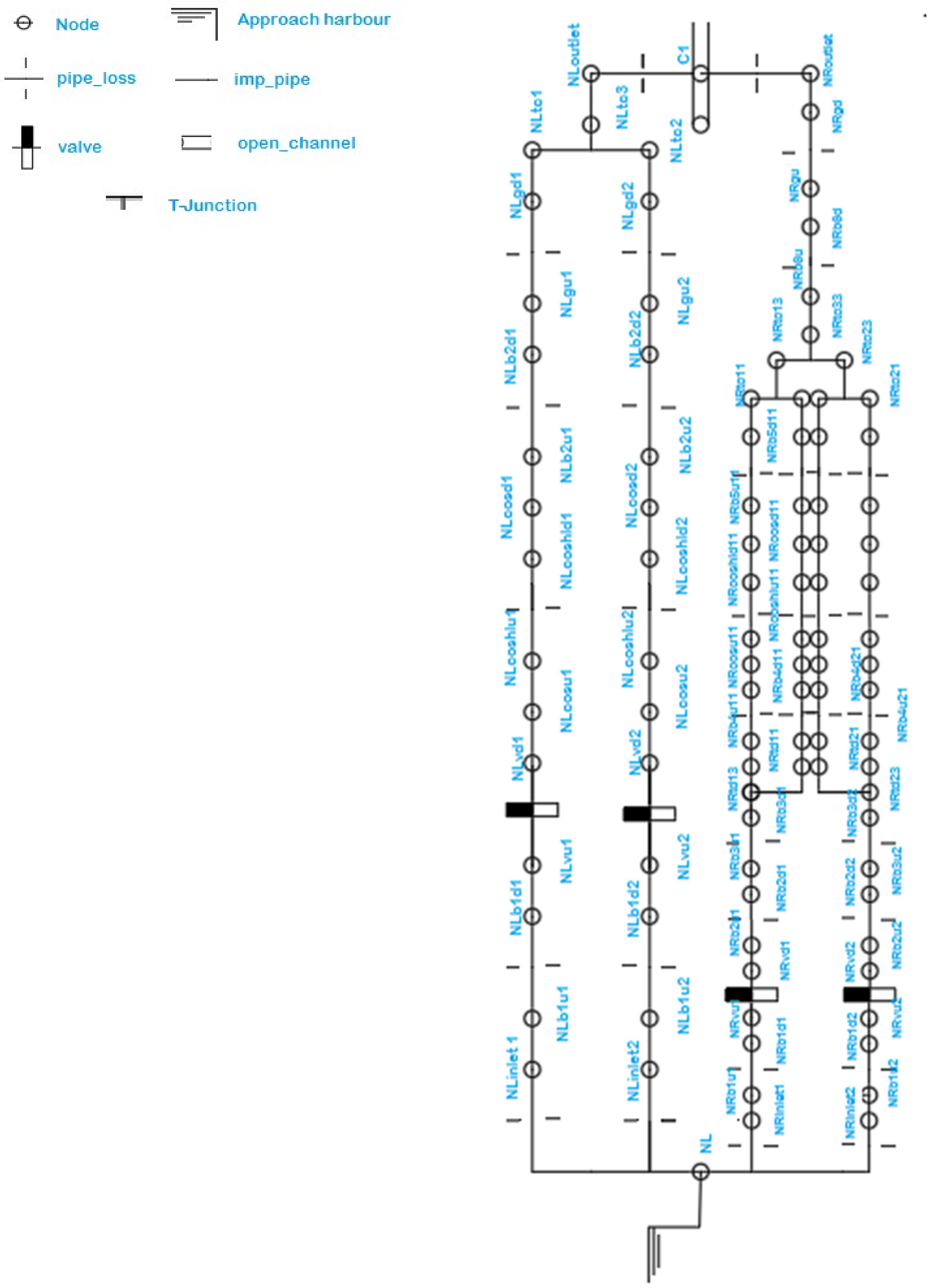


Table A.7 – Schematic representation of Scenario B (Ijmuiden case study)



ANNEX B

GRAPHICAL DISPLAY OF LOCKSIM POST PROCESSING RESULTS

In annex B, the graphical display of water depth variation, discharge variation and longitudinal forces variation as a function of time determined by the post processing phase inherent to the developed simulations in LOCKSIM.

Table B.1 – Scenario C1-V1 (D=0.8 m; Round configuration)

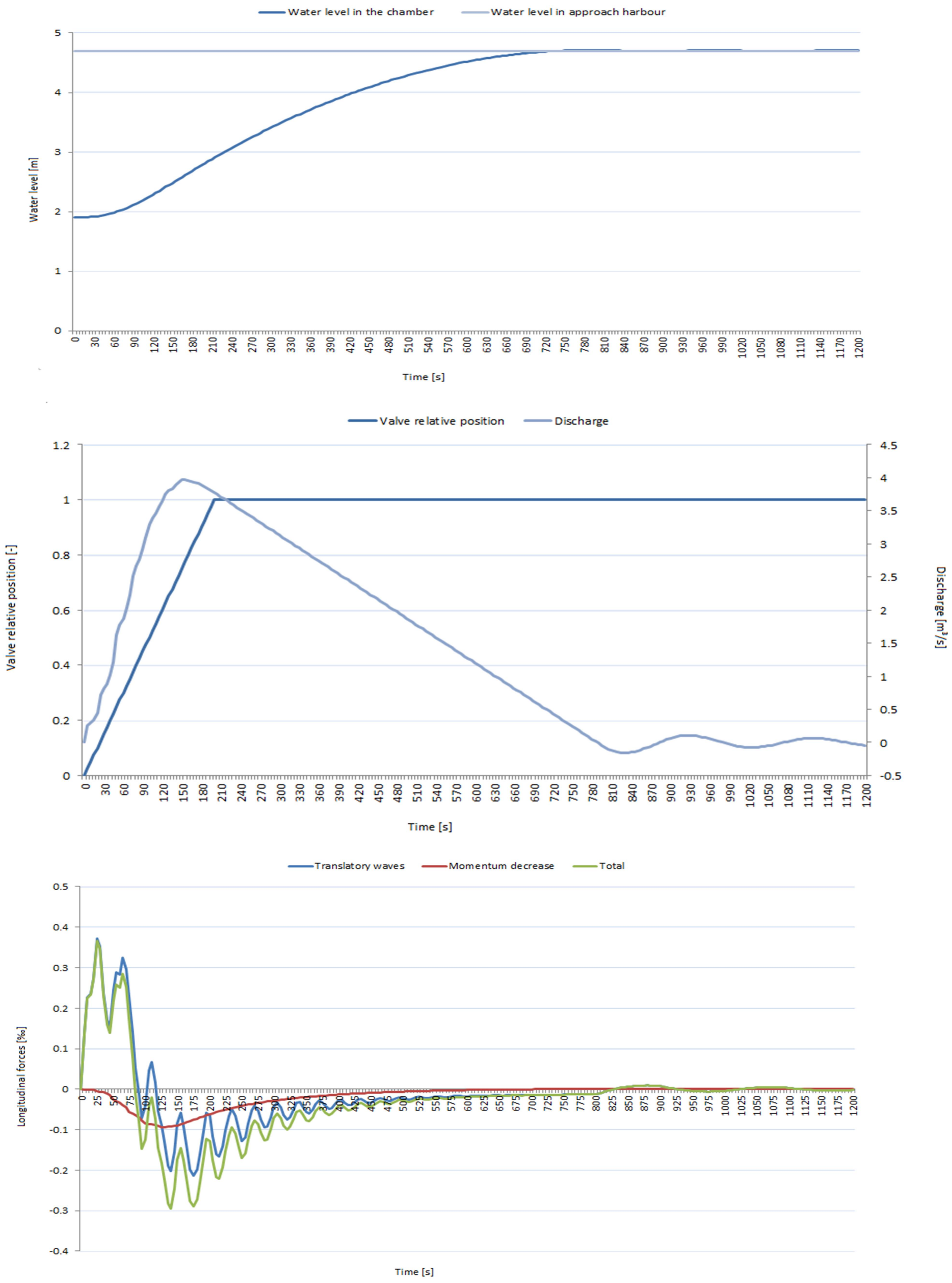


Table B.2 – Scenario C1-V1 (D=0.8 m; Straight configuration)

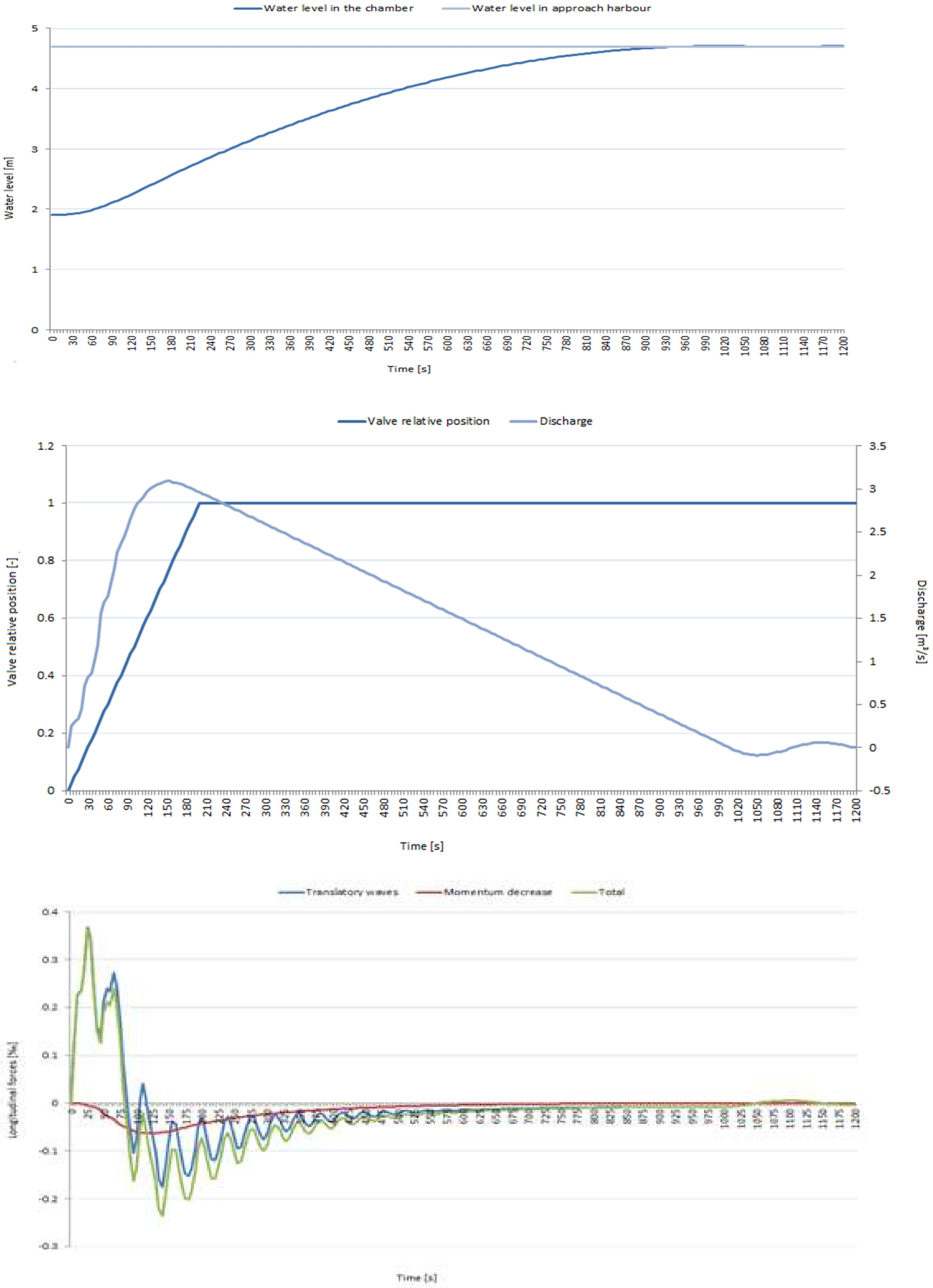
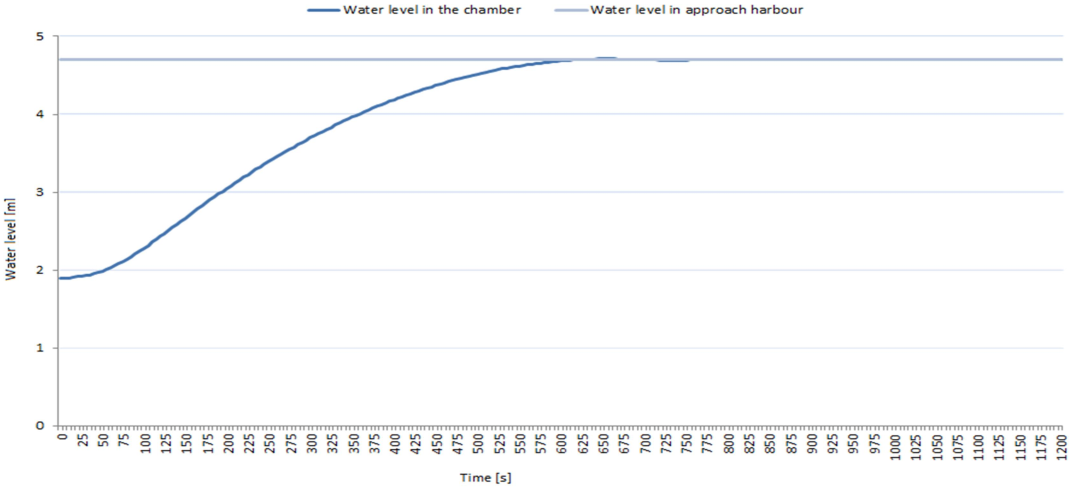
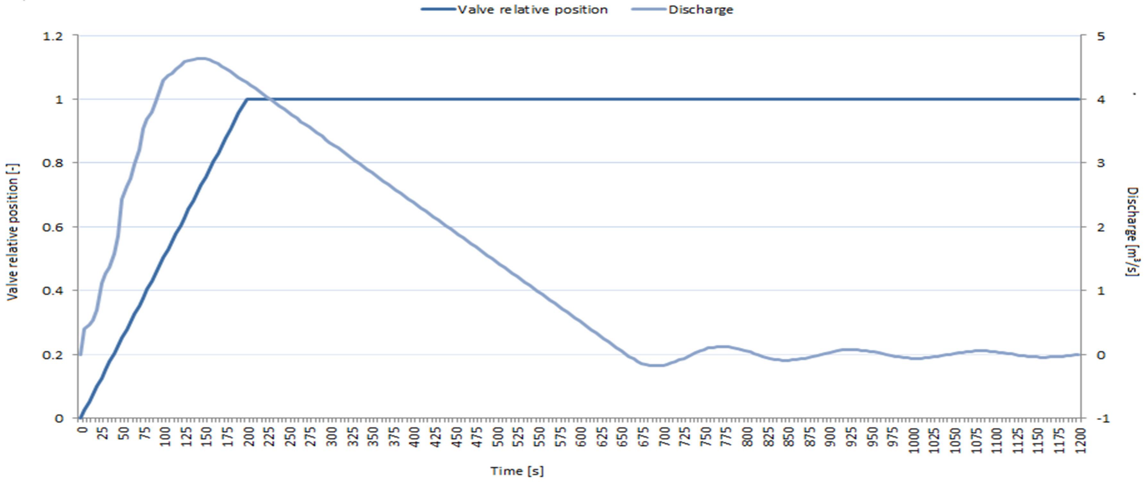


Table B.3 – Scenario C1-V1 (D=1.0 m; Round configuration)

Table B.4 – Scenario C1-V1 (D=1.0 m; Straight configuration)





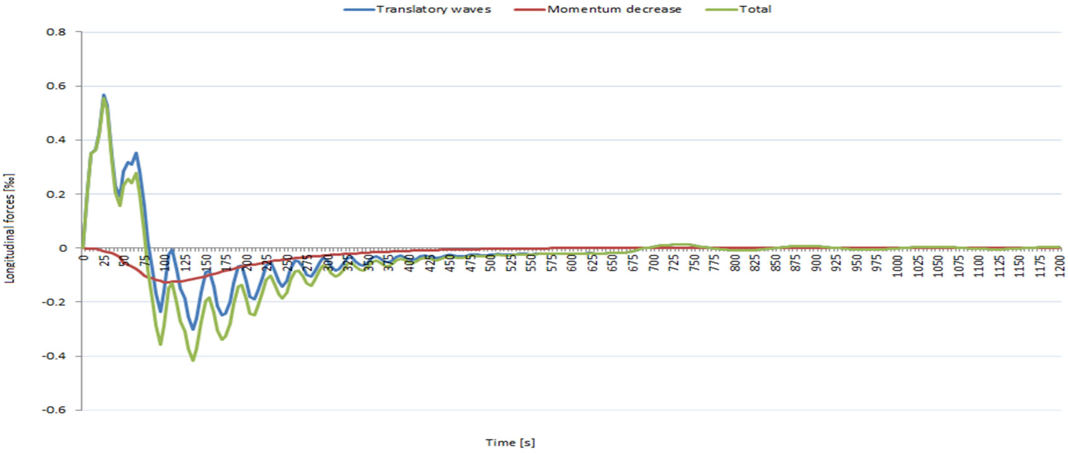
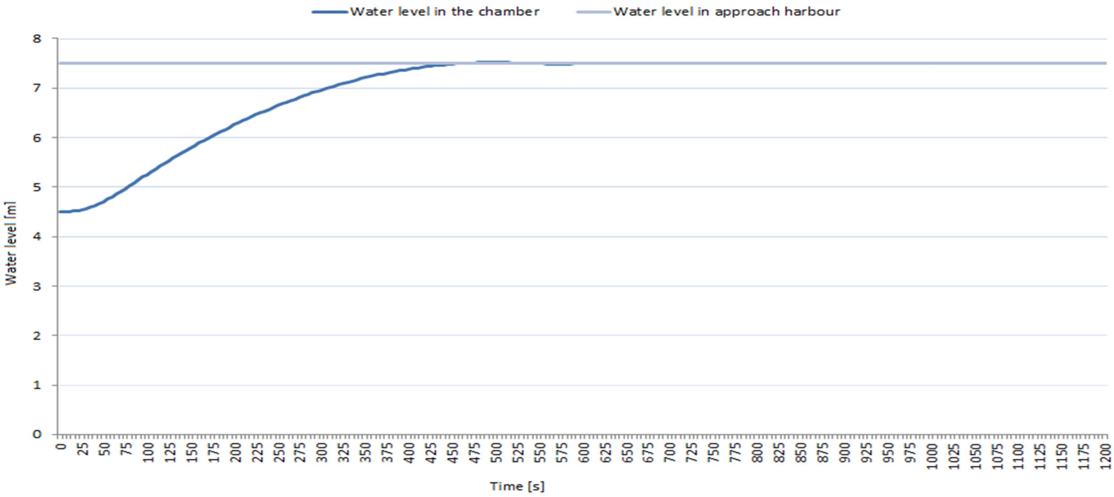
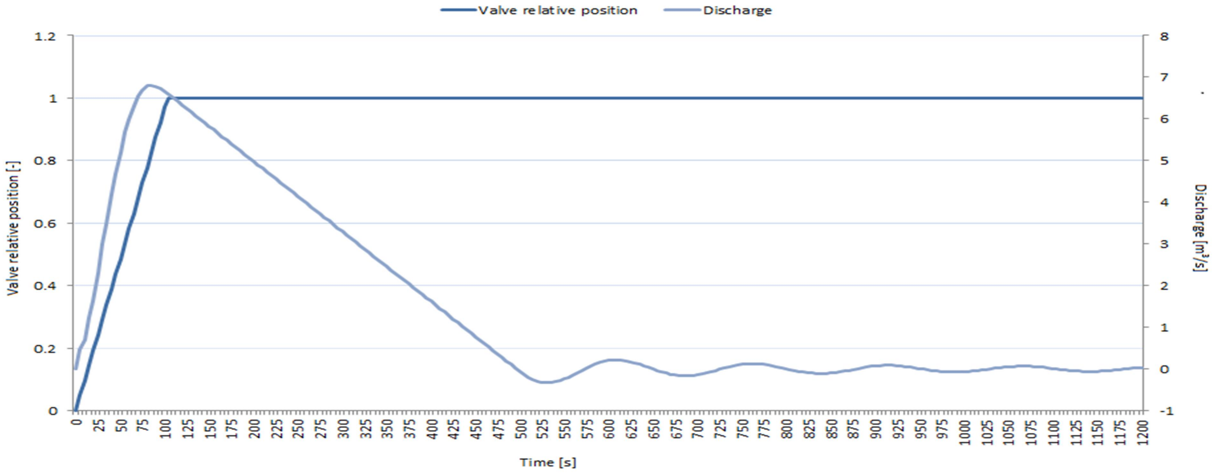


Table B.5 – Scenario C1-V2





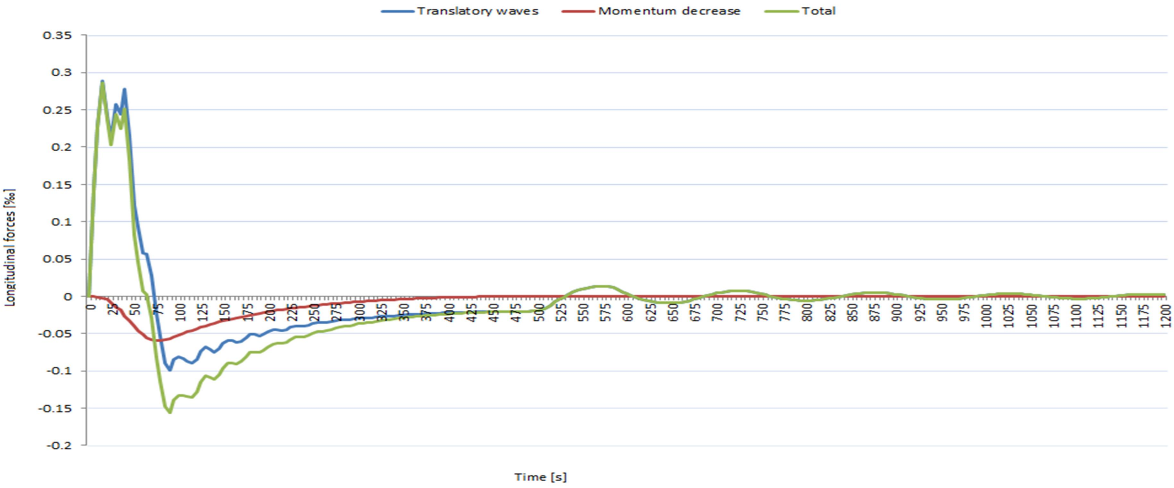
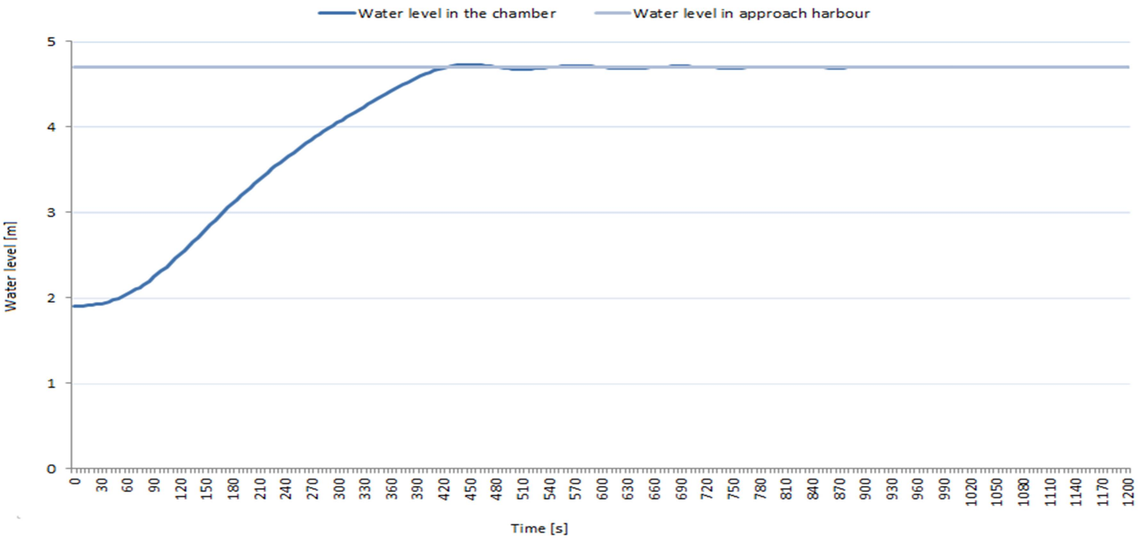
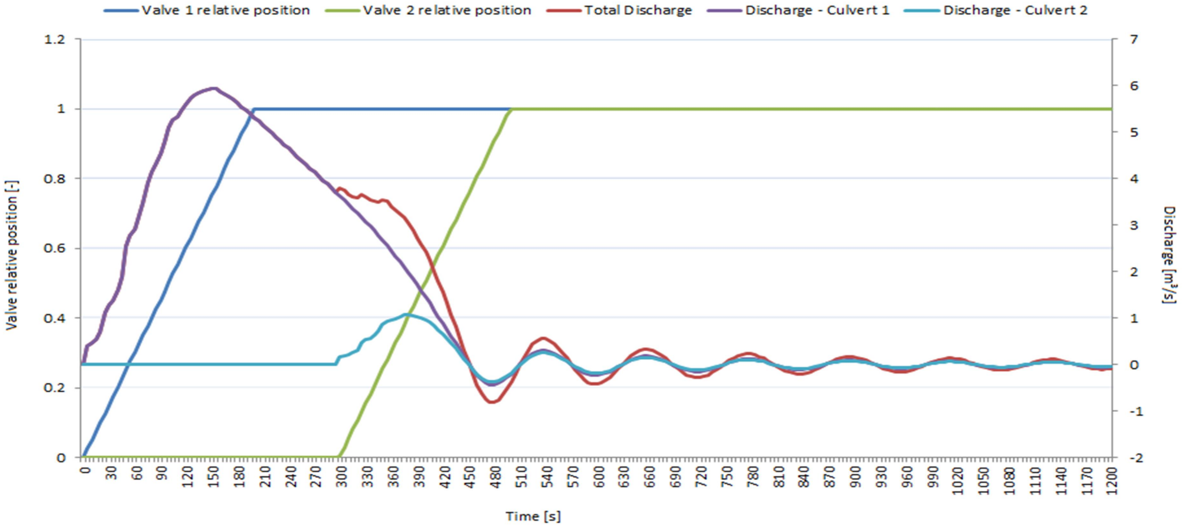


Table B.6 – Scenario C2-V1 (D=0.8 m; Round culvert)





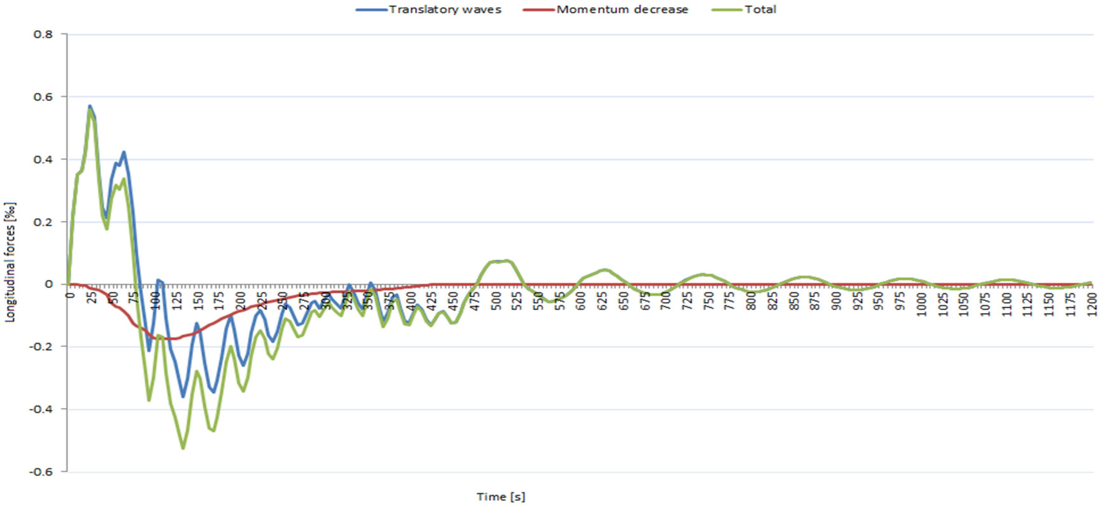
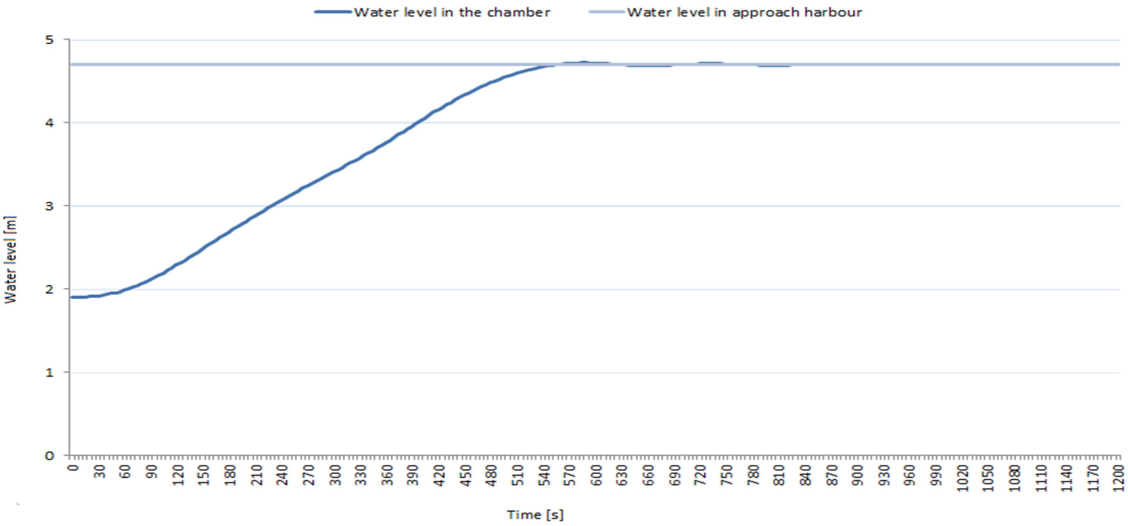
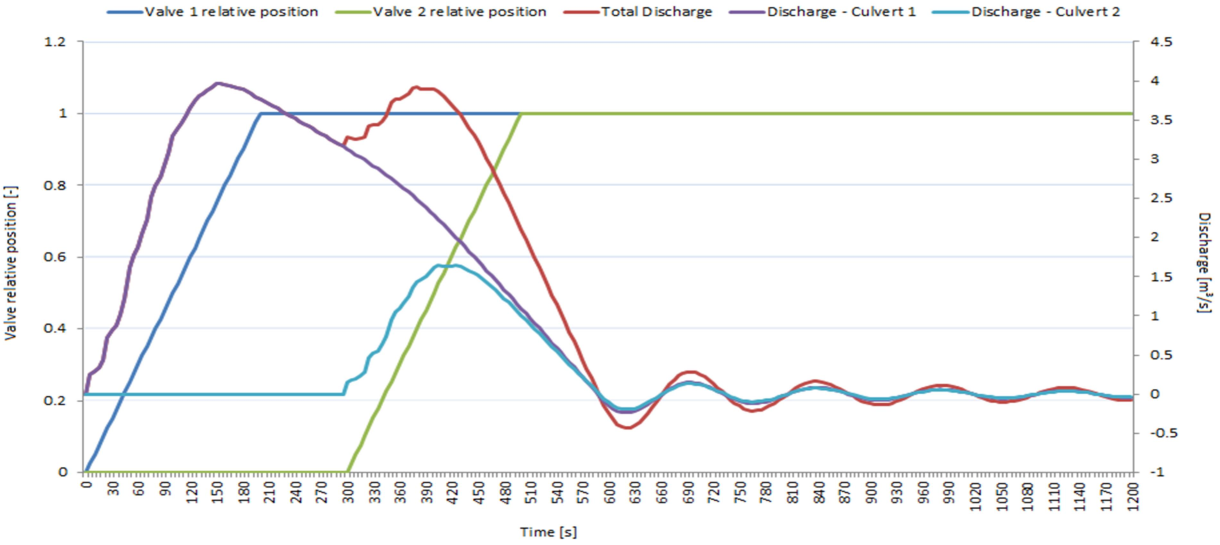


Table B.7 – Scenario C2-V1 (D=1.0 m; Round culvert)





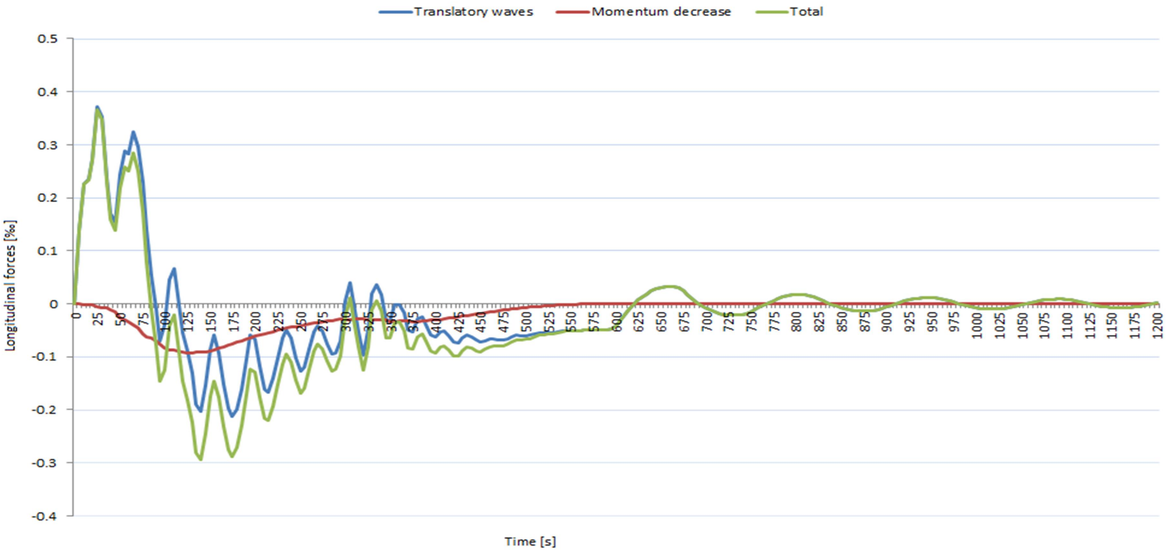
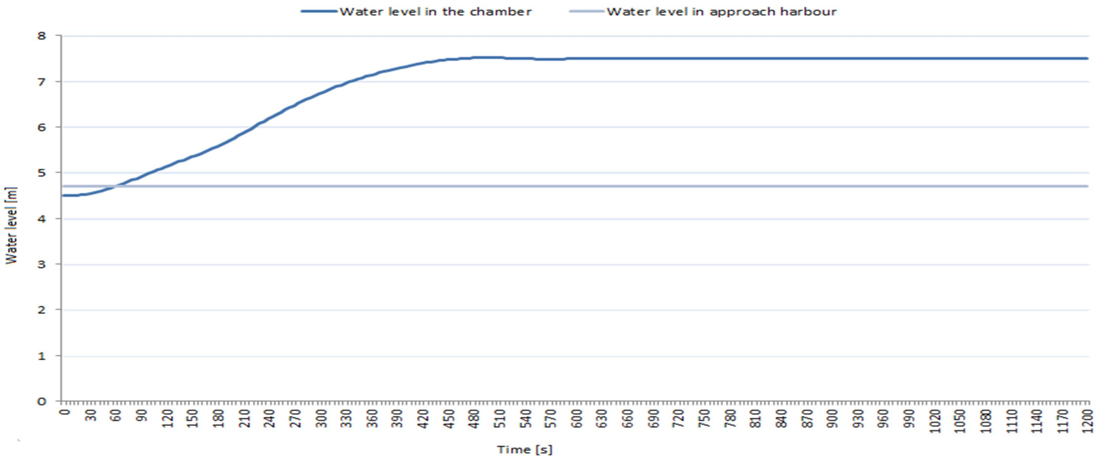
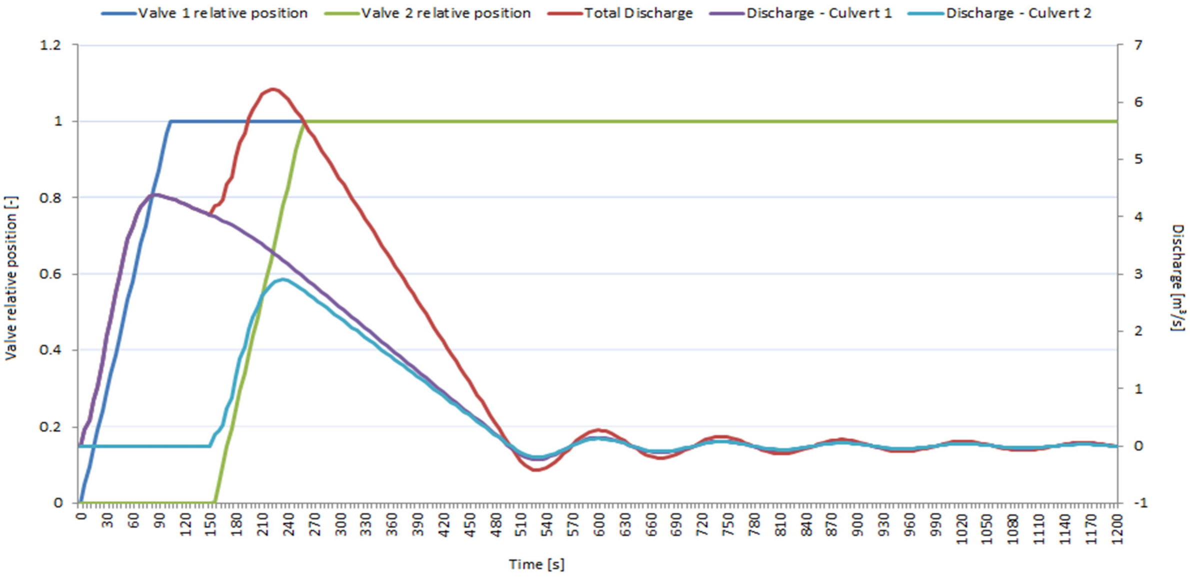


Table B.8 – Scenario C2-V2 (D=0.8 m; Round culvert)





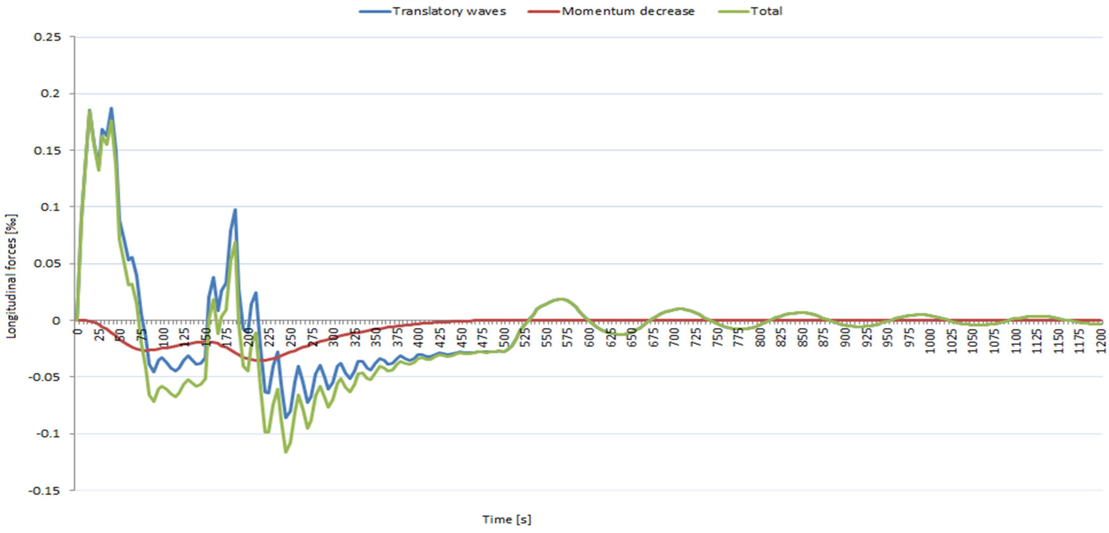
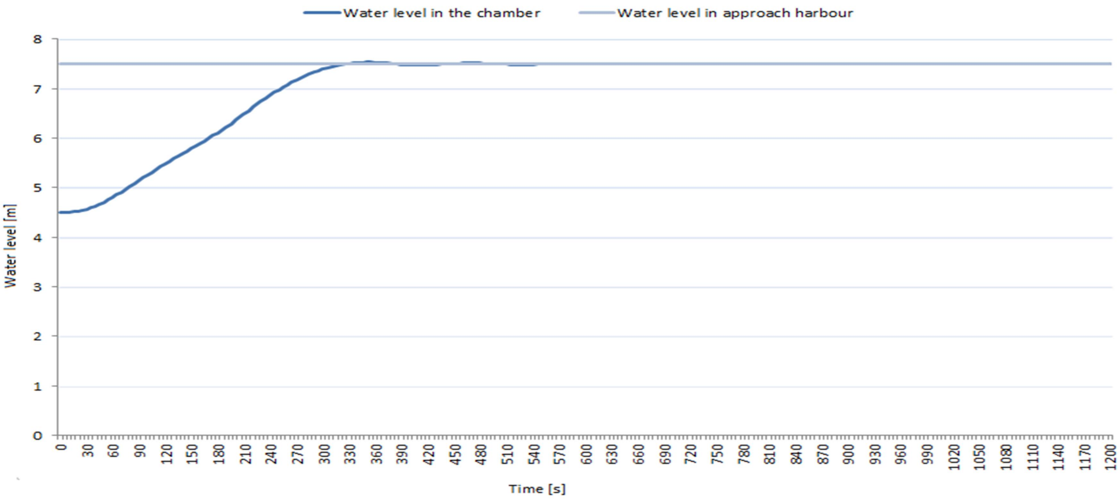
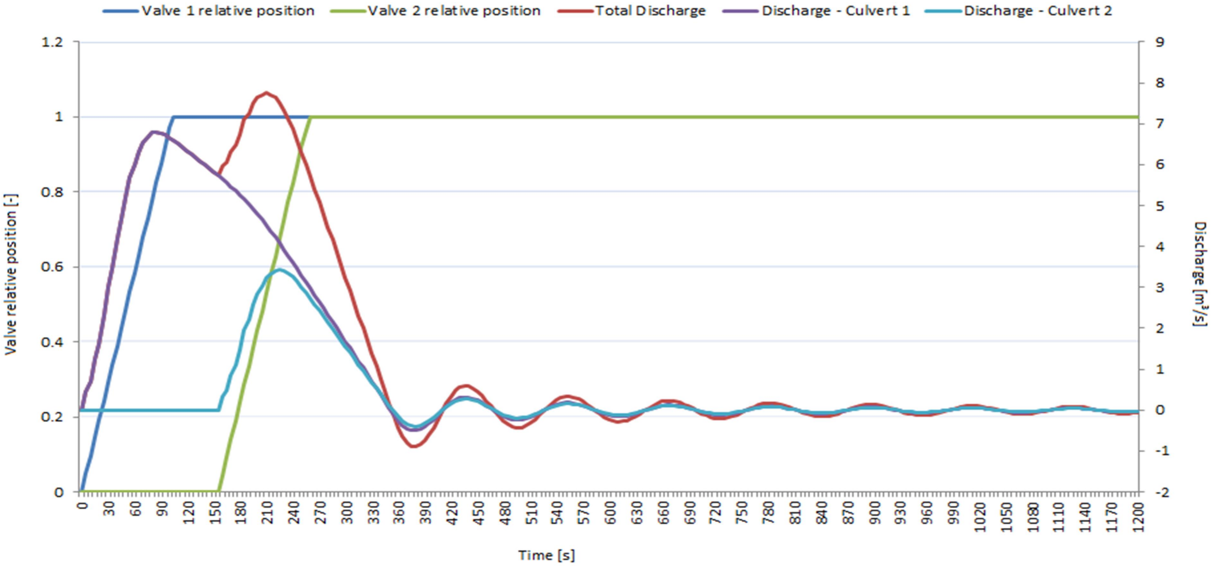


Table B.9 – Scenario C2-V2 (D=1.0 m; Round culvert)





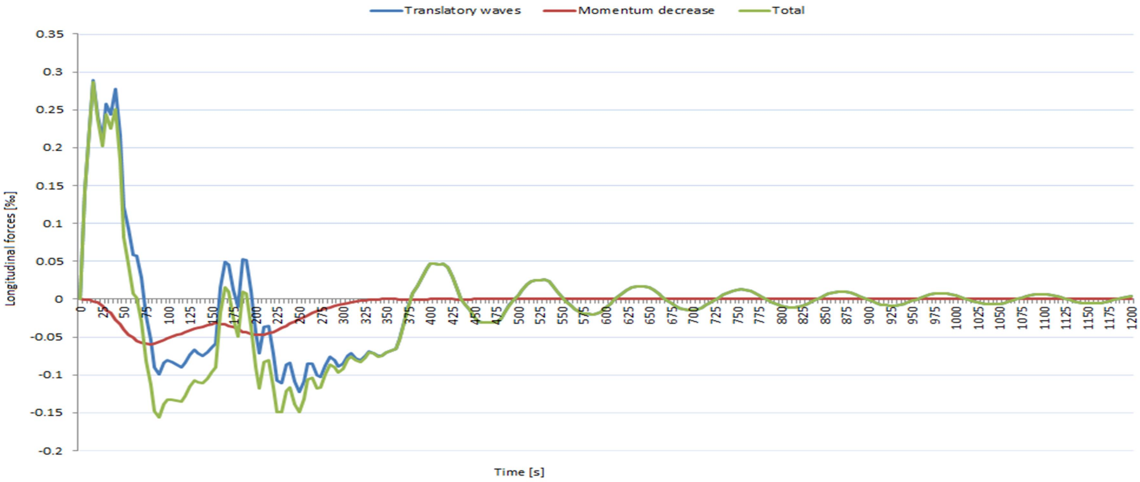


Table B.10 – Scenario C2-V2 (D=0.8 m; Emptying)

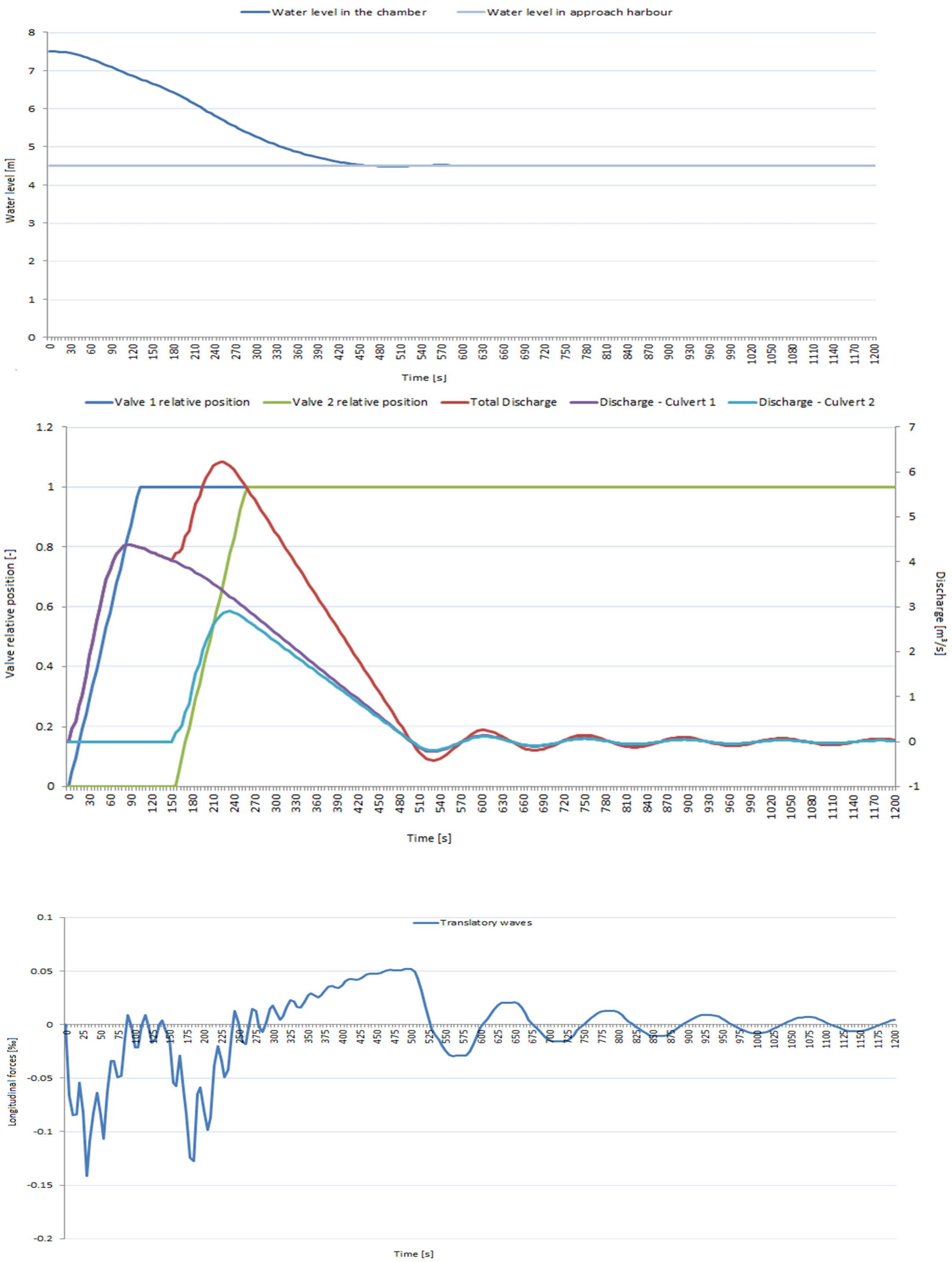
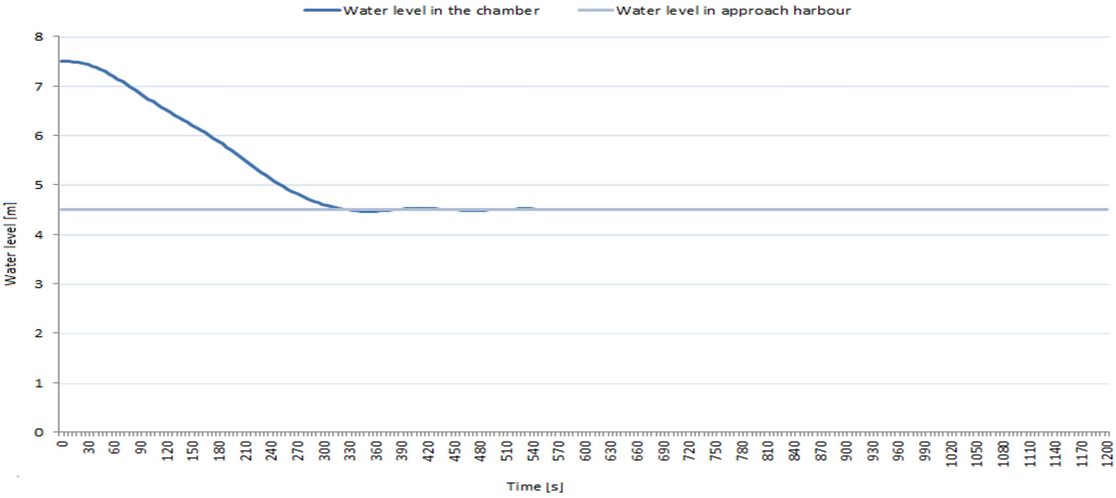
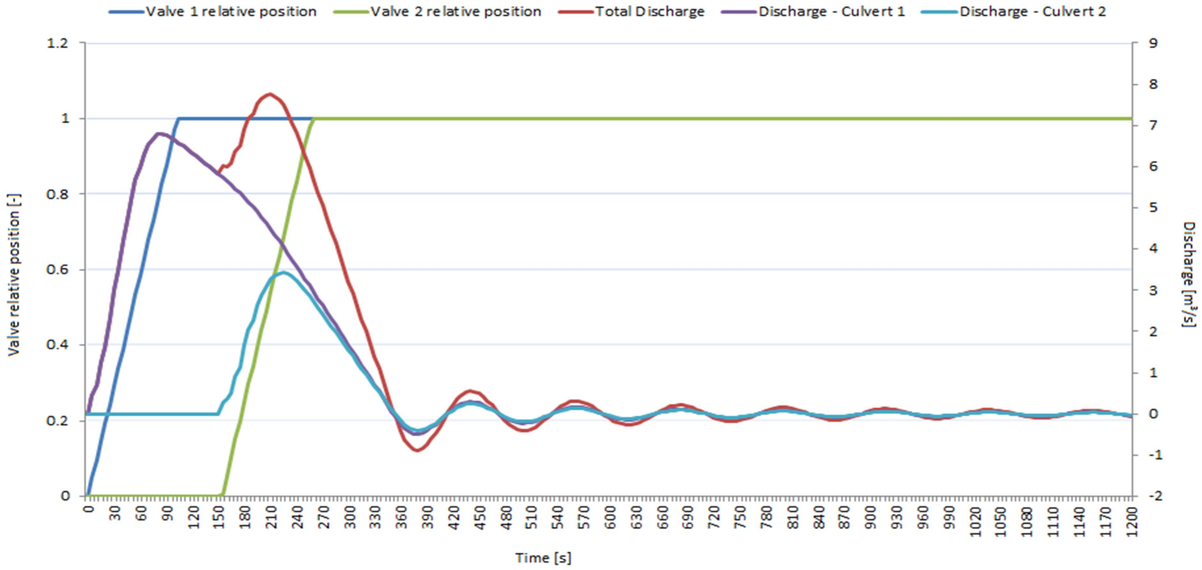


Table B.11 – Scenario C2-V2 (D=1.0 m; Emptying)





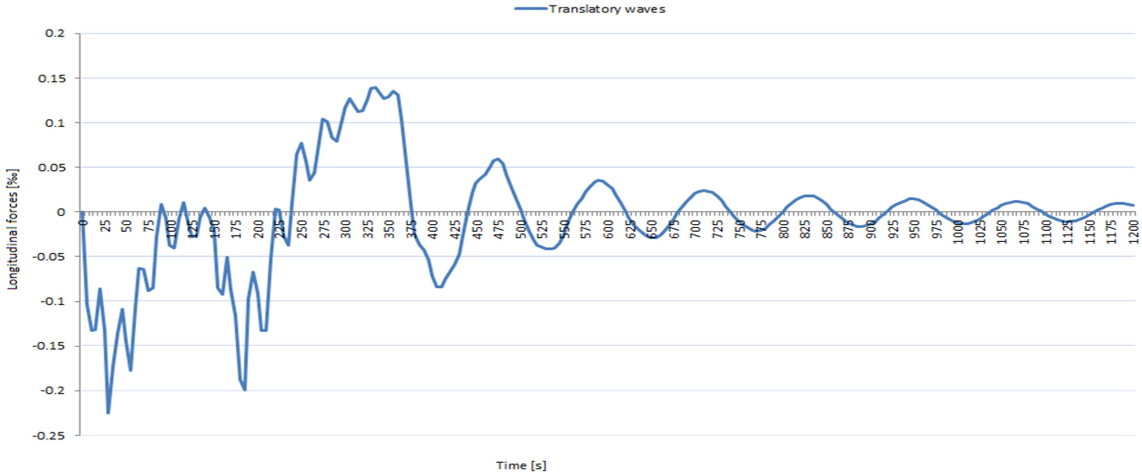
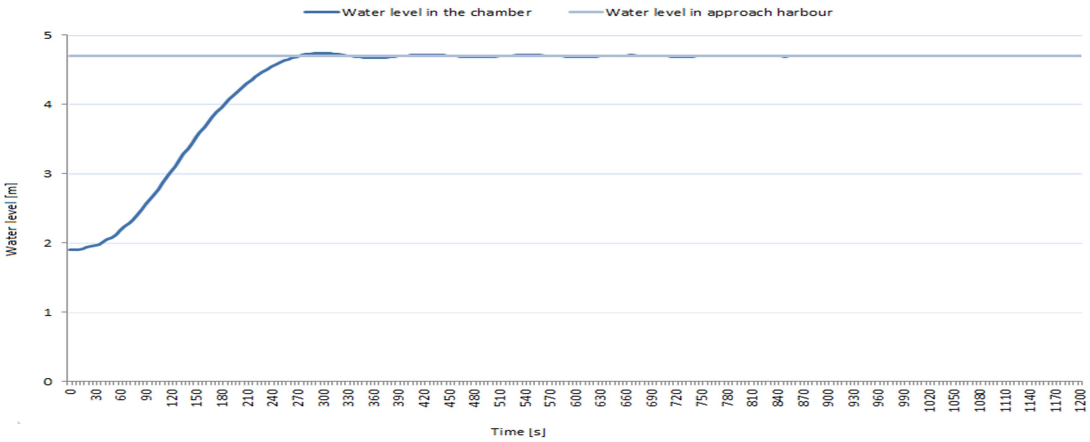


Table B.12 – Scenario C3-V1 (A)



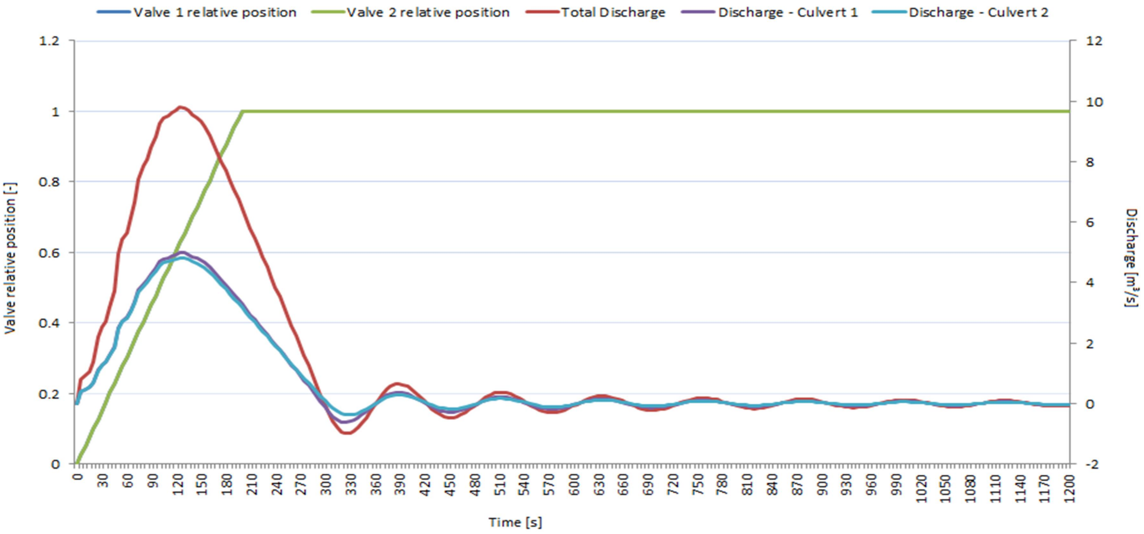


Table B.13 – Scenario C3-V1 (B)

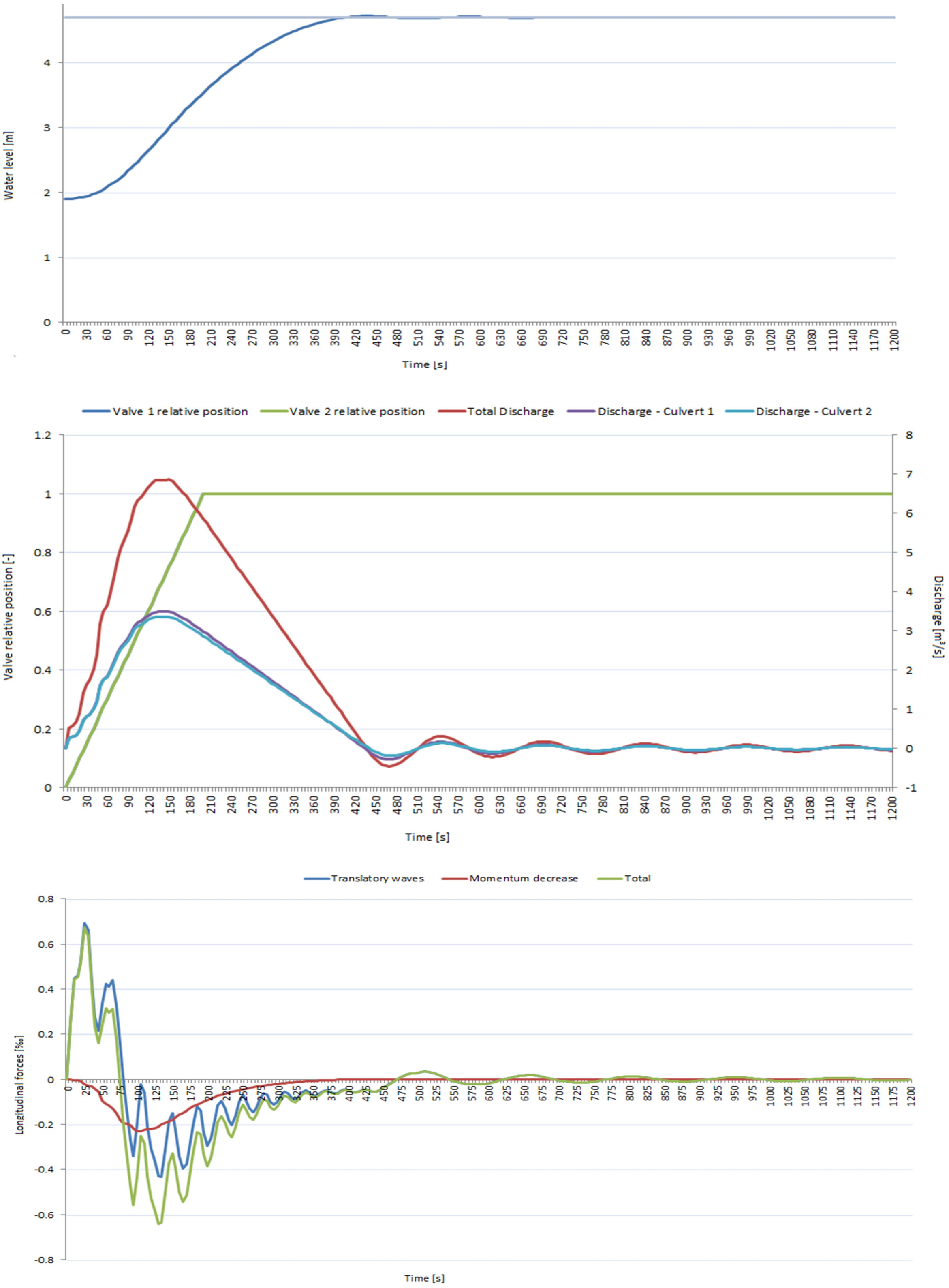
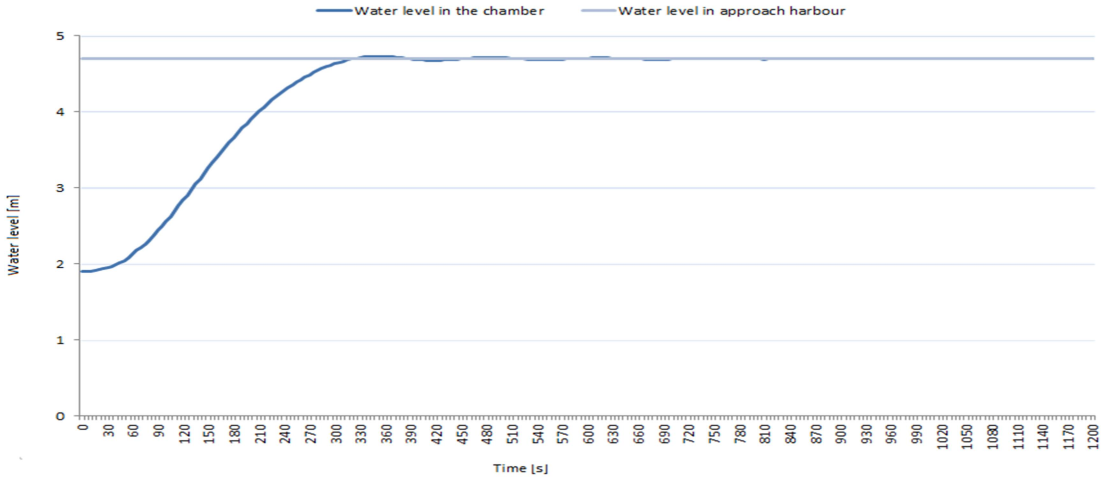
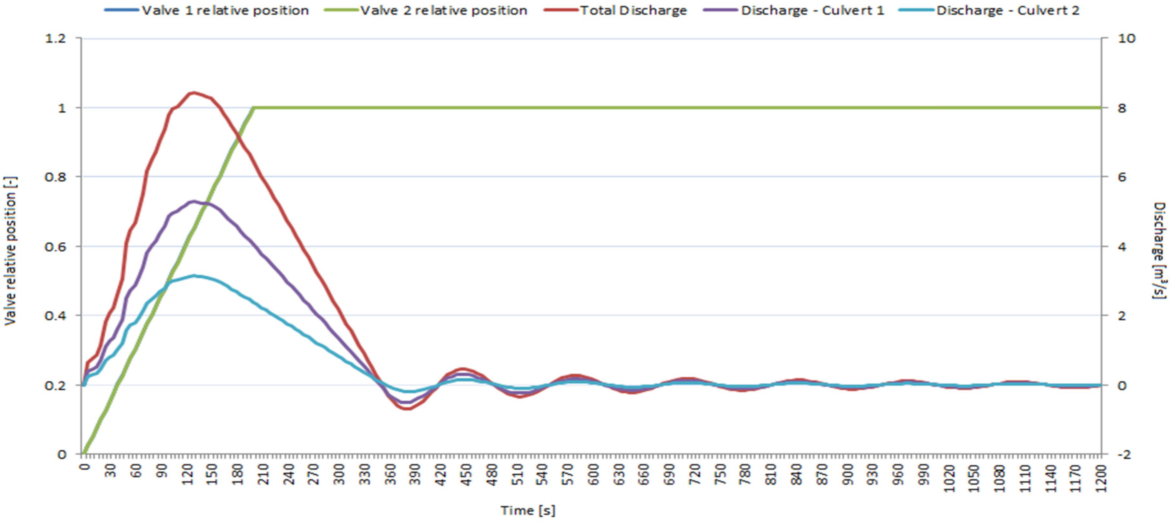


Table B.14 – Scenario C3-V1 (C)





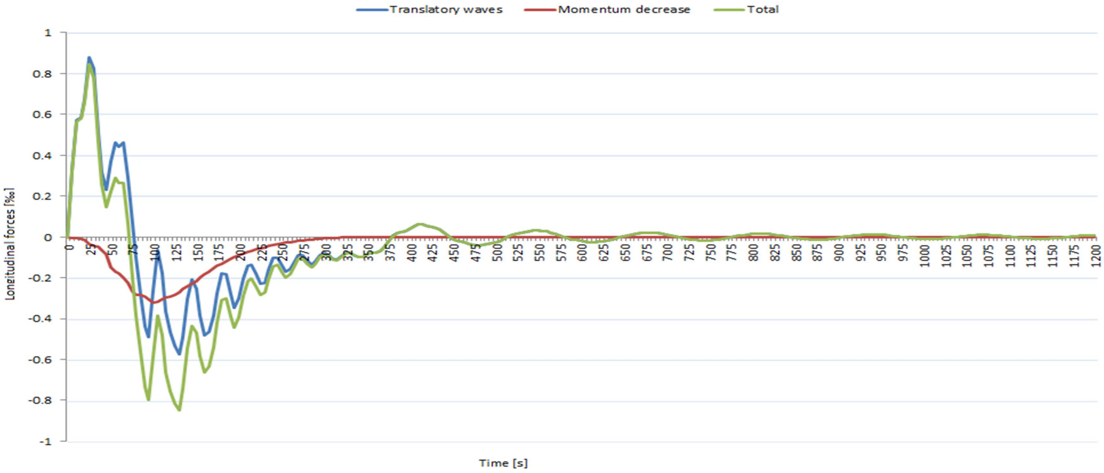
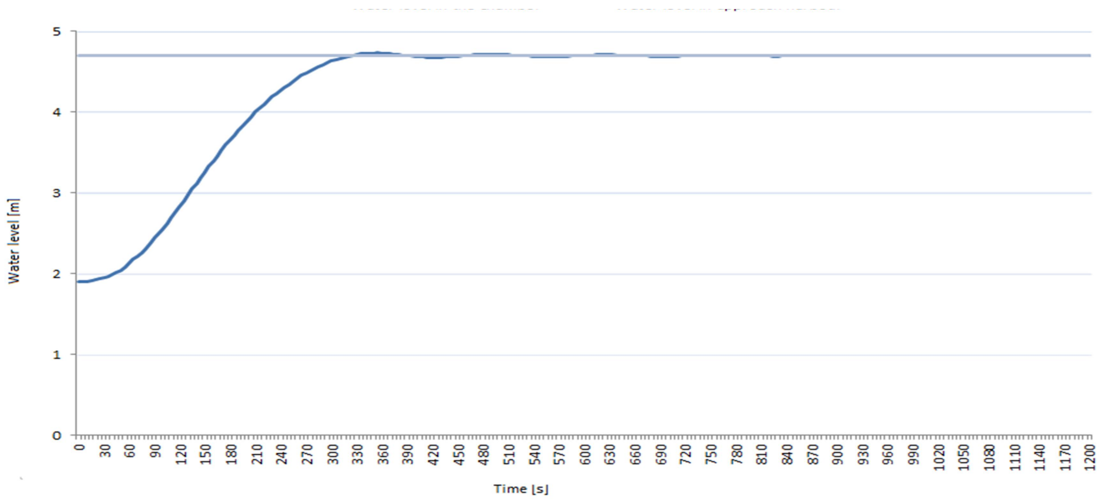
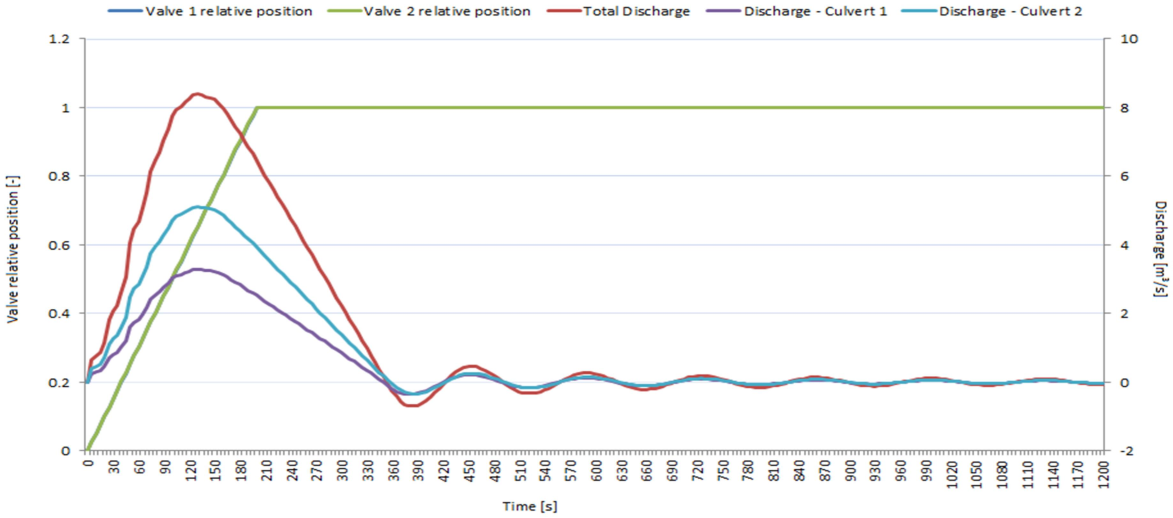


Table B.15 – Scenario C3-V1 (D)





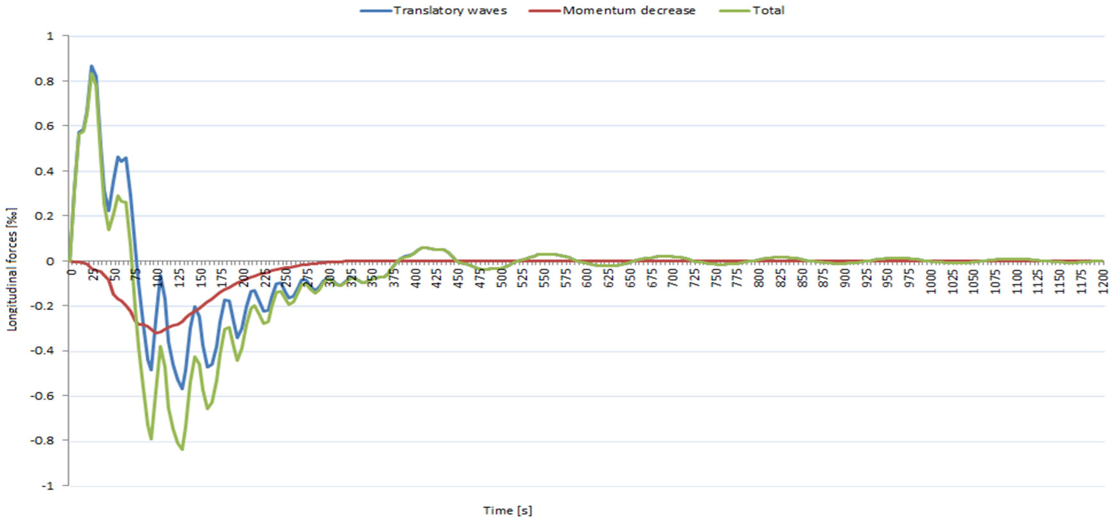


Table B.16 – Scenario C3-V2 (Hypothesis 1)

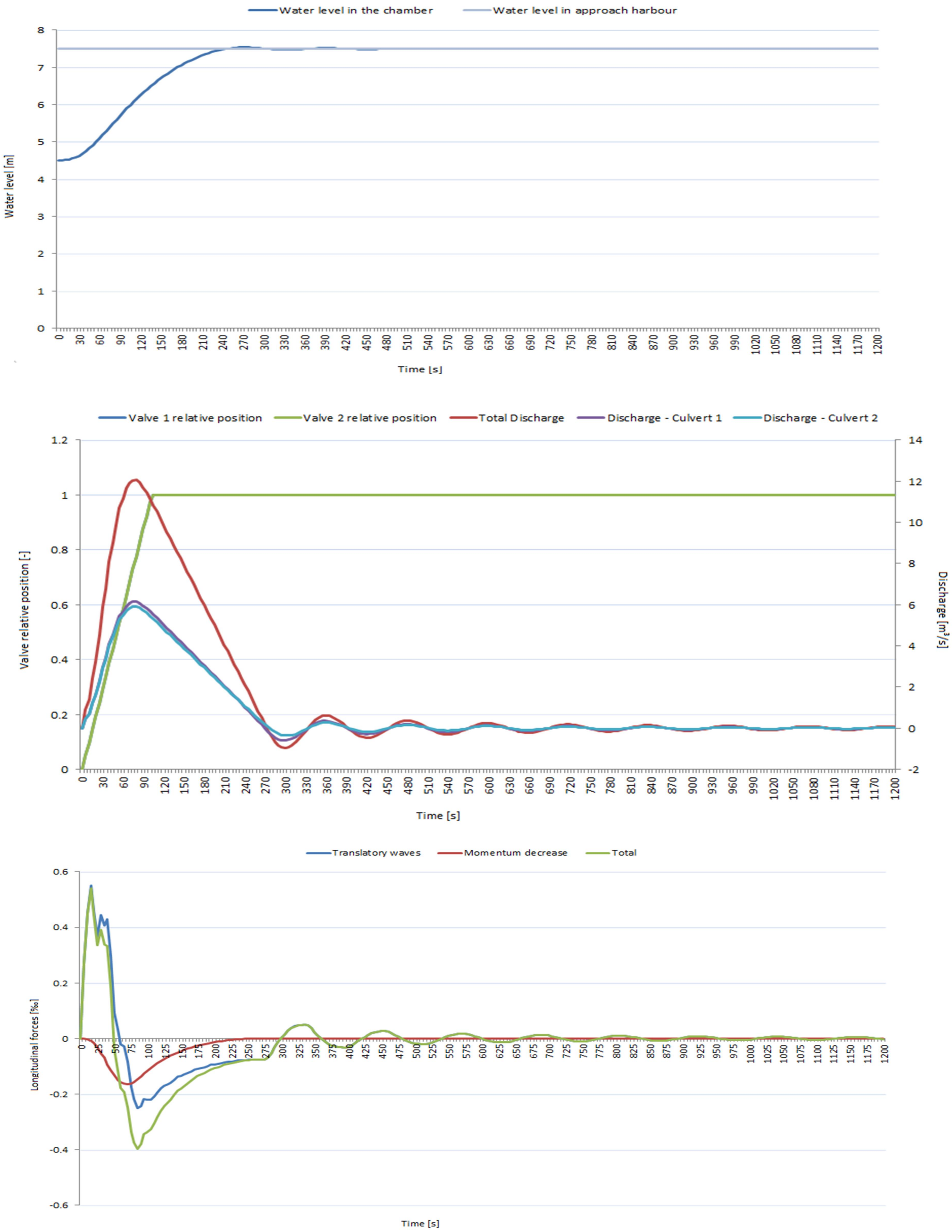
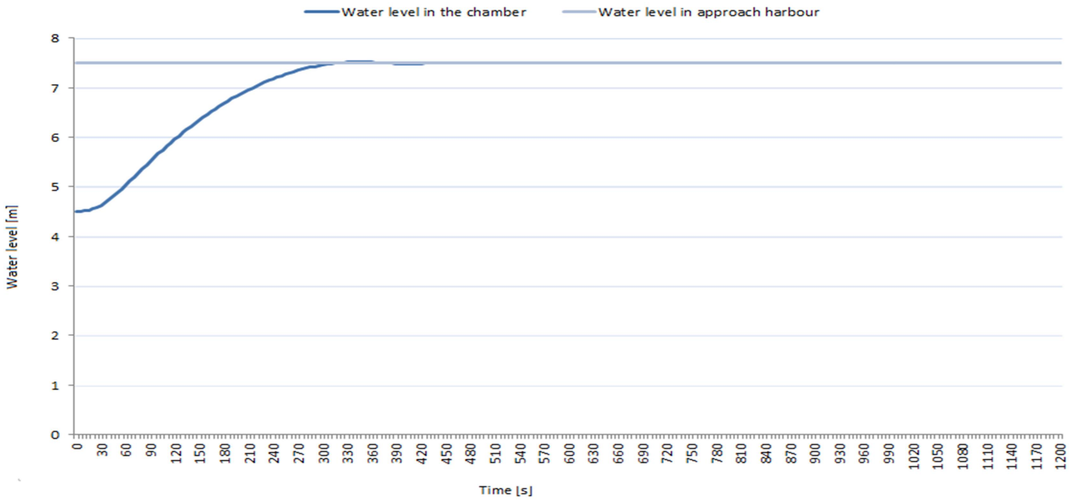
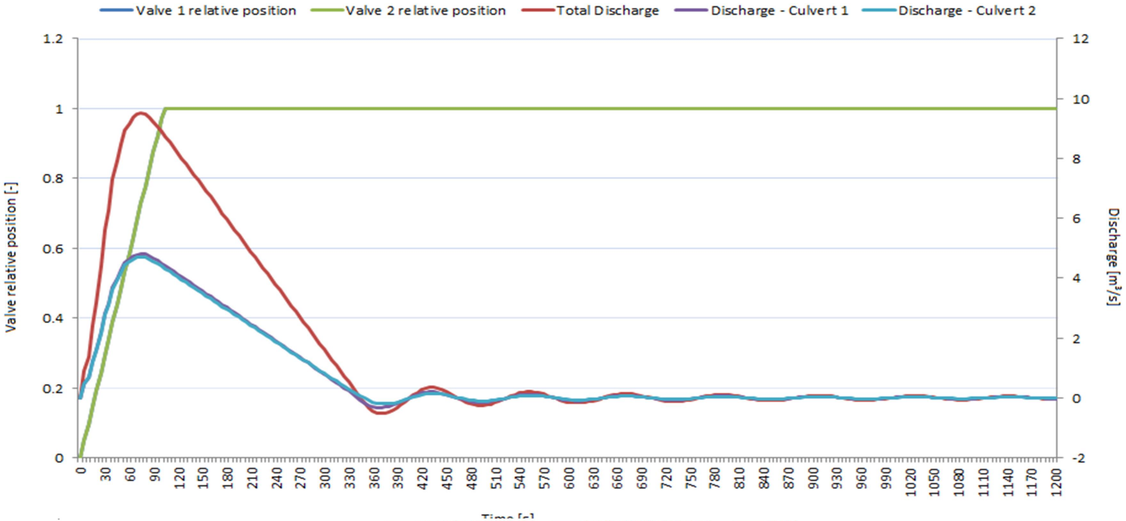


Table B.17 – Scenario C3-V2 (Hypothesis 2 - A)





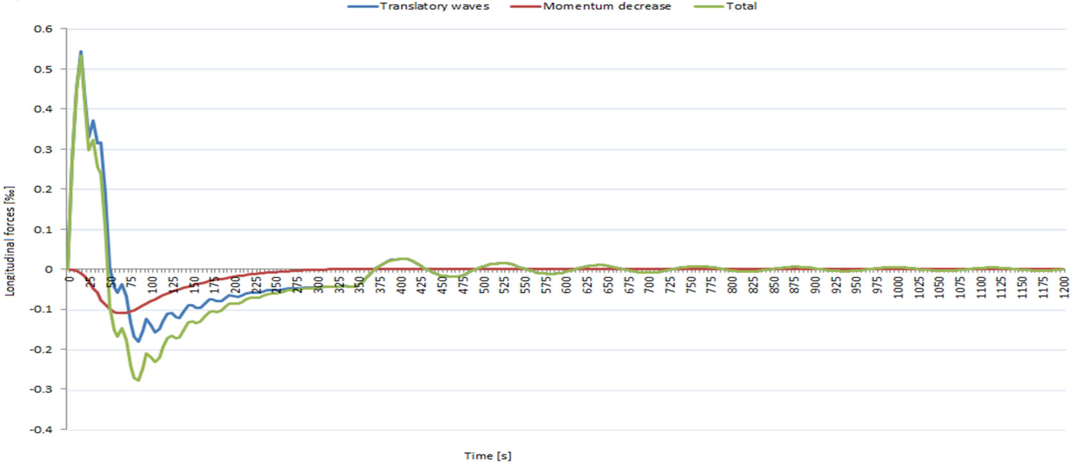
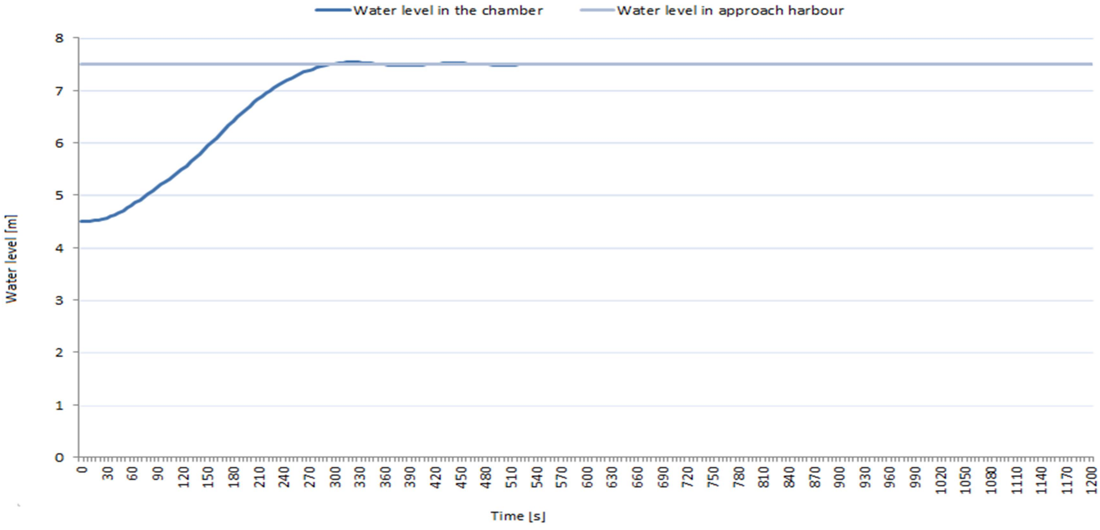
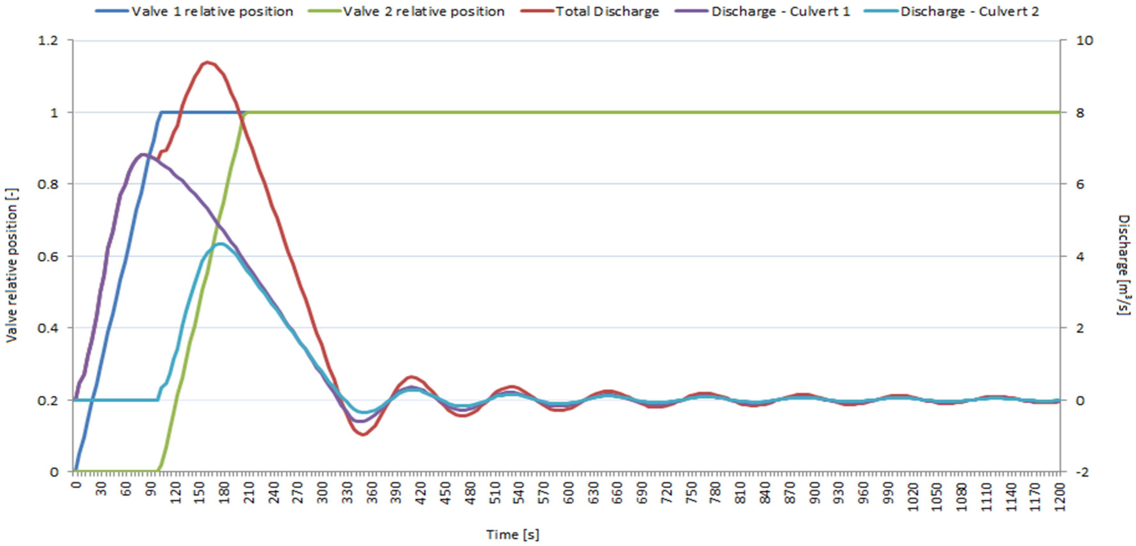


Table B.18 – Scenario C3-V2 (Hypothesis 2 - B)





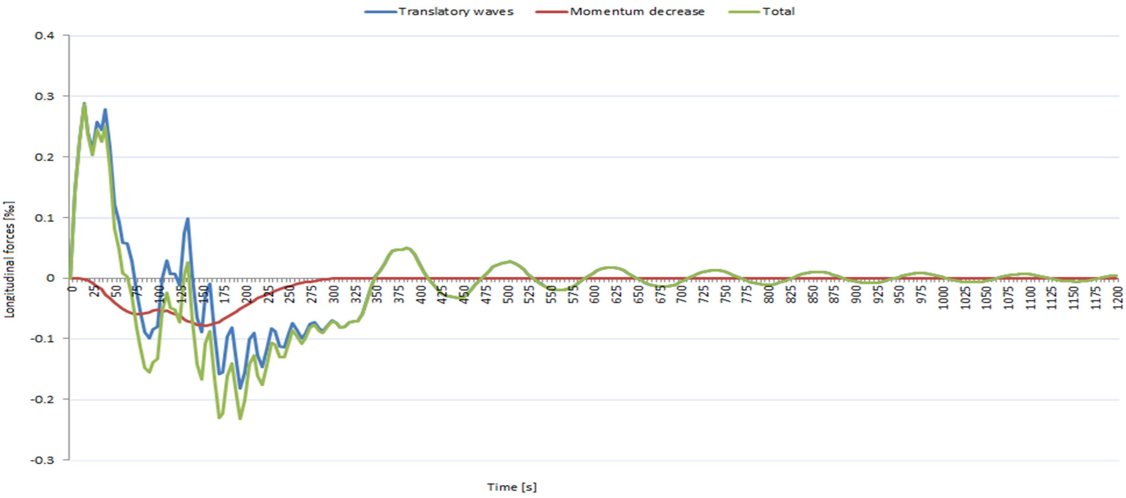
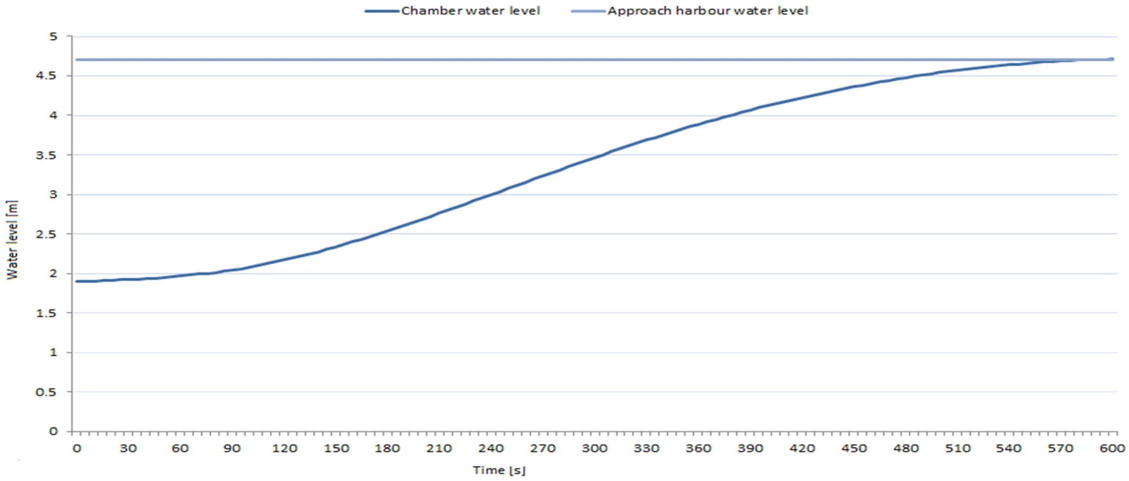
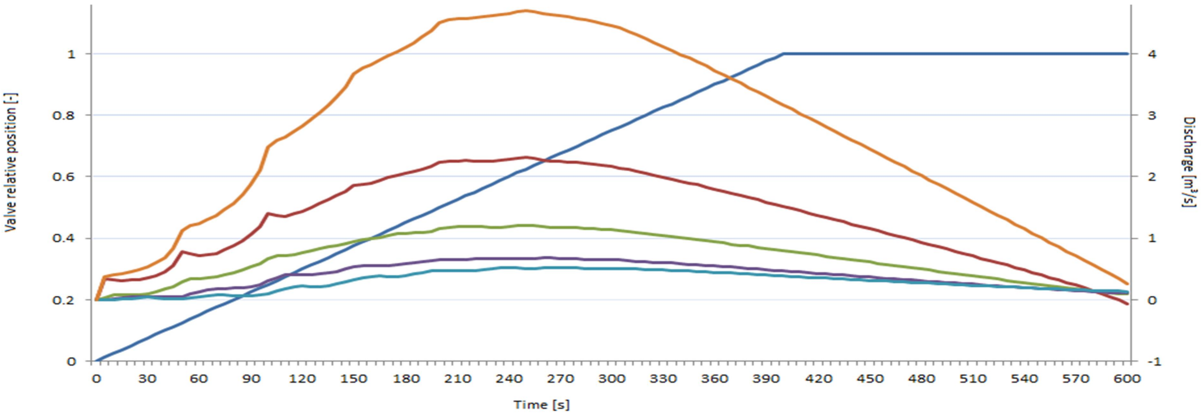


Table B.19 – Scenario L1-V1 (A)





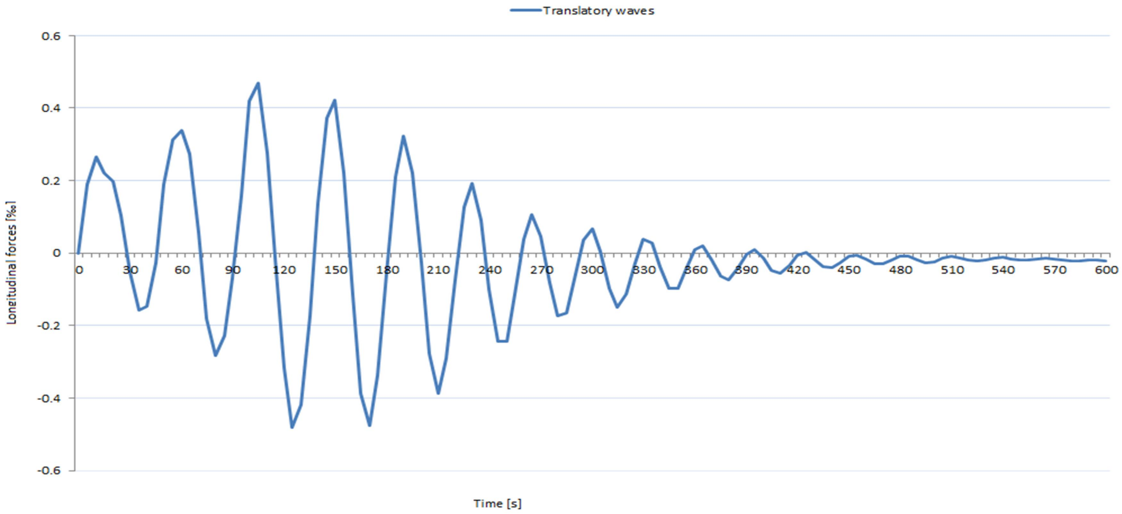
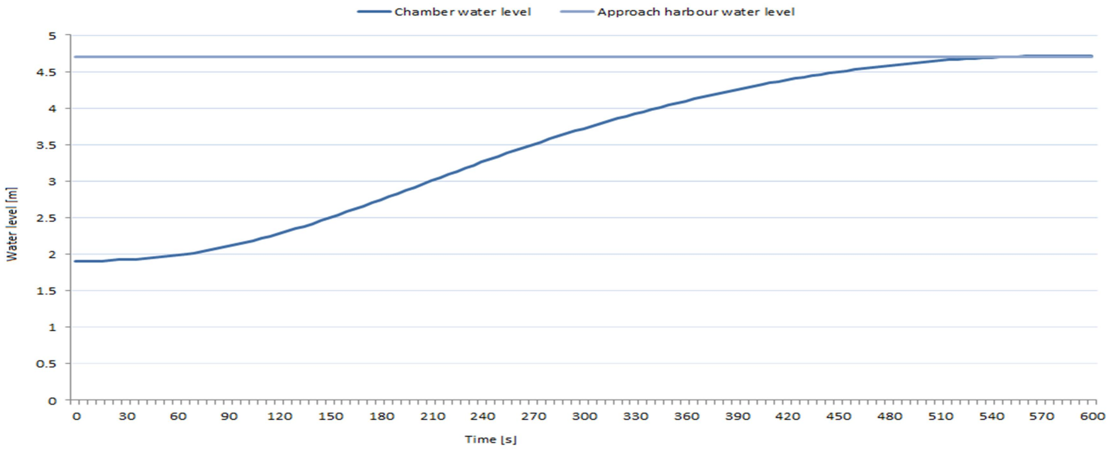
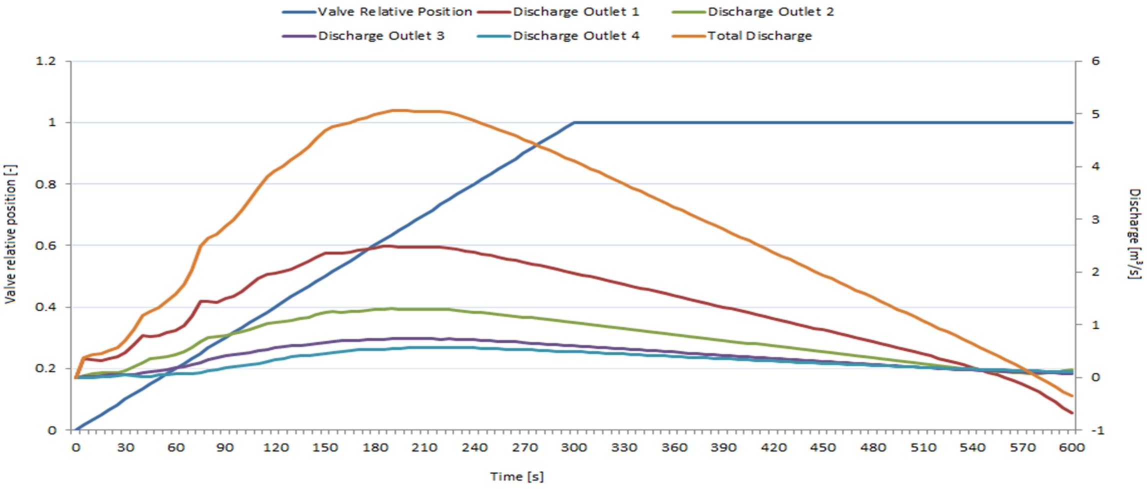


Table B.20 – Scenario L1-V1 (B)





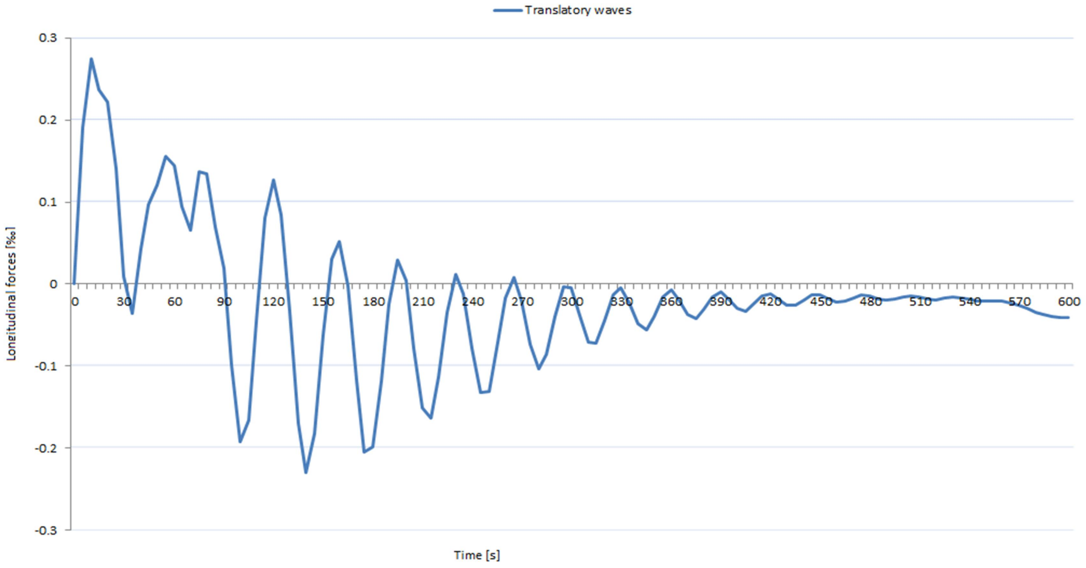
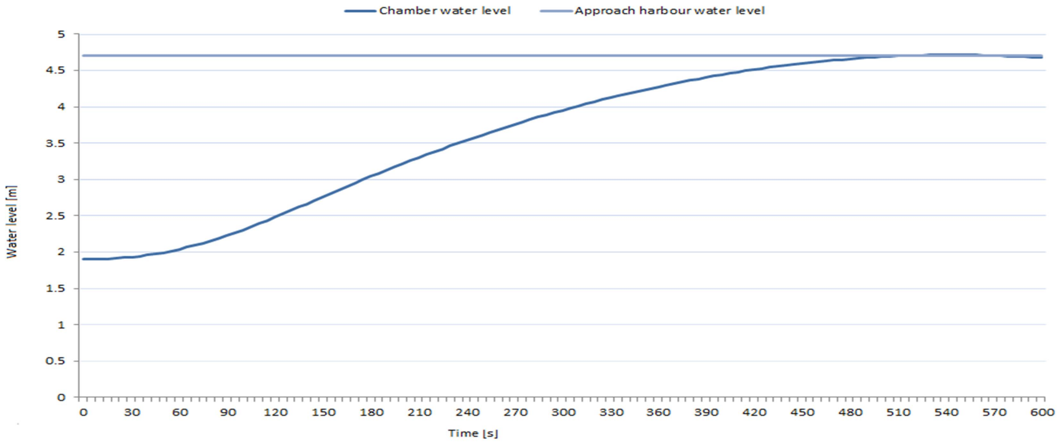
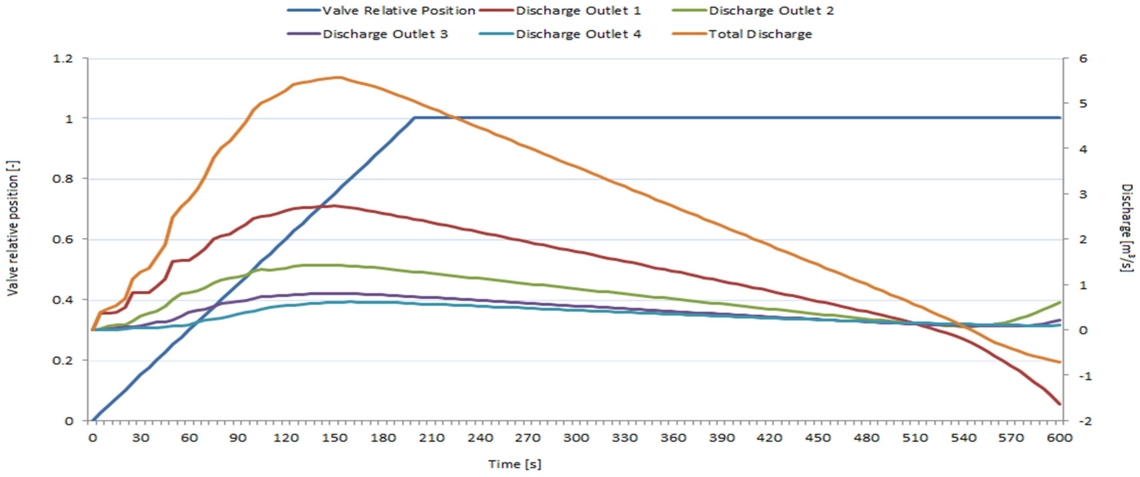


Table B.21 – Scenario L1-V1 (C)





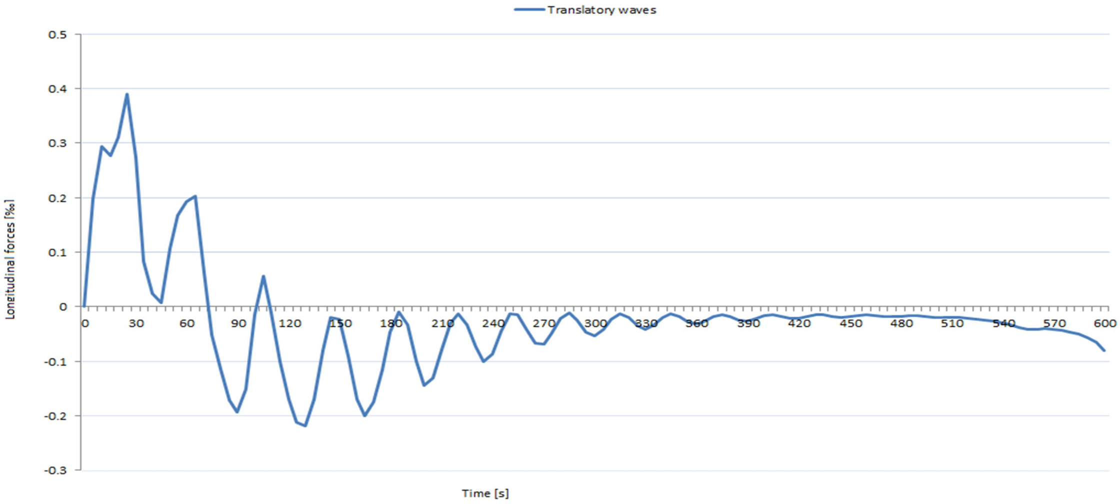
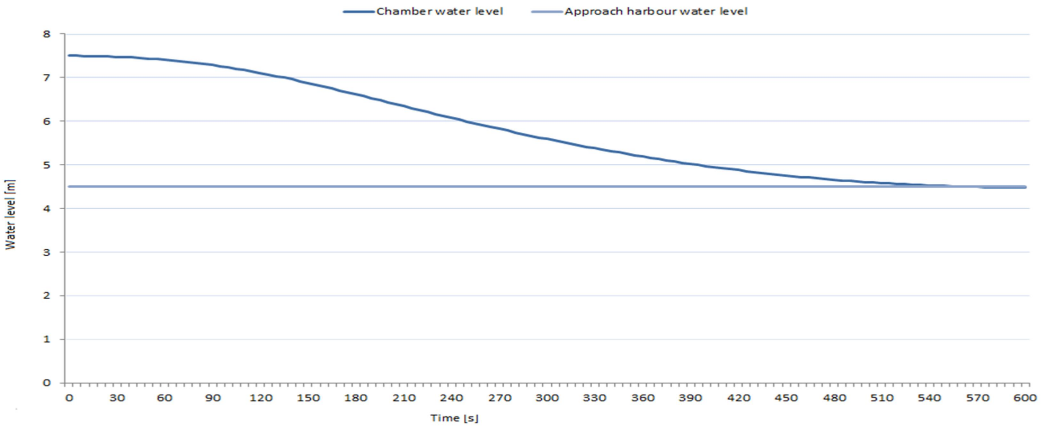
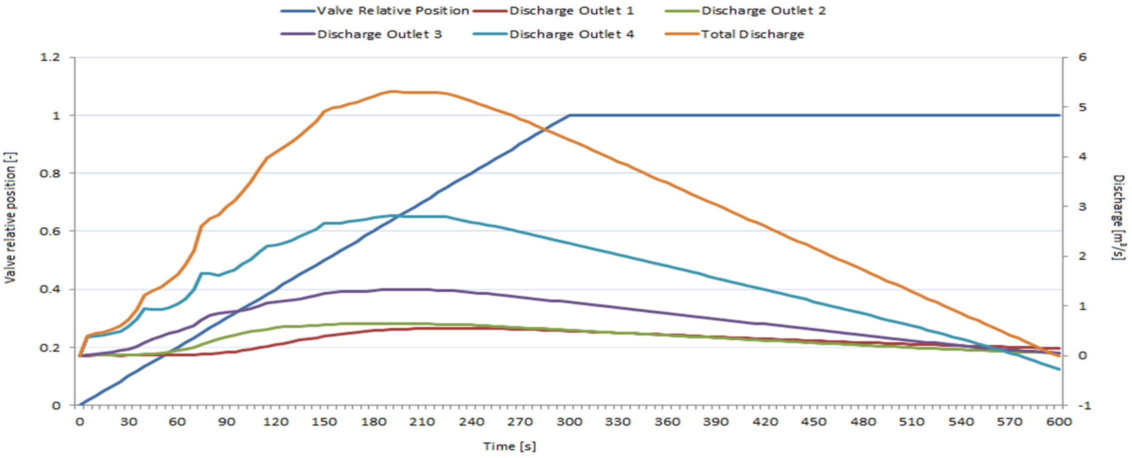


Table B.22 – Scenario L1-V2 (A)





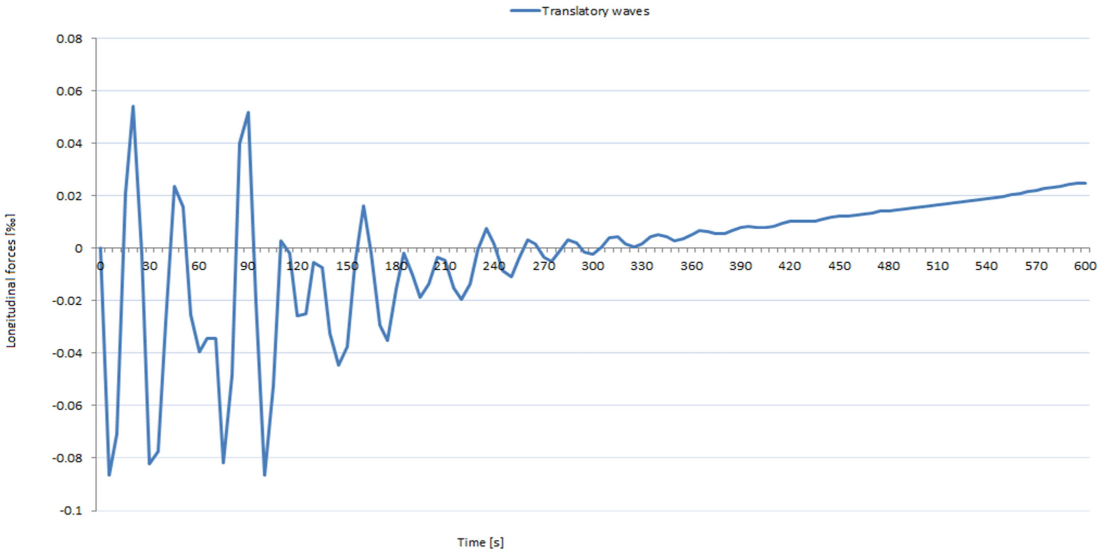
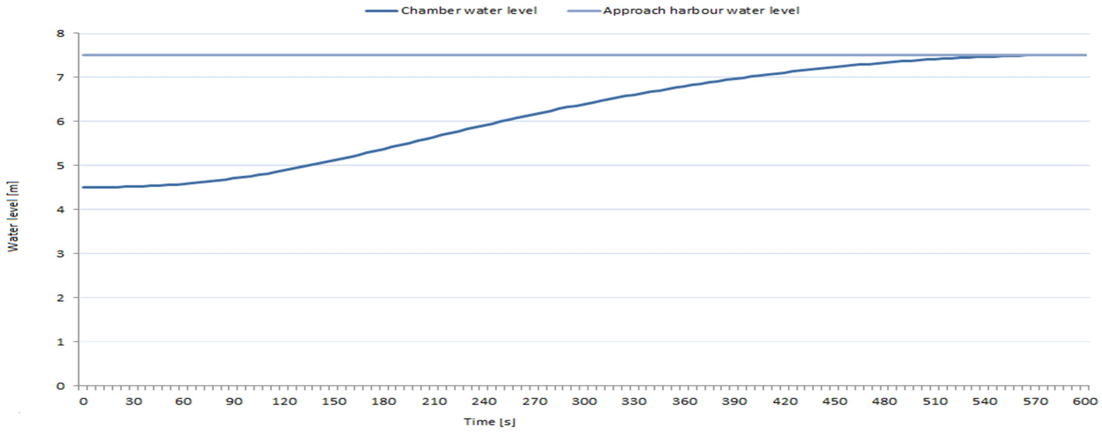
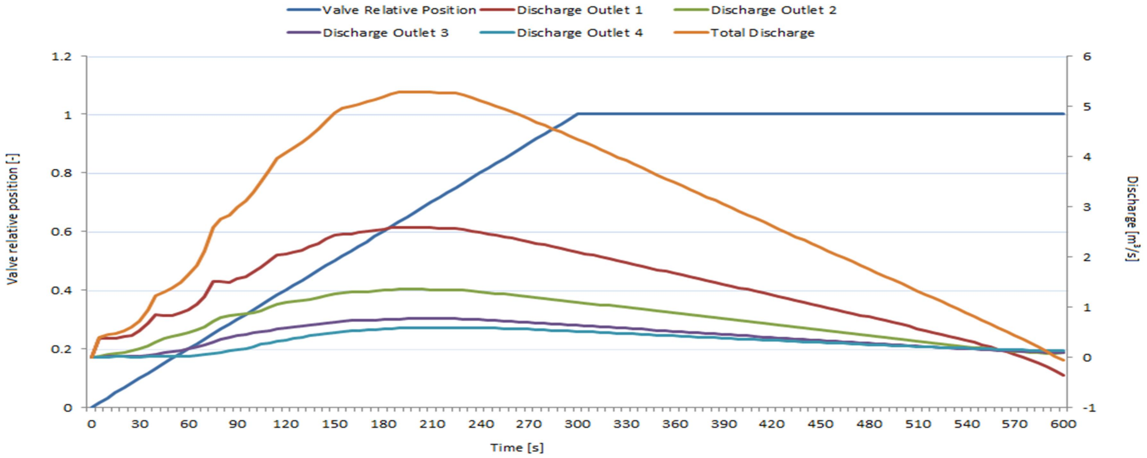


Table B.23 – Scenario L1-V2 (B)





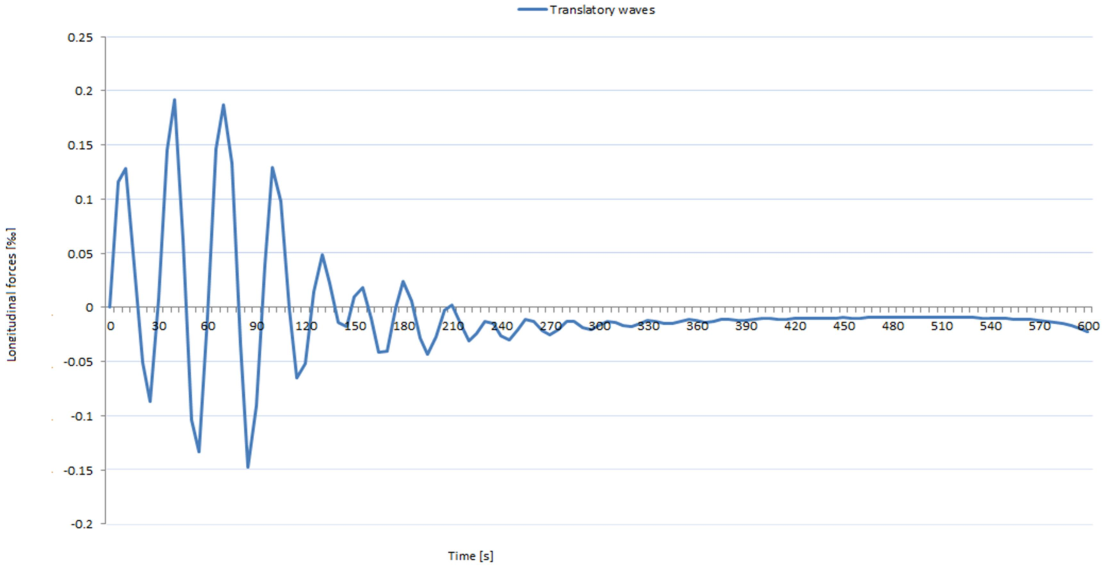
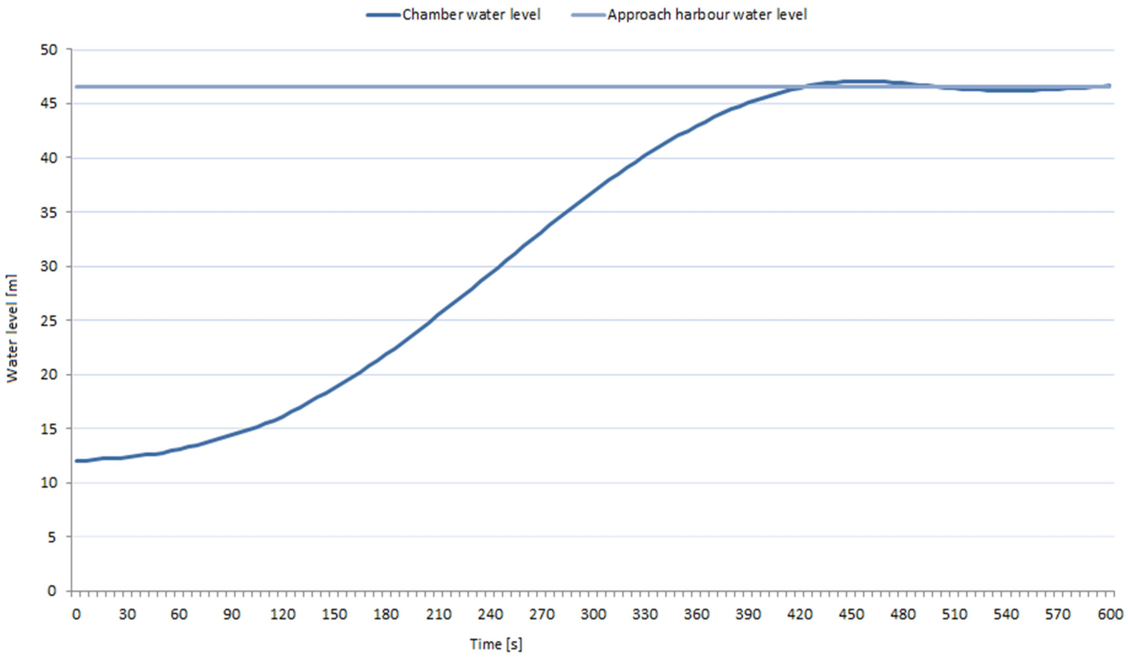


Table B.24 – Carrapatelo lock (A)



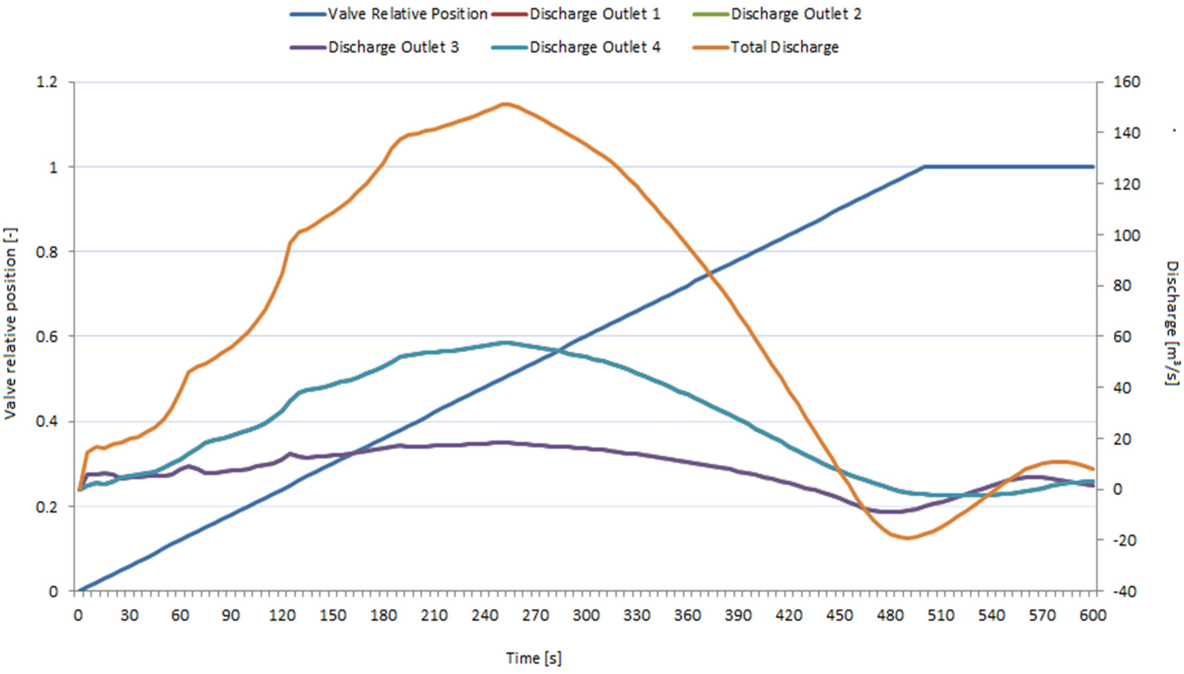
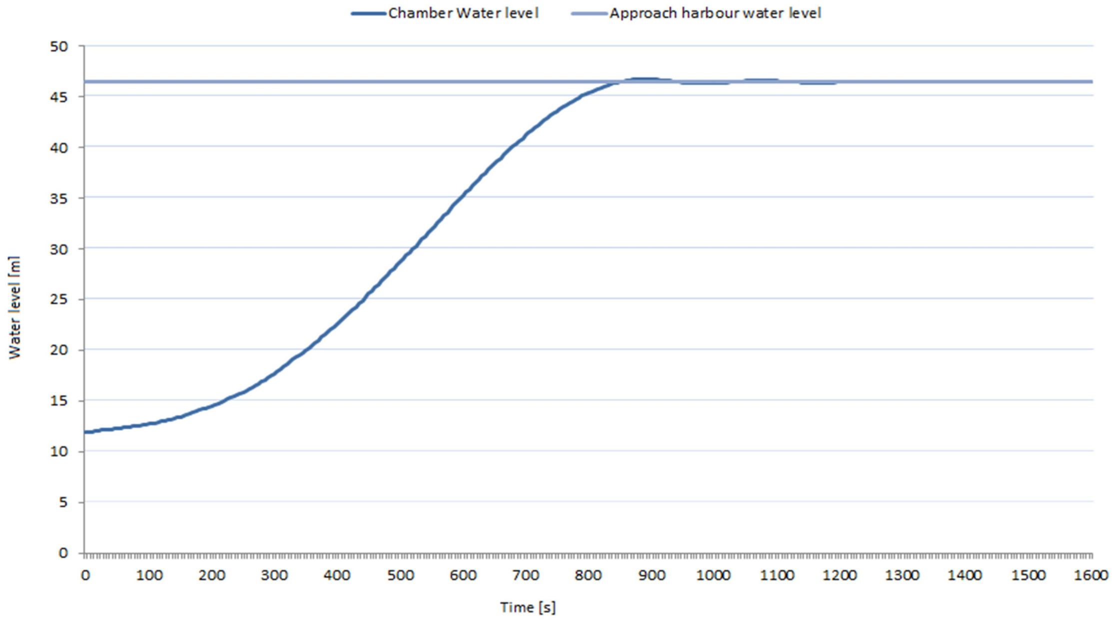


Table B.25 – Carrapatelo lock (B)



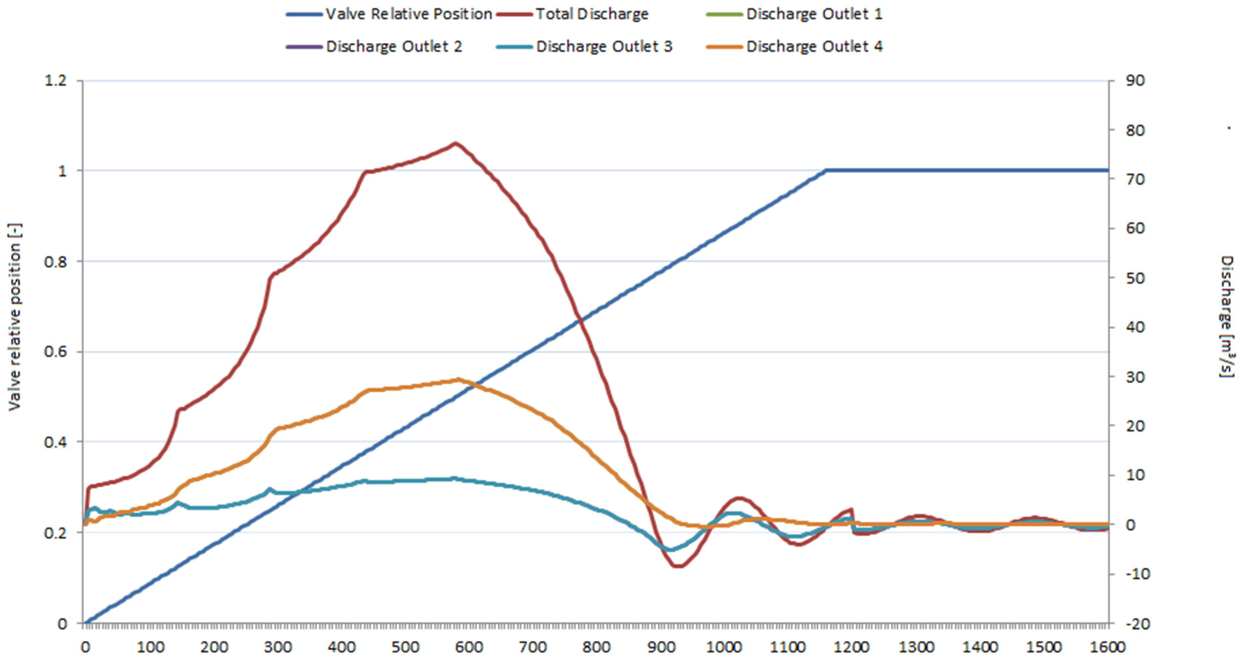


Table B.26 – Ijmuiden lock (A)

Table B.27 – Ijmuiden lock (B)