



# LOCKFILL

## User Manual



# **LOCKFILL**

## **User & Technical Manual**

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## **LOCKFILL, User & Technical Manual**

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# 1 Introduction

## 1.1 General

The computer program LOCKFILL can be used when making or evaluating the hydraulic design of the filling and emptying system of a navigation lock. The basic requirements for a good hydraulic design are to perform levelling within a limited time (for reasons of capacity of the lock) while also limiting the forces on the ships inside the lock (for reasons of safety and/or comfort). To this end LOCKFILL calculates the average water levels in the lock chamber, the levelling flow rate and the resulting longitudinal forces on a ship in the lock chamber. The results of the calculation are presented in a plot showing the behaviour of the calculation results as a function of time.

The calculation method of LOCKFILL is based on scale model research, desk studies and earlier developed calculation programs. It was developed by Deltares (formerly WL |Delft Hydraulics) during 1989-1993, commissioned by Rijkswaterstaat-Bouwdienst, resulting in LOCKFILL 3.1. In the period December 2002-January 2003 a new user-interface was developed by Deltares to make LOCKFILL available for Windows 95, 98, NT and XP, which resulted in LOCKFILL 4.1. This development was commissioned by Rijkswaterstaat-Bouwdienst. In 2012 Deltares was commissioned by Rijkswaterstaat-Dienst Infrastructuur (now Grote Projecten en Onderhoud) to make LOCKFILL available for third parties. This new version would be LOCKFILL 5.0. In 2014 Deltares continued the development of LOCKFILL as the result of experience with LOCKFILL 5.0 in several projects. This development was also commissioned by Rijkswaterstaat Grote Projecten en Onderhoud (RWS-GPO). This resulted in LOCKFILL 5.1.

This manual tries to give a comprehensive overview of the schematisations in LOCKFILL and how to use the program to obtain correct results. It is assumed that the reader is familiar with navigation locks and their design and the terminology used when describing a navigation lock. It is also assumed that the reader has read the Dutch handbook on the design of navigation locks, [Beem \*et al.\* \(2000b\)](#), or its English translation, [Beem \*et al.\* \(2000a\)](#). If the reader has not already done so, it is highly advised to do so before using LOCKFILL (especially [chapter 5](#)).

## 1.2 Basic Principles

LOCKFILL calculates the filling or emptying flow rate as a function of time. Using this flow rate, LOCKFILL calculates the longitudinal force on a predefined ship present in the lock chamber. LOCKFILL can take five force components into account; translatory waves, force due to momentum decrease, friction along the lock chamber walls, lock chamber bottom and the ship, effect of the filling jet and the effect due to a density difference. These five components make up the total longitudinal force exerted on the ship. The method was validated and further calibrated using the results from model experiments. The option to include a density difference is not available in the public release.



### 1.3 Applications of LOCKFILL

LOCKFILL can be used to analyse a navigation lock with a filling/emptying system through the lock head, i.e. it is not capable of analysing a navigation lock with a wall or bottom filling system. A filling/emptying system through the lock head includes filling and emptying through openings in the lock gates or filling through (short) culverts in combination with a stilling chamber that forms part of the lock head and emptying through short culverts around the lock gate. A filling/emptying system using only culverts (without a stilling chamber) cannot be simply analysed and demands further study. LOCKFILL also offers the possibility to analyse levelling by slightly opening the lock gates, however this method has to be used with caution due to the highly schematised nature.

LOCKFILL is meant to be used to analyse average situations from a Dutch perspective. A very high water level difference or very limited under keel clearance cannot be predicted accurately enough. Furthermore, LOCKFILL was developed with inland shipping in mind and is validated using model research on inland locks.

LOCKFILL does not analyse other hydraulic and nautical aspects of navigation locks like the forces on the lock gates or the forces on a ship when it sails in or out of the navigation lock.

LOCKFILL is not meant to replace scale model experiments. It can be used in an early stage of design to give an estimation of the expected levelling times and longitudinal forces. It can be further calibrated using the results of scale model experiments. If the geometry of the levelling system is very different from existing designs it is highly advised to use scale model experiments to obtain reliable results.

### 1.4 Options available to the user

Not all levelling systems present in LOCKFILL are available to the user because of the lack of validation, difficulty in defining the parameters or limited usability. The user will be able to perform calculations using several types of levelling openings in the lock gates (including shutter slides and butterfly valves) and short culverts (with stilling chamber). It is not possible to perform calculations with/without a density difference. Calculations using the other levelling options and the possibility to apply a density difference can only be performed using the development version. Calculations using the development version can be carried out by Deltares.

### 1.5 Limitations

The schematised one-dimensional nature of LOCKFILL assures a fast calculation, but it also introduces inaccuracies. Therefore LOCKFILL should be used with extra caution when applied to cases outside the range of validation against model experiments, such as for extreme cases where the initial head difference is very high, the distance between bow and lock gate is very small or the under keel clearance is very low. The method was tested and validated for a number of locks in [Jonge et al. \(1994\)](#). For situations not covered by the validations, additional scale model experiments should be considered.

There is no clear boundary for when LOCKFILL can still be applied. To aid the user, LOCKFILL checks the input on certain critical values and gives a warning when these values are exceeded. LOCKFILL can still be useful outside this range, results should however be interpreted with caution. Below follows a list of when LOCKFILL will issue a warning:

- ◇ For an initial head difference larger than 4 m when using gate openings it is strongly advised to perform additional hydraulic research. At larger head differences LOCKFILL can be used to give a first estimate. The accuracy of the calculation can be improved when

a filling curve is available to adjust the flow rate with the discharge coefficient. When applying LOCKFILL to head differences larger than 4 m, the program will issue a warning to alert the user, but will still continue the calculation.

- ◇ Application of LOCKFILL is limited to inland shipping and their typical shape and dimensions relative to the lock chamber. Applying LOCKFILL on yachts is especially discouraged and also not recommended for sleek ships like container carriers. As a rule of thumb, LOCKFILL is suitable for ships with a block coefficient (ratio of the ships underwater volume and the volume defined by  $L_{wl}$ ,  $B_{WL}$  and  $T$ ) of approximately 0.8 or higher. In case the block coefficient has a lower value, LOCKFILL will issue a warning, but the calculation will still continue.
- ◇ It must be prevented that the under keel clearance becomes so small that the flow is not properly described by a description based on the average flow, as used in LOCKFILL. Furthermore, in the Netherlands there are regulations on the under keel clearance. The minimal under keel clearance is 0.6 m up to CEMT-class III and 0.7 m for class IV and higher at minimum water level [Brolsma and Roelse \(2011\)](#). LOCKFILL will issue a warning when the under keel clearance becomes smaller than 0.7 m.
- ◇ A very large blockage (the ratio of the wet cross sections of the ship and the lock chamber) of the ship will also reduce the validity of the approximations in LOCKFILL. Although there is no precise range defined, LOCKFILL will issue a warning to alert the user when the blockage becomes larger than 0.75. This number is based on the maximum blockage mentioned in [Brolsma and Roelse \(2011\)](#) at which sailing in and out can still be done swiftly.
- ◇ For gate openings the LOCKFILL calculation is highly dependent on the values of the discharge coefficient. It is advised to obtain these values from measurements; however this is often not possible. The discharge coefficient usually has a value between 0.6 and 0.9. LOCKFILL will issue a warning if the discharge coefficient falls outside of this range.

## 1.6 Outline

[Chapter 2](#) explains how to control the program, using the GUI or the command line. [Chapter 3](#) and [chapter 4](#) treat the input and output files of LOCKFILL respectively. [Chapter 5](#) gives a general explanation of the schematisation in LOCKFILL and of the different levelling methods available in LOCKFILL.



## 2 Running LOCKFILL

In this chapter the method of creating a new input for LOCKFILL as well as control of the graphical user interface (GUI) and using the program from the command line will be treated. Furthermore the content of the generated output files will be treated. This chapter will not discuss the influence of the different variables on the calculation results.

LOCKFILL is delivered as a single executable that is used to open the GUI, but the executable can also be run from the command line to perform a LOCKFILL calculation from a batch script for example. There are thus two separate methods of controlling LOCKFILL.

In both methods the user edits the input file to match the case under investigation and runs the program using the newly created input file. The calculation results in several output files containing calculation data, plots and a summary of the results. An example of a Lockfill calculation is shown in [Appendix A](#) and an example of an input file is shown in [Appendix C](#).

### 2.1 Using the graphical user interface

When LOCKFILL starts the user is presented with the main window as shown in [Figure 2.1](#). This figure also shows the different components present in the interface. The *Controls* show the basic workflow of LOCKFILL; create or open an input file, edit the input file, run LOCKFILL and export the results. The *Preview pane* shows the currently selected input file for review purposes. The *Message pane* shows any messages given by LOCKFILL, for example errors. From the *Output pane* the user can view the results of a calculation before exporting the results

File controls can be found in the *File*-menu. *Language* preferences can be changed in the *Settings*-menu. For reporting purposes it is possible to change the language in the plots generated by LOCKFILL, the options are Dutch and English. The interface and textual output is in English. In the *Help*-menu information about LOCKFILL can be found.

#### 2.1.1 Starting a calculation

To start a calculation, LOCKFILL will need an input file. The user can choose to create a new input file based on a template included in the LOCKFILL distribution or based on an existing file by pressing the button *New from template*. This opens a Windows dialog in which the user can select the desired file. Alternatively, the user can open an existing input file by pressing *Open input file*. After opening the input file it will be shown in the *Preview pane*.

Once a file is selected the file can be edited by pressing *Edit input file* button. This will open the input file in the default text editor set in Windows. The text editor can be used to edit the input file. After editing is complete the input file must be saved and may be closed.

After opening or editing of the input file it is possible to run the calculation. Pressing the *Run LOCKFILL* button will start the calculation. Textual output generated by the program, such as errors and warnings, is shown in the *Message pane*.

Upon successful completion of the calculation it is possible to view the generated plots from the *Output pane*. Upon clicking one of the buttons a plot will be shown in a separate window. These windows, and the figures within, are scalable.

If the user is satisfied with the results, the *Export output files* button will let the user choose a location to export the output (plots, summary and calculation data) and input files to.



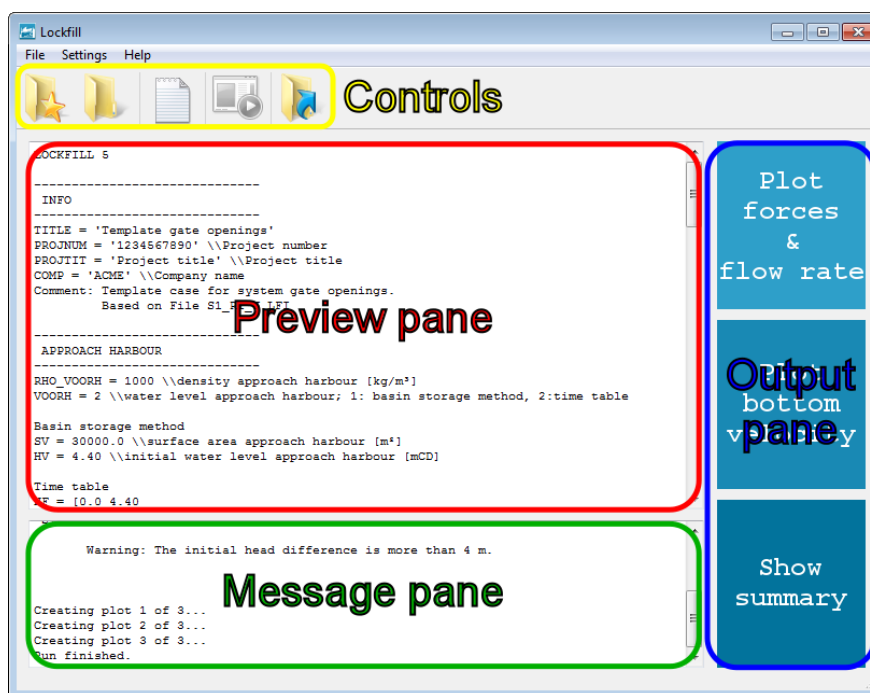


Figure 2.1: LOCKFILL main window

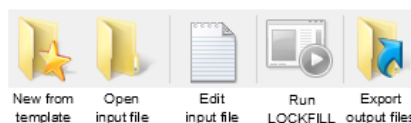


Figure 2.2: LOCKFILL buttons

## 2.2 From command line

LOCKFILL can also be used from a command line, which makes it easy to be used in custom made batch scripts or from other programs like Matlab, for example to run multiple calculations at once or automatically perform further post-processing. When using LOCKFILL from the command line the user should select the locations of an input file, the output directory and optionally the language used in the plots. The generated output is the same as when the GUI is used to export the output files.

The parameters used to define the input, output and optionally the language are shown in the help message. The help message is given by using the parameter `-h` and the result is shown in [Figure 2.3](#).

For example, if the user wants to perform a calculation using a file in `C:\lockfill\input` named `test.lfi` and wants to save the results in `C:\lockfill\output` with Dutch graphs, he types the following in the command line;

```
Lockfill.exe -i c:\lockfill\input\test.lfi -o c:\lockfill\output -l nl
```

```
usage: Lockfill.exe [-h] [-i INPUT] [-o OUTPUT] [-l LANGUAGE]
optional arguments:
  -h, --help            show this help message and exit
  -i INPUT, --input INPUT
                        Filename of input lfi-file.
  -o OUTPUT, --output OUTPUT
                        Export results to this directory.
  -l LANGUAGE, --language LANGUAGE
                        Specify plot language 'nl' or 'en'.
```

**Figure 2.3:** LOCKFILL help message

The ability to use Lockfill from the command line gives the ability to perform multiple calculations at once using a batch-script. A fully operational example script is included in the Lockfill-installation, called <LfBatch.bat>. Simply supply the script with the input-directory that contains the Lockfill input files and an output directory where the output files should be stored. The script will then execute Lockfill for each <lfi>-file in the input directory.

```
USAGE: LfBatch.bat [-h] [INPUT] [OUTPUT]
Optional arguments:
-h, --help            Show this help message and exit.
INPUT                Directory containing input LFI-files. Default is current
                    working dir.
OUTPUT               Preferred output directory. Default is a folder named output
                    in current working dir.
```

**Figure 2.4:** Lfbatch help message



### 3 Description of input file

In this chapter a description is given of the categories of input parameters present in the input file. An example of an input file is given in [Appendix C](#).

#### 3.1 General

For each type of levelling systems that can be described in LOCKFILL a template of an input file is included in the distribution. These templates serve as an example of how to generate an input file and how to define the different types of variables.

The file has a flexible set-up, not a fixed format. Thus it doesn't matter which line a certain input variable is on. This makes it possible to add additional comments in the input file or reorganise the input to the preferences of the user.

#### 3.2 Info

In this block the user can give a custom title to the case. Furthermore it is possible (although optional) to add the name of the project and the project number the calculation belongs to and a company name. These will be printed onto the plots generated by LOCKFILL for easy reference. An example of this 'stamp' is shown in [Figure 3.1](#).

1234567890 - Project title	26-05-2015
Calculation title	LOCKFILL 5.1
Company name	lfi-name

**Figure 3.1:** Stamp generated at bottom of LOCKFILL plots

This input block is also the recommended location to place an extra comment about the case with more information if deemed necessary by the user. This will not be shown on the plots.

#### 3.3 Approach harbour

In this block the variables regarding the approach harbour are defined. The user can choose if the water level of the approach harbour is calculated using the basin storage calculation or that the water level is defined using a table.

For normal approach harbours the levelling process has a negligible influence on the water level and the user can define a table with equal water levels at the start of the calculation and at the end. This table can also be used if the change in the water level is known beforehand.

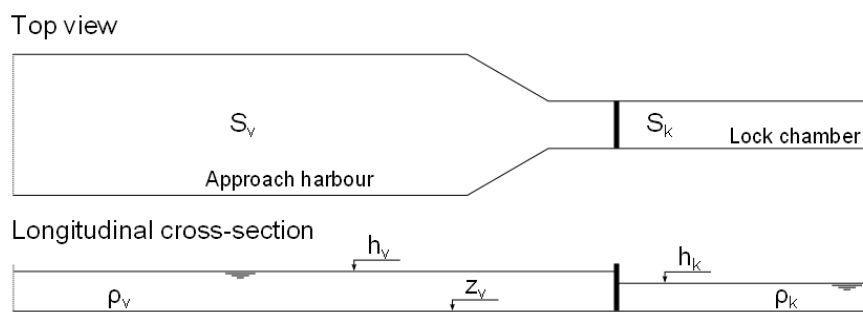
The basin storage calculation is particularly useful when doing a calculation in a staircase lock. The user only has to set the initial water level and the surface area of the approach harbour, i.e. the second lock chamber of the staircase lock. It can also be used in small approach harbours where the water level near the lock will be significantly affected by the levelling process.

The formation of a transitory wave in the approach harbour is not taken into account by LOCKFILL. The calculation of the levelling flow is based on the average water levels in the approach harbour and lock chamber.

The definition of the approach harbour in LOCKFILL is shown in [Figure 3.2](#).



<b>Approach harbour</b>		
<b>Name of variable</b>	<b>Description</b>	<b>Unit</b>
RHO_VOORH	Water density in the approach harbour	[kg.m <sup>-3</sup> ]
VOORH	Choose if the water level in the approach harbour is calculated using the basin storage approach or that the water level is given in a table as function of time 1: Basin storage calculation 2: Table of time dependent water levels	
<b>Basin storage</b>		
SV	Surface area of the approach harbour In the case that a basin storage approach is chosen	[m <sup>2</sup> ]
HV	Initial water level of the approach harbour	[mCD]
<b>Table of water levels</b>		
HF	A table with the water levels of approach harbour as function of time	[mCD]



**Figure 3.2:** Definition of the approach harbour in LOCKFILL

### 3.4 Lock chamber

In this block the variables regarding the lock chamber are defined. The difference between the initial water level in the lock chamber and the (initial) water level in the approach harbour define the initial water level difference.

If the density of the water in the lock chamber differs from the density in the approach harbour, the forces due to density differences can be generated by setting the flag in the *Mode* input block.

The length of the lock chamber is the hydraulic length, so in the case of rolling gates the length between the gates. In the case of mitre gates a representative length has to be defined that gives an average length of the lock chamber. This length is important for the calculation of the period of the translatory waves travelling through the lock chamber. This will directly influence the contribution of this force on the ship. The length is also used in the definition of the surface area of the lock chamber which is used in the calculation of the water level changes. So this parameter also has influence on the levelling time.

The width of the lock chamber is constant, so LOCKFILL assumes straight vertical walls, so the lock chamber is schematised as a rectangular box. This excludes the exact schematisation of so called 'green' lock chambers with sloped lock walls. Small deviations in lock chamber width can be modelled by an average width. The width is important in the calculation of the levelling volume and of the force by the decrease in momentum, friction and filling jet. A smaller width will lead to larger forces and vice versa. Together with the length and width the bottom level of the lock defines the geometry of the lock chamber. Small unevenness can be

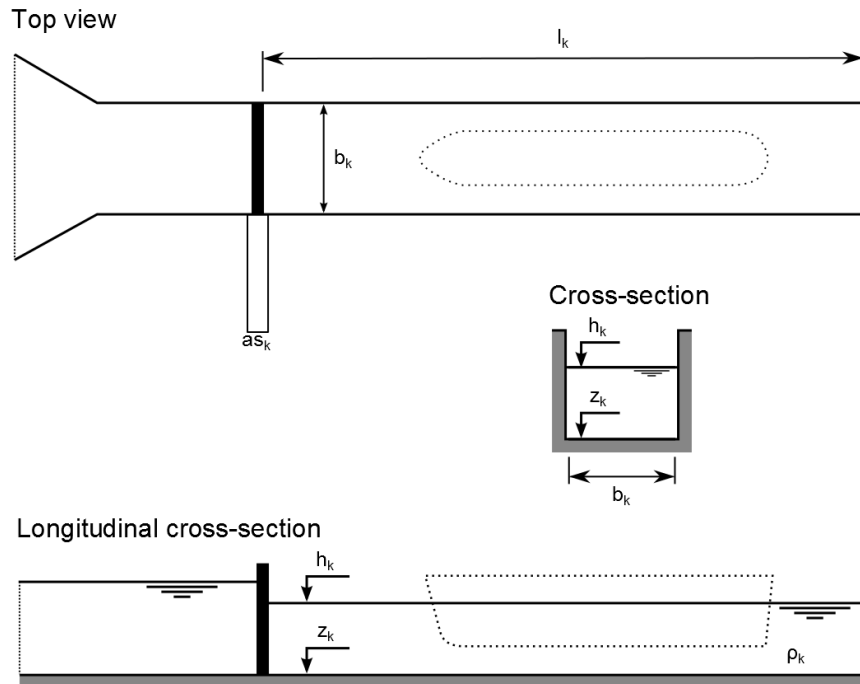
ignored.

In some cases the surface area of the gate recesses is significantly large that it may influence the flow rate. The surface area of the gate recesses has no influence on the force calculation by changing the width or hydraulic length of the lock chamber, but is only used to calculate the changes in water level during the flow rate calculation.

The roughness of both the lock chamber walls and floor is defined by a single parameter, the Nikuradse roughness. This parameter is important in the calculation of the friction force on the lock chamber walls and floor. This force component is usually of limited significance, but can be important when the hydraulic cross section is small with respect to the cross section of the ship or when the flow velocities in the lock chamber are high.

The definition of the lock chamber in LOCKFILL is shown in [Figure 3.3](#).

Lock chamber		
Name of variable	Description	Unit
HK	Initial water level in the lock chamber	[mCD]
RHOK	Water density in the lock chamber	[kg.m <sup>-3</sup> ]
LK	Length of the lock chamber	[m]
BK	Width of the lock chamber	[m]
ZK	Level of the lock chamber floor	[mCD]
ASK	Surface area of gate recesses	[m <sup>2</sup> ]
KI	Nikuradse roughness of the lock chamber walls and floor	[m]



**Figure 3.3:** Definition of the lock chamber in LOCKFILL

### 3.5 Filling and emptying system

The different filling and emptying systems and their parameters are discussed in detail in [section 1.1](#).

### 3.6 Ship

LOCKFILL was designed with inland cargo ships in mind and the calculation method was validated using measurements on inland cargo ships (resulting in some empirical parameters). For simplicity, and in line with the general shape of many inland cargo ships, the ship in the lock chamber is schematised as a rectangular box with a certain width, length and depth. For the calculation of most force components this box shape is used. However, in the calculation of the force due to the filling jet the shape of the bow is roughly taken into account. In this component the bow is schematised as two plates under an angle. It is therefore also necessary to set the vertical and horizontal angles of the bow.



**Note:** *The rough schematisation of the ship and the fact that LOCKFILL was tested only for inland cargo ships makes it difficult to apply LOCKFILL to different ship types that have more slender hull types or very different dimensions. It is thus not recommended to apply LOCKFILL sea-going ships or yachts.*

The mass of the ship is defined in LOCKFILL as the sum of the ship's weight and the cargo, i.e. the displacement. This parameter has a direct relation with the defined length ( $l_s$ ), breadth ( $b_s$ ) and draft ( $t_s$ ) as these parameters together with the water density in the lock chamber ( $\rho_k$ ) define the block coefficient;

$$C_b = \frac{M_s}{\rho_k l_s b_s t_s} \quad (3.1)$$

The block coefficient is used in the calculation of the force due to translatory waves ([section 5.3](#)). This implies that when changing the displacement, also the draft should be modified.

As LOCKFILL was developed with inland cargo ships in mind the breadth and draft can be taken as constant along the length of the ship. The ship length in LOCKFILL is defined as the length at the waterline (LWL) and the draft the maximum distance from the bottom of the keel to the waterline.



**Note:** *The ship weight is defined as the displacement, the ship mass including the cargo. It is defined using the ship length, breadth, draft and water density. When the user changes the displacement, he also has to adjust the draft and vice versa.*

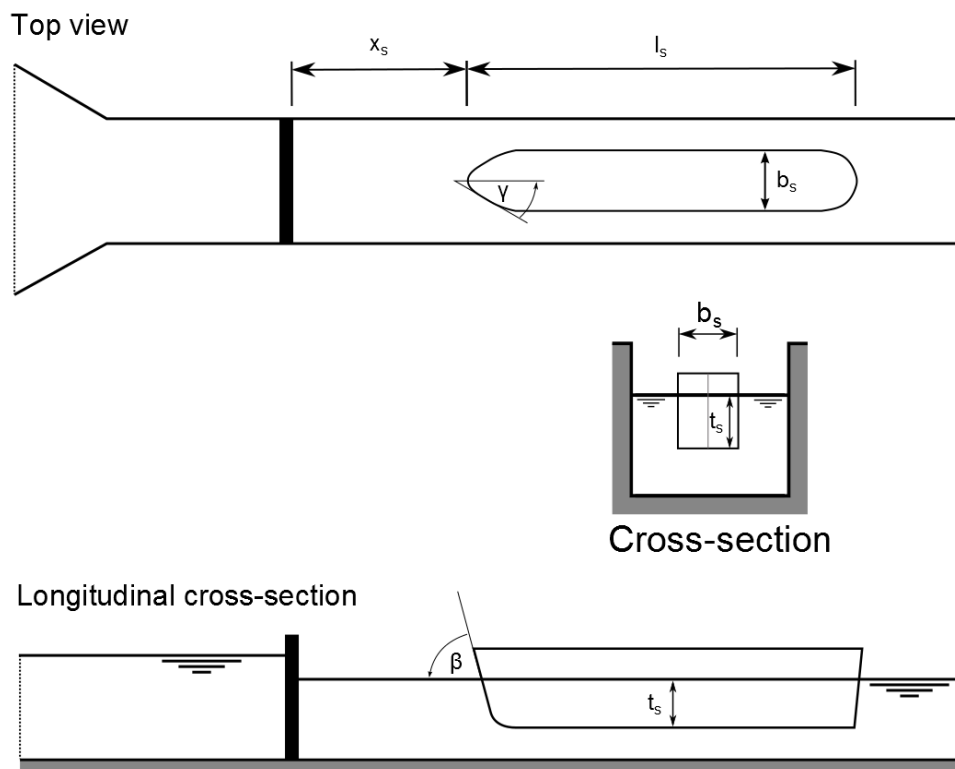
For the friction force the Nikuradse roughness of the hull also has to be defined. A ship hull is smoother than the lock walls or bottom, thus this value is smaller. A recommended value is 0.001 m.

The distance from the bow to the lock gate is defined as the distance at the waterline between the ship and the lock gate. Usually the closest distance, up to the stop line, is the most conservative case. However, it is recommended to check the influence of positioning the ship at different locations.

The vertical angle is the angle the bow makes with the waterline. The horizontal angle is the angle the bow makes with the ship axis, basically the sharpness of the bow.

A definition of the ship in LOCKFILL is shown in [Figure 3.4](#).

Ship		
Name of variable	Description	Unit
MS	Ship displacement (ships' mass including cargo)	[kg]
LS	Ship length	[m]
BS	Ship breadth	[m]
TS	Ship draft	[m]
KII	Nikuradse roughness of ship hull	[m]
XS	Distance from bow to lock gate	[m]
BETA	Vertical angle of bow	[°]
GAMMA	Horizontal angle of bow	[°]



**Figure 3.4:** Definition of the ship in the lock chamber in LOCKFILL

### 3.7 Mode

In this block the user can choose to activate the calculation of bottom velocities or the automatic calculation of the lifting velocity of the sluice gates. A detailed description of these options can be found in [section 6.6](#).

### 3.8 Calculation parameters

In this block the calculation time and time step can be defined. A time step of 1 s should be sufficient for normal calculation. Lowering the time step will increase accuracy, but usually not significantly and is usually not necessary. Limitations in the translatory wave formulation may cause a limitation of the time step depending on lock chamber length and levelling time. For long lock chambers and/or long levelling times a higher time step may be necessary.

Furthermore some empirical parameters are defined in this block. In normal situations these should not be changed from their default value, unless based on scale model tests. Based on the situation, a fresh or a salt lock chamber, only the parameter that influences the velocity of

the density wave (CIC) needs to be changed by the user. The recommended values for both situations are present in the input file.



**Note:** It is highly advised that the user does not change these empirical parameters.

<b>Calculation parameters</b>	
<b>Name of variable</b>	<b>Description</b>
TEND	End time of calculation
DT	Time step
<b>It is not advised to change parameters below!</b>	
C1	Correction of pressure build-up at bow
C3	Correction for flow profile behind stern
<b>When a density difference is present</b>	
CIC	Front velocity coefficient Recommended values: fresh lock chamber/salt approach harbour – 0.42 salt lock chamber/fresh approach harbour – 0.46
MENG	Entrainment coefficient
PI	Coefficient for deviation from uniform flow

## 4 Description of output files

LOCKFILL generates a number of output files, named after the input file (*<name>.lfi*) to which they belong;

- ◇ *<name>\_lockplot.pdf/png* A plot of the results in PDF and PNG format
- ◇ *<name>\_outmima.lfo* A summary of the results containing minimum and maximum forces, levelling time, etc.
- ◇ *<name>\_outtime.lfo* A table containing the calculation results per time step

When culverts are being used two additional output files containing the flow rates through the different culverts will be generated;

- ◇ *<name>\_outriool.pdf/png* A plot of the culvert flow rates in PDF and PNG format
- ◇ *<name>\_outriool.lfo* A table containing the culvert flow rates per time step

In the case a calculation of the bottom velocities is performed, two additional files will be generated;

- ◇ *<name>\_bodvplot.pdf/png* A plot of the bottom velocities in PDF and PNG format
- ◇ *<name>\_outbodv.lfv* A table containing the calculated bottom velocities

The input file (*<name>.lfi*) is also copied to the output directory.

To regenerate the calculation results, only the input file is needed.

### 4.1 Plots

LOCKFILL can generate two three plots. The standard plot shows the results of the levelling process; water levels in the lock chamber and approach harbour, surface area of the gate opening, flow rate and the longitudinal forces. The second plot is only shown when performing a calculation with culverts. The third plot will only be generated in the case the user has turned on the option for bottom velocities. This third plot shows the calculated velocities at the bottom behind the gate openings. An example of both plots will be given below.

The standard plot consists of three separate graphs. The first graph shows the water levels in the lock chamber as a function of time. The second graph shows the flow rate through the gate openings and the surface area of the gate openings. The third graph shows the calculated longitudinal forces. The force is calculated in permillage of the ship displacement because longitudinal force criteria are usually given in this form. For convenience the right vertical axes also shows the force in kN. In all graphs the vertical black line shows the time at which there is a head difference of 0.1 m between lock chamber and approach harbour. In the Dutch situation this usually marks the time at which the doors can be opened. Below the graphs some other useful calculation results are given; the total levelling time, the time until a head difference of 0.1 m and the maximum average vertical velocity of the water level. In the Dutch situation this velocity is limited to 1.0 m/min (0.0167 m/s) when using fixed bollards. An example is shown in [Figure 4.1](#).

The plot for the bottom velocities contains one graph in which the velocities at the bottom behind the gate openings are plotted at a few locations behind the gate openings. These locations are specified in the input file. Below the graph the maximum calculated velocity is shown. Be warned that this only the maximum velocity obtained from the plotted data. It is very well possible there is a higher velocity at a different location behind the levelling



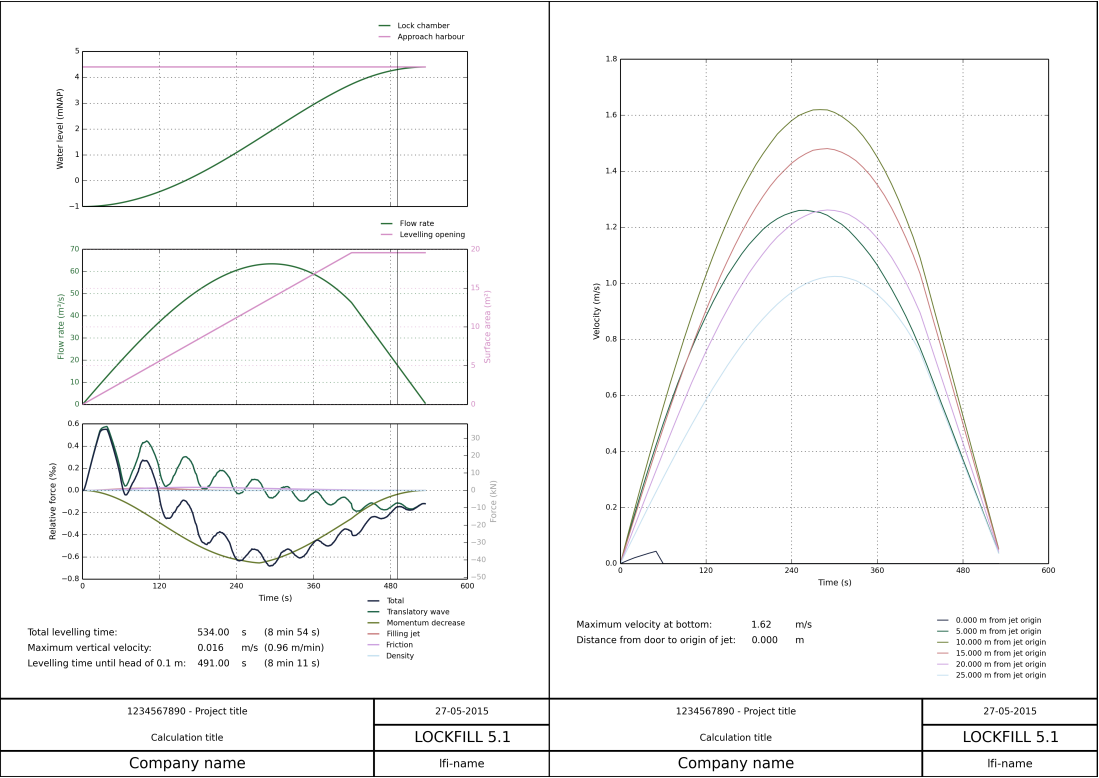
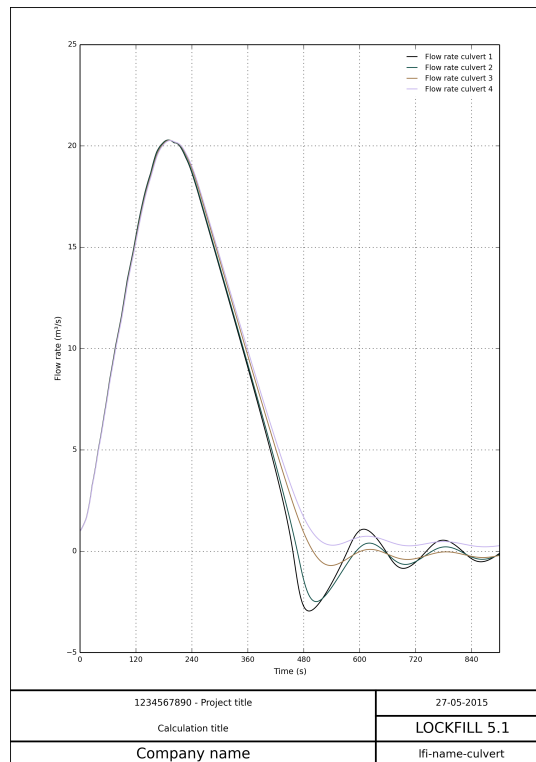


Figure 4.1: Example of plot with the calculation results.

Figure 4.2: Example of plot of the bottom velocities.

gates. The distance from the gate to the origin of the jet is specified as the distance between the downstream side of the gate and the location where the filling jet starts. In the case of breaking bars this is behind the breaking bars and when there are no breaking bars present the filling jet already forms inside the gate. This will be treated in more detail in [section 1.1](#). An example is shown in [Figure 4.2](#).

The plot for culvert flow rates contains a single graph containing the calculated flow rate for each culvert. Up to 16 culverts can be included in the calculation. Addition of all flow rates in this graph leads to the total flow rate as shown on the standard plot. The input parameters for the levelling system with culverts (and stilling chamber) are treated in more detail in [section 6.2](#). An example of the plot is shown in [Figure 4.3](#).



**Figure 4.3:** Example of plot of the culvert flow rates

## 4.2 Summary

The summary gives a short overview of the results of a calculation. The first block shows the calculation time, the time to entirely fill or empty the lock chamber and the time until a head difference of 0.1 m is reached. The second block shows the maximum and minimum flow rate, the maximum increase and maximum decrease in flow rate and the maximum vertical velocity, including the time at which these occur. The third block shows the largest values in both directions of each force component and the total force including the time at which these occur. In case the maximum lift velocity of the sluice gates is calculated (see [section 7.2](#)) the results of the iteration are shown at the end of the file. An example of the summary is shown in [Figure 4.4](#).

Calculation has ended	at t =	534.00 s
Lock chamber filled	at t =	534.00 s
Head difference of 10 cm	at t =	491.00 s
Flow rate:		
Qmax = 63.459 m <sup>3</sup> /s	at t =	295.00 s
Qmin = 0.000 m <sup>3</sup> /s	at t =	0.00 s
Flow rate increase (dQ/dT):		
Max = 0.336 m <sup>3</sup> /s <sup>2</sup>	at t =	1.00 s
Min = -0.400 m <sup>3</sup> /s <sup>2</sup>	at t =	525.00 s
Vertical velocity water level (dHk/dt):		
Max = 0.016 m/s	at t =	295.00 s
Force due to translatory waves:		
Fgmax = 0.577 %	at t =	38.00 s
Fgmin = -0.187 %	at t =	427.00 s
Force due to momentum decrease:		
Fimax = 0.000 %	at t =	0.00 s
Fimin = -0.654 %	at t =	276.00 s
Force due to friction:		
Fwmax = 0.028 %	at t =	171.00 s
Fwmin = 0.000 %	at t =	0.00 s
Force due to filling jet:		
Fsmax = 0.020 %	at t =	101.00 s
Fsmin = 0.000 %	at t =	0.00 s
Total longitudinal force on moored ship:		
Ftmax = 0.551 %	at t =	37.00 s
Ftmin = -0.682 %	at t =	291.00 s

**Figure 4.4:** Example of a summary of the results

### 4.3 Tables

The table output is basically the text version of the plot generated by LOCKFILL. It contains data on water levels and forces at each time step. This file can be imported into an external program for further processing by the user. A part of such a file is shown in [Figure 4.5](#). The columns contain the following data (from left to right);

- ◇ Time (T)
- ◇ Water level approach harbour (HV)
- ◇ Water level lock chamber (HK)
- ◇ Flow rate (QTL)
- ◇ Force due to translator wave (FSG)
- ◇ Force due to momentum decrease (FSI)
- ◇ Force due to filling jet (FSS)
- ◇ Force due to friction (FSW)
- ◇ Force due to density difference (FR)
- ◇ Total force (FSTL)
- ◇ Surface area of gate opening (AHT)
- ◇ Average density in lock chamber (RHOR)

T,	HU,	HK,	QTL,	FS 0,	FS1,	FSS,	FSW,	FR,	FSTL,	QNT,	RHOR,
1.0000,	4.4000,	-1.0000,	0.3361,	0.0000,	0.0000,	0.0000,	0.0000,	0.0000,	0.0000,	0.0000,	0.0000,
2.0000,	4.4000,	-0.9998,	0.6721,	0.0028,	-0.0001,	0.0000,	0.0000,	0.0000,	0.0027,	0.0933,	0.0000,
3.0000,	4.4000,	-0.9996,	1.0079,	0.0167,	-0.0002,	0.0000,	0.0000,	0.0000,	0.0166,	0.1400,	0.0000,
4.0000,	4.4000,	-0.9993,	1.3436,	0.0337,	-0.0004,	0.0001,	0.0001,	0.0000,	0.0335,	0.1866,	0.0000,
5.0000,	4.4000,	-0.9990,	1.6792,	0.0528,	-0.0007,	0.0001,	0.0001,	0.0000,	0.0523,	0.2333,	0.0000,
6.0000,	4.4000,	-0.9985,	2.0146,	0.0745,	-0.0009,	0.0002,	0.0001,	0.0000,	0.0739,	0.2799,	0.0000,
7.0000,	4.4000,	-0.9980,	2.3498,	0.0971,	-0.0013,	0.0003,	0.0002,	0.0000,	0.0962,	0.3266,	0.0000,
8.0000,	4.4000,	-0.9973,	2.6849,	0.1200,	-0.0017,	0.0003,	0.0002,	0.0000,	0.1189,	0.3732,	0.0000,
9.0000,	4.4000,	-0.9966,	3.0198,	0.1433,	-0.0021,	0.0004,	0.0003,	0.0000,	0.1419,	0.4199,	0.0000,
10.0000,	4.4000,	-0.9958,	3.3545,	0.1666,	-0.0026,	0.0005,	0.0003,	0.0000,	0.1648,	0.4666,	0.0000,
11.0000,	4.4000,	-0.9949,	3.6898,	0.1908,	-0.0032,	0.0006,	0.0004,	0.0000,	0.1877,	0.5132,	0.0000,
12.0000,	4.4000,	-0.9940,	4.0233,	0.2129,	-0.0038,	0.0008,	0.0005,	0.0000,	0.2104,	0.5599,	0.0000,
13.0000,	4.4000,	-0.9929,	4.3574,	0.2359,	-0.0044,	0.0009,	0.0005,	0.0000,	0.2329,	0.6065,	0.0000,
14.0000,	4.4000,	-0.9918,	4.6913,	0.2586,	-0.0051,	0.0010,	0.0006,	0.0000,	0.2551,	0.6532,	0.0000,
15.0000,	4.4000,	-0.9906,	5.0249,	0.2812,	-0.0059,	0.0012,	0.0007,	0.0000,	0.2772,	0.6998,	0.0000,
16.0000,	4.4000,	-0.9893,	5.3583,	0.3036,	-0.0067,	0.0014,	0.0008,	0.0000,	0.2990,	0.7465,	0.0000,
17.0000,	4.4000,	-0.9879,	5.6915,	0.3257,	-0.0076,	0.0015,	0.0009,	0.0000,	0.3206,	0.7931,	0.0000,
18.0000,	4.4000,	-0.9865,	6.0245,	0.3477,	-0.0085,	0.0017,	0.0010,	0.0000,	0.3419,	0.8398,	0.0000,
19.0000,	4.4000,	-0.9849,	6.3571,	0.3694,	-0.0094,	0.0019,	0.0011,	0.0000,	0.3630,	0.8864,	0.0000,
20.0000,	4.4000,	-0.9833,	6.6896,	0.3910,	-0.0104,	0.0021,	0.0013,	0.0000,	0.3839,	0.9331,	0.0000,

**Figure 4.5:** Part of the standard output table generated by LOCKFILL

In case there is also a calculation for the bottom velocities, a table with these results will also be generated. This file contains the calculated velocity at the different locations given in the input file. A part of such a file is shown in [Figure 4.6](#). The first column shows the time and the other columns the bottom velocities at the different locations. The downstream positions are given above the columns. The first row defines the location of the start of the jet relative to the downstream side of the gate. The second row gives the horizontal distance between the downstream side of the gate and the monitoring location. The columns contain the following data (from left to right);

- ◇ Time
- ◇ Velocity monitor location 1
- ◇ Velocity monitor location 2
- ◇ Velocity monitor location 3
- ◇ Velocity monitor location 4
- ◇ Velocity monitor location 5
- ◇ Velocity monitor location 6

X (distance from gate to start jet) = 0.000 m							
	0.000	5.000	10.000	15.000	20.000	25.000	
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
10.000	0.011	0.090	0.098	0.083	0.067	0.052	
20.000	0.021	0.177	0.194	0.166	0.134	0.103	
30.000	0.029	0.262	0.288	0.247	0.201	0.155	
40.000	0.037	0.344	0.380	0.327	0.267	0.206	
50.000	0.044	0.423	0.470	0.406	0.332	0.256	
60.000	0.000	0.499	0.559	0.483	0.397	0.306	
70.000	0.000	0.571	0.645	0.559	0.461	0.355	
80.000	0.000	0.641	0.727	0.633	0.524	0.403	
90.000	0.000	0.706	0.808	0.704	0.585	0.450	
100.000	0.000	0.769	0.885	0.773	0.646	0.496	
110.000	0.000	0.828	0.959	0.840	0.702	0.541	
120.000	0.000	0.883	1.030	0.904	0.757	0.585	
130.000	0.000	0.935	1.098	0.966	0.809	0.627	
140.000	0.000	0.983	1.162	1.025	0.860	0.667	
150.000	0.000	1.028	1.222	1.080	0.907	0.707	

**Figure 4.6:** Part of table with bottom velocities generated by LOCKFILL

The resulting flow rates through the different culverts are also given in a table format. This field contains the flow rate per culverts per time step. A part of such a file is shown in [Figure 4.7](#). The first column shows the time and the other columns a flow rate per culvert in the same order as in the input file. The columns contain the following data (from left to right);

- ◇ Time (T)
- ◇ Flow rate culvert 1 (QR)
- ◇ Flow rate culvert 2 (QR)
- ◇ Flow rate culvert 3 (QR)
- ◇ Flow rate culvert 4 (QR)

T	QR	QR	QR	QR
1.0000	1.0217	1.0213	1.0205	1.0200
2.0000	1.0500	1.0492	1.0467	1.0452
3.0000	1.0907	1.0898	1.0868	1.0848
4.0000	1.1328	1.1318	1.1289	1.1269
5.0000	1.1767	1.1756	1.1723	1.1701
6.0000	1.2222	1.2210	1.2175	1.2151
7.0000	1.2695	1.2682	1.2643	1.2618
8.0000	1.3185	1.3171	1.3130	1.3103
9.0000	1.3694	1.3679	1.3635	1.3605
10.0000	1.4223	1.4207	1.4159	1.4127
11.0000	1.4772	1.4755	1.4703	1.4669
12.0000	1.5342	1.5323	1.5267	1.5231
13.0000	1.5934	1.5913	1.5853	1.5814
14.0000	1.6673	1.6644	1.6561	1.6508
15.0000	1.7614	1.7576	1.7466	1.7395
16.0000	1.8617	1.8578	1.8460	1.8381
17.0000	1.9668	1.9623	1.9491	1.9405
18.0000	2.0785	2.0735	2.0586	2.0489
19.0000	2.1957	2.1902	2.1738	2.1631
20.0000	2.3200	2.3137	2.2953	2.2834

**Figure 4.7:** Part of table with culvert flow rates generated by LOCKFILL

## 5 Force schematisation

### 5.1 General

LOCKFILL describes the levelling process of a navigation lock by calculating the average water levels and the flow rates entering or leaving the navigation lock as a function of time. From these water levels and flow rates the resulting levelling forces on the ship are determined. LOCKFILL assumes there is only one ship present in the lock chamber and uses a one-dimensional approach of the levelling process.

LOCKFILL can be used as a design tool; by varying parameters like the size of the gate openings or the lifting velocity of the sluice gates an optimal levelling time can be achieved while still complying with the criteria for the maximum longitudinal force on the ship, often referred to as 'hawser force criterion'. Besides that LOCKFILL can also be used as a tool to analyse an existing navigation lock to check if it still performs within the force criteria despite changes in hydraulic boundary conditions and/or ship types and sizes.

The calculation method of LOCKFILL is based on multiple studies, [Bosma \(1978\)](#); [Vrijburcht, A., et al \(1988\)](#); [Haas and Vrijburcht \(1988\)](#); [Vrijburcht \(1991\)](#). It was tested and validated by comparison with existing model tests in [Jonge et al. \(1994\)](#).

The result of the one-dimensional approach is that only the longitudinal forces are considered and symmetry is implicitly assumed. This is a valid approximation because the longitudinal forces are dominant when compared with lateral forces in head filling systems. LOCKFILL has a limited geometric representation of the lock and the ship in the lock chamber. The lock is represented as a rectangular box with a constant width and a horizontal floor. This excludes the exact schematisation of so called 'green' lock chambers with sloped lock walls. In the case of mitre gates the location of the lock gate has to be estimated to give a similar 'wet' surface area of the lock chamber. Ships are also simplified as rectangular boxes, although for certain force components the angle of the bow is roughly taken into account.

In the case of an initial head of more than 4 m when using gate openings, it is strongly advised to perform additional hydraulic research. For culverts in combination with a stilling chamber, additional hydraulic research is almost always advised. Additional research is also advised in the case of a very high blockage by the ship.

The calculation results given by LOCKFILL strongly depend on a few input parameters, especially the discharge coefficients. The discharge coefficients can be accurately determined using scale model tests. If it is not possible to perform model tests, the discharge coefficient can be estimated using model tests on a similar geometry. In this case it is advised to perform calculations for a range of discharge coefficients.

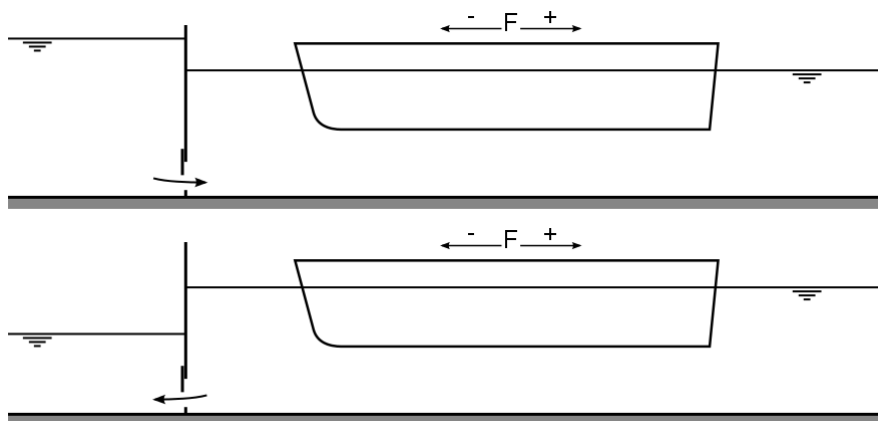
LOCKFILL implicitly assumes a good hydraulic design of the gate openings or culverts/stilling chamber. This means that in general the hydraulic design should comply with the rules given in [Beem et al. \(2000b,a\)](#).

This chapter will shortly describe the calculation of the different force components. The schematisation of the supported levelling methods is the subject of [chapter 6](#). This description will also include a list of the relevant parameters in the input file, including a short description.



## 5.2 Longitudinal force

To analyse the quality of the levelling system, LOCKFILL calculates the longitudinal force exerted on a ship in the lock chamber. The ship has a fixed position, i.e. the calculated force will not result in a movement of the ship. The longitudinal force is defined as follows for both filling and emptying: the force is positive when directed away from the lock head through which the levelling takes place (see also [Figure 5.1](#)).



**Figure 5.1:** Definition of longitudinal force during filling and emptying

LOCKFILL presents the longitudinal force as a permillage of the ships displacement (including cargo) in tons by dividing the absolute force by the given displacement of the ship. This is convenient because the force criteria are usually given as a permillage of the ships displacement. For convenience, the plots created by LOCKFILL also show the absolute force.



**Note:** LOCKFILL will use the actual displacement of the ship given in the input file. So if the user changes the draft of the ship, he will also need to change the displacement as these are correlated. The same goes for width and length. Not correcting the displacement will result in adverse results. The results presented by LOCKFILL apply to this corrected displacement.

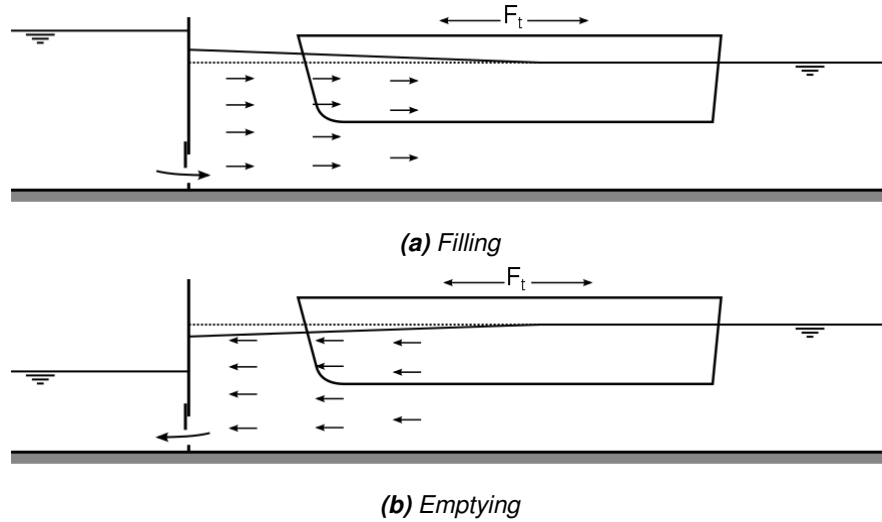
The flow, entering or leaving the lock chamber, results in wave and flow phenomena in the lock chamber. The ship present in the lock chamber will be subjected to these phenomena, resulting in mostly longitudinal forces. The longitudinal force on the ship can be divided into five components, namely;

- 1 Translatory waves
- 2 Decrease in momentum (in longitudinal direction)
- 3 Friction
- 4 Effect of filling jet
- 5 Effect of density difference

The total longitudinal force is obtained by a summation of these components. Usually components a. and b. will give the largest contribution. In general during filling the total longitudinal force has an oscillating behaviour due to the translatory waves. In the beginning of the levelling process the value of the longitudinal force is mainly positive and mainly negative after the maximum flow rate has been reached. During emptying the oscillating behaviour is also present, but starts out negative and is positive in the end.

### 5.3 Translatory waves

Translatory waves are generated by the non-constant flow rate through the gate openings or culverts. These waves travel to and fro in the lock chamber with a complete reflection against the lock doors and a partial reflection against the bow and stern of the ship. This will result in an oscillating motion of the water in the lock chamber.



**Figure 5.2:** Schematic of the translatory wave force when a) filling and b) emptying

LOCKFILL calculates the translatory wave by the flow rate at the gate openings or culverts. At the reflection points (lock gates, bow and stern) all incoming waves are split into outgoing waves. The reflections at the bow and the stern are dependent on the blockage by the ship. The waves result in water level differences between bow and stern which will generate an oscillating force on the ship. During filling the force will be mainly positive in the beginning of the levelling process and after the maximum flow rate has been reached it will be mainly negative. During emptying this force will be mainly negative in the beginning and mainly positive after reaching the maximum flow rate with a maximum value at the end of the levelling process.

The ship is assumed to be a rectangular box with a constant draft. The draft is assumed to be constant during the levelling process, the so called flexible ship approximation. The wave velocities are calculated using the shallow water approximation. Two wave velocities can be identified in the lock chamber, one velocity in the part where the ship is present and another in the parts where there is no ship present. These wave velocities are defined respectively as

$$c_s = \sqrt{g \frac{(h_k - z_k)b_k - t_s b_s}{b_k}} \quad (5.1)$$

$$c_k = \sqrt{g(h_k - z_k)} \quad (5.2)$$

with  $b_k$  the width of the lock chamber,  $b_s$  the width of the ship and  $t_s$  the draft. This results in a wave period in the lock chamber of

$$T_k = 2 \left( \frac{l_k - l_s}{c_k} + \frac{l_s}{c_s} \right) \quad (5.3)$$

in which  $l_k$  is the hydraulic length of the lock chamber and  $l_s$  is the length of the ship.

The force (in permillage of displacement) on the ship due to the translator waves is, without damping, given by

$$F_t = \frac{h_{bow} - h_{stern}}{l_s C_b} \quad (5.4)$$

$h_{bow}$  and  $h_{stern}$  are the water levels at the bow and stern respectively and  $C_b$  is the block coefficient. In LOCKFILL this term is compensated for damping by the gate openings or culverts and the spreading of the reflections against the ship as the bow and stern are not sudden transitions as modelled in LOCKFILL.

The final, damped, longitudinal force on the ship is given by

$$F_{tw} = F_t - (F_t - F_p) \left(1 - e^{-C_e \frac{t}{T_k}}\right) \quad (5.5)$$

$$F_p = \frac{\left(l_k - x_b - \frac{l_s}{2}\right) \frac{dQ}{dt}}{C_b g l_k ((h_k - z_k) b_k - t_s b_s)} \quad (5.6)$$

$$C_e = 0.07 + 0.4 \frac{t_s b_s}{b_k (h_k - z_k)} \quad (5.7)$$

where  $x_b$  is the distance from the gate to the bow of the ship. This damping term is validated using model tests and prototype measurements in the navigation lock of Eefde in the Twentekanaal (Jonge *et al.*, 1994).

#### 5.4 Decrease in momentum, friction and filling jet

The forces due to the decrease in momentum, friction and filling jet are derived using a momentum balance along the length of the lock. Therefore these forces are combined in this paragraph.

##### **Decrease of momentum**

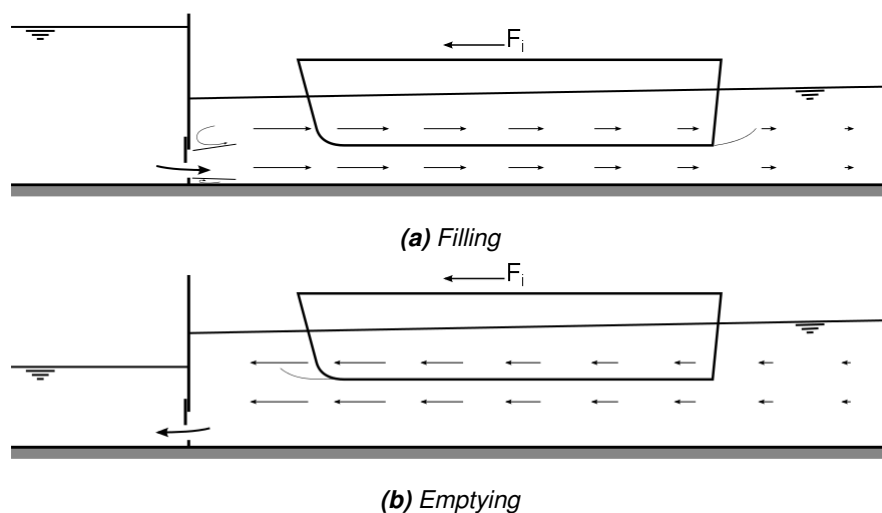
The concentrated filling jet which occurs when filling with gate openings contains high flow velocities that decrease in the longitudinal direction. Furthermore, the average flow rates at a slice in the lock chamber also decrease in longitudinal direction because behind this slice a shorter part of the lock chamber has to be filled. These effects cause a total decrease of the momentum in the longitudinal direction which results in water level differences between bow and stern and thus a longitudinal force. At short distances from the filling gate this component has a negative value (a force towards the filling gate) with a maximum value just before the maximum flow rate is reached. At large distances from the filling gate this component can have a positive value. During the emptying process this force is also negative, but less pronounced because there is no filling jet present. A schematic representation of this force is shown in [Figure 5.3](#).

##### **Friction**

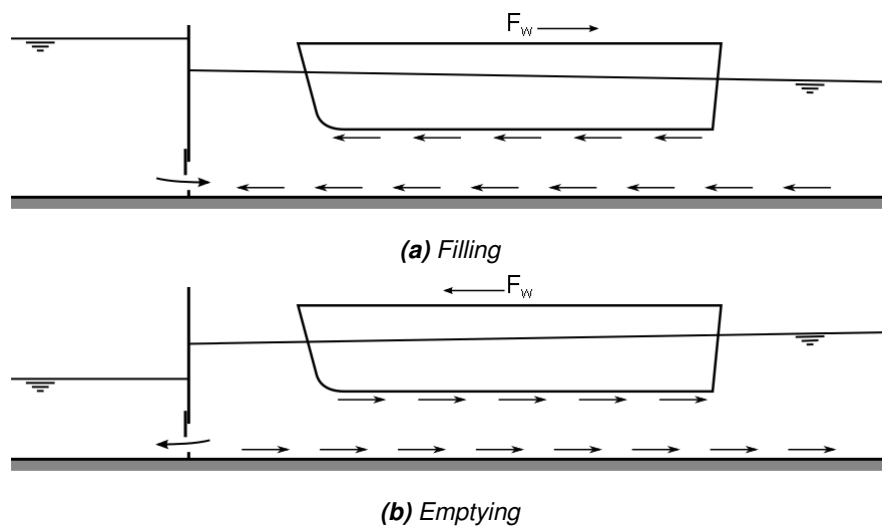
The friction of the flow with the lock chamber floor and walls causes a water level difference and there is a friction force against the ship. The resulting friction effect is calculated using the Chézy formulation. The force is positive and obtains its maximum value when the flow rate is maximal. This force is in the negative direction during emptying. A schematic representation of this force is shown in [Figure 5.4](#).

### Filling jet

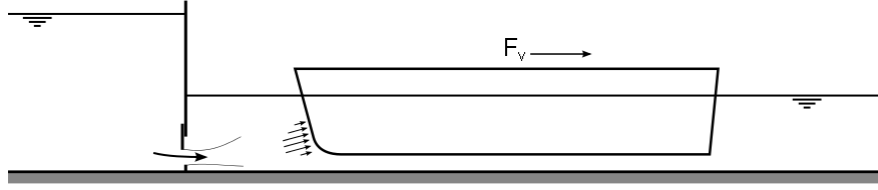
The filling jet (a combination of the separate filling jets from the different gate openings) collides with the bow of the ship. This force component is calculated using the formulation of the flow pressure against a plate under an angle. This gives, especially during the beginning of the levelling process a positive force. When the ship has risen far enough the jet can pass under the ship and this force component disappears. This component is not present when filling using culverts or when emptying. A schematic representation of this force is shown in [Figure 5.5](#).



**Figure 5.3:** Schematic of the force due to momentum decrease when filling and emptying



**Figure 5.4:** Schematic of the friction force when filling and emptying



**Figure 5.5:** Schematic of the force by the filling jet when filling

The forces caused by the decrease in momentum, friction and the filling jet are derived simultaneously using one-dimensional continuity and momentum equations at the bow, along the hull and at the stern of the ship. These equations result in water level differences that result in a force on the ship from which three separate force terms can be distilled. During the derivation, the following assumptions are made:

- ◇ Between the bow and the stern, the flow has a uniform distribution
- ◇ The average flow rate decreases linearly with distance between bow and stern
- ◇ Aft of the stern, the flow separates from the hull of the ship
- ◇ At the bow, the pressure is hydrostatic for a water level in front of the bow, with a deviation for the jet pressure and flow along the bow (Dutch: afstromend water langs de boeg)
- ◇ Between the bow and the stern there is friction and a momentum decrease
- ◇ The pressure at the stern is hydrostatic for the water level at the side of the ship

The filling jet is parameterised using a geometric representation based on the work of [Rajaratnam \(1976\)](#) and extended to include reflections in Note 6 of [Vrijburcht, A., et al \(1988\)](#). This method calculates the momentum of the filling jet at the bow, necessary for the momentum equation over the bow. It must be noted that the transient character of the filling process is not taken into account and neither is the presence of breaking bars.

The complete derivation of the force components is too cumbersome to present here, however it can be found in [Haas and Vrijburcht \(1988\)](#). Therefore only the resulting expressions will be presented.

#### 5.4.1 Decrease in momentum

The force due to the decrease in momentum during filling through gate openings is given by

$$F_{si} = \frac{\rho t_s b_s}{h_k b_k - t_s b_s} \left( -\frac{l_k - x_s}{l_k} S_b \cos \alpha + \frac{Q^2}{h_k b_k - t_s b_s} \left( \frac{l_k - x_s - l_s}{l_k} \right)^2 \right) \quad (5.8)$$

where  $\alpha$  is the vertical angle of the filling jet and  $S_b$  is a measure of the filling jet momentum at the bow.

When filling through culverts there will be no filling jet present and the first term in brackets in [Equation 5.8](#) will not be present. It is assumed that the levelling current will leave the stilling chamber evenly distributed. The force due to the decrease of momentum is given by

$$F_{si} = -Q |Q| \frac{\rho t_s b_s}{h_k b_k - t_s b_s} \left( \frac{\left( \frac{l_k - x_s}{l_k} \right)^2}{b_k h_w} - \frac{\left( \frac{l_k - x_s - l_s}{l_k} \right)^2}{h_k b_k - t_s b_s} \right) \quad (5.9)$$

$h_w$  is a modified water level in the case that the water level in the lock chamber is lower than

the water level in the stilling chamber. It is defined as

$$h_w = \min \left( h_{woel} + \frac{0.1667}{2} x_s, h_k \right) \quad (5.10)$$

During the emptying process for both gate openings and culvert there is no filling jet present and the force due to momentum decrease, for both cases, is given by

$$F_{si} = Q |Q| \frac{\rho t_s b_s}{h_k b_k - t_s b_s} \left( \frac{\left( \frac{l_k - x_s}{l_k} \right)^2}{h_k b_k - t_s b_s} - \frac{\left( \frac{l_k - x_s - l_s}{l_k} \right)^2}{h_k b_k} \right) \quad (5.11)$$

#### 5.4.2 Friction

The force due to friction is the same during filling or emptying. The friction force is calculated using the average flow velocity along the hull, the Chézy formula and the formulas of Strickler and White-Colebrook. It is given by

$$F_w = F_{bw} \left( \frac{t_s b_s}{h_k b_k - t_s b_s} \right) + F_{sw} \left( \frac{h_k b_k}{h_k b_k - t_s b_s} \right) \quad (5.12)$$

with

$$F_{bw} = C_3 \rho g \left( \frac{2l_k - 2x_s - l_s}{2l_k} \right)^2 \frac{Q |Q|}{(h_k b_k - t_s b_s)^2} \frac{(b_k + 2h_k) l_s}{C^2} \quad (5.13)$$

$$F_{sw} = C_3 \rho g \left( \frac{2l_k - 2x_s - l_s}{2l_k} \right)^2 \frac{Q |Q|}{(h_k b_k - t_s b_s)^2} \frac{(b_s + 2t_s) l_s}{C^2} \sqrt[4]{\frac{k_{II}}{k_I}} \quad (5.14)$$

$$C = 18^{10} \log \left( \frac{12R_I}{k_I} \right) \quad (5.15)$$

$$R_I = \frac{h_k b_k - t_s b_s}{\sqrt[4]{\frac{k_{II}}{k_I}} (b_s + 2t_s) + (b_k + 2h_k)} \quad (5.16)$$

$C_3$  is a coefficient to correct for the flow profile immediately behind the stern,  $C$  is the Chézy coefficient and  $k_I$  and  $k_{II}$  are the Nikuradse roughnesses of the lock chamber and the ship respectively.

#### 5.4.3 Filling jet

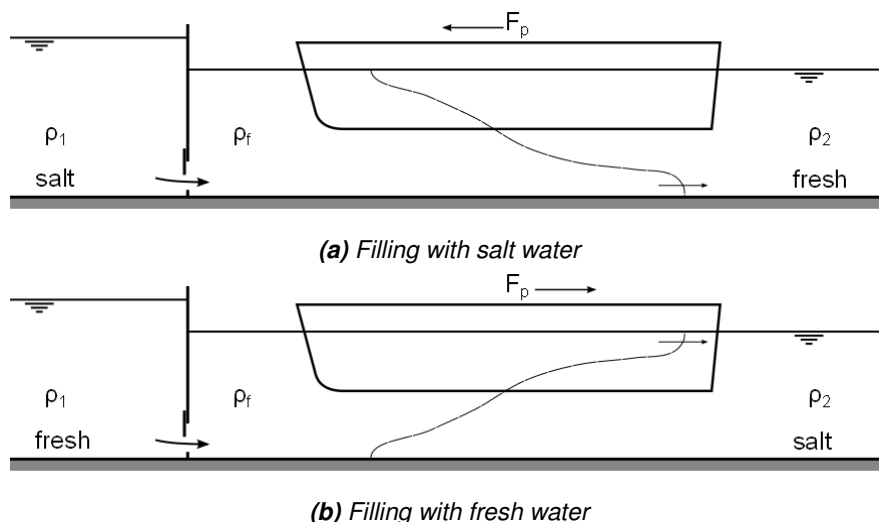
When filling through gate openings there will be a filling jet present. The force of the filling jet on the bow of the ship is given by

$$F_{ss} = \left( \frac{\rho h_k b_k}{h_k b_k - t_s b_s} \right) \left( C_1 C_2 Q \frac{l_k - x_s}{l_k} v_1 \sin \alpha + \beta \sin \beta \sin \gamma \right) \quad (5.17)$$

In which  $C_1$  is a correction for the pressure build up at the bow,  $C_2$  is defined as the ratio of the surface area of the jet that hits the bow and the total surface area of the jet,  $v_1$  is the flow velocity in front of the bow,  $\beta$  is the vertical angle of the bow and  $\gamma$  is the horizontal angle of the bow. During emptying or when filling through culverts this force term is not present and those cases  $F_{ss} = 0$ .

## 5.5 Effect of density difference – Not available in public release

In the case there is a density difference between the lock chamber and the approach harbour, the filling process will induce the formation of a density current in the lock chamber. This density current travels through the lock chamber and will reflect against the ship and the lock gates. The density current results in water level differences in the longitudinal direction.



**Figure 5.6:** Schematic of force due to density difference when filling with salt and fresh water

The processes involved when filling with a levelling current that has a different density than the water already present in the lock chamber are quite complex. It is not possible to capture all these effects in a one-dimensional model. Therefore, the stratified flow in the lock chamber is parameterised based on an analysis of results from model experiments. In the derivation of the force due to the density difference a few assumptions are made; the influence of the density currents on the transitory waves is neglected and the behaviour of the filling jet is not changed as it is mostly determined by momentum.

From experiments three situations can be distilled, a large blockage by the ship or a small distance between gate and bow, a limited blockage and a small blockage in which the ship has a limited effect on the density current entering the lock chamber. Thus, in total six cases can be identified:

- 1 Fresh lock chamber, salt approach harbour
  - 1.1 Large blockage, short distance between filling gate and bow
  - 1.2 Limited blockage
  - 1.3 Small blockage
- 2 Salt lock chamber, fresh approach harbour
  - 2.1 Large blockage, short distance between filling gate and bow
  - 2.2 Limited blockage
  - 2.3 Small blockage

A short description of cases 1 to 3 will be given.

**Case 1**

In the case of a large blockage or when the bow of the ship is located very close to the gate the levelling process will result in a mixing zone in front of the bow. The entire water column in front of the bow will have a more or less constant density that changes over time as more salt water enters the lock chamber. A salt layer with this density will then travel towards the stern and lower head. At the lower head it will reflect and travel back. The velocity of the salt wedge is given by

$$c_1 = c'_1 \sqrt{\frac{1}{2} E g (h_{v,i} + h_{k,i})} \quad (5.18)$$

In which  $c'_1$  is a coefficient for the front velocity and  $E$  is the maximum relative density difference, i.e. the relative density difference at the beginning of the levelling process,  $h_{v,i}$  is the initial water level in the approach harbour and  $h_{k,i}$  is the initial water level in the lock chamber. The default value of  $c'_1$  is 0.45. Recommended values are 0.42 for a fresh lock chamber/salt approach harbour and 0.46 for a salt lock chamber/fresh approach harbour. The results can be sensitive to this value and it is difficult to give an accurate prediction. The most secure method is to perform a model test.

**Case 2**

When there is a limited blockage by the ship, there will again be a mixing zone in front of the bow, however it will not fill the entire water column. The height of the mixing zone will change in time and reach a maximum when there is a maximum flow rate into the lock chamber. The density in this mixing zone is dependent on the level of entrainment from the fresh layer. A measure for this entrainment is given by the entrainment or mixing coefficient  $\beta$ . A value of 0.5 will mean that the density in the mixing zone will be the average of the densities in the lock chamber and approach harbour. A value of 1 means there is no entrainment at all. The value is usually between 0.5 and 0.8. LOCKFILL uses a value of 0.8, according to [Vrijburcht \(1991\)](#) this value can only be determined by prototype or scale model investigation.

**Case 3**

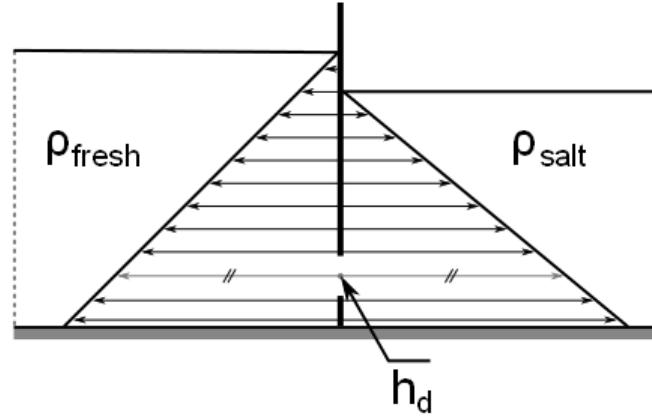
In the case of a small blockage it is assumed that the ship has only a limited effect on the density current entering the lock chamber. At the filling openings some entrainment will occur and a salt wedge will travel through the lock; first to the bow, then the stern and reflects at the lower gate and travel back

The force due to density difference is calculated by comparing the longitudinal force in the case of a homogenous density with the longitudinal force when there is a density difference present. The longitudinal force is calculated by calculating the water level difference between bow and stern from the momentum transport along the ship. In the momentum equations, the presence and evolution of the different densities in the lock chamber is taken into account. The way in which the evolution of the density layers is calculated depends on the previously mentioned six cases. The implementation in LOCKFILL is based on the calculation method presented in [Vrijburcht \(1991\)](#). The reader is referred to this work to review the formulation.

**5.5.0.0.1 Additional water level difference**

If there is a density difference between lock chamber and approach harbour this will influence the flow rate and it will also result in a water level difference after the levelling process is completed. At that moment there will be a pressure balance between lock chamber and approach harbour at the gate openings or culverts, but the difference in density between

lock chamber and approach harbour results in a water level difference. This is illustrated by [Figure 5.7](#).



**Figure 5.7:** Illustration of pressure balance between fresh and salt water at the position of the gate opening resulting in a level difference over the gate between the fresh and salt volumes.



**Note:** LOCKFILL assumes a homogeneous density distribution in the lock chamber and approach harbour prior to levelling. Assuming the highest density (usually found near the bottom) can possibly result in an overestimation of the forces.

It is therefore not possible to use the absolute level difference  $\Delta h = h_v - h_k$  in the calculation of the flow rate. Instead an effective water level difference ( $\Delta h_d$ ) is used, which is calculated using the average level of the gate openings ( $h_d$ ). At default the average level of the gate openings is given by

$$h_d = 0.25h_{k,i} + 0.75z_k \quad (5.19)$$

With  $h_{k,i}$  the initial water level in the lock and  $z_k$  the level of the lock floor, both with respect to the reference level. This means that average level of the gate openings is positioned at one-quarter of the initial water level in the lock. However, the user also has the option to specify the average level of the gate openings ( $h_d$ ) in the input file. At default the average level of the culvert openings is

$$h_{d,r} = 0.2h_{k,i} + 0.8z_k \quad (5.20)$$

so at one-fifth of the initial water level in the lock chamber. The user also has the option to specify the separate levels per culvert. When the average level of the gate openings or the culverts is not specified LOCKFILL will use equations [Equation 5.19](#) and [Equation 5.20](#).

If there is a density difference present, the water level difference used in the flow rate calculation is corrected. This is shown in detail in [section E.5](#).

## 6 Supported levelling methods

This chapter described the schematisation of the supported levelling methods. This description will also include a list of the relevant parameters in the input file, including a short description of those parameters.

LOCKFILL implicitly assumes a good hydraulic design of the gate openings or culverts/stilling chamber. This means that in general the hydraulic design should comply with the rules given in [Beem et al. \(2000b,a\)](#).

### 6.1 Gate openings

#### 6.1.1 'Standard' gate openings (openings in lock gates)

In this method LOCKFILL assumes that the gate openings are well divided over the width of the lock chamber and that there are breaking bars present at the downstream side of the gate. This assumed configuration assures a good distribution of the filling jet over the width of the lock chamber. The calculation assumes that the width of the filling jet is equal to 80% of the lock chamber width. The necessary variables to define this levelling system are given in [Table 6.1](#).

This method of calculating the flow rate and water levels into (or out of) the lock chamber is also applied to the other type of gate openings that will be discussed in [section 6.1.2](#), [section 6.3](#) and [section 6.4](#). The gate openings discussed in these sections only differ in their definition of the surface area of the opening and the size and position filling jet.

The flow rate in or out of the lock chamber through gate openings is calculated using the instantaneous water level difference between lock and approach harbour and the surface area and discharge coefficient of the gate openings. This gives

$$Q = \mu A_h \sqrt{2g |\Delta h|} \frac{|\Delta h|}{\Delta h} \quad (6.1)$$

In which  $\mu$  is the discharge coefficient,  $A_h$  the surface area of the gate openings,  $g$  the gravitational acceleration and  $\Delta h$  the head over the gate. The derivation of the formulation for the flow rate and the calculation of the new water levels in the lock chamber (and approach harbour) are given in [section E.1](#).

**Note:** This is the only levelling system in which the options to calculate the bottom velocities or calculate a lift velocity from a predefined hawser force criterion can be used.



**Table 6.1:** Variables to define the levelling system gate openings

Gate openings		
Name of variable	Description	Unit
ZHMAXD	Maximum height of opening  The distance between the bottom and the top of a gate opening. During the calculation the height of the sluice gate is maximized by this distance. This makes it possible to simply define a constant lift velocity during the entire calculation, without having to calculate the end time of the lifting process.	[m]

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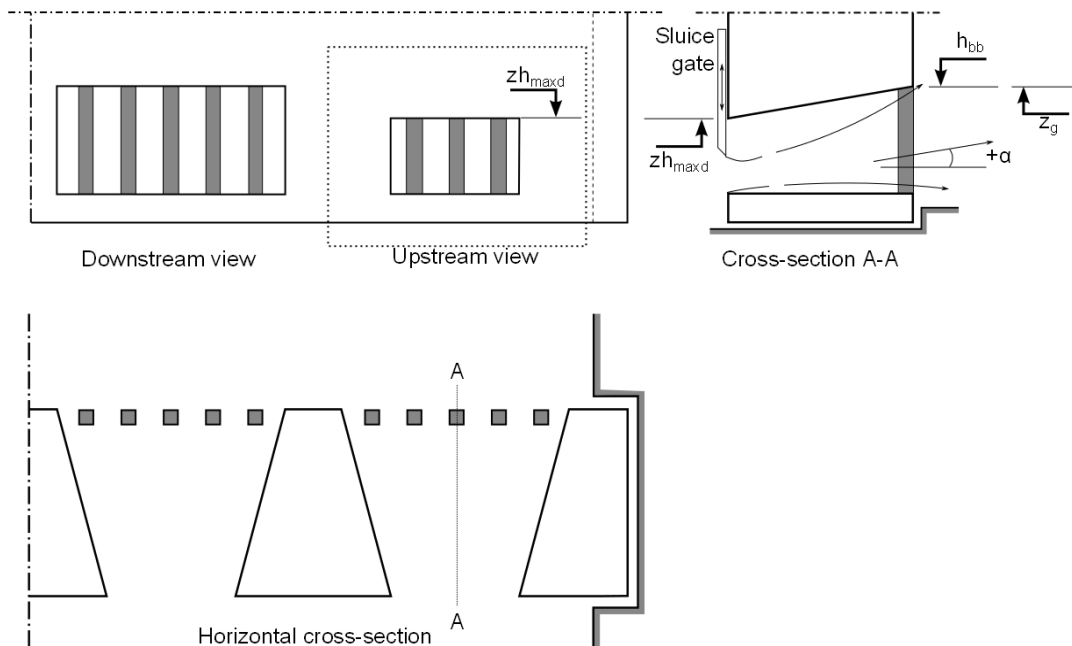
**Table 6.1:** Variables to define the levelling system gate openings

<b>Gate openings</b>		
<b>Name of variable</b>	<b>Description</b>	<b>Unit</b>
VHD	<p>Table with lift velocities as function of time</p> <p>Because it is a function of time it is possible to define a certain lift programme in which the lift velocity changes in time. For example, using a low velocity at the beginning of the filling process can reduce the effect of the initial translatory wave.</p>	[m/s]
BH	<p>The (total) upstream width of all gate openings combined as a function of the (dimensionless) gate height</p> <p>The gate height is made dimensionless using the maximum height of the opening. This means that the width can change during lifting of the sluice gates to accommodate certain shapes of the gate openings. Some examples of different shapes and the influence of these shapes on the surface area of the openings is given in <a href="#">Figure 6.3</a>. A different shape will influence the evolution of the flow rate during levelling and thus the resulting longitudinal forces.</p>	[m]
MUH	<p>Table with discharge coefficient as function of (dimensionless) gate height</p> <p>The discharge coefficient is not a constant during opening and dependent on the shape of the gate openings and the position of the sluice gates. This parameter is defined relative to the area under the sluice gate and includes the effect of the breaking bars. This parameter can best be obtained from scale model research. If that is not possible it can be estimated from scale model research on a similar geometry or by a hydraulic expert.</p>	[-]
ALFA	<p>Vertical angle of the filling jet</p> <p>The angle the filling jet makes with the horizontal when entering the lock chamber. This parameter is important for the force by the filling jet.</p>	[°]
ABB	<p>Surface area of the filling jet behind the breaking bars</p> <p>As it is assumed that the breaking bars are designed well, the resistance by the breaking bars will cause the filling jet to be divided over a larger area, assumed to be approximately equal to the area of the outflow of the gate, including the area covered by the breaking bars. This parameter is a measure of how well the filling jet is distributed over the height of the breaking bars. Although in reality this height will not be completely constant during the levelling process, it is assumed constant during the calculation.</p>	[m <sup>2</sup> ]

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**Table 6.1:** Variables to define the levelling system gate openings

Gate openings		
Name of variable	Description	Unit
ZG	Level of top of filling jet behind the breaking bars  This parameter defines at what height the filling jet enters the lock chamber, which is important for the calculation of the force by the filling jet. It is assumed constant during the levelling process. This implies that the initial water level inside the lock is above the upper end of the breaking bars.	[mCD]
HD	Level of centreline of gate openings  This parameter defines the average level of all gate openings. It is used in the calculation of the flow rate in case of a density difference between lock chamber and approach harbour.	[mCD]

**Figure 6.1:** Schematic of 'standard' gate openings in a lock gate

### 6.1.2 Gate openings with filling jet of limited width or without breaking bars

The method to define gate openings from [section 6.1.1](#) is limited to cases where the openings are well divided over the width of the lock and there are breaking bars present. However, in many navigation locks there are no breaking bars or gate openings are not well divided over the width of the lock chamber. Or the lock has mitre gates that result in a concentrated filling jet in the middle of the lock chamber because of the angle between the two gates. This method can be used if the previously discussed method is not sufficient. In comparison with the method discussed in [section 6.1.1](#), this method can describe the following new cases (also see [Figure 6.2](#)):

- 1 Limited distribution of gate openings of the width of the lock. Although usually the gate openings are well distributed, cost consideration (less sluice gates) can lead to a concen-

tration of the gate openings

- 2 The use of mitre gates without vanes in the openings to direct the flow might lead to a concentrated filling jet in the centre of the lock chamber. This can be modelled as single gate opening in the centre of the gates by estimating the width of this filling jet.
- 3 Lack of breaking bars at the downstream side of the gate openings will lead to a concentrated filling jet with a varying height. The height of the filling jet is defined by the vertical position of the sluice gate, resulting in a thin filling jet in the first part of the levelling process. The start position of the filling jet is at the position of maximum contraction. When there are breaking bars present, the start position of the filling jet is just behind the breaking bars.
- 4 The vertical angle of filling jet can change during the levelling process as the average level of the upstream opening changes during the levelling process while the average level of the downstream side stays constant when there are breaking bars present.
- 5 An off-centre position of the ship with respect to the lock axis can also be taken into account. Especially in the case of a thin filling jet or a wide lock chamber relative to the ship this can have a significant effect.

The necessary variables to define this levelling system are given in [Table 6.2](#).

This method influences the force components by the momentum decrease and the filling jet. The calculation method is equal to the method of 'normal' gate openings and differ only in the how the size of the filling jet is defined. So it uses the same geometric representation of the filling jet and there is only spreading in the vertical direction.

The vertical angle of the filling jet is strongly dependent on the design of the gate openings and if there are breaking bars, vanes and/or a horizontal breaking bar present. The angle and it's evolution during the levelling process can be determined by a scale model or could possibly be estimated by a hydraulic expert.



**Note:** *If one of the parameters for this option (shown below) is present in the input file, this option is activated. Lockfill will give an error therefore if not all parameters are defined in the input file.*

**Table 6.2:** Variables to define the system gate openings with filling jet of limited width or without breaking bars

Gate openings with filling jet of limited width or without breaking bars		
Name of variable	Description	Unit
YP	Distance between axis ship and axis lock chamber  This defines the off-centre position of the ship in the lock chamber. In case of a thin filling jet this will have a significant effect on the resulting force on the ship. Because of the rough schematisation of the shape of the bow it is advised to use this option carefully.	[m]

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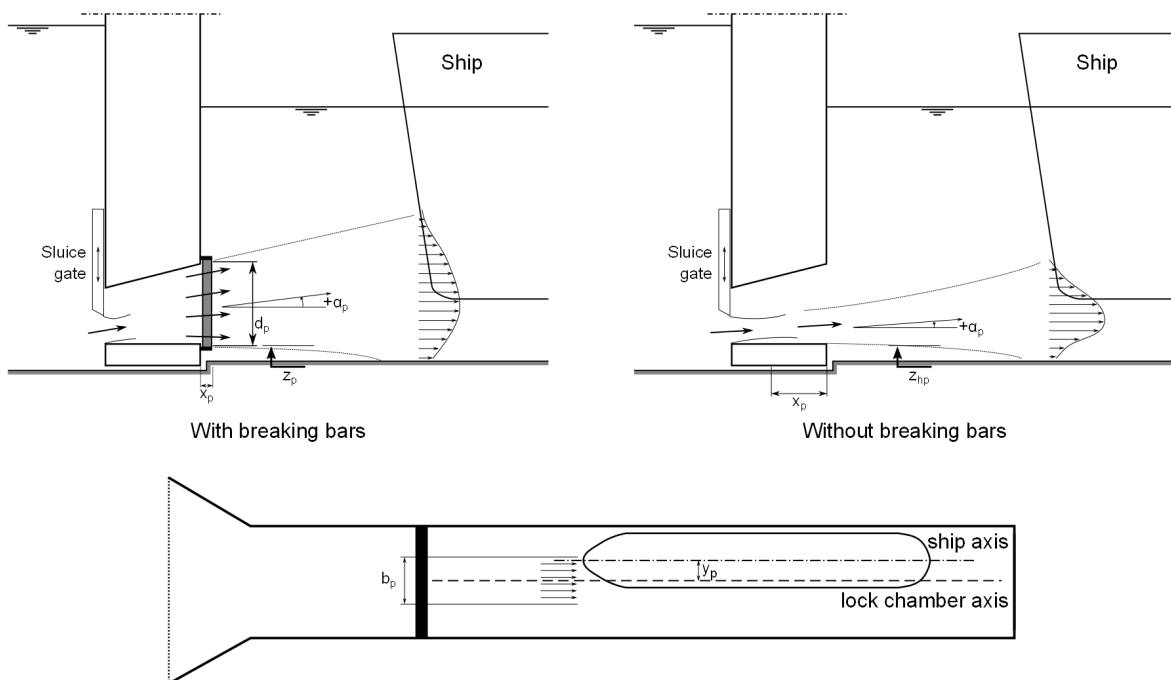
**Table 6.2:** Variables to define the system gate openings with filling jet of limited width or without breaking bars

<b>Gate openings with filling jet of limited width or without breaking bars</b>		
<b>Name of variable</b>	<b>Description</b>	<b>Unit</b>
XP	Distance between start of filling jet and lock chamber side of gate  When breaking bars are present the origin of the filling jet is defined just after the breaking bars. If there are no breaking bars present, the filling originates at the point of maximum contraction. If the sluice gates are at the upstream side of the gate this position will probably be inside the gate opening and if the sluice gates are at the downstream side this position will be at the downstream side, inside the lock chamber.	[m]
ALFAALFP	Table with angle of filling jet as function of gate height  Similar to the variable ALFA in <a href="#">section 6.1.2</a> , but it is possible to change this angle as a function of the gate height. This is a more accurate representation of reality as this angle usually changes because the average level of the upstream opening (under the sluice gates) changes when the gates are lifted.	[°]
BREEKP	Choose if there are breaking bars present  When breaking bars are present the filling jet will be spread in the vertical direction. Without breaking bars the height of the filling jet is defined by the height of the sluice gates.	[-]
<b>With breaking bars</b>		
BP	Total width of filling jet  The width of the filling jet depends on the position of the gate openings. Be reminded that only spreading in the vertical is taken into account. The width of the filling jet can be estimated by a hydraulic expert.	[m]
ZP	Level of underside of the gate openings  This defines the underside of the filling jet.	[mCD]

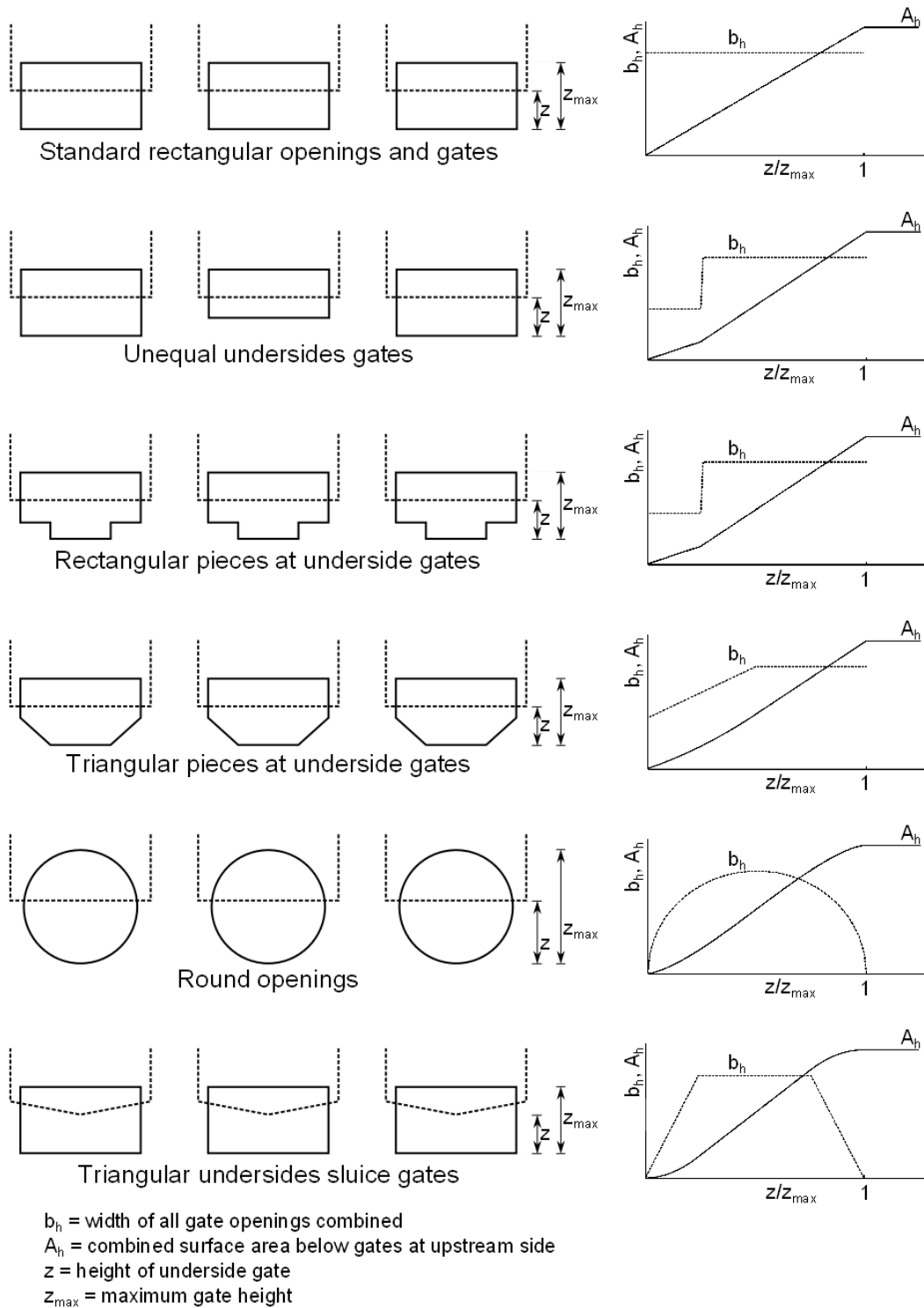
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**Table 6.2:** Variables to define the system gate openings with filling jet of limited width or without breaking bars

Gate openings with filling jet of limited width or without breaking bars		
Name of variable	Description	Unit
DP	<p>Table with height of filling jet as function of water level in lock chamber</p> <p>Especially at the beginning of the filling process the breaking bars might not provide enough resistance to properly spread the filling jet in the vertical direction. It is also possible to extent the breaking bars well above the upper side of the gate openings, or even extending out of the water (for example the Prinses Irenesluis near Wijk bij Duurstede, the Netherlands). The height of the filling jet can thus be defined as a function of the water level in the lock chamber.</p>	[m]
<b>Without breaking bars</b>		
ZHP	<p>Level of underside of the gate openings</p> <p>This defines the underside of the filling jet.</p>	[mCD]



**Figure 6.2:** Schematic of gate openings of limited width or without breaking bars and asymmetric position of ship in lock chamber.



**Figure 6.3:** Overview of the implementation of different shapes of gate openings in LOCK-FILL and curves of the width of the opening under the edge of the sluice gate and of the resulting surface area of the opening, both as functions of the vertical position of the sluice gate.

## 6.2 Culverts with stilling chamber

This method models a levelling system that consists of culverts and a stilling chamber in the upper head and culverts with valves through the lower head for emptying. The schematisation applies specifically to the levelling system used in the Maasbracht lock complex and navigation locks based on this system, for example in the lock complexes of Born and Heel. The necessary variables to define this levelling system are given in [Table 6.3](#).

These methods are suited to overcome large differences in water level (at Maasbracht the head difference is over 11 m). It consists of two culverts at the upper head that flow into a stilling chamber where the kinetic energy of the flowing water is reduced using breaking bars and the flow is directed into the lock chamber by large vanes. Inside the culverts there are valves present to control the flow rate.

Emptying is also done by culverts that go through the lower head and around the lower gates. The culverts are assumed to flow out into the approach harbour in front of the gates. A schematic overview of system with culvert and a stilling chamber is shown in [Figure 6.4](#).

Although this method was designed to model the Maasbracht system, it can be applied to similar levelling systems. In case there is no stilling chamber, but the culvert outlets are directed towards each other at the upper head (for example the Noordersluis at IJmuiden) it is possible to adjust this method to give a good estimate. However, the results should be interpreted with caution and is dependent on the quality of the hydraulic design of the levelling system. This option is not suited for longitudinal filling systems which have culvert outlets over the entire length of the lock chamber.

When culverts are used, the inertia of the water in the culverts is taken into account and thus the effect of the so called overtravel. The discharge coefficient is replaced by loss coefficients to be more in line with literature on loss coefficients in pipe flow systems.

It is possible to model up to sixteen different culverts. 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. The derivation of the flow rate through the culverts into the lock chamber and the water levels is given in [section E.2](#). The water levels are calculated using the same method as gate openings.

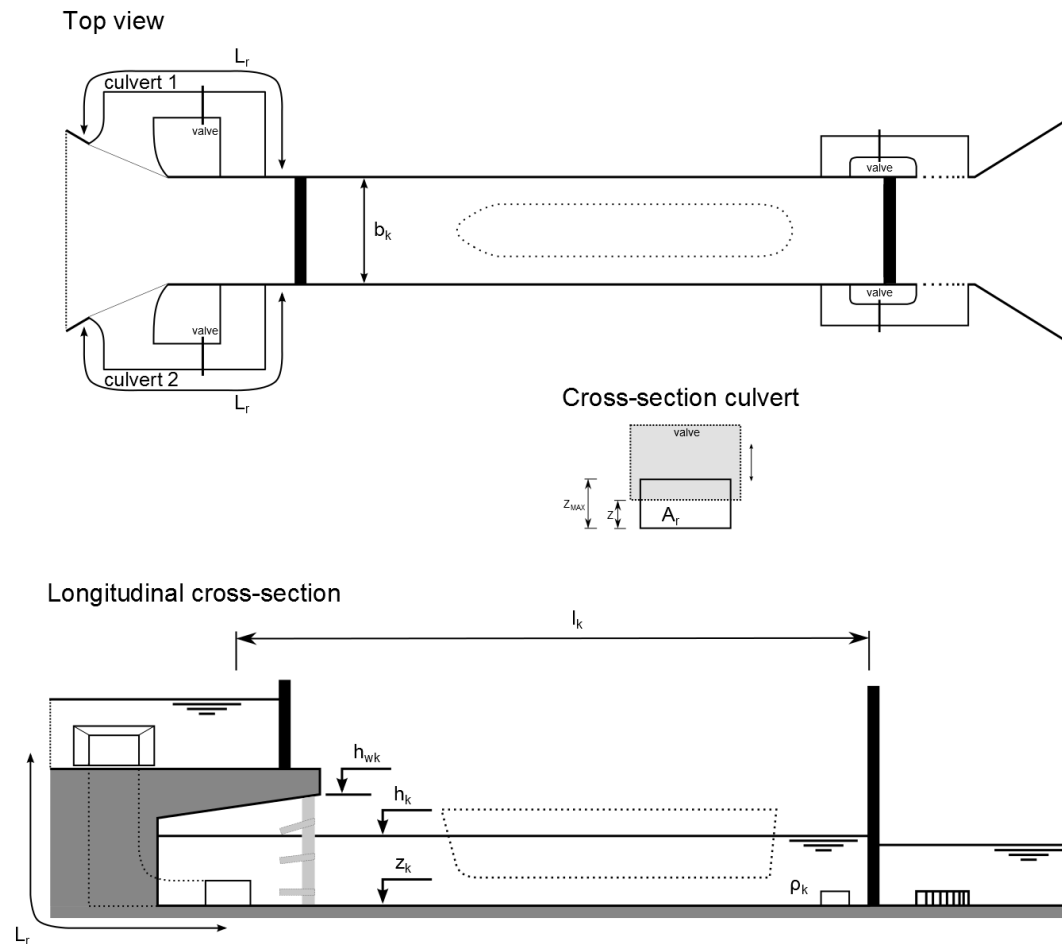
**Table 6.3:** Variables to define the levelling system culverts with stilling chamber

Culverts		
Name of variable	Description	Unit
NHR	Number of culverts (1 up to 16)  In LOCKFILL it is possible to define one sixteen culverts. Two culverts in combination with a stilling chamber correspond to the usual design of the Maasbracht-type navigation locks common in the Netherlands.  The asymmetry in the inflow in the lock chamber when filling with only one side culvert is not taken into account in the calculation.	[-]
HWOEL	Level of stilling chamber ceiling	[mCD]

continued on next page

**Table 6.3:** Variables to define the levelling system culverts with stilling chamber

<b>Culverts</b>		
<b>Name of variable</b>	<b>Description</b>	<b>Unit</b>
<b>Culvert x (x is the culvert number, these variables have to be defined for each culvert)</b>		
LRx	Length of culvert x  The hydraulic length of the culvert from intake to outfall in the stilling chamber.	[m]
ARx	Cross sectional area of culvert x  The cross section of the culvert. If the cross section varies it has to be averaged to obtain a representative cross section that gives a good prediction of the flow rate and inertia effects.	[m <sup>2</sup> ]
KSIRx	Residual resistance coefficient of culvert x  Summation of all resistance coefficients (of the intake, outfall, bends, etc.) except the resistance over the sluice gate.	[-]
ZHMAXRx	Maximum valve height of culvert x  Maximum height of the sluice gate.	[m]
VHRx	Table of valve lift velocity culvert x  Lift velocity of the sluice gate as a function of time.	[m.s <sup>-1</sup> ]
KSIHx	Table with loss coefficient as function of valve height of culvert x  Loss coefficient of the valve as a function of the height of the valve.	[-]
HDRx	Level of centreline of culvert opening at downstream side  This parameter defines the average level of all gate openings. It is used in the calculation of the flow rate in case of a density difference between lock chamber and approach harbour.	[mCD]



**Figure 6.4:** Schematic of a lock with culverts and stilling chamber

### 6.3 Butterfly valves

Instead of using gate openings closed off with sluice gates it is also possible to use butterfly valves. An example is the Pierre Vandammesluis at Zeebrugge. To limit the number of valves the diameters of the valves will be maximized, leading to very short tubes with a length approximately equal to the diameter.

The resistance of a butterfly valve decrease very slowly from closed position ( $90^\circ$ ) to approximately  $50^\circ$ , leading to a low flow rate. After this angle the resistance decrease faster leading to a larger increase in flow rate. Even at completely opened valves, the presences of the valves in the tubes still cause some resistance. Because of this resistance pattern it is advised to change the turning velocity of the valve during the levelling process. To decrease the resistance it is advised to round off the inlet to the tube. LOCKFILL assumes there are breaking bars present at the downstream side of the tubes to spread the flow rate.

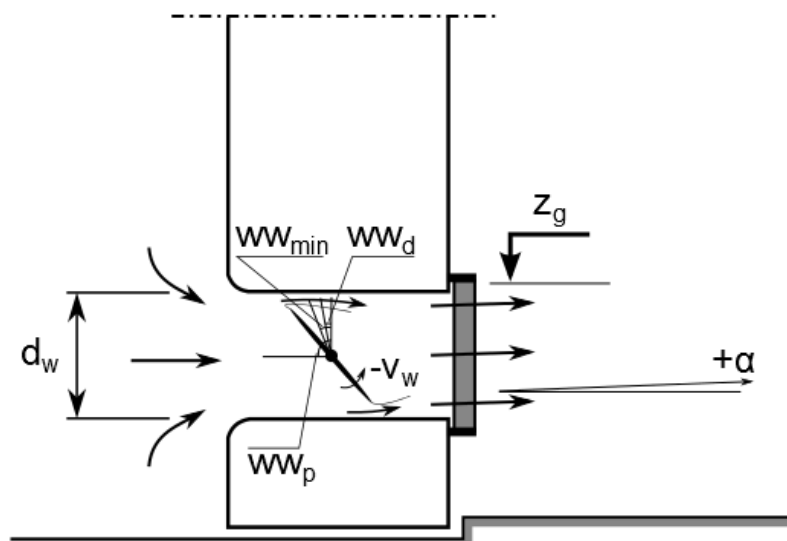
The resistance of butterfly valves is usually given as a resistance coefficient ( $\xi$ ) as function of the valve position by the manufacturer. However, these values of the resistance only apply when the butterfly valve is placed in a long tube and does not include the effect of breaking bars. When it is used for levelling a navigation lock, the tube length might be as small as the tube diameter and there might also be breaking bars present. So the values supplied by the manufacturer cannot be simply applied. Therefore LOCKFILL uses a discharge coefficient of the tube cross-section as a function of the valve position. In [Vrijburcht \(1994a\)](#) a relation between the resistance coefficient of a butterfly valve in a long tube and the discharge coefficient

of a butterfly valve in a short tube with a round off at the upstream side and no breaking bars was established. This relation is given by

$$\mu = \frac{1}{1 + \sqrt{\xi}} \quad (6.2)$$

This relation will differ for an even shorter tube with breaking bars. However, this has to be investigated per case.

<b>Butterfly valves</b>		
<b>Name of variable</b>	<b>Description</b>	<b>Unit</b>
NW	Number of tubes  The number of butterfly valves in one head. It is assumed that the openings are well divided over the width of the lock chamber.	[-]
DW	Inner diameter of tubes  It is assumed that all valves have the same diameter.	[m]
WWD	Angle at which valve is closed  The angle at which the valve is completely closed.	[°]
WWP	Angle at which valve is opened  The minimum possible angle of the valve.	[°]
WWMIN	Minimum valve angle  The minimum angle to which the valve is rotated. This value cannot be larger (in absolute values) than the minimum possible angle wwp.	[°]
VW	Table with valve velocity as function of time  Angular velocity (°/s) of the valve as a function of time.	[° .s <sup>-1</sup> ]
MW	Table of discharge coefficient as function of valve position  The discharge coefficient as a function of valve position. This value can be roughly estimated from factory specified loss coefficients using <a href="#">Equation 6.2</a> applying corrections for the limited tube length and the presence of breaking bars.	[-]
ALFA	Angle of filling jet  Similar to ALFA in <a href="#">section 7.1</a> .	[°]
ABB	Surface area of filling jet behind breaking bars  Similar to ABB in <a href="#">section 7.1</a> .	[m <sup>2</sup> ]
ZG	Level of top of filling jet behind breaking bars  Similar to AG in <a href="#">section 7.1</a> .	[mCD]



**Figure 6.5:** Schematic of a butterfly valve in LOCKFILL.

#### 6.4 Shutter slides

Shutter slides consist of a series of gate openings above each other (mostly two) which are opened by the same number of coupled sluice gates. The gate openings are located between the cross members. A few advantages of this type of gate openings is that the structure of the lock gate is not impaired, that only one operating mechanism is needed per series of gate openings and the gate openings give a vertical distribution of the filling jet. This type of gate openings is usually applied in mitre gates with one to three series of openings per gate. An example of a navigation lock with shutter slides is the Noordersluis in Utrecht, the Netherlands.

This configuration leads to a series of jets entering the lock chamber above each other. Thus there is immediately some vertical spreading. When applied in mitre gates it is advised to use multiple series of openings per gate to prevent the formation of a narrow filling jet in the middle of the lock chamber. Because the height of the openings is small the lift velocity of the sluice gates has to be low to prevent a rapid increase in the flow rate entering the lock.

In comparison with the 'standard' gate openings LOCKFILL uses a different method to calculate the surface area of the gate openings and dimensions of the filling jet. Furthermore, the user can choose between the normal vertical spreading of the filling jet or horizontal spreading.

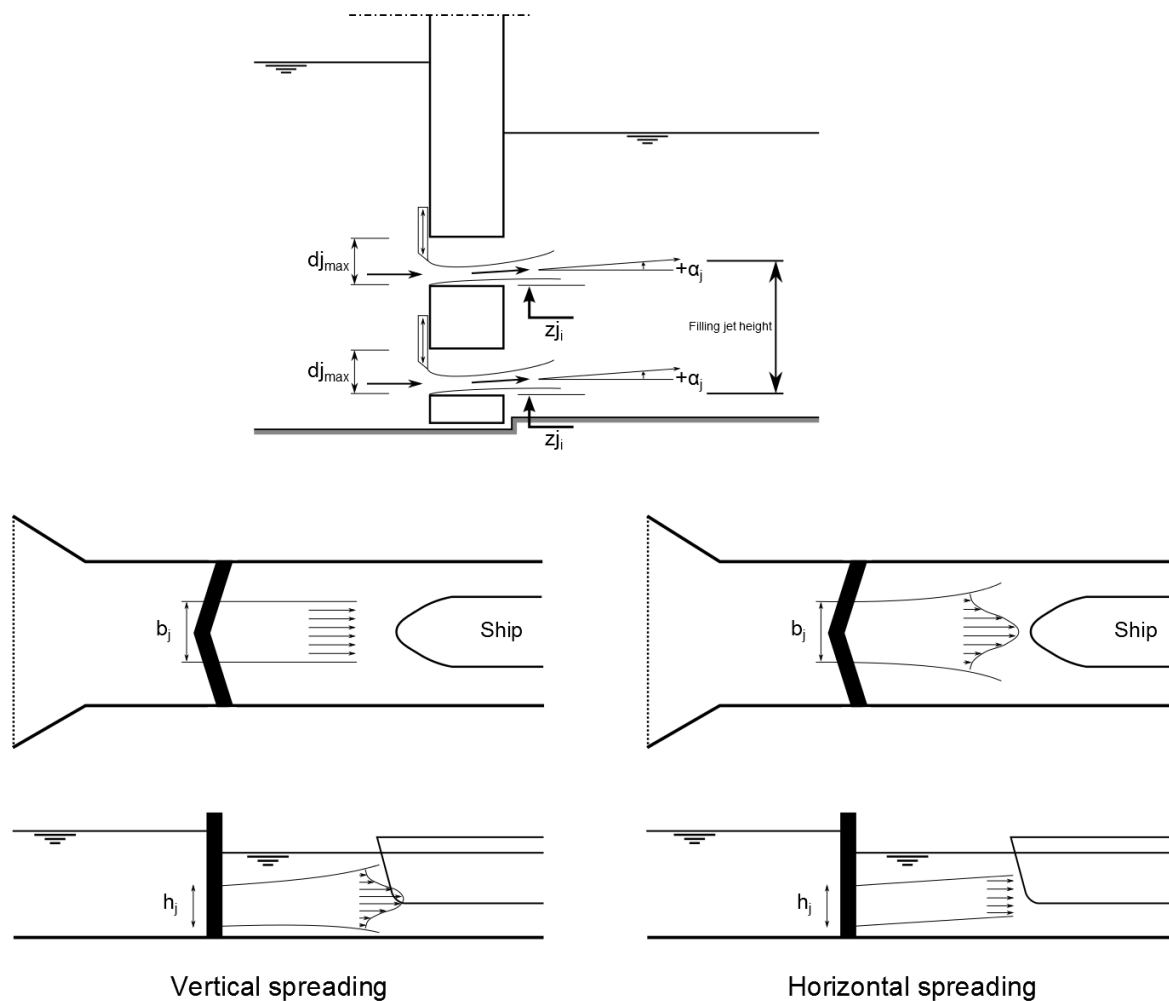
LOCKFILL assumes that the gate openings placed next to each other are identical so they can be schematised into one gate opening (similar to the 'standard' gate openings). The user can input the properties for each row of openings. LOCKFILL can calculate up to a maximum of five opening above each other.

In the horizontal direction the width of the filling jet is equal to the width of the gate openings combined. In the vertical direction the multiple jets emerging from the gate openings are schematised as one jet with a height from the top of the top gate opening to the underside of the bottom gate opening. The user can choose to specify vertical spreading or horizontal spreading. In the first case the filling jet is restricted by the lock chamber bottom and the water surface and in the latter case by the lock chamber walls.

<b>Shutter slides</b>		
<b>Name of variable</b>	<b>Description</b>	<b>Unit</b>
SPREIDJ	Choose if the filling jet spreads in the horizontal or vertical direction 0: Horizontal 1: Vertical  It depends on the geometry and positions of the gate openings which option should be applied. It is advised to check the sensitivity by calculating for both options.	[-]
ALFJ	Angle of filling jet  Similar to ALFA in <a href="#">section 7.1</a> .	[°]
VJ	Table of gate velocity as function of time  Similar to VHD in <a href="#">section 7.1</a> .	[m.s <sup>-1</sup> ]
NJ	Number of openings in vertical direction (maximum of 5)  Only one opening is similar to 'standard' gate openings.	[-]
<b>Opening 1</b>		
DJMAX1	Maximum height of gate opening	[m]
ZJI1	Initial level of underside sluice gate at the downstream side.	[mCD]
BJ1	Table with width of gate opening as function of gate height of opening 1	[m]
MUJ1	Table with discharge coefficient as function of gate height of opening 1	[-]
<b>Opening 2</b>		
DJMAX2	Maximum height of gate opening	[m]
ZJI2	Initial level of underside sluice gate	[mCD]
BJ2	Table with width of gate opening as function of gate height of opening 2	[m]
MUJ2	Table with discharge coefficient as function of gate height of opening 2	[-]
<b>Opening 3</b>		
DJMAX3	Maximum height of gate opening	[m]
ZJI3	Initial level of underside sluice gate	[mCD]
BJ3	Table with width of gate opening as function of gate height of opening 3	[m]
MUJ3	Table with discharge coefficient as function of gate height of opening 3	[-]
<b>Opening 4</b>		
DJMAX4	Maximum height of gate opening	[m]
ZJI4	Initial level of underside sluice gate	[mCD]
BJ4	Table with width of gate opening as function of gate height of opening 4	[m]
MUJ4	Table with discharge coefficient as function of gate height of opening 4	[-]

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Shutter slides		
Name of variable	Description	Unit
<b>Opening 5</b>		
DJMAX5	Maximum height of gate opening	[m]
ZJI5	Initial level of underside sluice gate	[mCD]
BJ5	Table with width of gate opening as function of gate height of opening 5	[m]
MUJ5	Table with discharge coefficient as function of gate height of opening 5	[-]



**Figure 6.6:** Schematic of shutter slides and the two types of spreading available.

## 6.5 Vertical slit – Not available in public release

Besides levelling through openings in the lock gates or culverts around the lock gates it is also common to level a navigation lock by slightly opening the lock gates themselves to let water flow past the gates into the lock chamber. Three gate types can be used, a rolling gate, mitre gates and a single leaf gate.

Using the width of the slit, bottom levels and water levels of lock chamber and approach harbour the net surface area of the slit can be calculated. Using the method presented in paragraph 6.4 of [Vrijburcht \(1994b\)](#) the flow rate through the vertical slit is calculated. The flow rate induced by the gate movement is taken into account in this method. Water level

variations near the gate are not taken into account and neither the decreased reflection of translator waves when the gate is opened. Although it is possible to take a density difference into account, the calculation method is not changed while in reality the flow will differ from the situation with gate openings.

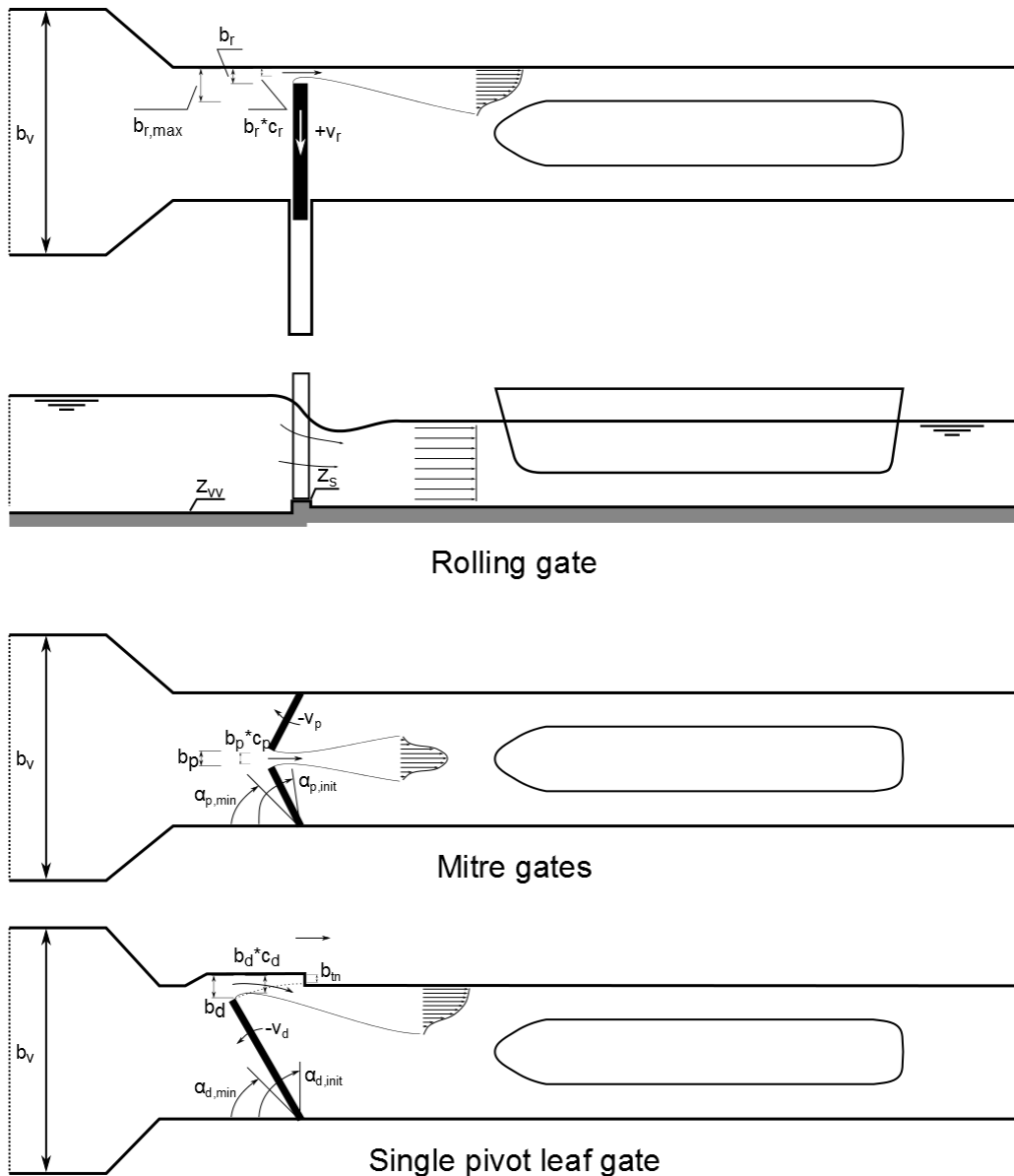
The user is warned that this method is highly schematised. When applied on small water level differences and small gate velocities the results are reasonably reliable. For larger water level differences and/or higher gate velocities the results can only be used qualitatively.

A summary of the calculation method presented in [Vrijburcht \(1994b\)](#) is given in [section E.3](#).

<b>Vertical slit</b>		
<b>Name of variable</b>	<b>Description</b>	<b>Unit</b>
BV	Width of approach harbour  In front of the lock gate.	[m]
ZVV	Bottom level of approach harbour at vertical slit  In front of the lock gate.	[mCD]
ZS	Bottom level of vertical slit  The bottom level under the lock gate	[mCD]
DEUR_TYPE	Choose the gate type 1: Rolling gate 2: Mitre gate 3: Single leaf gate	[-]
<b>Rolling gate</b>		
BRMAX	Maximum width of slit  Defines how far the gate is opened during the levelling, not the total width of the lock head.	[m]
VR	Table with gate velocity as function of time	[m.s <sup>-1</sup> ]
CR	Table with contraction coefficient as function of gate position  Similar to the discharge coefficient in gate openings.	[-]
<b>Mitre gate</b>		
INUITP	Choose if the gates point into or out of the lock chamber 1: Gates point inwards 2: Gates point outwards	[-]
APINIT	Angle at which the gates are closed  The initial angle the gates make when they are in closed position.	[°]
APMIN	Minimum gate angle  The angle at which the gates are maximally opened during levelling.	[°]

continued on next page

<b>Vertical slit</b>		
<b>Name of variable</b>	<b>Description</b>	<b>Unit</b>
VP	Table with gate velocity as function of time  The turning velocity of the gates in $^{\circ}.\text{s}^{-1}$ .	$[^{\circ}.\text{s}^{-1}]$
CP	Table with contraction coefficient as function of gate position	[-]
<b>Single pivot leaf gate</b>		
INUITP	Choose if the gates point into or out of the lock chamber 1: Gates point inwards 2: Gates point outwards  With respect to the lock chamber. This is important for the calculation of the flow rate.	[-]
BTN	Minimum distance between front hinge and gate recess  This parameter is used in calculating the size of the gap through which is being levelled.	[m]
ADINIT	Angle at which the gate is closed  The angle the gate makes at the closed position, when the gate is at this position BTN should be estimated.	$[^{\circ}]$
ADMIN	Minimum gate angle  The angle at which the gate is maximally opened during levelling.	$[^{\circ}]$
VD	Table with gate velocity as function of time  The turning velocity of the gates in $^{\circ}.\text{s}^{-1}$ .	$[^{\circ}.\text{s}^{-1}]$
CD	Table with contraction coefficient as function of gate position	[-]



**Figure 6.7:** Schematic of the vertical split for different gate types.

## 6.6 Lift gate

The option to level using a lift gate was specifically developed to be able to calculate the filling process of the old filling system of the navigation lock at Eefde, the Netherlands (also see [Vrijburcht \(1995\)](#)). This navigation lock had a design in which filling of the lock chamber was achieved by lifting the upper gate in combination with a stilling chamber. This system is not in use anymore and replaced by a system with gate openings that lead the flow into the stilling chamber without lifting the gate.

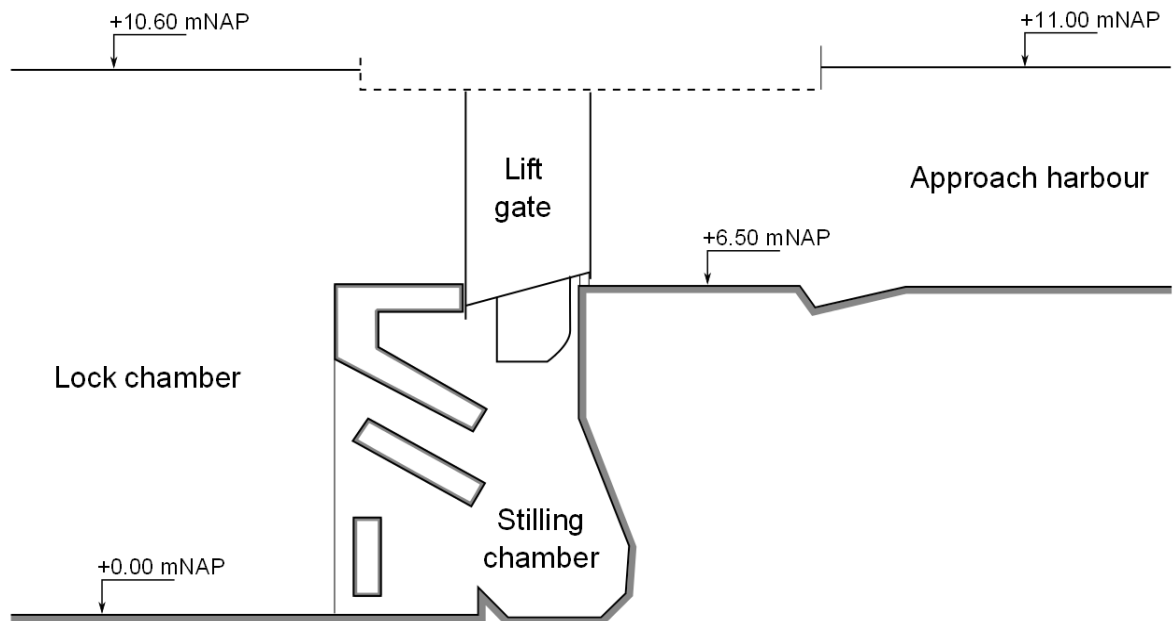
In the old filling process three regimes can be identified. In the first the water level in the lock chamber is below the top of the stilling chamber and the flow rate depends on the level difference between the opening below the gate to the stilling chamber and the water level in the approach harbour. As the water level in the lock chamber reaches the first transitional level, the flow rate is partly dependent on the level difference between the opening below the gate and the approach harbour and partly on the water level difference between lock chamber and approach harbour. When the water level in the lock chamber has reached the second

transitional level the flow rate is solely dependent on the water level difference between lock chamber and approach harbour. It is not possible to take density differences into account in this option. The derivation of the flow rate through the lift gate is given in [section E.4](#).



**Note:** *This option is only applicable to navigation locks similar to the Eefde navigation lock. A lift gate without stilling chamber can be modelled by defining gate openings similar to the gap below the lift gate.*

Lift gate		
Name of variable	Description	Unit
DEEMAX	Maximum lift height of gate	[m]
BE	Width of slit under gate	[m]
VE	Table with maximum lift heights and lift velocities as function of water level in the lock chamber.	[m]/[m.s <sup>-1</sup> ]/[mCD]
SE	Table with slit height as function of lift height	[m]/[m]
MUE	Table of discharge coefficient as function of relative lift height	[-]
ZSEI	The initial outflow level	[mCD]
ZE1	Lock chamber water level at which the first transition between formulations occurs	[mCD]
ZE2	Lock chamber water level at which the second transition between formulations occurs	[mCD]
BWE	Width of jet	[m]
XWE	Distance between start of filling jet and lock chamber side of gate	[m]
ALFW	Angle of filling jet as function of lock chamber water level	[°]/[mCD]
DWE	Height of filling jet as function of lock chamber water level	[m]/[mCD]
ZWE	Level of underside filling jet as function of lock chamber water level	[mCD]/[mCD]



**Figure 6.8:** Schematic of the lift gate and stilling chamber in the navigation lock at Eefde, the Netherlands.



## 7 Other options

LOCKFILL offers two additional options for specific purposes. Both are only available for the 'standard' gate openings. The first is to calculate the bottom velocities behind the gate openings. This option is activated with the *BODEM\_V* parameter in the input file. The second option is to automatically calculate the lift velocity of the sluice gates using a predefined force criterion. This option is activated using the parameter *PROMILLAGE* in the input file.

Mode	
Name of variable	Description
BODEM_V	Choose if LOCKFILL has to calculate the velocities at the bottom behind the gate openings (only usable if SYSTYPE=1, i.e. gate openings) 0: No 1: Yes
PROMILLAGE	Choose if LOCKFILL has to automatically calculate a maximum sluice gate lift velocity (only usable if SYSTYPE=1, i.e. gate openings) 0: No 1: Yes

### 7.1 Calculate bottom velocities

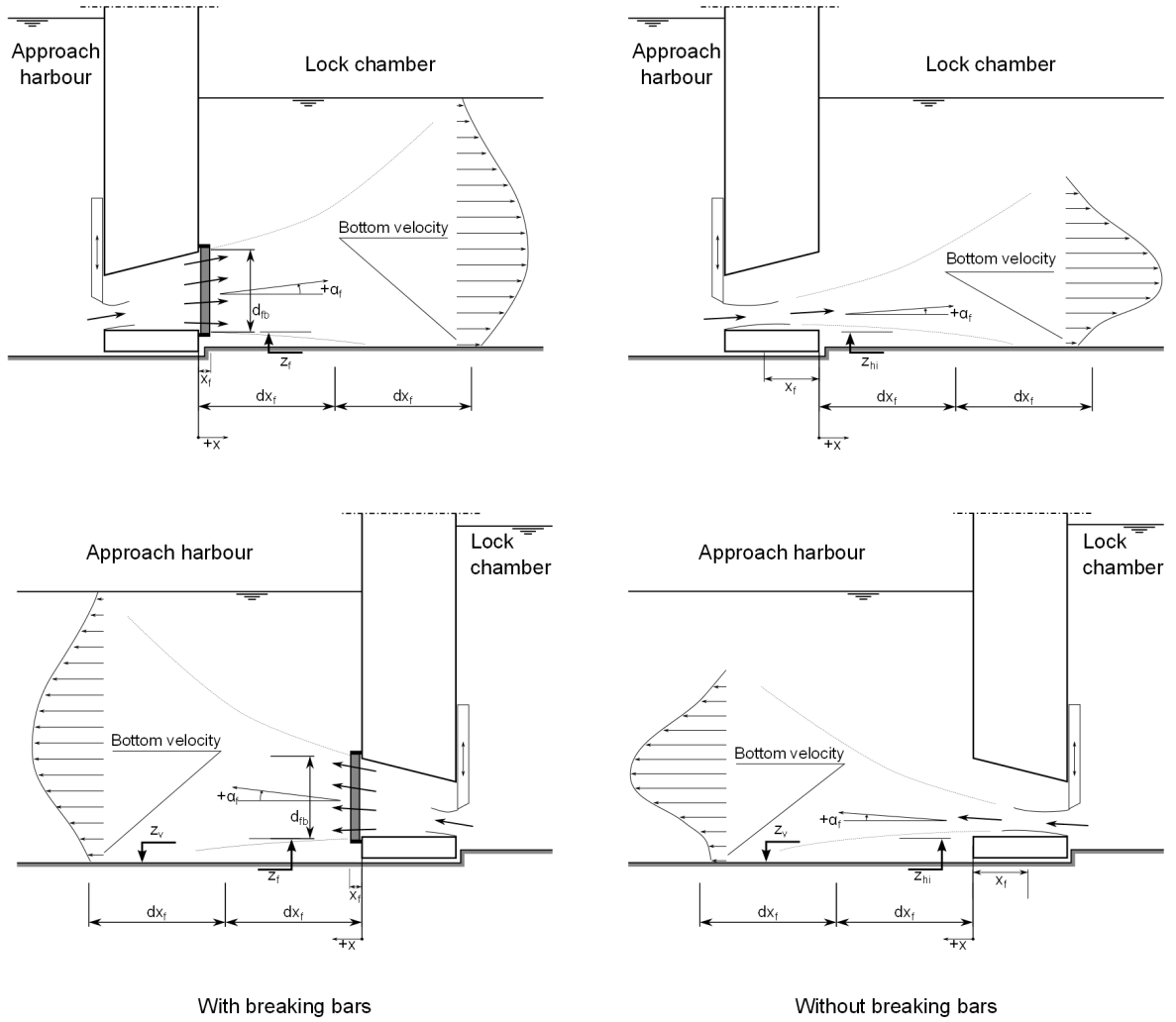
For the calculation of the bottom velocities, the same schematisation of the filling (or emptying) jet is assumed as in the calculation of the longitudinal forces. Instead of calculating the flow rate at the bow of the ship, the velocities at the bottom are calculated using the schematised jet profile. The bottom velocities are calculated at six positions behind the lock gate with an equal distance between each position. These positions can be changed by the user. It must be noted that the bottom velocities reported by LOCKFILL are average velocities. No turbulence intensity is calculated although this intensity will most likely be high, especially right behind the breaking bars. Only spreading in the vertical direction is taken into account.

Bottom velocities		
Name of variable	Description	Unit
XF	Start of filling jet with respect to the downstream side of the gate  When breaking bars are present the origin of the filling jet is defined just after the breaking bars. If there are no breaking bars present, the filling originates at the point of maximum contraction. If the sluice gates are at the upstream side of the gate this position will probably be inside the gate opening and if the sluice gates are at the downstream side this position will be at the downstream side, inside the lock chamber.	[m]
DXF	Horizontal distance between output locations  This is the distance between downstream side of the gate and the first location at which the bottom velocities is calculated and the distance between the subsequent locations.	[m]

continued on next page



<b>Bottom velocities</b>		
<b>Name of variable</b>	<b>Description</b>	<b>Unit</b>
ALFF	Angle of filling jet  Similar to ALFA in <a href="#">section 7.1</a> .	[°]
BREEKB	Are there breaking bars present at the outflow side of the gate openings? 0: No 1: Yes	[-]
<b>Without breaking bars</b>		
ZHI	Level underside of gate opening  Underside of the opening at the downstream side.	[mCD]
<b>With breaking bars</b>		
DFB	Height of filling jet  Vertical dimension of the filling jet behind the breaking bars.	[m]
BFB	Width of filling jet  Width behind the breaking bars.	[m]
ZF	Level underside jet  Underside of the filling jet behind the breaking bars.	[mCD]
<b>In case of emptying</b>		
ZV	Bottom level of approach harbour behind the gate openings	[mCD]



**Figure 7.1:** Schematic of the calculation of bottom velocities

## 7.2 Calculation of lift velocity for predefined criterion

This option calculates the maximum possible lift velocity (and in the case of emptying also the maximum lifting height) of the sluice gates for a given (by the user) criterion as permillage of the ships displacement, the variable PROM in the input file. This option can only be used in combination with the 'standard' gate openings described in [section 7.1](#). All other parameters will not be varied.

The lift velocity is calculated using an iterative process. The first calculation uses the lift velocity given by the user. From the resulting longitudinal force and the permillage criterion a factor is calculated. The lift velocity is multiplied by this factor resulting in a new longitudinal force and a new factor. This factor is calculated as follows;

$$f_{new} = 0.2f_{old} + 0.8 \frac{\%_{crit}}{F_{max}} f_{old} \quad (7.1)$$

$f_{new}$  and  $f_{old}$  are the new and old factors,  $\%_{crit}$  is the permillage criterion set by the user and  $F_{max}$  is the absolute value of the calculated maximum longitudinal force.

The criterion will be calculated up to an accuracy of 2 %. A maximum of 15 iterations will be performed. If the user supplies multiple lift velocities in the input, the entire table for the lift velocity will be multiplied by the same factor and the time of the entries will not change.

When emptying, not only the lift velocity of the sluice gates will be changed, but also the maximum lifting height. The calculation is also done using an iterative process similar to the method during filling; the lift velocity and lifting height both have their own respective factors which differ from the previous formulation.

Because the iteration process is more complicated because two variables are varied, the criterion will be calculated up to an accuracy of 4 %.

<b>Promillage</b>		
<b>Name of variable</b>	<b>Description</b>	<b>Unit</b>
PROM	Desirable permillage at end of iteration	[‰]

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- Vrijburcht, A., et al, 1988. *Langskracht op een schip door de vulstraat in een sluis stand van zaken van de berekeningen*. Tech. rep., Waterloopkundig Laboratorium.





## A Appendix

In this appendix an example of a LOCKFILL calculation of a simple (fictional) lock will be given. The geometry of the lock is based on a lock type that is very common in the Netherlands, a lock with mitre gates and levelling openings in the gates with breaking bars.

### A.1 Drawings

The geometry of the lock is most easily obtained from construction drawings. These drawings usually contain a lot of information, however only a limited amount is necessary for the LOCKFILL calculation. The sketches from [Figure A.1](#) and [Figure A.3](#) show the most relevant dimensions of the lock that are important for the calculation. The user should try to obtain at least these dimensions from the technical drawings.

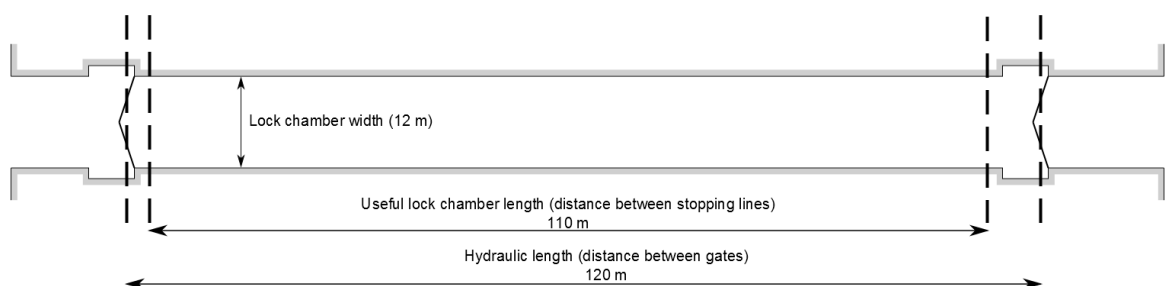
**Note:** The location of the stop lines are not always shown on the drawings. If they are it is easy to measure the distance between the stop lines and the gates. In the case of mitre gates the location of the gate is halfway the triangle formed by the gate, as shown in [Figure A.1](#). If the stop lines are not on the drawing, the user has to estimate the distance, for example by using pictures. Beware that the distance is not always the same when filling and emptying, especially not when using mitre gates because of the gate recesses.

**Note:** In this case the lock is relatively simple, having straight walls and well defined water levels. However, the user could also encounter locks with walls that are not straight or have a concrete skirt at the upper part of the lock chamber. To get a good measure of the levelling times, the user should choose the lock dimensions in such a way that the exchanged volume during locking is the same. For the forces it is important to choose the same hydraulic length and width.

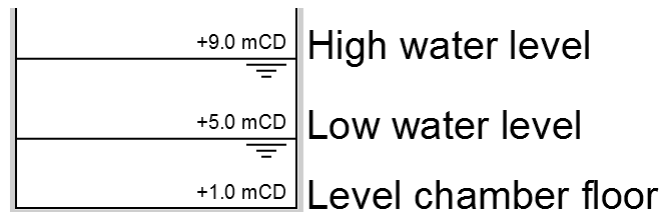
**Note:** It is also possible to have levelling gates that are not square, but have a changing width. This can be defined in LOCKFILL as shown in [Figure 6.3](#).

**Note:** In tidal areas the water levels are not constant, so the user has to find the normative conditions that can occur.

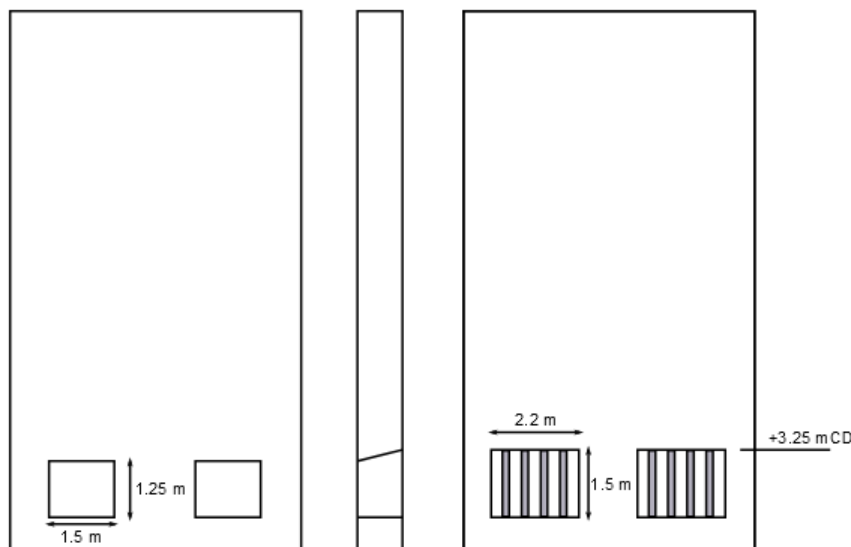
**Note:** In the case of a levelling system with culverts, the dimensions of the culvert system need to be known.



**Figure A.1:** Top view of the lock with some relevant dimensions.



**Figure A.2:** Cross-section of the lock showing some relevant parameters.



**Figure A.3:** Frontal view, cross-section and back view of the lock gates including some relevant dimensions.

## A.2 Other relevant data

A few relevant parameters cannot be obtained from drawings, these are the lift velocity of the sluice gates and the discharge coefficient of the gate openings (as a function of sluice gate height).

In the case of an existing lock, this data can sometimes be obtained from design reports. If that is not the case, measurements can be performed at the lock. The discharge coefficient can also be approximated using literature and expert judgment. This however leads to a lower level of accuracy. It is therefore advised to perform calculations for a certain range of discharge coefficients.

In this example the values of the parameters are:

- ◇ Lift velocity of sluice gates
  - 0.005 m/s
- ◇ Discharge coefficient
  - 0,7-0,65

Note: In a levelling system using culverts, the user needs to obtain values for the resistance coefficient. This value is divided in a constant value, belonging to the bends, inlets and outlets and a time dependent value belonging to the levelling gate. These values are preferably

obtained from scale model or prototype measurements, but can be estimated using literature.

### A.3 Normative ship

In the calculation of the forces it is important to choose the correct ship type. Usually the biggest ship that passes the navigation lock is also the normative ship in terms of longitudinal forces, but it is good practice to also perform calculations using a smaller ship. Especially in the case of large transitory waves as the length of the ship may coincide with half a wave length of the transitory waves.

In this example we will use a standard CEMT-IV ship, a so called Rhine-Herne Canal ship. The following dimensions of the ship are used:

Length 80 m  
 Width 9.45 m  
 Draft 2.8 m  
 Displacement 1650 ton  
 Force criteria  
     filling 1.1 ‰  
     emptying 1.5 ‰

The distance between the bow and the levelling gate is obtained from the distance between the stop lines and the gates.

### A.4 Input file

Now that the necessary input parameters are known, the input file can be made. After starting LOCKFILL, choose the option *New from template* and select the file *template\_gateopenings*. Save the new input file in the desired location with the desired name. Now choose the option *Edit input file* to change the input parameters using the information obtained from the drawings above. The resulting input file is shown below and the results are shown in [Figure A.4a](#) and [Figure A.4b](#).

**Table A.1:** Contents of the input file of the example calculation.

LOCKFILL 5
INFO
TITLE = 'Calculation title'
PROJNUM = '1234567890' \\Project number
PROJTIT = 'Project title' \\Project title
COMP = 'Company name' \\Company name
Comment: Example case for the LOCKFILL manual
APPROACH HARBOUR
RHO_VOORH = 1000 \\density approach harbour [kg/m <sup>3</sup> ]
VOORH = 1 \\water level approach harbour; 1: basin storage method, 2:time table
Basin storage method
SV = 1000 \\surface area approach harbour [m <sup>2</sup> ]

HV = 9.0 \initial water level approach harbour [mCD]

Time table

HF = [0.0 9.0

900.0 9.0] \water level approach harbour as function of time; time [s], water level [mCD]

---

## LOCK CHAMBER

---

HK = 5.0 \initial water level lock chamber [mCD]

RHOK = 1000 \water density lock chamber [kg/m<sup>3</sup>]

LK = 120.0 \length lock chamber [m]

BK = 12.0 \width lock chamber [m]

ZK = 1.0 \level lock chamber bottom [mCD]

KI = 0.005 \Nikuradse roughness lock chamber walls and bottom [m]

---

## FILLING AND EMPTYING SYSTEM

---

SYSTYPE = 1 \levelling system type; 1: gate openings, 2: culverts with stilling chamber, 3: vertical slit, 4: butterfly valves, 5: shutter slides, 6: lift gate

1: gate openings

ZHMAXD = 1.25 \maximum height of opening [m]

VHD = [0.0 0.0035

900.0 0.0035] \lift velocities sluice gates as function of time; time [s], lift velocity [m/s]

BH = [0.0 6.0

1.0 6.0] \total width of all combined gate openings as function of relative lift height; relative lift height [-], width gate openings [m]

MUH = [0.0 0.70

1.0 0.65] \discharge coefficient as function of relative lift height; relative lift height [-], discharge coefficient [-]

1: gate openings or 4: butterfly valves

ALFA = 0.0 \angle of filling jet with horizontal [°]

ABB = 13.2 \surface area of filling jet behind breaking bars [m<sup>2</sup>]

ZG = 3.25 \level of top of filling jet behind breaking bars [mCD]

---

## SHIP

---

MS = 1650000 \ship mass [kg]

LS = 80 \ship length [m]

BS = 9.45 \ship breadth [m]

TS = 2.8 \ship draft [m]

KII = 0.005 \Nikuradse roughness ship hull [m]

XS = 3 \distance between bow and lock gate [m]

BETA = 90 \bow angle in vertical plane [°]

GAMMA = 45 \bow angle in horizontal plane [°]

---

## MODE

---

DELTA\_RHO = 0 \presence of density difference; 0: no, 1: yes

PROMILLAGE = 0 \\calculate lift velocity using a maximum permillage; 0: no, 1: yes  
 BODEM\_V = 0 \\calculate bottom velocities; 0: no, 1: yes

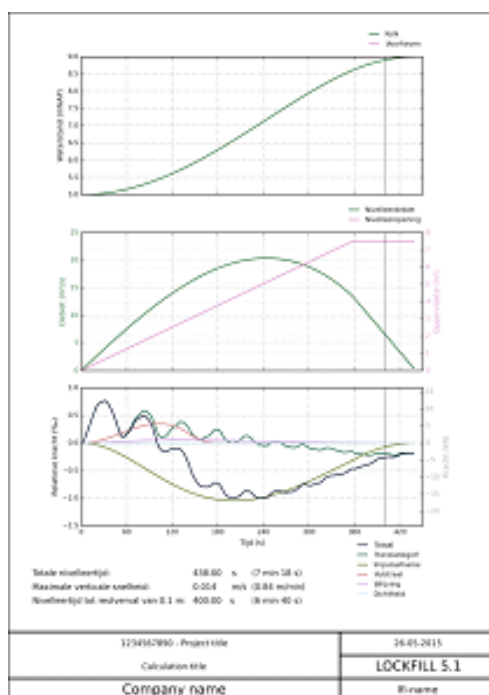
### SIMULATION PARAMETERS

TEND = 900 \\end time of calculation [s]

DT = 2 \\time step [s]

C1 = 0.90 \\coefficient pressure build up at bow [-]

C3 = 0.90 \\coefficient boundary layer development due to the flow profile at the stern [-]



(a) Graphical output of the example calculation.

Calculation has ended at t = 438.00 s  
 Lock chamber filled at t = 438.00 s  
 Head difference of 10 cm at t = 400.00 s

Flow rate:

- Qmax = 20.378 m<sup>3</sup>/s at t = 244.00 s
- Qmin = 0.000 m<sup>3</sup>/s at t = 0.00 s

Flow rate increase (dQ/dt):

- Max = 0.180 m<sup>3</sup>/s<sup>2</sup> at t = 2.00 s
- Min = -0.165 m<sup>3</sup>/s<sup>2</sup> at t = 438.00 s

Vertical velocity water level (dHk/dt):

- Max = 0.014 m/s at t = 244.00 s

Force due to transitory waves:

- Fgmax = 0.765 kN at t = 32.00 s
- Fgmin = -0.221 kN at t = 376.00 s

Force due to momentum decrease:

- Fimax = 0.000 kN at t = 0.00 s
- Fimin = -1.048 kN at t = 202.00 s

Force due to friction:

- Ffmax = 0.055 kN at t = 132.00 s
- Ffmin = 0.000 kN at t = 0.00 s

Force due to filling jet:

- Femax = 0.353 kN at t = 102.00 s
- Femin = 0.000 kN at t = 0.00 s

Total longitudinal force on moored ship:

- Ftmax = 0.765 kN at t = 32.00 s
- Ftmin = -1.006 kN at t = 234.00 s

(b) Summary of the example calculation.



## B List of variables

Approach harbour		
Name of variable	Description	Unit
RHO_VOORH	Water density in the approach harbour	[kg.m <sup>-3</sup> ]
VOORH	Choose if the water level in the approach harbour is calculated using the basin storage approach or that the water level is given in a table as function of time 1: Basin storage calculation 2: Table of time dependent water levels	
Basin storage		
SV	Surface area of the approach harbour In the case that a basin storage approach is chosen	[m <sup>2</sup> ]
HV	Initial water level of the approach harbour	[mCD]
Table of water levels		
HF	A table with the water levels of approach harbour as function of time	[mCD]

Lock chamber		
Name of variable	Description	Unit
HK	Initial water level in the lock chamber	[mCD]
RHOK	Water density in the lock chamber	[kg.m <sup>-3</sup> ]
LK	Length of the lock chamber	[m]
BK	Width of the lock chamber	[m]
ZK	Level of the lock chamber floor	[mCD]
KI	Nikuradse roughness of the lock chamber walls and floor	[m]

Gate openings		
Name of variable	Description	Unit
ZHMAXD	Maximum height of opening  The distance between the bottom and the top of a gate opening. During the calculation the height of the sluice gate is maximized by this distance. This makes it possible to simply define a constant lift velocity during the entire calculation, without having to calculate the end time of the lifting process.	[m]
VHD	Table with lift velocities as function of time  Because it is a function of time it is possible to define a certain lift programme in which the lift velocity changes in time. For example, using a low velocity at the beginning of the filling process can reduce the effect of the initial translatory wave.	[m/s]

continued on next page



<b>Gate openings</b>		
<b>Name of variable</b>	<b>Description</b>	<b>Unit</b>
BH	<p>The (total) upstream width of all gate openings combined as a function of the (dimensionless) gate height</p> <p>The gate height is made dimensionless using the maximum height of the opening. This means that the width can change during lifting of the sluice gates to accommodate certain shapes of the gate openings. Some examples of different shapes and the influence of these shapes on the surface area of the openings is given in <a href="#">Figure 6.3</a>. A different shape will influence the evolution of the flow rate during levelling and thus the resulting longitudinal forces.</p>	[m]
MUH	<p>Table with discharge coefficient as function of (dimensionless) gate height</p> <p>The discharge coefficient is not a constant during opening and dependent on the shape of the gate openings and the position of the sluice gates. This parameter is defined relative to the area under the sluice gate and includes the effect of the breaker bars. This parameter can best be obtained from scale model research. If that is not possible it can be estimated from scale model research on a similar geometry or by a hydraulic expert.</p>	[-]
ALFA	<p>Vertical angle of the filling jet</p> <p>The angle the filling jet makes with the horizontal when entering the lock chamber. This parameter is important for the force by the filling jet.</p>	[°]
ABB	<p>Surface area of the filling jet behind the breaking bars</p> <p>As it is assumed that the breaking bars are designed well, the resistance by the breaking bars will cause the filling jet to be divided over a larger area, assumed to be approximately equal to the area of the outflow of the gate, including the area covered by the breaking bars. This parameter is a measure of how well the filling jet is distributed over the height of the breaking bars. Although in reality this height will not be completely constant during the levelling process, it is assumed constant during the calculation.</p>	[m <sup>2</sup> ]

continued on next page

<b>Gate openings</b>		
<b>Name of variable</b>	<b>Description</b>	<b>Unit</b>
ZG	<p>Level of top of filling jet behind the breaking bars</p> <p>This parameter defines at what height the filling jet enters the lock chamber, which is important for the calculation of the force by the filling jet. It is assumed constant during the levelling process. This implies that the initial water level inside the lock is above the upper end of the breaking bars.</p>	[mCD]

<b>Gate openings with filling jet of limited width or without breaking bars</b>		
<b>Name of variable</b>	<b>Description</b>	<b>Unit</b>
YP	<p>Distance between axis ship and axis lock chamber</p> <p>This defines the off-centre position of the ship in the lock chamber. In case of a thin filling jet this will have a significant effect on the resulting force on the ship. Because of the rough schematisation of the shape of the bow it is advised to use this option carefully.</p>	[m]
XP	<p>Distance between start of filling jet and lock chamber side of gate</p> <p>When breaking bars are present the origin of the filling jet is defined just after the breaking bars. If there are no breaking bars present, the filling originates at the point of maximum contraction. If the sluice gates are at the upstream side of the gate this position will probably be inside the gate opening and if the sluice gates are at the downstream side this position will be at the downstream side, inside the lock chamber.</p>	[m]
ALFP	<p>Table with angle of filling jet as function of gate height</p> <p>Similar to the variable ALFA in <a href="#">section 6.1.2</a>, but it is possible to change this angle as a function of the gate height. This is a more accurate representation of reality as this angle usually changes because the average level of the upstream opening (under the sluice gates) changes when the gates are lifted.</p>	[°]
BREEKP	<p>Choose if there are breaking bars present</p> <p>When breaking bars are present the filling jet will be spread in the vertical direction. Without breaking bars the height of the filling jet is defined by the height of the sluice gates.</p>	[-]

continued on next page

<b>Gate openings with filling jet of limited width or without breaking bars</b>		
<b>Name of variable</b>	<b>Description</b>	<b>Unit</b>
<b>With breaking bars</b>		
BP	<p>Total width of filling jet</p> <p>The width of the filling jet depends on the position of the gate openings. Be reminded that only spreading in the vertical is taken into account. The width of the filling jet can be estimated by a hydraulic expert.</p>	[m]
ZP	<p>Level of underside of the gate openings</p> <p>This defines the underside of the filling jet.</p>	[mCD]
DP	<p>Table with height of filling jet as function of water level in lock chamber</p> <p>Especially at the beginning of the filling process the breaking bars might not provide enough resistance to properly spread the filling jet in the vertical direction. It is also possible to extent the breaking bars well above the upper side of the gate openings, or even extending out of the water (for example the Prinses Irenesluis near Wijk bij Duurstede, the Netherlands). The height of the filling jet can thus be defined as a function of the water level in the lock chamber.</p>	[m]
<b>Without breaking bars</b>		
ZHP	<p>Level of underside of the gate openings</p> <p>This defines the underside of the filling jet.</p>	[mCD]

<b>Culverts</b>		
<b>Name of variable</b>	<b>Description</b>	<b>Unit</b>
NHR	<p>Number of culverts (1 or 2)</p> <p>In LOCKFILL it is possible to define one or two culverts, which corresponds to the usual design of the Maasbracht-type navigation locks common in the Netherlands. A greater number of culverts will have to be carefully schematised to one or two culverts to be able to use this option.</p>	
HWOEL	Level of stilling chamber ceiling	[mCD]
<b>Culvert 1</b>		
LR1	<p>Length of culvert 1</p> <p>The hydraulic length of the culvert from intake to outfall in the stilling chamber.</p>	[m]

continued on next page

<b>Culverts</b>		
<b>Name of variable</b>	<b>Description</b>	<b>Unit</b>
AR1	Cross sectional area of culvert 1  The cross section of the culvert. If the cross section varies it has to be averaged to obtain a representative cross section that gives a good prediction of the flow rate and inertia effects.	[m <sup>2</sup> ]
KSIR1	Residual resistance coefficient of culvert 1  Summation of all resistance coefficients (of the intake, outfall, bends, etc.) except the resistance over the sluice gate.	[-]
ZHMAXR1	Maximum sluice gate height of culvert 1  Maximum height of the sluice gate.	[m]
VHR1	Table of sluice gate lift velocity culvert 1  Lift velocity of the sluice gate as a function of time.	[m.s <sup>-1</sup> ]
KSIH1	Table with loss coefficient as function of sluice gate height of culvert 1  Loss coefficient of the sluice gate as a function of the height of the sluice gate.	[-]
<b>Culvert 2</b>		
LR2	Length of culvert 2	[m]
AR2	Cross sectional area of culvert 2	[m <sup>2</sup> ]
KSIR2	Residual resistance coefficient of culvert 2	[-]
ZHMAXR2	Maximum sluice gate height of culvert 2	[m]
VHR2	Table of sluice gate lift velocity culvert 2	[m.s <sup>-1</sup> ]
KSIH2	Table with loss coefficient as function of sluice gate height of culvert 2	[-]

<b>Butterfly valves</b>		
<b>Name of variable</b>	<b>Description</b>	<b>Unit</b>
NW	Number of tubes  The number of butterfly valves in one head. It is assumed that the openings are well divided over the width of the lock chamber.	[-]
DW	Inner diameter of tubes  It is assumed that all valves have the same diameter.	[m]
WWD	Angle at which valve is closed  The angle at which the valve is completely closed.	[°]
WWP	Angle at which valve is opened  The minimum possible angle of the valve.	[°]

continued on next page

<b>Butterfly valves</b>		
<b>Name of variable</b>	<b>Description</b>	<b>Unit</b>
WWMIN	Minimum valve angle  The minimum angle to which the valve is rotated. This value cannot be larger (in absolute values) than the minimum possible angle wwp.	[°]
VW	Table with valve velocity as function of time  Angular velocity (°/s) of the valve as a function of time.	[°.s <sup>-1</sup> ]
MW	Table of discharge coefficient as function of valve position  The discharge coefficient as a function of valve position. This value can be roughly estimated from factory specified loss coefficients using Equation <a href="#">Equation 6.2</a> applying corrections for the limited tube length and the presence of breaking bars.	[-]
ALFA	Angle of filling jet  Similar to ALFA in <a href="#">section 7.1</a> .	[°]
ABB	Surface area of filling jet behind breaking bars  Similar to ABB in <a href="#">section 7.1</a> .	[m <sup>2</sup> ]
ZG	Level of top of filling jet behind breaking bars  Similar to AG in <a href="#">section 7.1</a> .	[mCD]

<b>Shutter slides</b>		
<b>Name of variable</b>	<b>Description</b>	<b>Unit</b>
SPREIDJ	Choose if the filling jet spreads in the horizontal or vertical direction 0: Horizontal 1: Vertical  It depends on the geometry and positions of the gate openings which option should be applied. It is advised to check the sensitivity by calculating for both options.	[-]
ALFJ	Angle of filling jet  Similar to ALFA in <a href="#">section 7.1</a> .	[°]
VJ	Table of gate velocity as function of time  Similar to VHD in <a href="#">section 7.1</a> .	[m.s <sup>-1</sup> ]
NJ	Number of openings in vertical direction (maximum of 5)  Only one opening is similar to 'standard' gate openings.	[-]

continued on next page

<b>Shutter slides</b>		
<b>Name of variable</b>	<b>Description</b>	<b>Unit</b>
<b>Opening 1</b>		
DJMAX1	Maximum height of gate opening	[m]
ZJ11	Initial level of underside sluice gate at the downstream side.	[mCD]
BJ1	Table with width of gate opening as function of gate height of opening 1	[m]
MUJ1	Table with discharge coefficient as function of gate height of opening 1	[-]
<b>Opening 2</b>		
DJMAX2	Maximum height of gate opening	[m]
ZJ12	Initial level of underside sluice gate	[mCD]
BJ2	Table with width of gate opening as function of gate height of opening 2	[m]
MUJ2	Table with discharge coefficient as function of gate height of opening 2	[-]
<b>Opening 3</b>		
DJMAX3	Maximum height of gate opening	[m]
ZJ13	Initial level of underside sluice gate	[mCD]
BJ3	Table with width of gate opening as function of gate height of opening 3	[m]
MUJ3	Table with discharge coefficient as function of gate height of opening 3	[-]
<b>Opening 4</b>		
DJMAX4	Maximum height of gate opening	[m]
ZJ14	Initial level of underside sluice gate	[mCD]
BJ4	Table with width of gate opening as function of gate height of opening 4	[m]
MUJ4	Table with discharge coefficient as function of gate height of opening 4	[-]
<b>Opening 5</b>		
DJMAX5	Maximum height of gate opening	[m]
ZJ15	Initial level of underside sluice gate	[mCD]
BJ5	Table with width of gate opening as function of gate height of opening 5	[m]
MUJ5	Table with discharge coefficient as function of gate height of opening 5	[-]

<b>Vertical slit</b>		
<b>Name of variable</b>	<b>Description</b>	<b>Unit</b>
BV	Width of approach harbour	[m]
	In front of the lock gate.	
ZVV	Bottom level of approach harbour at vertical slit	[mCD]
	In front of the lock gate.	
ZS	Bottom level of vertical slit	[mCD]
	The bottom level under the lock gate	

continued on next page

<b>Vertical slit</b>		
<b>Name of variable</b>	<b>Description</b>	<b>Unit</b>
DEUR_TYPE	Choose the gate type 1: Rolling gate 2: Mitre gate 3: Single leaf gate	[-]
<b>Rolling gate</b>		
BRMAX	Maximum width of slit  Defines how far the gate is opened during the levelling, not the total width of the lock head.	[m]
VR	Table with gate velocity as function of time	[m.s <sup>-1</sup> ]
CR	Table with contraction coefficient as function of gate position  Similar to the discharge coefficient in gate openings.	[-]
<b>Mitre gate</b>		
INUITP	Choose if the gates point into or out of the lock chamber 1: Gates point inwards 2: Gates point outwards	[-]
APINIT	Angle at which the gates are closed  The initial angle the gates make when they are in closed position.	[°]
APMIN	Minimum gate angle  The angle at which the gates are maximally opened during levelling.	[°]
VP	Table with gate velocity as function of time  The turning velocity of the gates in Åž.s <sup>-1</sup> .	[°.s <sup>-1</sup> ]
CP	Table with contraction coefficient as function of gate position	[-]
<b>Single pivot gate</b>		
INUITP	Choose if the gates point into or out of the lock chamber 1: Gates point inwards 2: Gates point outwards  With respect to the lock chamber. This is important for the calculation of the flow rate.	[-]
BTN	Minimum distance between front hinge and gate recess  This parameter is used in calculating the size of the gap through which is being levelled.	[m]
ADINIT	Angle at which the gate is closed  The angle the gate makes at the closed position, when the gate is at this position BTN should be estimated.	[°]

continued on next page

<b>Vertical slit</b>		
<b>Name of variable</b>	<b>Description</b>	<b>Unit</b>
ADMIN	Minimum gate angle  The angle at which the gate is maximally opened during levelling.	[°]
VD	Table with gate velocity as function of time  The turning velocity of the gates in °.s <sup>-1</sup> .	[°.s <sup>-1</sup> ]
CD	Table with contraction coefficient as function of gate position	[-]

<b>Lift gate</b>		
<b>Name of variable</b>	<b>Description</b>	<b>Unit</b>
DEEMAX	Maximum lift height of gate	[m]
BE	Width of slit under gate	[m]
VE	Table with maximum lift heights and lift velocities as function of water level in the lock chamber.	[m]/[m.s <sup>-1</sup> ]/[mCD]
SE	Table with slit height as function of lift height	[m]/[m]
MUE	Table of discharge coefficient as function of relative lift height	[-]
ZSEI	The initial outflow level	[mCD]
ZE1	Lock chamber water level at which the first transition between formulations occurs	[mCD]
ZE2	Lock chamber water level at which the first transition between formulations occurs	[mCD]
BWE	Width of jet	[m]
XWE	Distance between start of filling jet and lock chamber side of gate	[m]
ALFW	Angle of filling jet as function of lock chamber water level	[°]/[mCD]
DWE	Height of filling jet as function of lock chamber water level	[m]/[mCD]
ZWE	Level of underside filling jet as function of lock chamber water level	[mCD]/[mCD]

<b>Ship</b>		
<b>Name of variable</b>	<b>Description</b>	<b>Unit</b>
MS	Ship displacement (ships' mass including cargo)	[kg]
LS	Ship length	[m]
BS	Ship breadth	[m]
TS	Ship draft	[m]
KII	Nikuradse roughness of ship hull	[m]
XS	Distance from bow to lock gate	[m]
BETA	Vertical angle of bow	[°]
GAMMA	Horizontal angle of bow	[°]

Mode	
Name of variable	Description
BODEM_V	Choose if LOCKFILL has to calculate the velocities at the bottom behind the gate openings (only usable if SYSTYPE=1, i.e. gate openings) 0: No 1: Yes
PROMILLAGE	Choose if LOCKFILL has to automatically calculate a maximum sluice gate lift velocity (only usable if SYSTYPE=1, i.e. gate openings) 0: No 1: Yes

Promillage		
Name of variable	Description	Unit
PROM	Desirable permillage at end of iteration	[‰]

Bottom velocities		
Name of variable	Description	Unit
XF	Start of filling jet with respect to the downstream side of the gate  When breaking bars are present the origin of the filling jet is defined just after the breaking bars. If there are no breaking bars present, the filling originates at the point of maximum contraction. If the sluice gates are at the upstream side of the gate this position will probably be inside the gate opening and if the sluice gates are at the downstream side this position will be at the downstream side, inside the lock chamber.	[m]
DXF	Horizontal distance between output locations  This is the distance between downstream side of the gate and the first location at which the bottom velocities is calculated and the distance between the subsequent locations.	[m]
ALFF	Angle of filling jet  Similar to ALFA in <a href="#">section 7.1</a> .	[°]
BREEKB	Are there breaking bars present at the outflow side of the gate openings? 0: No 1: Yes	[-]

continued on next page

<b>Bottom velocities</b>		
<b>Name of variable</b>	<b>Description</b>	<b>Unit</b>
<b>Without breaking bars</b>		
ZHI	Level underside of gate opening  Underside of the opening at the downstream side.	[mCD]
<b>With breaking bars</b>		
DFB	Height of filling jet  Vertical dimension of the filling jet behind the breaking bars.	[m]
BFB	Width of filling jet  Width behind the breaking bars.	[m]
ZF	Level underside jet  Underside of the filling jet behind the breaking bars.	[mCD]
<b>In case of emptying</b>		
ZV	Bottom level of approach harbour behind the gate openings	[mCD]

<b>Calculation parameters</b>	
<b>Name of variable</b>	<b>Description</b>
TEND	End time of calculation
DT	Time step
<b>It is not advised to change parameters below!</b>	
C1	Correction of pressure build-up at bow
C3	Correction for flow profile behind stern
<b>When a density difference is present</b>	
CIC	Front velocity coefficient Recommended values: fresh lock chamber/salt approach harbour – 0.42 salt lock chamber/fresh approach harbour – 0.46
MENG	Entrainment coefficient
PI	Coefficient for deviation from uniform flow



## C Example input file

```
LOCKFILL 5.0
-----
INFO
-----
TITLE = 'Template'
PROJNUM = '' \\Project number
PROJTIT = '' \\Project title
COMP = '' \\Company name
Comment: Template case for system gate openings.
Based on File S1_R1_J.LFI
-----
APPROACH HARBOUR
-----
RHO_VOORH = 1000 \\density approach harbour [ $kg/m^3$ ]
VOORH = 2 \\water level approach harbour; 1: basin storage method, 2: time table

Basin storage method
SV = 30000.0 \\surface area approach harbour [ $m^2$ ]
HV = 4.40 \\initial water level approach harbour [mCD]

Time table HF = [0.0 4.40 900.0 4.40] \\water level approach harbour as function
of time; time [s], water level [mCD]
-----
LOCK CHAMBER
-----
HK = -1.0 \\initial water level lock chamber [mCD]
RHOK = 1000 \\water density lock chamber [ $kg/m^3$ ]
LK = 182.50 \\length lock chamber [m]
BK = 22.0 \\width lock chamber [m]
ZK = -6.330 \\level lock chamber bottom [mCD]
KI = 0.005 \\Nikuradse roughness lock chamber walls and bottom [m]
-----
FILLING AND EMPTYING SYSTEM
-----
SYSTYPE = 1 \\levelling system type; 1: gate openings, 2: culverts with stilling
chamber, 3: vertical slit, 4: butterfly valves, 5: shutter slides, 6: lift gate
1: gate openings
ZHMAXD = 1.30 \\maximum height of opening [m]
VHD = [0.0 0.0031 900.0 0.0031] \\lift velocities sluice gates as function of time;
time [s], lift velocity [m/s]
BH = [0.0 15.05
1.0 15.05] \\total width of all combined gate openings as function of relative lift
height; relative lift height [-], width gate openings [m]
MUH = [0.0 0.70
1.0 0.65] \\discharge coefficient as function of relative lift height; relative
lift height [-], discharge coefficient [-]

1: gate openings or 4: butterfly valves
ALFA = 0.0 \\angle of filling jet with horizontal [ $^{\circ}$ ]
ABB = 27.40 \\surface area of filling jet behind breaking bars [ $m^2$ ]
ZG = -3.830 \\level of top of filling jet behind breaking bars [mCD]
-----
```



## SHIP

-----

MS = 6.5e6 \\ship mass [kg]  
LS = 135.5 \\ship length [m]  
BS = 16.84 \\ship breadth [m]  
TS = 3.2 \\ship draft [m]  
KII = 0.005 \\Nikuradse roughness ship hull [m]  
XS = 10 \\distance between bow and lock gate [m]  
BETA = 63 \\bow angle in vertical plane [°]  
GAMMA = 30 \\bow angle in horizontal plane [°]

-----

## MODE

-----

DELTA\_RHO = 0 \\presence of density difference; 0: no, 1: yes  
PROMILLAGE = 0 \\calculate lift velocity using a maximum permillage; 0: no, 1: yes  
BODEM\_V = 1 \\calculate bottom velocities; 0: no, 1: yes

Calculate lift velocity PROM = 0.85 \\specified maximum permillage [‰]

Calculate bottom velocities

XF = 0.0 \\start position of filling jet with respect to the downstream side of the gate [m]  
DXF = 1.0 \\distance between output locations [m]  
ALFF = -15.0 \\angle of filling jet with horizontal (+ is upwards) [°]  
BREEKB = 0 \\breaking bars at downstream side of gates; 0: no, 1: yes

Without breaking bars

ZHI = -3.75 \\level underside of gate opening [mCD]

With breaking bars

DFB = -3.75 \\height filling jet [mCD]  
BFB = 12.8 \\width filling jet [m]  
ZF = -3.75 \\level underside of filling jet [mCD]

When emptying

ZV = -6.75 \\level of approach harbour bottom [mCD]

-----

## SIMULATION PARAMETERS

-----

TEND = 900 \\end time of calculation [s]  
DT = 1 \\time step [s]  
C1 = 0.90 \\coefficient pressure build up at bow [-]  
C3 = 0.90 \\coefficient boundary layer development due to the flow profile at the stern [-]

Density difference

CIC = 0.45 \\coefficient for density wave velocity [-]; recommended to use 0.42 for a fresh lock chamber/salt approach harbour and 0.46 for a salt lock chamber/fresh approach harbour  
MENG = 0.80 \\mixture coefficient for fresh and salt water in mixing zone [-]  
PI = 1.00 \\momentum coefficient to account for deviation from uniform flow [-]

## D Ship classification

Navigation locks are designed to be able to accommodate ships up to a certain size, matching the current of projected size restriction of the connecting waterway. The most widely used classification of ship dimensions is the CEMT (Conférence européenne des ministres des Transports) classification. However, within a CEMT-class there can still be a large variety of sizes and displacements. The Dutch Rijkswaterstaat has issued a classification based on the Dutch inland fleet which introduces sub-classes within the CEMT-classification that shows the large deviations in size and cargo capacity within a CEMT-class [Brolsma and Roelse \(2011\)](#). However, the user usually only encounters specifications based on the CEMT-classification. To introduce unity in the use of ship dimensions, a list of standard sizes and displacements is given here to use as input for LOCKFILL.

**Table D.1:** Overview of standard LOCKFILL input for different CEMT-classes

CEMT-class	Length [m]	Width [m]	Draft [m]	Displacement [ton]	Vertical angle( $\beta$ )	Horizontal angle ( $\gamma$ )
I	38.50	5.10	2.40	450	90	45
II	50.00	6.60	2.50	725	90	45
III	67.00	8.20	2.50	1200	90	45
IV	80.00	9.45	2.80	1650	90	45
Va	110.00	11.40	2.80	2890	90	45
Va*	76.50	11.40	3.30	2700	30	90
Vb*	153.00	11.40	3.90	6100	30	90
VI*	76.50	22.80	3.90	6100	30	90
VI*	153.00	22.80	3.90	12200	30	90

\* Push-tow train

It is possible that maximum ships size for a certain navigation lock differs from these standard ships or that there is a draft limitation.

**Note:** [Table D.1](#) is based in the CEMT-classification. In the Netherlands Rijkswaterstaat may also use the RWS-classification, which introduces sub-classes within the CEMT-classification. Depending on current research [Table D.1](#) may be revised.



**Note:** The current longitudinal force criteria as given in [Table D.2](#) are currently being refined in on-going research. This research is not yet concluded but will most likely lead to a new definition of the force criteria in the near future. In the case of Rijkswaterstaat force criteria should be defined by the client.



## D.1 Adapting criterion to displacement

The longitudinal force criterion is defined per CEMT-class. [Table D.2](#) shows these criteria for several CEMT-classes. For more information on longitudinal force criteria (also called hawser force criteria) the reader is referred to [Beem et al. \(2000a\)](#). These criteria are defined for a ship at design draft. It can occur that for a certain canal or lock there is a draft restriction, limiting the maximum draft of the ship that enters the lock that is under investigation. Lowering of the draft will influence the displacement. In LOCKFILL the actual displacement (and draft) must be used, not the design draft en displacement.

Because the displacement is used in the calculation of the longitudinal force (in ‰ of displacement), the criterion has to be corrected as the longitudinal force criterion in Newton should not change. The corrected criterion is given by

$$\%_{corrected} = \% \frac{M}{M_{corrected}} \quad (D.1)$$

in which % and  $M$  are the criterion and displacement at design draft and  $M_{corrected}$  is the corrected displacement. [Equation D.1](#) shows that when the displacement decreases, the criterion in ‰ of displacement increases. However, the absolute force in Newton at both criterions is the same.

**Table D.2:** Longitudinal force criteria for several CEMT-classes ([Beem et al., 2000b,a](#))

CEMT-class	Longitudinal force criteria (in ‰ of displacement)	
	Filling	Emptying (or filling with floating bollards)
III	1,50	2,00
IV	1,10	1,50
Va	0,85	1,15

## E LOCKFILL formulations

### E.1 Flow rate gate openings

The flow rate in or out of the lock chamber through gate openings is calculated using the instantaneous water level difference between lock and approach harbour and the surface area and discharge coefficient of the gate openings. The difference in water level is given as

$$\Delta h = h_v - h_k \quad (\text{E.1})$$

In which  $h_v$  is the water level in the approach harbour and  $h_k$  the water level in the lock chamber, both in mNAP. The instantaneous flow rate can then be calculated using Bernoulli;

$$Q = \mu A_h \sqrt{2g |\Delta h|} \frac{|\Delta h|}{\Delta h}, \quad (\text{E.2})$$

$\mu$  is the discharge coefficient,  $A_h$  the surface area of the gate openings. The new water level in the lock chamber can then be calculated as follows

$$h_k = h_{k,0} + \frac{Q \Delta t}{S_k} \quad (\text{E.3})$$

where  $h_{k,0}$  is the water level in the lock chamber at the previous time,  $\Delta t$  is the time step and  $S_k$  is the horizontal surface area of the lock chamber. In the case that the water level in the approach harbour is influenced by the filling process, this water level is given by

$$h_v = h_{v,0} - \frac{Q \Delta t}{S_v} \quad (\text{E.4})$$

in which  $S_v$  is the horizontal surface area of the approach harbour.

### E.2 Flow rate culverts with stilling chamber

When culverts are used, the inertia of the culverts is also taken into account and the discharge coefficient is replaced by loss coefficients. It is possible to model up to two different culverts. 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. For one culvert these are given by

$$\frac{dh_v}{dt} = \frac{Q}{S_v} \quad (\text{E.5})$$

$$\frac{dh_k}{dt} = \frac{Q}{S_k} \quad (\text{E.6})$$

$$h_v - h_k = (\xi_s + \xi_r) \frac{Q |Q|}{2gS_c^2} + \frac{L_r}{gS_c} \frac{dQ}{dt} \quad (\text{E.7})$$

In which  $\xi_s$  and  $\xi_r$  are the loss coefficients of the valve and the culvert respectively,  $S_c$  is the cross sectional area and  $L_r$  the length of the culvert.

Equation E.7 can be numerically solved by

$$\overline{(h_v - h_k)} = \bar{\xi} \frac{Q |Q_0|}{2gS_c^2} + \frac{L_r}{gS_c} \frac{Q - Q_0}{\Delta t} \quad (\text{E.8})$$



In which

$$\bar{\xi} = \frac{\xi_{s,0} + \xi_s}{2} + \xi_r \quad (\text{E.9})$$

And

$$\overline{(h_v - h_k)} = \frac{h_{v,0} + h_v}{2} - \frac{h_{k,0} + h_k}{2} \quad (\text{E.10})$$

Using

$$h_k = h_{k,0} + \frac{(Q + Q_0) \Delta t}{2S_k} \quad (\text{E.11})$$

$$h_v = h_{v,0} - \frac{(Q + Q_0) \Delta t}{2S_v} \quad (\text{E.12})$$

Equation E.8 can be written as

$$Q = \frac{\Delta h - Q_0 \left( f - \frac{L_r}{gS_c \Delta t} \right)}{\bar{\xi} |Q_0| \frac{1}{2gS_c^2} + \frac{L_r}{gS_c \Delta t} + f} \quad (\text{E.13})$$

In which

$$f = \frac{\Delta t}{4} \left( \frac{1}{S_k} \right) \quad (\text{E.14})$$

In the case there are multiple culverts, the total flow rate is found by summation;

$$Q_{total} = Q_1 + Q_2 \quad (\text{E.15})$$

The water level in the lock chamber is still given by Equation E.3. In the case the water level in the approach is not fixed, this water level is given by Equation E.4 and in this case Equation E.14 transforms into

$$f = \frac{\Delta t}{4} \left( \frac{1}{S_k} + \frac{1}{S_v} \right) \quad (\text{E.16})$$

### E.3 Flow rate vertical slit

#### E.3.1 Surface area and induced flow rate

##### ***Sliding gate***

The sliding gate is the simplest case as there will be no induced flow rate. The width of the slit ( $b_r$ ) is calculated from the gate velocity. The surface area of the vertical slit is given by

$$A_{ss} = b_r (h_k - z_s) \quad (\text{E.17})$$

In which  $z_s$  is the bottom level of the slit. Using the contraction coefficient the net surface area can be calculated.

### Mitre gates

From the initial angle ( $\theta_0$ ) and the angular velocity specified by the user, the instantaneous angle ( $\theta$ ) of the gates can be calculated. The length of the gate is defined by

$$l_p = \frac{b_k}{2 \sin(\theta_0)} \quad (\text{E.18})$$

In which  $b_k$  is the width of the lock chamber. Using the gate length and the instantaneous angle, the minimum width of the gap is calculated using

$$b_p = b_k - 2l_p \sin(\theta) \quad (\text{E.19})$$

From the slit width the surface area can be calculated using [Equation E.17](#).

The induced flow rate for mitre gates turning into the lock chamber is given by

$$Q_{sr} = -l_p^2 (h_k - z_k) \tan(v_p) \quad (\text{E.20})$$

In which  $v_p$  is the angular velocity of the gates. When the gates turn outward the flow rate is in the opposite direction and this expression is multiplied by -1.

### Single leaf gate

The calculation for the single leaf gate is similar to the calculation of the mitre gates, except that there is one door. The instantaneous angle ( $\theta$ ) is calculated from the initial angle ( $\theta_0$ ) and the angular velocity. During the first part of opening when the angles are large, the tip of the gate will still be in the gate recess. The width of the slit is then calculated by

$$b_d = b_k - b_k \sin(\theta) + b_{tn} \quad (\text{E.21})$$

Where  $b_{tn}$  is the minimal distance between the tip of the gate and the gate recess. When the angle gets larger the width of the slit is calculated by

$$b_d = b_k \tan(\theta_0 - \theta) \quad (\text{E.22})$$

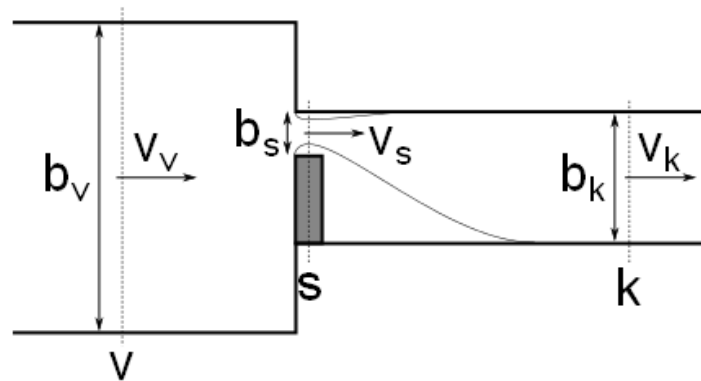
At each moment the smallest calculated width of these formulations is taken as the current width.

The induced flow rate by the movement of the gate when turning into the lock the chamber is given by

$$Q_{sr} = -\frac{1}{2} b_k^2 (h_k - z_k) \tan(v_d) \quad (\text{E.23})$$

Again, when turning outwards the flow rate is opposite and this expression is multiplied by -1.

### E.3.2 Flow rate



**Figure E.1:** Schematic overview of a sudden flow expansion behind a lock gate

The flow rate through the vertical slit is calculated using Bernoulli's principle and the Borda-Carnot equation for a sudden flow expansion. From using [Figure E.1](#) and Bernoulli's principle follows that

$$h_v + \frac{v_v^2}{2g} = h_s + \frac{v_s^2}{2g} \quad (\text{E.24})$$

From the Borda-Carnot equation follows that

$$h_s + \frac{v_s^2}{2g} = h_k + \frac{v_k^2}{2g} + \frac{(v_s - v_k)^2}{2g} \quad (\text{E.25})$$

From continuity between v, s and k follows

$$b_v(h_v - z_v)v_v = \mu_s b_s(h_s - z_s)v_s \quad (\text{E.26})$$

and

$$\mu_s b_s(h_s - z_s)v_s = b_k(h_k - z_k)v_k \quad (\text{E.27})$$

with  $\mu$  the contraction coefficient. By combining [Equation E.24](#) to [Equation E.27](#) and defining  $Q_s = \mu_s b_s(h_s - z_s)v_s$ , the flow rate through the vertical slit can be written as

$$Q_s = (\mu_s b_s(h_s - z_s)) \sqrt{\frac{2g(h_v - h_k)}{C_{III}}} \quad (\text{E.28})$$

With

$$C_I = \mu_s b_s(h_s - z_s)/b_v(h_v - z_v) \quad (\text{E.29})$$

$$C_{II} = \mu_s b_s(h_s - z_s)/b_k(h_k - z_k) \quad (\text{E.30})$$

$$C_{III} = 1 - C_I^2 + 2C_{II}^2 - 2C_{II} \quad (\text{E.31})$$

LOCKFILL assumes that  $h_s$  is equal to the water level in the lock chamber ( $h_k$ ). And thus, using [Equation E.17](#), [Equations E.28](#) and [Equation E.29](#) reduce to

$$Q_s = A_{ss} \sqrt{\frac{2g(h_v - h_k)}{C_{III}}} \quad (\text{E.32})$$

and

$$C_I = A_{ss}/b_v(h_v - z_v) \quad (\text{E.33})$$

$$C_{II} = A_{ss}/b_k(h_k - z_k) \quad (\text{E.34})$$

$$C_{III} = 1 - C_I^2 + 2C_{II}^2 - 2C_{II} \quad (\text{E.35})$$

The total flow rate is the summation of the flow rate from [Equation E.32](#) and the induced flow rate from [section E.3.1](#).

#### E.4 Flow rate lift gate

A summary of the calculation method presented in [Vrijburcht \(1994b\)](#) is shown below.

#### E.4.1 Surface area

The lifting program is designed as such that the maximum lifting height and the lifting velocity are dependent on the water level in the lock chamber. This program is given as input by the user. From the instantaneous lifting velocity and maximum lifting height the instantaneous gate height ( $d_{ee}$ ) is calculated. The outflow level at the gap below the gate is given by

$$z_{se} = z_{se,i} + d_{ee} \quad (\text{E.36})$$

in which  $z_{se,i}$  is the initial outflow level. From the input by the user the gap height and corresponding discharge coefficient are determined. The surface area of the filling opening created by the gap is given by

$$A_{ht} = b_e s_e \quad (\text{E.37})$$

with  $b_e$  the width of the gap and  $s_e$  the gap height.

#### E.4.2 Flow rate

As mentioned before three regimes can be distinguished during the filling process. In the first regime the flow rate is given by

$$Q = \mu A_{ht} \sqrt{2g(h_v - z_{se})} \quad (\text{E.38})$$

After the water level in the lock chamber reaches the first transitional water level ( $z_{e1}$ ) the flow rate is given by

$$Q = \mu A_{ht} \sqrt{2g\Delta h_e} \quad (\text{E.39})$$

In which  $\Delta h_e$  is given by

$$\Delta h_e = \frac{z_{e2} - h_k}{z_{e2} - z_{e1}} (h_v - z_{se}) + \frac{h_k - z_{e1}}{z_{e2} - z_{e1}} (h_v - h_k) \quad (\text{E.40})$$

After the water level in the lock chamber reaches the second transitional level ( $z_{e2}$ ) the flow rate is determined by

$$Q = \mu A_{ht} \sqrt{2g|\Delta h|} \frac{|\Delta h|}{\Delta h} \quad (\text{E.41})$$

Where  $\Delta h = h_v - h_k$  the water level difference between approach harbour and lock chamber.

#### E.5 Density difference correction

In the case of a density difference between approach harbour and lock chamber, the water level difference used in the calculation of the flow rate must be corrected for this.

In the case of a salt approach harbour and a fresh lock chamber, the average density in the lock chamber during the filling process is given by

$$\rho_{av} = \frac{(h_{k,i} - z_k) \rho_2 + (h_k - h_{k,i}) \rho_1}{(h_k - z_k)} \quad (\text{E.42})$$

Where  $\rho_1$  is the density of the salt water and  $\rho_2$  is the density of the fresh water. The effective water level difference between lock chamber and approach harbour is given by

$$\Delta h_d = \frac{\rho_1(h_v - h_d) - \rho_{av}(h_k - h_d)}{\rho_2} \quad (\text{E.43})$$

In the case of a fresh approach harbour and a salt lock chamber, the average density in the lock chamber during the filling process is given by

$$\rho_{av} = \frac{(h_{k,i} - z_k) \rho_1 + (h_k - h_{k,i}) \rho_2}{(h_k - z_k)} \quad (\text{E.44})$$

and the effective water level difference water level difference is given by

$$\Delta h_d = \frac{\rho_2(h_v - h_d) - \rho_{av}(h_k - h_d)}{\rho_2} \quad (\text{E.45})$$

In both cases the flow rate, when using gate openings ([section 7.1](#), [section 6.1.2](#) and [section 6.3](#) to [section 6.5](#)), is given by

$$Q = \mu A_h \sqrt{2g |\Delta h_d|} \frac{|\Delta h_d|}{\Delta h_d} \quad (\text{E.46})$$

and

$$Q = \frac{\Delta h_d - Q_0 \left( f - \frac{L_r}{g S_c \Delta t} \right)}{\xi |Q_0| \frac{1}{2g S_c^2} + \frac{L_r}{g S_c \Delta t} + f} \quad (\text{E.47})$$

when the filling is performed using culverts.

For the emptying process with density differences, the formulation for the effective water level difference needs to be changed. For a salt approach harbour and a fresh lock chamber the effective water level difference during emptying is given by

$$\Delta h_d = \frac{\rho_1(h_v - h_d) + \rho_2(h_d - h_k)}{\rho_2} \quad (\text{E.48})$$

For a fresh approach harbour and a salt lock chamber the effective water level difference is given by

$$\Delta h_d = \frac{\rho_2(h_v - h_d) + \rho_1(h_d - h_k)}{\rho_2} \quad (\text{E.49})$$





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