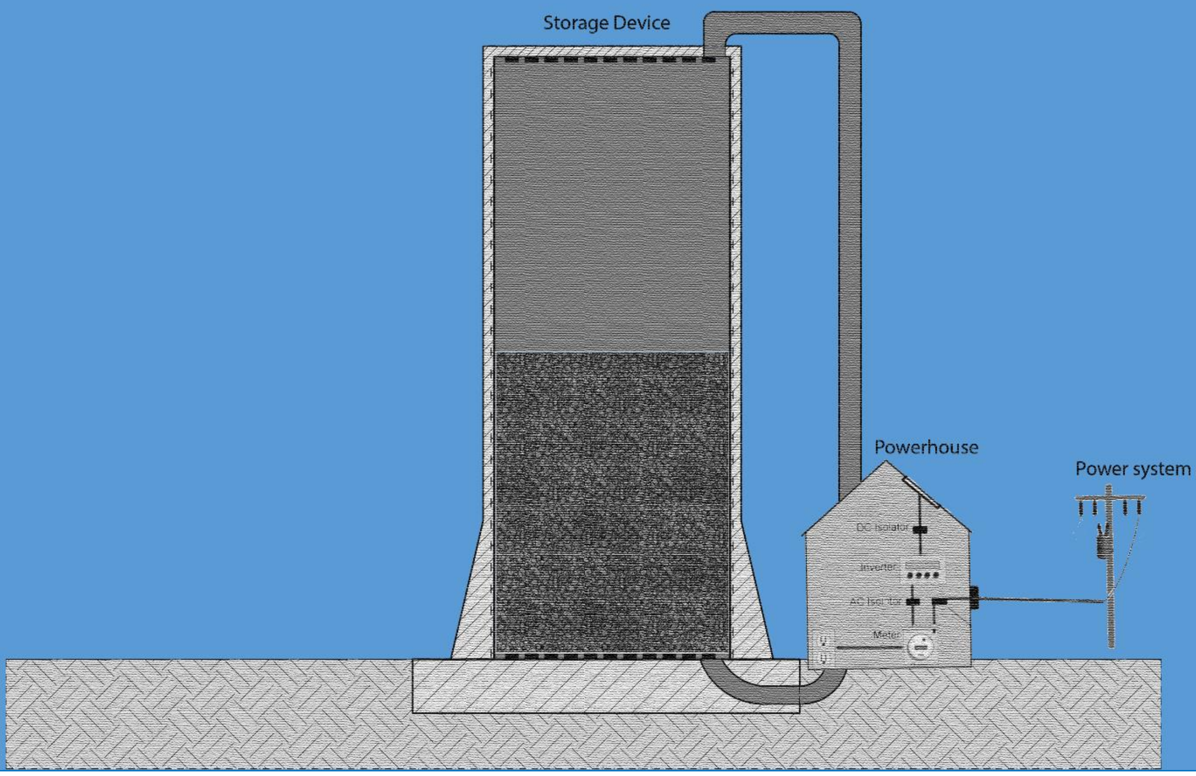
Part Two

Gravity Power Storage

A preliminary feasibility study

CASE STUDY - DESIGN – CONSTRUCTION- ENERGY - COST



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ABSTRACT

A gravity storage device is an enclosed system consisting of a pump/turbine, a generator/motor and a piston (a great mass) as can be seen in Figure I. The container where the piston is situated is called the main storage container or tank (red boundary); this is where potential energy is being stored. In the energy *generation mode,* the piston is released by, for example, opening a valve. The piston exerts a pressure force on the fluid which results in the flow of the fluid counter clockwise. The kinetic fluid flow enters the turbine which converts kinetic flow energy to mechanical energy. Mechanical energy is then converted to electrical energy in the generator.

In the energy *storage mode*, electricity is supplied to the motor, which converts electrical energy to mechanical energy. The pump converts mechanical energy to a kinetic flow energy (in the clockwise direction) which drives the piston to the top. The great advantage of a gravity power device is that it does not depend on natural height differences which means it could be implemented anywhere.

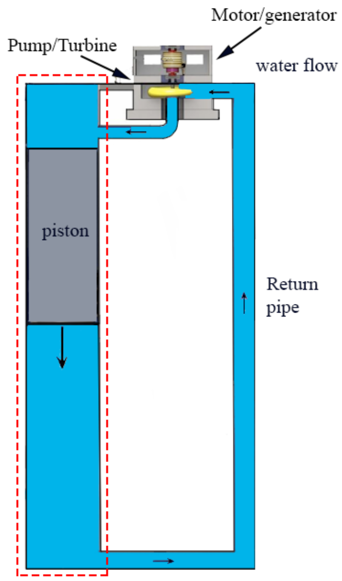

Figure I Storage device

The initial tank size is based on LNG containers which resides in current Maasvlakte and is built with the same material: prestressed concrete. It became clear that a relatively large tank size is necessary in order to store a relatively small amount of energy. In order to economically compete with other power plants, it should be utilized to supply energy during peak hours. The initial design has been further optimized through boundary condition which is then called the preliminary design. The tank in the preliminary design has a diameter of 28 m, a height of 56 meter and has a buffering capacity of 28,000 kWh (Figure II).

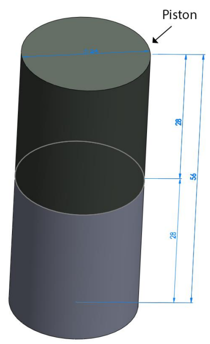

Figure II storage tank

The preliminary design has been assessed concerning the most decisive factors that determine the feasibility of a project: the stability (both external and internal), the construction and cost.

The most critical (structural) component of the storage device is the prestressed concrete wall. The wall has been modelled as a bending girder on elastic foundation, in which the initial thickness has been taken as one meter. It was found that the occurring moment due to the loads on the wall was, at the toe of the wall (the wall-bottom slab connection), too large. In order to counter this, the thickness of the lower part of the wall had to be increased to four meters.

When constructing such a device, the most problematic aspects are the mass and sealing of the piston. The piston was initially assumed to be of relative high quality lead which as a large density. If one would cast the piston full of lead, the piston would become so heavy that if maintenance was required, the piston could not be lifted by cranes. The practical solution was to use lead ore instead. Sealing requires a certain smoothness of the wall that cannot be met by concrete alone. The surface must therefore be treated in order to ensure optimal functioning of the sealing. Additionally, construction errors by a combination of pouring concrete and formwork may also induce challenges for sealing the piston.

From the material cost of the most significant components of the storage device, it followed that the piston made of lead ore was extremely expensive relative to the other structural and mechanical components: it took up 96% of all the material cost.

The goal of the storage device is to aim for an energy production cost which can compete with the energy production cost of power plants having a similar purpose: the supply of energy during peak hours. In order to do so, the estimated requirement taking into account only the material cost, was to meet an energy production cost of 0.04 €/kWh. The energy production cost of the storage device with a lead ore piston is equal to 1.13 €/kWh (during 50 years).

In order to reach an energy production cost of 0.04 €/kWh optimization is necessary. Two optimization approaches have been considered: changing the material of the piston and changing the container/piston dimensions. During optimization process, three other materials have been considered: iron, concrete and sand. By changing the material of the piston into sand, the production cost had been decreased to 0.20 €/kWh. In order to decrease the costs even further, a second optimization was necessary. The dimensions of the piston/main container had been changed. With a sand piston, it was found that in order to reach an energy production cost of 0.04 €/kWh, the container had to be increased in size having a height of at least 140 m with a diameter and a piston thickness which are both halve the tank height (70m). At this size, the device has a storage capacity of 3.3 MW. These numbers are rough estimates, determining the true feasibility requires numerous optimization iterations in which many more aspects must be taken into account.

CONTENTS

INTRODUCTION

I. Problem statement

In *part one* of this paper, it became clear that storage was one of the keys to diminish the current and near future challenges in the power system. The main reason for implementation of a storage device is to regulate energy (electricity) so that supply and demand of energy are in equilibrium

This part of the paper is a feasibility (design) study to one of the newer concepts of hydro storage: *gravity power*, which has already been introduced in *part one*. The storage device, conform part one, will be located in the Maasvlakte 2, the Netherlands and will store wind energy from the imminent windmills. What becomes clear during the course of this paper, is how one can design such a device and what aspects are involved and must be taken into account.

In *Chapter 4,* the concept of gravity power is analyzed and compared with other methods of hydraulic energy storage. In *Chapter 5,* the buffer size is determined; in addition a preliminary design will be made. In *Chapter 6,* this design will be assessed concernging stability, construction and costs and will be further optimized in *Chapter 7*. *Chapter 8* contains conclusions, recommendations and a final evaluation. Note that this paper initiates with chapter 4 as chapter 1-3 belongs to *part one* of this paper.

II. Scope of Part Two

The storage device is a concept based on already existing components from different sections; designing such a device requires the expertise of different fields of technology such as structural, hydropower, (fluid) mechanical, electrical, etc., As the author of this paper is a student of the field hydraulic structures, emphasize have been laid on the structural aspects of the storage device. Nonetheless, components concerning other fields have also been taken into account.

OBJECTIVES PART TWO

The objective of this part of the paper is to analyze and determine the economic and technical feasibility of a storage device based on the concept *gravity power*. In order to so, the following main-question has been formulated:

"*How can an energy storage device based on gravity power be technically realized in order to be economically competitive in the Dutch power grid?*"

In order to answer the main question, the following sub-questions will be discussed in this paper:

- How does the storage device compare to current methods of storing energy in the field of hydraulics in terms of functionality and storage capacity?
- What will be the buffer capacity of the storage device?
- How large, in terms of width and height, will this device be?
- How can this energy device be utilized most cost-effectively?
- How to construct such a storage device?
- How much energy can it produce?
- How much does it cost?

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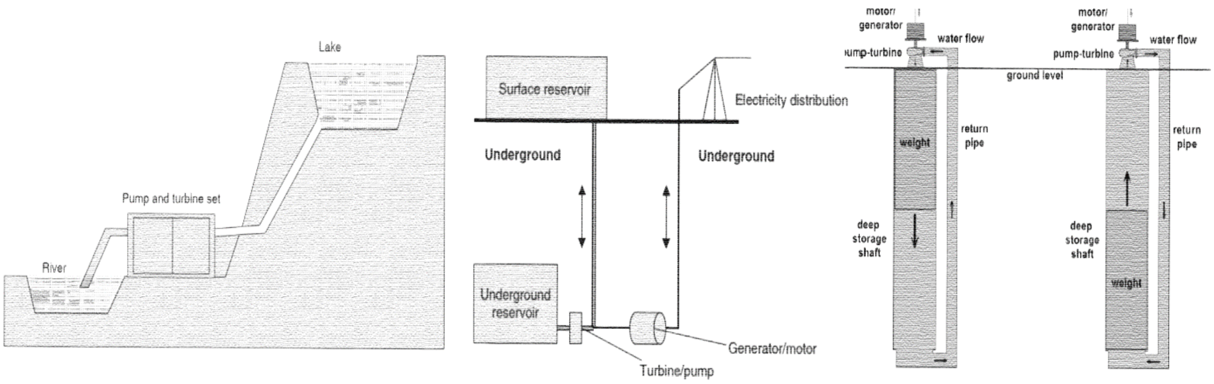
CHAPTER 4. HYDRO STORAGE SYSTEMS



Contents

4.1 INTRODUCTION

In this chapter different types of hydro energy storage devices, which were already briefly discussed in part one, are compared. Among them is the gravity power variant which, will be further elaborated in this part of the paper (part two). Prior to the comparison, some basic definitions and principles which are required to understand the principles of each storage device are explained.

4.2 BASIC DEFINITIONS, PRINCIPLES AND PHYSICAL QUANTITIES

4.2.1 DIMENSION AND UNITS

This chapter contains some basic dimensions, and units which are essential for understanding the technical aspects in this paper. In order to describe a physical quantity, a quantitative description is required which can be provided with the nine *fundamental dimensions*: length, mass, time, temperature, the amount of a substance, electric current, luminous intensity, plane angle, and solid angle. Dimensions of all quantities can be expressed in terms of this fundamental dimension. Newton's law, for example, is expressed with the quantity *force* which can be associated with the fundamental dimension, mass, length and time. The (second) law of newton can be expressed as:

$$F = m \cdot a \qquad \text{Eq. (4.1)}$$

Where:

- m is a dimension of *mass* M → [m]=M
- a is the acceleration and is in a dimension of *time* and *length* L/T^2 → $[a]=L/T^2$
- and therefore *force* is a quantity in a dimensions of mass, time and length →$[F]= M \cdot L/T^2$

These quantities of dimensions are expressed in so-called *units*. Mass, for example, can be expressed in the unit kilo grams (or kg) and length can be expressed in a unit of meters (m). The most important fundamental dimensions with respect to this paper and their units are displayed in Table 1.

Table 1 Fundamental dimensions and their units

Quantity	Dimension	Unit
Length $\boldsymbol{l}$	L	meter m
Mass $\boldsymbol{m}$	M	kilogram kg
Time $\boldsymbol{t}$	T	second s

One of the most important properties of a fluid is the *density*, denoted with the Greek symbol ρ, which describes the mass per unit of volume (M/L^3). Water, for example, has a density of 1000 kg/m^3. Another relevant quantity is *pressure* p (=force/Area) which has a dimension of M/T^2L. When a fluid flows, the amount of flow (Q) also known as discharge is the multiplication of a velocity v and an area m^2 and has a dimension of M^3/T. Quantities such as *energy* and *work* (which has been discussed in *part one*) will be widely used in this part of the paper. For now, the most important *quantities* derived from the *fundamental dimensions* are presented in Table 2.

Table 2 Derived units

Quantity	Dimension	Unit
Area *A*	L^2	m^2
Volume *V*	L^3	m^3
Velocity *v*	L/T	m/s
Acceleration *a*	L/T^2	m/s^2
Force *F*	ML/T^2	$kg{\cdot}m/s^2$ N (newton)
Density *ρ*	M/L^3	kg/m^3
Pressure *p*	M/LT^2	N/m^2
Stress *τ*	M/LT^2	N/m^2
Energy *E*	ML^2/T^2	N·m J (joule)
Work *W*	ML^2/T^2	N·m J (joule)
Power *P* $\dot{W}$	ML^2/T^3	J/s W (watt)
Flow rate *Q*	M^3/T	m^3/s
Mass flow rate $\dot{m}$	M/T	kg/s

Note that in Table 2 some quantities have a dot above their symbol, this means that it is a time derivative of the shown quantity. The mass flow rate $\dot{m}$, for example, is the time derivative of the mass or: mass flow rate = mass/time. Acceleration (L/T^2) is a time derivative of the velocity (L/T) which means that the acceleration could also be denoted as $\dot{v}$.

Units can be of very large and/or very small numerical value and is therefore often referred to with a prefix. One million Newton's is often written as one mega newton or 1 MN. A giga newton is a 1 Newton with 9 zero's and has a multiplication factor of $1 \cdot 10^9$. The most common used prefixes and multiplication factors are shown in Table 3.

Table 3 Multiplication factor

Multiplication factor	prefix	Symbol
10^0	-	-
10^3	kilo	k
10^6	mega	M
10^9	giga	G

4.2.2 POTENTIAL ENERGY

As is clear from *part one*, hydro energy storage is based on gravitational power by *potential energy*. But what is potential energy? For clarification purposes an example will be given Figure 1.

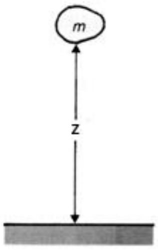


Figure 1 Potential Energy (Potential, n.d.)

If an object with a mass m is elevated from ground level to a height z then the amount of *potential energy* it has gained, is equal to the work done in lifting it to this height. In formula form, this *work* can be described by:

$$Work = Force \cdot Height \quad \text{Eq. (4.2)}$$

The force F subjected to the body is its weight, which is equal to the *mass* times the gravitational influence g. In addition, since this is the work done, it is also the energy that the body had *before* it fell (potential energy). In formula form *potential energy* can be written as follows:

$$E = m \cdot g \cdot z \quad \text{Eq. (4.3)}$$

Where:

- E is the potential energy [J]
- m is the mass in kilograms [kg]
- g is the gravitational acceleration [9.81 m/s^2]
- z is the elevation height in meters [m]

4.3 HYDRO STORAGE VARIANTS

In *part one* three variants of hydro storage plants have been described namely (Figure 2):

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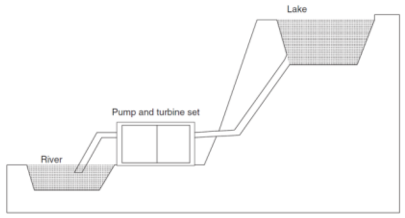
<td>
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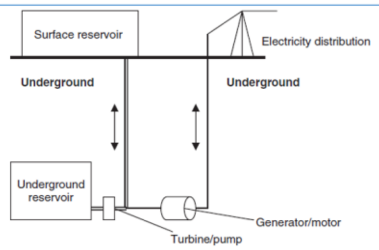
<td>
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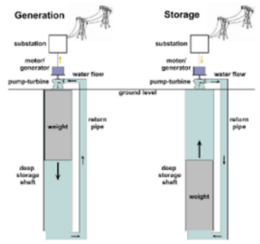
<td>
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<td>Conventional Pumped hydro storage (PHS)</td>
<td>Underground pumped hydro storage (UPHS)</td>
<td>Gravity pumped hydro storage (GPHS)</td>
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Figure 2 Three variants of hydro storage plants

The conventional Pumped hydro energy storage (PHES) is the dominant technology currently employed to store large amounts of energy. Worldwide, there more than 100 conventional PHES plants, and most activity of these projects lies in Europe (worldwide-pumped-storage, n.d.). Unfortunately, as is clear from *part one*, the feasibility of such system is highly dependent on the local geography, geology, local regulations and water usage policy. In 1980 in the Netherlands, for example, the company Lievense wanted to create a PHES with reservoirs in the Markermeer, but as of today the project plan has still not been given consent due to environmental policy (Dertig jaar Plan Lievense, n.d.).

In order to reduce geographical dependencies, concepts for an underground pumped hydro storage (UPHS) have been proposed. The UPHS requires only one upper reservoir; the lower elevated reservoir can be stationed below ground level which makes it less geographical dependent. The lower elevated reservoirs could be an old mine shift or tunnel system; basically any underground space could be suitable provided that it has the capability to store water without compromising the structural integrity. As stated before, UPHS is only a proposition, as of today no evidence of a working UPSH system can be found (Martin, 2010). In the late 1970 and early 1980, there were great amounts of interest in those UPSH devices but interest has been fallen of since then (Martin, 2010). The reason for this is probably large costs due to building, sealing and maintaining of the underground structure.

In 2011 the company calling itself "gravity power" proposed an (underground) storage device (GPHS) which does not need two reservoirs but instead only uses one storage volume in a so called enclosed water tank, this means that it does not need a tunnel or mining system. In addition, this company also introduced a piston in this concept. Due to the piston, the amount of energy that can be stored requires a smaller storage volume as will be clear, later in this chapter. Note 1: GPHS is just a variant of a UPHS but has been denoted differently so that they can be distinguished. Note 2: even though this device carries the name Gravity Pumped Hydro System, all these variants depend on the gravitational (mechanical) energy (A.3 Hydro storage analysis, p110).

4.4 HYDRO STORAGE ANALYSIS

In this paragraph, is briefly discussed how each variant produces and stores energy. For a more detailed hydro storage analysis is referred to [Appendix A: Principles of fluid mechanics, p105], which also illuminates the basic concept in fluid mechanical terms that are required to show that these variants are based on potential energy.

4.4.1 PHS & UPHS

The operation of the PHS and UPHS system are quite similar, of these two, only the PHS system is further elaborated in detail. At the end of this section, the difference between PHS and UPHS will be discussed briefly.

In Figure 3 can be seen that the PHS exists of two reservoirs, each having a different elevation height, (1) and (2) respectively. Those two reservoirs are connected with a pipe and at the end of the pipe, a turbine/pump and a generator/motor is present.

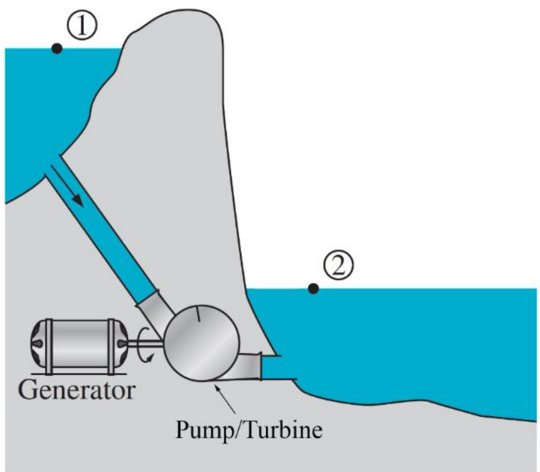

Figure 3 PHS: Hydro storage

When the system is in the *generation mode* (Figure 5), potential energy from the higher elevated reservoir is converted to kinetic flow (the beginning of a flow) when it enters the pipe. The flow is entering the turbine which converts the energy from the flow into mechanical energy. Mechanical energy is converted to electrical energy through the generator. Sometimes a transformer is added to the system which converts (DC to AC).

In *storage mode*, electrical energy is supplied to the motor which converts electrical to mechanical energy. The motor drives the pump which converts mechanical energy to kinetic flow energy (it pumps flow from the *lower elevated* reservoirs to the *higher elevated* reservoir).

These energy conversions can be linked to *power* conversions. The conversion of electrical energy to mechanical energy which happens in the motor, corresponds with the power conversion from $P_{electricity}$ to $P_{mechanical}$.

Power definitions can be described as follows:

- $P_{electricity} = UI$
- $P_{mechanical} = T\omega$
- $P_{flow} = pQ$

Where:

- U is the voltage [V]
- I is the current [Ampère]
- T is the torque moment force and is defined as a radius (or arm) $r \cdot$ Force N [Nm]
- ω rotational speed [rad/s]
- p pressure [N/m²]
- Q discharge [m³/s]

The power and energy conversions occurring in PHS system, have been illustrated for both *generation mode* and *storage mode* in Figure 4.

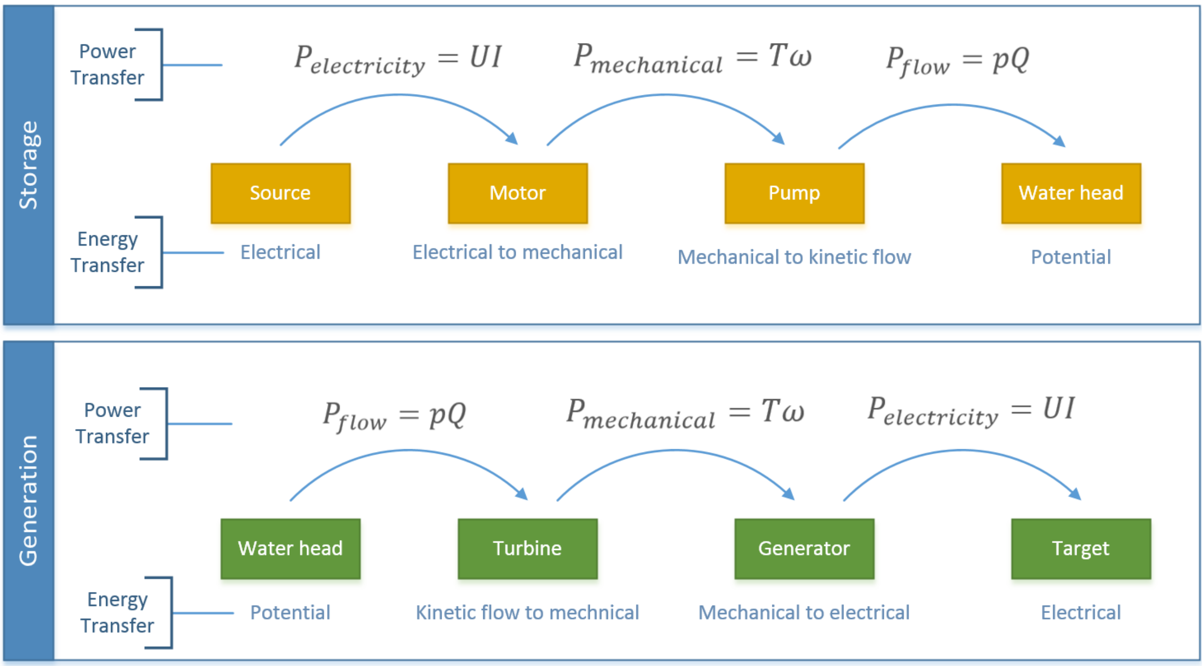

Figure 4 Energy/Power transfers of a PSH system

PHS vs. UPHS

Both variants these operate within the concept potential energy. The PHS variant uses *large reservoirs* from nature, the elevation head can often not be changed: the power output is maximized by the discharge Q. The UPHS variant often uses a smaller (surface) reservoir and power output is maximized by the increasing elevation height h.

4.4.2 GRAVITY POWER

Gravity power is slightly different from the other two, but essentially generates power through potential mechanical energy just like the other two variants as will be clear, shortly.

Unlike the other two variants (PHS and UPHS), gravity power is an *enclosed* system consisting of a turbine/pump, generator/motor and a piston as can be seen in Figure 5. The container where the piston is situated is called the *main storage container* or *tank* (red boundary); this is where all the magic happens: storage of potential energy.

In the *generation mode* the piston is released (via, for example, the opening of a valve which is not drawn in the picture). The piston exerts a pressure force on the fluid which results in the flow of the fluid counter clockwise. The *kinetic* fluid flow enters the turbine which converts kinetic flow energy to mechanical energy. Mechanical energy is then converted to electrical energy in the generator. A transformer (not drawn in the picture) is added to the system if necessary.

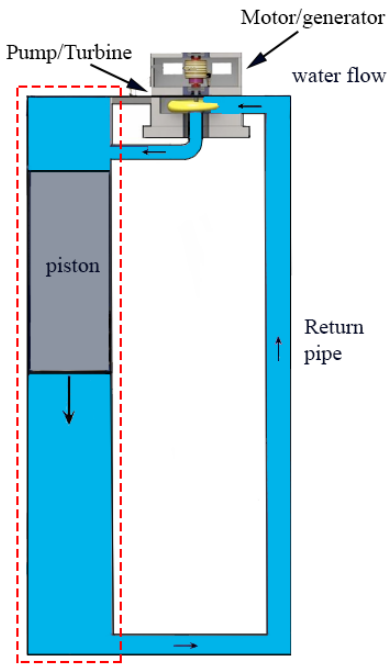

Figure 5 Generation mode gravity power

In the *storage mode*, electricity is supplied to the motor, which converts electrical energy to mechanical energy. The pump converts mechanical energy to a kinetic flow energy (in clockwise direction) which drives the piston to the top.

How power/energy is transferred/converted between these components can be seen in Figure 6.

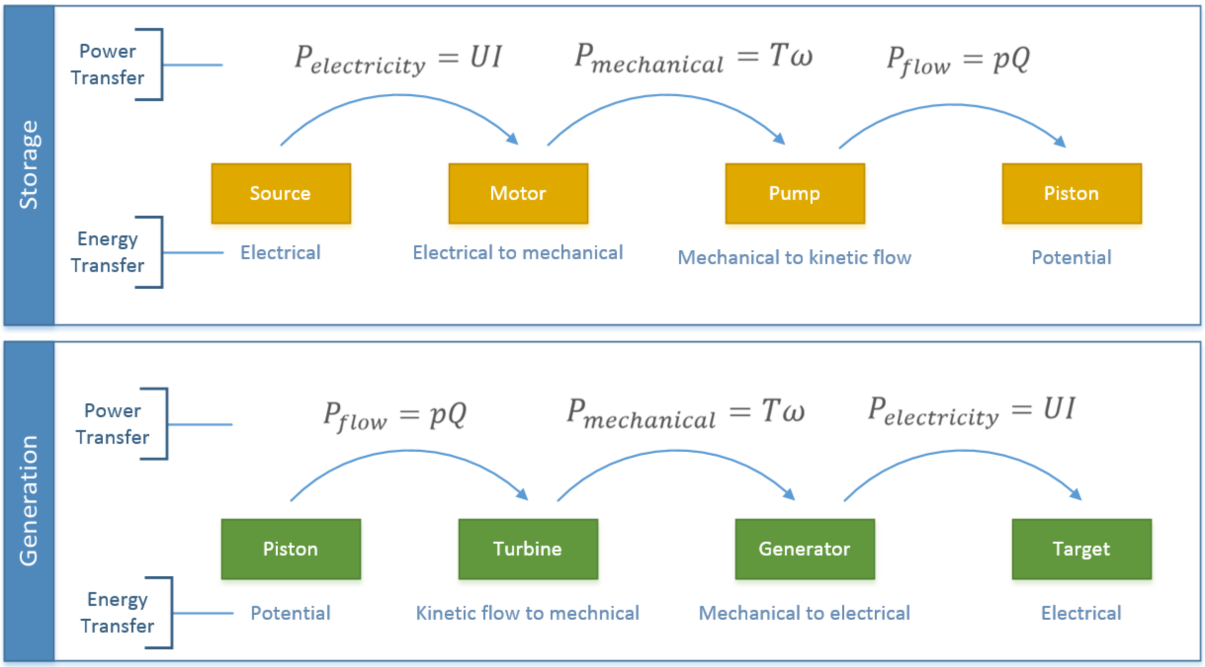

Figure 6 Power/energy transfer GPHS

The piston acts as an extra pressure force. It transfers *work* to the fluid as it translates a distance ds; $W_{piston} = p \cdot A\ ds$ (Figure 7). The presence of the piston acts as an extra-large water column, resulting in a lower required amount of volume for the same amount of energy storage. This can be explained as follows:

The piston is chosen to be heavier than water, which means that it has a larger density then water $\rho_{piston} > \rho_{water}$. It is assumed that the density of the piston is ten times as great as water: $\rho_{piston} = 10 \cdot \rho_{water}$. Imagine a closed container full of water with a height h, the pressure on top would be equal to $p_{top} = 0$ and at the bottom the pressure would be equal to $p_{bottom} = \rho gh$. Now suppose that the top part of the container a piston is present with a height dx. The pressure at top would still be $p_{top} = 0$, the bottom would however have the following pressure:

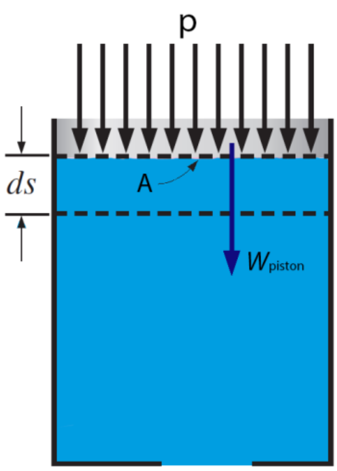

Figure 7 Piston act as extra *work* in the system (Huggins, 2010)

$$p_{bottom} = \rho g(h - dx) + 10 \cdot \rho g \cdot dx = \rho gh + 9\rho gdx$$

A pressure surplus of $9\rho gdx$. As the power from flow $P_{flow} = p \cdot Q$ includes the pressure, the amount of power (storage) increases by including a piston as can be seen in Figure 8.

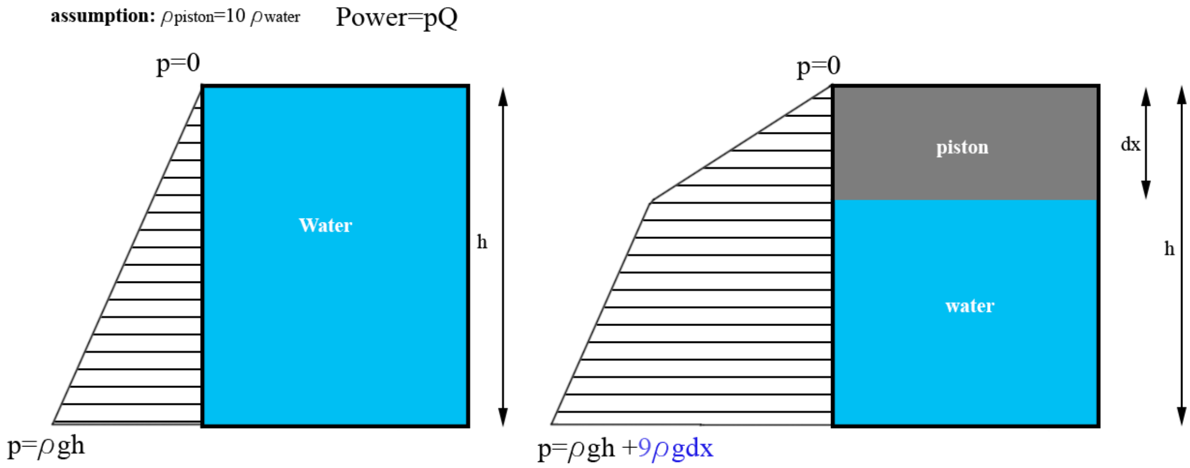

Figure 8 Extra energy storage due to piston

Another obvious difference is that the PHS (and UPHS) have *two* reservoirs in which the energy balance boundary was defined upon (the input from reservoir 1 is the output to reservoir 2 in *generation mode*). This difference is, however, not necessarily true. The GPHS has so called *virtual* reservoirs as is explained as follows (Figure 9):

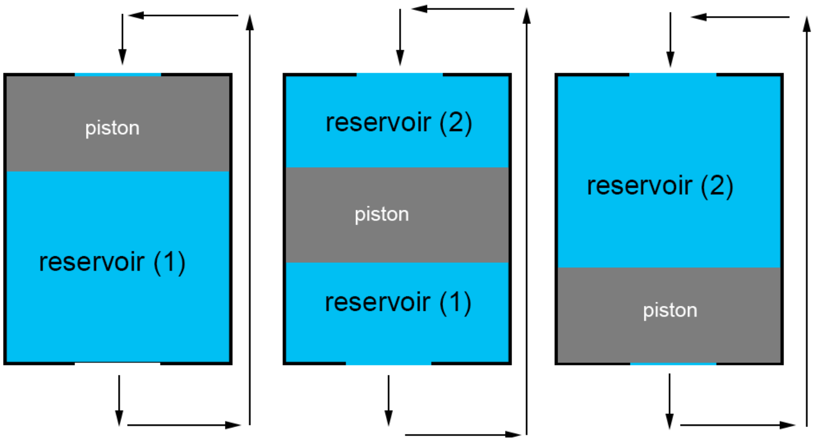

Figure 9 The main storage container representing both (virtual) reservoir

First of all, the boundaries are set upon the *main storage container* as this is the place where energy is stored. When the piston is at the top of the storage container, the water beneath the piston can be seen as a virtual reservoir denoted as virtual reservoir (1). As the piston moves down to generate electricity, the volume of virtual reservoir (1) is decreasing and on top of the piston a new volume arises which is called virtual reservoir (2) when the piston has reached the bottom of the system only reservoir (2) left. The main container represents thus both reservoirs. Note these figures are only for clarification purposes.

4.4.3 COMPARISON

As is clear from (A.3 Hydro storage analysis, p110), all these variants generate power through potential energy. For each variant the (dis)advantages are shown in Table 4. Furthermore, Table 5 shows a Multi-Criteria-Analysis which purpose is to compare the variants.

Table 4 Characteristics of each variant

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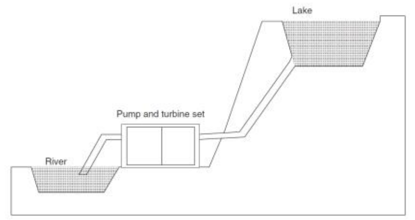

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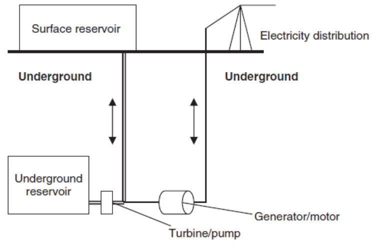

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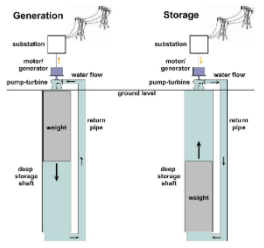

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</tr>
<tr>
<td>Advantages
Much experience/low risks
Relatively cheap</td>
<td>Advantages
Only 1 upper reservoir required</td>
<td>Advantages
Water tank as reservoir
More energy storage with lesser volume due to piston</td>
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<tr>
<td>Disadvantages
Great geological and geographic dependencies</td>
<td>Disadvantages
Only in concept (never executed)
Technically challenging
Requires an already underground structure or is economically probably not feasible
Requires hard rock as soil</td>
<td>Disadvantages
Only in concept (never executed)
Technically challenging
Requires good soil conditions
Might be economically unattractive</td>
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The MCA entails the following criteria:

- **Deploy ability.** What is the deploying ability of each variant in geographical- and geological senses?
- **Environment friendly.** How environment friendly is each variant? One can imagine that PHS involves changes in natural reservoirs which might do more harm than implementing a GPHS device somewhere.
- **Efficiency.** How efficient is each variant? This criterion is primarily based on the complexity of a system.
- **Storage Capacity.** How much energy can each variant store per unit of volume?

The scoring of the MCA has been defined with "+". The more "+", the more positive the score. A high amount "+" in the criteria *efficiency*, for example, coincides with a high *efficiency*.

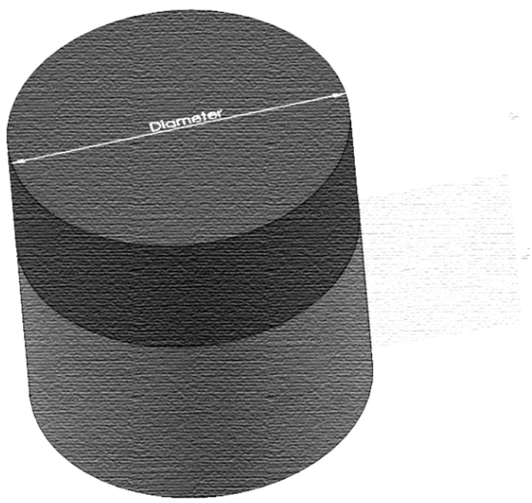
Table 5 Multi criteria Analysis

Criteria\variant	PHS	UPHS	Gravity Power (GPHS)
Availability	+	+++	+++++
Environment friendly	++	+++	++++
Efficiency	+++++	+++	+++
Storage capacity	+++	+++	++++

Note 1: Table 5 only provides a rough estimation (or guess) of how one variant compares to another variant. Note 2: the variants have been compared relatively, meaning that all variants have the same storage volume and elevation height. Therefore, the gravity power variant which requires less volume to store a certain capacity (due to the piston), scores better than the PHS. In absolute sense, however, the PHS has a much larger storage capacity.

In this paper the gravity power (GPHS) variant will be further investigated. The following chapter entails a case study subject to GPHS, including the location of the GPHS, buffer scale and a preliminary design.

CHAPTER 5. BUFFER CAPACITY & PRELIMINARY DESIGN



Contents

5.1 INTRODUCTION

In this chapter, the buffer capacity will be determined. From the buffer capacity, an initial design of the storage device follows. The initial design will be optimized with boundary conditions, which is then called the preliminary design.

5.2 BUFFER CAPACITY

The buffer capacity of the storage device can be defined as the amount of energy that can be stored into the storage device. In this paragraph, the required size/buffer capacity of the gravity storage device will be determined.

5.2.1 CAPACITY

Energy is expressed in joules but also often expressed in kW and kWh (the difference has been explained in *part one)*. Even though, the amount of energy storage is meant for a harbor, for simplicity, the amount of energy (capacity) will, for now, be expressed in *households (quantity)* and *days (time)*. One household, requires approximately 4000 kWh per year (www.energielijn.nl, n.d.), which is on average 4000/365 = 11 kWh per day. Two households would require 22 kWh per day; per week, this becomes 22 · 7= 154 kWh and so on. Basically, the capacity is a function of time and households as can be seen in Figure 10.

Figure 10 Capacity is a function of time and households

The buffer capacity can, assuming it is fixed, be linked to the different energy loads according to Table 6. With a fixed capacity one can supply a few households over a longer period (option 1), a large number of households for a smaller time scale (option 3) or in between (option 2).

Table 6 Households versus time

Buffer scale	Households	Time
Option 1		
Option 2		
Option 3		

In sum, it can be said that in order to buffer for more households, a larger capacity is required. The same applies to time: the larger amount of days the storage device should buffer for, the larger the required storage capacity. The relation between the capacity and the (gravity storage) tank size can be described with the energy equation Eq. (5.1) and Figure 11. Note that this equation has been derived in [Appendix C: The energy equation, p117].

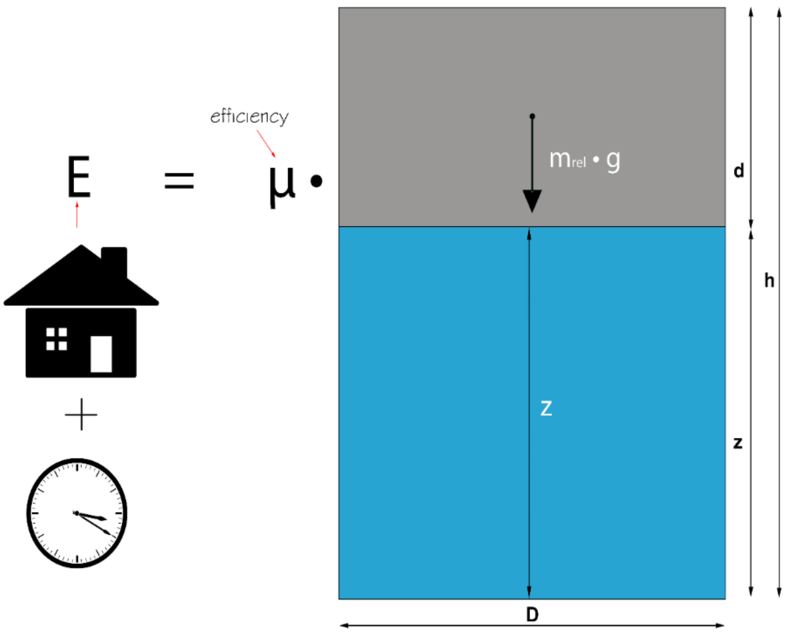


Figure 11 Energy storage vs. tank size

$$E = (\rho_{piston} - \rho_{water}) \cdot \frac{1}{4} \pi D^2 \cdot d \cdot g \cdot z \cdot \mu \qquad \text{Eq. (5.1)}$$

Where:

- E is the total amount of energy that can be stored [J]
- D is the diameter of the storage device [m]
- d is the thickness/height of the piston [m]
- g is the gravitational acceleration 9.81 [m/s^2]
- z is the potential elevation height [m]
- μ is the system efficiency [-]
- π is a constant of 3.1415 [-]
- ρ_{piston} is the density of the piston [kg/m^3]
- ρ_{water} is the density of water 1000 [kg/m^3]

5.2.2 APPROACH

In order to get an idea of how large the tank must be to hold a certain capacity, the following approaches can be followed through:

1. Design a tank size for a certain storage demand.
2. Design a tank size based on the technical feasibility

In *part one*, it became clear that the amount of installed wind power in the Maasvlakte 2, will be up to 60 MW. It also became clear that in order to determine the buffer capacity based on the equilibrium of energy demand and supply, would require complex statistical probabilistic calculations, a detailed risk analysis and a thorough energy management study. For this reason, chosen has been for approach number 2.

From Eq. (5.1), it follows that increasing the diameter D is most effective concerning the capacity. The diameter will therefore be changed accordingly, the remaining parameters, that is, the efficiency μ, the piston density ρ and the remaining dimension parameters, will be elaborated in the following section.

5.2.3 TANK PARAMETERS

The parameters that will be determined in this section are:

- z the potential elevation height [m]
- d the thickness/height of the piston [m]
- h the container height [m]
- μ the system efficiency [-]
- ρ_{piston} the density of the piston [kg/m³]

Initial tank size

The tank will be constructed of (prestressed) concrete, as will be explained later in this paper. In order to get an idea of the technical feasibility (size wise) it will be compared to other reference project such as the three *concrete* LNG (Liquefied Natural Gas) tanks which have an 84 meter diameter and have a height of 42 meter and is currently located in the Maasvlakte (Figure 12).

Figure 12 LNG container Maasvlakte

As the gravity storage device also includes a piston, the initial storage tank size will be chosen slightly smaller. It has been chosen to use a piston with a thickness d of 20 meters and a container height h of 50 meters.

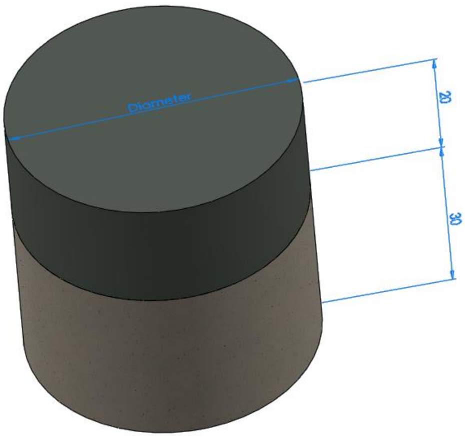


Figure 13 Diameter Storage device

The efficiency μ: 0.57 [-]

The efficiency μ of the system is probably one of the most important parameter: it determines how much energy is lost and has been extensively discussed in [Appendix D: Efficiency, p120]. Here follows a summary.

The following losses can be expected:

- **Conversion losses.** Losses due to power conversion (e.g. from electrical to mechanical)
- **Local losses.** Losses due to friction
- **External losses.** Losses in cables

From [Appendix D: Efficiency, p120], it follows that the total system efficiency is equal to 0.57 [-].

The density of the piston ρ: 12000 kg/m^3 [-]

The greater the mass, the greater the amount energy capacity. Chosen has been for a lead piston which has a density of 12000 kg/m^3

Overview tank parameters

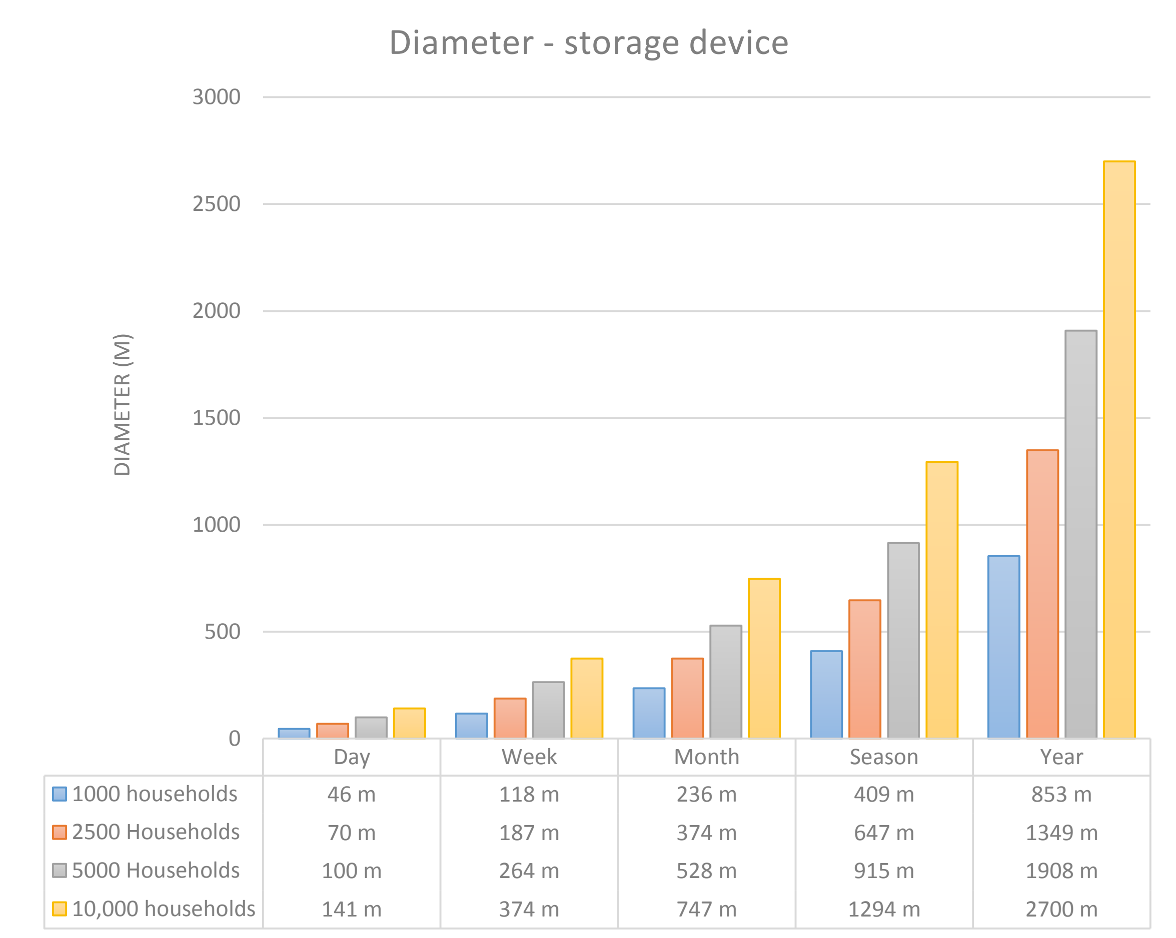
An overview of the tank parameters are shown in Table 7.

Table 7 Tank parameters

Parameter	Value
z	30 m
d	20 m
μ	0.57
D	Variable
h	50 m
ρ	12000 kg/m^3

5.2.4 TANK SIZE VS CAPACITY

The capacity of the device has been determined for a fixed number of households: 1000, 2500, 5000 and 10,000 - and the following periods of time: one day, a week, a month, a season and a year; the results can be found in Figure 14.



	Day	Week	Month	Season	Year
1000 households	46 m	118 m	236 m	409 m	853 m
2500 Households	70 m	187 m	374 m	647 m	1349 m
5000 Households	100 m	264 m	528 m	915 m	1908 m
10,000 households	141 m	374 m	747 m	1294 m	2700 m

Figure 14 Buffer scale in households

It can be seen that more than a day of buffering would require a vast storage device: in order to buffer 5000 households during one day, for example, one must increase the diameter to 100 meter. The LNG container tanks have a diameter of 80 meter. Therefore will be looked into daily storage only. The amount of energy that coincides with one day storage for an "x" number of households can be seen in Figure 15.

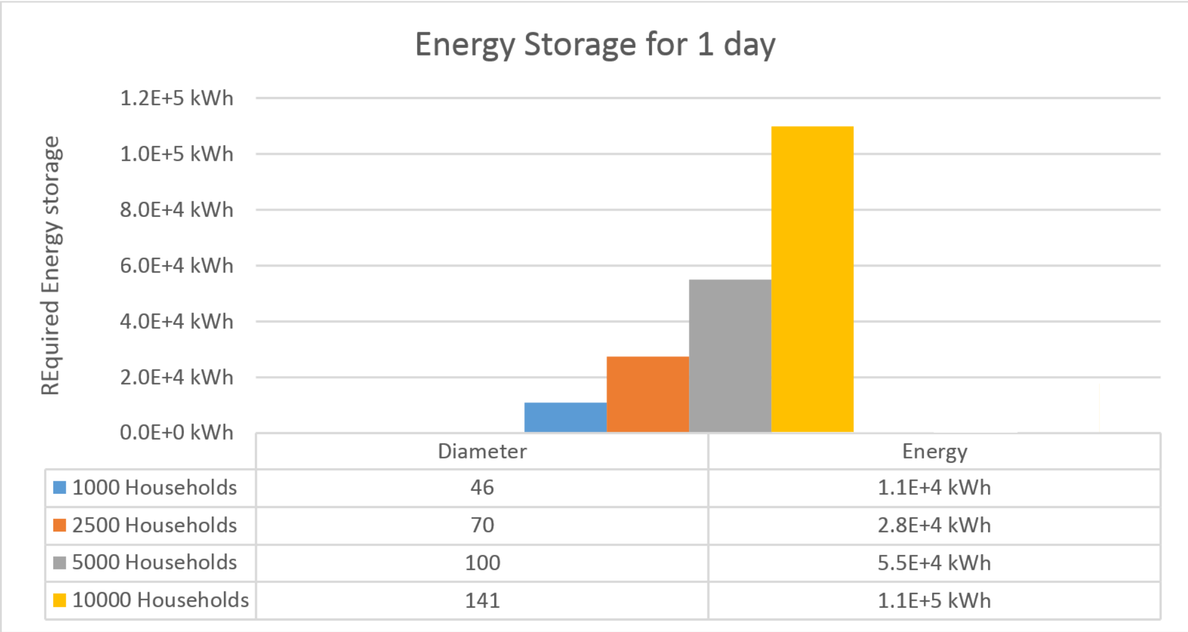


Figure 15 Buffer histogram —households/energy

It has been decided to construct a tank with a daily energy capacity of 28,000 kWh (coinciding with 2500 households and a tank diameter of 70 diameter).

5.2.5 PEAK LOAD BUFFERING

In *part one,* it became clear that a power plant subject to hydro energy was able to provide all types of loads, that is, *base load*, *intermediate load*, and *peak load*. If the storage device is intended to cover the base load, it should be active for more than 90% within that period. If it would be used to provide daily *base* storage, for example, the storage device should be active for approximately 23 hour per day. For intermediate load, the load factor is between 40-60%, and for covering peak load, the load factor is between 5-15%.

The storage device will be used for daily peak cycles: it recharges and discharges every single day. The load capacity factor for peak hour is approximately 4 hours. By buffering/supplying for peak hours, more "households" can be addressed. In addition, it is economically more attractive to compete with peak hour load supply (as is clear from *part one*).

In sum, the storage device will be designed having a buffer capacity to provide peak load energy (28,000 kWh) during a day. The device will be a *daily* cycling device, meaning that it is charged in the night and discharged during daytime (discharge time is approximately four hours).

In the following paragraph, the preliminary dimensions of the tank will be determined.

5.3 PRELIMINARY TANK DESIGN

In this paragraph, the preliminary design will be made according to an energy amount of 28000 kWh. In the previous paragraph, the diameter D had been changed, and the piston thickness d and container height h were fixed. Here, it becomes clear that there is an optimum amount of energy that can be stored by changing the ratio between the container height h and the piston thickness d. Before determining the preliminary tank design, the proper value of the energy amount for which the tank will be designed, is discussed.

Energy Storage E: 24.75GJ (*daily storage*)

The structure must be designed for approximately 28,000 kWh per day. *Per four hours* this equal to 4,580 kWh. However, the actual design energy storage will be higher as is explained as follows:

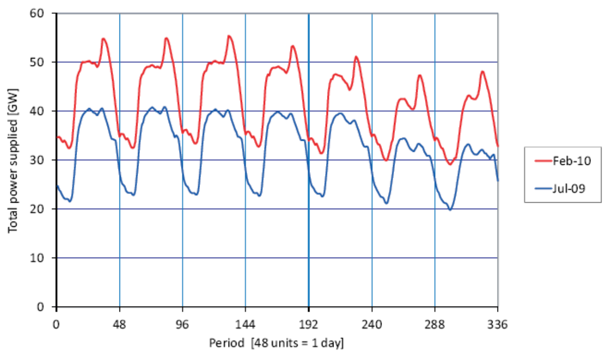


Figure 16 Energy variation during a winter- (blue) and summer (summer) week (Energy Consumption, 2009)

In *part one,* it became obvious that energy demand load is variable along the day, week – and even season. It is therefore important that the most critical time laps is chosen which, in Northern Hemisphere, is in the winter. According to Figure 16, which shows the energy variation during a winter and summer week, the lowest power load measured is 21 GW, the highest power load measured is 55 GW , the average power load is equal to $\frac{55+21}{2}$ = 38.5 GW. To go from the average to the highest measured power load, the average power load must increase with approximately 43%.

In order to ensure *four hours* of buffering/storage the average energy demand, for the GPHS device, will be increased by 50%, making the total energy storage demand E=6,875 kWh. In unit of joules (one kWh is equal to 3.6 MJ) this becomes $24{,}750 MJ\ or\ 24.75\ GJ$.

5.3.1 BOUNDARY CONDITIONS

This paragraph discusses the boundary conditions with respect to the preliminary design. The following boundary conditions are considered:

Table 8 Boundary conditions preliminary design

Boundary condition	Description	Value
B.C.1	The ratio between the height of the container h and the thickness of the piston d	$\frac{h}{d} = \frac{2}{1}$
B.C.2	The maximum piston thickness d_{max}	$d_{max} = 40$ m
B.C.3	The maximum container height h_{max}	$h_{max} = 80$ m
B.C.4	The ratio between the thickness of the piston d_{piston} and the diameter of the piston D_{piston}	$\frac{d}{D} \geq 1$
B.C.5	The ratio between the height of the container $h_{container}$ and the diameter of the piston D_{piston}	$\frac{h}{D} \geq 2$

B.C.1 Ratio between height container and piston thickness: $\frac{h}{d} = \frac{2}{1}$

The first boundary condition defines the ratio between the height of the container $h_{container}$ and thickness of the piston d_{piston}. A greater piston thickness results in a larger mass and therefore, a larger energy storage capacity. However, as the height of the container is the sum of the elevation height and the thickness of the container ($h = d + z$), a greater piston thickness will also result in a smaller elevation height, and a smaller elevation height leads to a decrease of the energy storage capacity. This boundary condition is the optimal ratio as will be explained as follows:

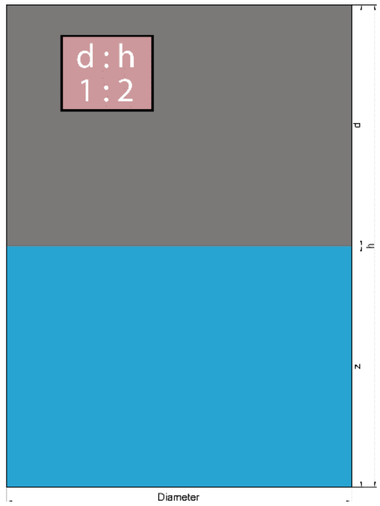


Figure 17 Ratio height of the container and thickness of the piston

The (initial) energy equation has been defined as:

$$E = (\rho_{piston} - \rho_{water}) \cdot \frac{1}{4}\pi D^2 \cdot d \cdot g \cdot z \cdot \mu \quad \text{Eq. (5.2)}$$

Because $h = d + z$ this can be rewritten into

$$\frac{E}{\left(\rho_{piston} - \rho_{water}\right) \cdot \frac{1}{4}\pi D^2 \cdot g \cdot \mu} = d \cdot (h - d) = d \cdot h - d^2$$

Optimizing for piston thickness d results in:

$$\frac{\Delta\left[\frac{E}{\left(\rho_{piston} - \rho_{water}\right) \cdot \frac{1}{4}\pi D^2 \cdot g \cdot \mu}\right]}{\Delta d} = \frac{\Delta\left[d \cdot h - d^2\right]}{\Delta d} \rightarrow 0 = h - 2 \cdot d \rightarrow h = 2 \cdot d$$

In other words: the optimal ratio between the thickness of the piston and the container height, in which the greatest amount of energy can be stored, is 1:2. This means that the piston thickness d is would be most optimal for an equal potential height z or: $z = d = \frac{h}{2}$

B.C.2 Maximum Piston thickness d_{max}: 40 meter

The piston is the component in this system which exerts large forces on the foundation and the tank. These forces regenerate *tensile stresses* in the tank. As is stated earlier, the tank is made of concrete which has low tensile resistance. The maximum mean tensile strength of concrete lies in the order of 5 MPa (Mega Pascal or $1 \cdot 10^6$ N/m^2) according to (Eurocode 2, C90). The tensile forces due to the piston σ_{piston} occurring in the concrete, can be written as a function of the mass and volume of the piston - and can be calculated as follows:

$$\sigma_{piston} = \frac{F_{piston}}{A_{piston}} = \frac{V_{piston} \cdot \rho_{piston} \cdot g}{A_{piston}} = d_{piston} \cdot \rho_{piston} \cdot g \qquad \text{Eq. (5.3)}$$

Rewriting Eq. (5.3), the maximum piston thickness becomes: $d_{piston;max} = \frac{\sigma_{piston}}{\rho_{piston} \cdot g} = \frac{5\text{MPa}}{12.000 \cdot 9.81} \approx 40\text{ m}$. Note that even though the tensile stresses will be primarily resisted by reinforcement, this is a measure to make sure that the tensile stresses remain limited.

B.C.3 Maximum container height h_{max}: 80 meter

Restricting the maximum container height is to limit the load on the *foundation* and tank. A larger height will lead to more tensile forces in the structure which is to be avoided. Because of the B.C.1 and B.C.2, the maximum height of the container is fixed at 80 meters.

B.C.4 Ratio Thickness/Diameter piston: $\frac{d}{D} \geq 1$

The piston has a probability of jamming if the ratio between height (thickness) and length (diameter) of the piston is too small; one can imagine that a narrow and deep drawer is easier to pull than a wide and shallow drawer. Jamming depends on the friction between the piston and the wall F_f, and the force on the piston F_1 as can be seen in Figure 18. Note that in this subsection, the piston thickness has been denoted with h instead of d!!!

If the piston rotates, while sliding downwards, a friction force occurs on both sides of the piston:

(1) $F_f = \mu \cdot F$

The piston jams when the sum of the friction forces is greater than the force on the piston:

(2) $2F_f > F_1$

The normal force F follows from the moment balance:

(3) $F \cdot h = F_1 \cdot e$

From these three equations it follows that the system becomes self-locking when $\mu > \frac{h}{2e}$:

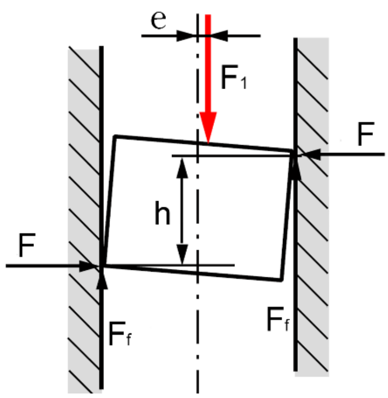


Figure 18 Piston jamming (Beek, 2012)

$$\left.\begin{array}{l} F_f = \mu \cdot F \\ 2F_f > F_1 \\ F \cdot h = F_1 \cdot e \end{array}\right\} \rightarrow \mu > \frac{h}{2e}$$

Where μ is the (dynamic) friction coefficient between the piston and the wall which is approximately 0.5 in case of steel to concrete (FRICTION, n.d.). Whether the piston jams or not can be described with:

$$\underset{\text{Jamming}}{\frac{h}{e} < 1} \qquad \leftrightarrow \qquad \underset{\text{no jamming}}{\frac{h}{e} > 1}$$

As the force F_1 is the resultant of the water distribution on the piston, the eccentricity is expected to be quite small. In the worst case scenario the resultant force F_1 is at a location near the wall, meaning that the eccentricity is half of the length (or diameter). Which means that the minimum piston height equals to

$$\frac{h}{e} = \frac{h}{\frac{1}{2}D} > 1 \rightarrow h > 0.5D$$

In this paper, it is assumed that, the ratio between the piston thickness d (again, in this subsection denoted as h) and the piston diameter D is: $\frac{d}{D} \geq 1$ in order to prevent piston jamming. Whether this is theory is true must be validated in practice which goes beyond the scope of this paper.

B.C.5 Ratio between container height and piston diameter $\frac{h}{D} \geq 2$

From B.C.1 $\left(\frac{\mathrm{h}}{\mathrm{d}} = \frac{2}{1}\right)$ and B.C.4 $\left(\frac{d}{D} \geq 1\right)$ it follows that the ratio between the height of the container h and the diameter of the piston D is equal to $\left(\frac{h}{D} \geq 2\right)$ or:

$$\left.\begin{array}{l} \text{B.C.1 } \frac{h}{d} = 2 \\ \text{B.C.4 } \frac{d}{D} \geq 1 \end{array}\right\} \rightarrow \text{B.C.5 } \frac{h}{D} \geq 2$$

5.3.2 THE OPTIMAL ENERGY EQUATION

In [Appendix C: The energy equation, p117] the following energy equation has been derived:

$$E = (\rho_{piston} - \rho_{water}) \cdot \frac{1}{4}\pi D^2 \cdot d \cdot g \cdot z \cdot \mu \qquad \text{Eq. (5.4)}$$

Where:

- E is the total amount of energy that can be stored [J]
- D is the diameter of the storage device [m]
- d is the thickness/height of the piston [m]
- g is the gravitational acceleration [m/s²]
- z is the potential elevation height [m]
- μ is the system efficiency [-]
- π is a constant of 3.1415 [-]
- ρ_{piston} is the density of the piston [kg/m³]
- ρ_{water} is the density of water 1000 [kg/m³]

In Eq. (5.4) there are 3 variables: the piston thickness d, the potential height z and the container diameter D. The first two parameters both depend on the container height h. By applying B.C.2 which states that the most energy can be stored/generated if the thickness of the piston is exactly half the height of the container or: $d = z = \frac{h}{2}$, the energy equation Eq. (5.4) can be written as:

The optimal energy equation:

$$E = (\rho_{piston} - \rho_{water}) \cdot \frac{1}{16}\pi D^2 \cdot g \cdot h^2 \cdot \mu \qquad \text{Eq. (5.5)}$$

One can see that increasing the diameter has the same effect as increasing the height with respect to the energy storage capacity. The final dimensions that are chosen is based on this equation and will be discussed in the following paragraph.

5.3.3 CONTAINER SIZE DETERMINATION

Overview Design conditions phase I

Before commencing the determination of the preliminary main container size, a brief overview of the most important design criteria and boundary conditions has been summarized in Table 9.

Table 9 Design criteria design phase I

Design Criteria	Parameter	Symbol	Value
Energy Storage	Constant	E	24.75GJ
Efficiency	Constant	μ	0.57
Gravitational Acceleration	Constant	g	9.81 m/s^2
ρ_{piston} (lead)	Constant	ρ_{piston}	12,000 kg/m^3
ρ_{water}	Constant	ρ_{water}	1000 kg/m^3
Piston thickness	Variable	d	$\frac{h}{2}$
Container height	Variable	h	
Container Diameter	Variable	D	
Ratio between the height container and the piston thickness	B.C. 1 (boundary condition)	$\frac{h}{d}$	$\frac{h}{d} = \frac{2}{1}$
(Absolute) Maximum piston thickness	B.C. 2	d_{max}	40 m
(Absolute) Maximum container height	B.C. 3 (follows from B.C.1)	h_{max}	$h_{max} = 80\ m$
Ratio thickness/diameter of the piston	B.C. 4	$\frac{d}{D}$	$\frac{d}{D} \geq 1$
Ratio between height container and piston diameter	B.C. 5	$\frac{h}{D}$	$\frac{h}{D} \geq 2$

Determining the container size

The design area will be (visually) represented step by step according to the following scheme:

- **Step 1.** Schematizing the boundary conditions
- **Step 2.** The energy line
- **Step 3.** The design area
- **Step 4.** Determining the container size

Step 1: The design boundary conditions

The boundary conditions are shown in Figure 19 where:

- The vertical axis represents the container *height* and the horizontal axis represents the container *diameter*
- B.C. 3 results in the *maximum* container height is 80 m (red dashes)
- B.C. 5 represent the ratio between the *height* and the *diameter* of the container (green dots)

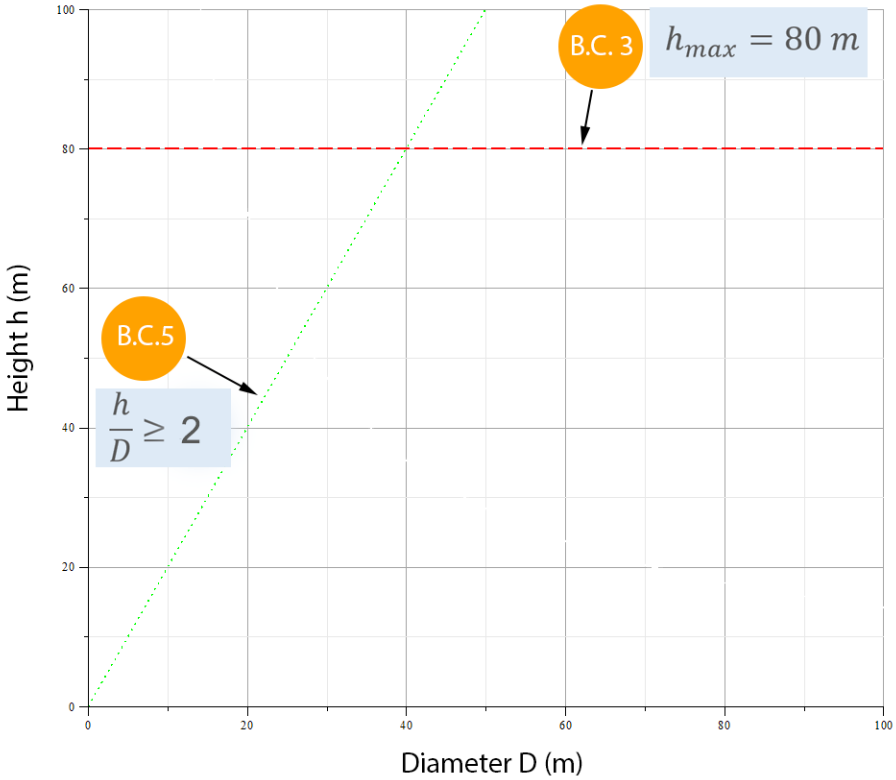


Figure 19 The boundary conditions (B.C.)

Step 2: The plot (energy line)

In Figure 20, the optimal energy equation has been plotted. It can be seen that the equation is not linear, this is due to the fact that $h^2 \propto \frac{1}{D^2}$. Note that every coordinate of this curve corresponds to an energy amount of approximately 25 GJ.

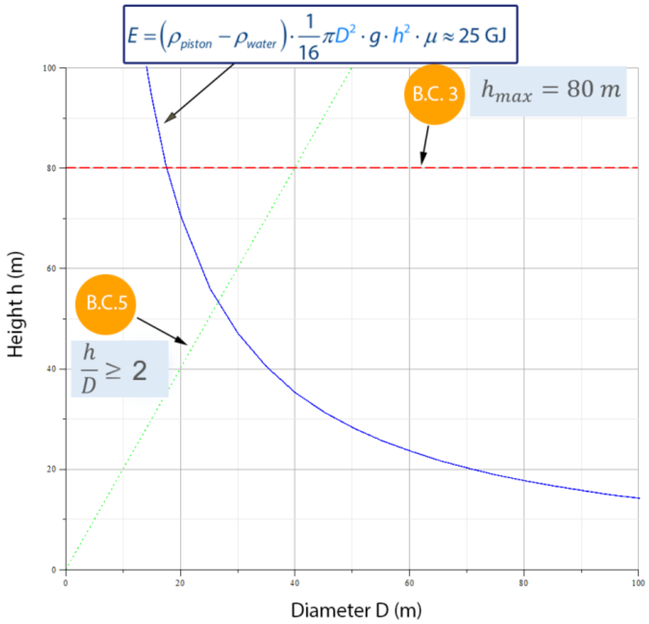


Figure 20 The energy line

Step 3: The design area

Combining the energy line and the boundary conditions the following plot is generated:

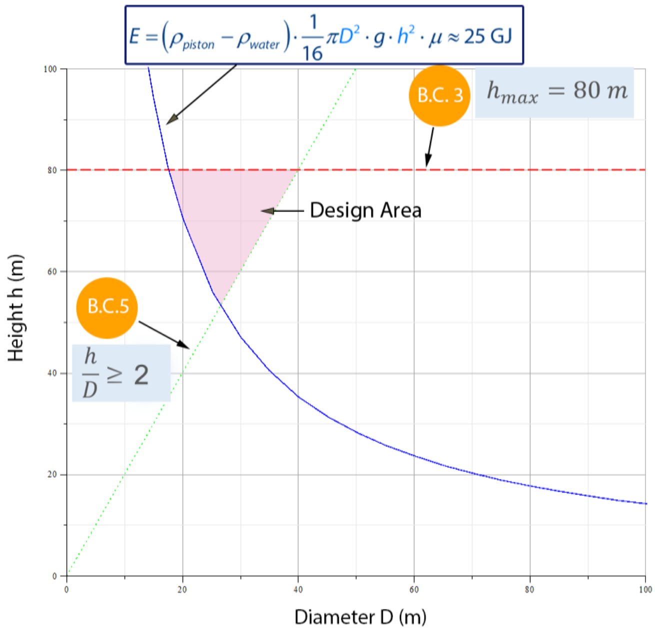


Figure 21 Design area

Step 4: Determining container size

Now that the design area has been plotted, the size of the container can be determined. Technically, any choice on the actual design area would be appropriate. However, the design point must be chosen close to the energy line in order to avoid oversizing of the container. The location of the design point is decided to be at (24, 56), for the dimensions this means that:

- The diameter D of the container is 24 meters
- The height h of the container is 56 meters
- Piston thickness d follows from B.C.1 which is 28 meters
- Elevation height $z = h - d = 28$ meters

5.3.4 FINAL DESIGN SPECIFICATIONS

In the previous paragraphs it became clear how the *main container* of the storage device has been dimensioned involving different parameters and boundary conditions among other aspects. The final preliminary design has been illustrated in Figure 22. The technical/economic feasibility of this design will be discussed in detail in the next chapter.

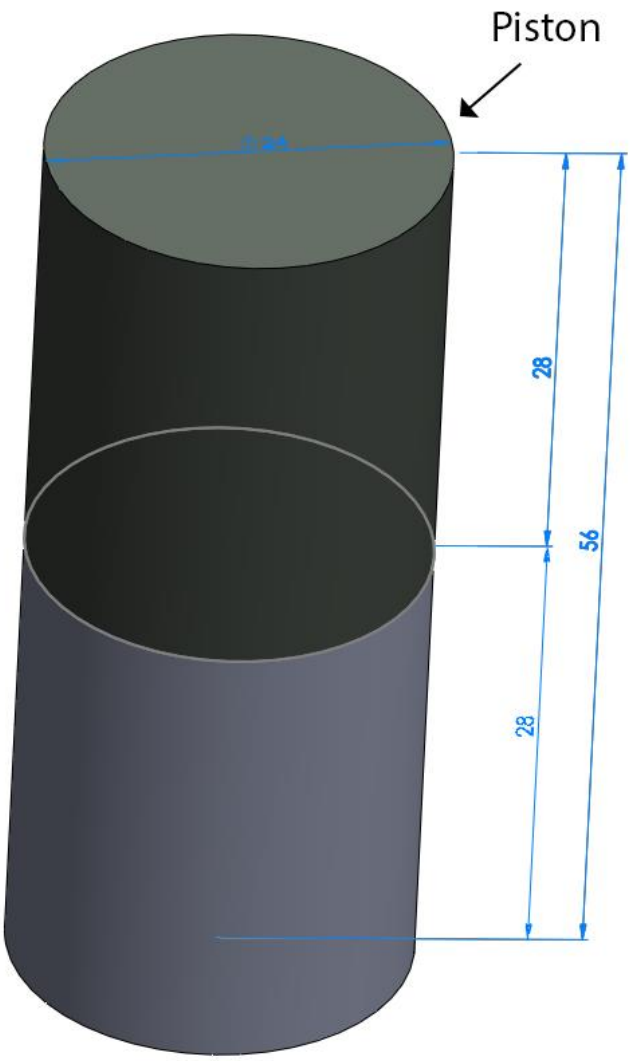


Figure 22 Final dimensions preliminary design

CHAPTER 6. TECHNICAL DESIGN

Contents

6.1 INTRODUCTION

Designing is done from rough to detail, by iteration and optimization. Accordingly, in order to effectively approach the design of the storage device, designing has been sub-divided into different design facets. This chapter provides an overview of what and how the storage device is designed.

6.1.1 DESIGN SCHEME

Normally, in a design project, large amount of aspects have to be taken into account. In this paper however, only the three most important aspects concerning the feasibility of a project, will discussed: *stability*, *construction* (constructability) and *costs*. This chapter follows the following design scheme (Figure 23):

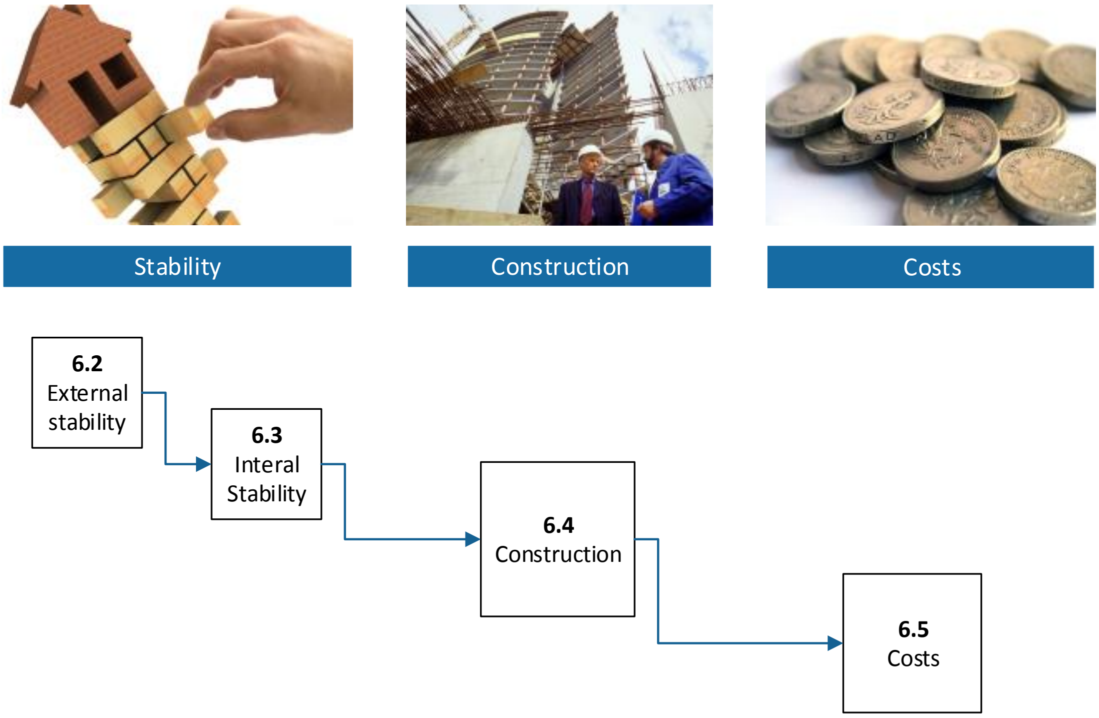


Figure 23 Technical design scheme

The external & internal stability, the construction and the (material) cost of the preliminary design will be discussed. The purpose is to economically and technically evaluate the structure and to ascertain the possibility for optimizations. Depending on the outcome, some necessary steps will be taken in the optimization of the structure which will be done in the next chapter

6.1.2 GENERAL REQUIREMENTS

General

- The structure and its components should be designed so that the design strength is larger than the (factored) design load during the life span of the structure (50 years).
- The tanks should be designed to eliminated/minimize any leakage or measurable loss of liquid through the wall and floor
- The allowable stresses should be limited with the purpose to provide protection against corrosion and leakage and provide a high level durability.
- Cracking of the concrete should be avoided/limited to preserve liquid tightness

- Sections containing prestressed reinforcement should have limited allowable stress in order to prevent from cracks reaching the tendon.

Wall

- The cylindrical wall should be designed so that it has enough bearing capacity for the water and piston load. This means that the wall should be (partially) pre-stressed in order to bear the loads. The wall should be as frictionless as possible to ensure a smooth piston sliding.

Floor

- Potentially construction flaws and leakage are difficult to locate and correct in the floor and therefore requires special attention. The floor of the tank should be watertight and should be able to cope with the pressure from the water- and piston loads. Also differential settlement should be considered into the design.

Joints

- Joints are often the weakest points in the structure, special attention should be used in their design to ensure water tightness. Joints between the wall – base slab and wall and roof must be designed in such a way, that it can cope with the loads as effective as possible.

For an overview of the material properties used in this chapter, one is referred to [G.1.1 Material properties, p129].

6.1.3 PLACEMENT STORAGE DEVICE

The GPHS device was essentially intended for underground application. The idea, according (Gravity Power: Construction Plan, n.d.), is to put them below urban areas for energy storage. This device however, could also be placed aboveground. This paragraph compares three different placement settings of the storage device namely: above ground, underground and semi–underground (which combines both above- and underground) placement as can be seen in Figure 25.

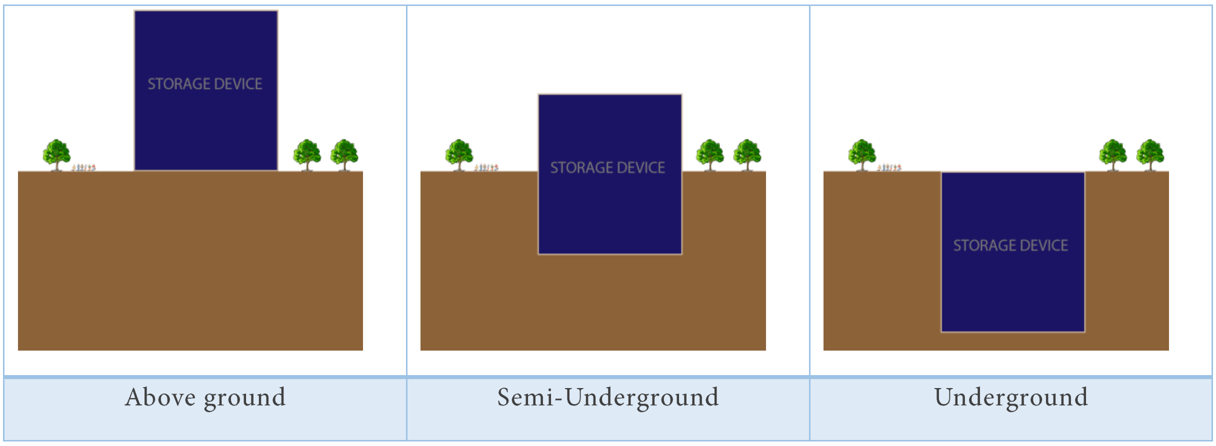


Figure 24 Placement storage device

Advantages for underground placement (=disadvantages for aboveground placement)

1) **Aesthetics.** Having it built underground, no attention has to be paid to aesthetics.
2) **Reliability due to (lacking of) weather loads.** Increased reliability during large wind or even storm loads on the structure. Resulting in *less damage* during severe weather condition and *lower storm restoration cost.*
3) **Fewer interruptions.** There are fewer interruptions which means that the space above grounds could be used for something else.
4) **Great Stability.** The structure is will be relatively heavy and large. Meaning a large load on the foundation. However when building underground, the whole structure could be seen as a foundation itself. In which the structure could have a multi-functional purpose (storage & foundation for, for example, homes).
5) **Great deploy ability.** An underground structure can be applied anywhere (provided that there are no obfuscations in the underground).

Disadvantages for underground placement (=advantages for aboveground placement)

1) **High Cost.** The high cost of building underground corresponds to construction- and maintenance cost. This aspect is often the reason underground-projects are no-go.
2) **Extra loading from water/soil pressure.** The deeper the structure, the greater the soil/water pressures on the structure.

The most preferable situation would be the low cost coinciding with the above ground situation and extra stability of the underground situation. The *Semi-underground* situation combines (most of) the aspects of both worlds. The energy storage device is intended for energy suppliers; their purpose is to make as much profit as possible: the storage device will be implemented *above ground*. Note that there is a large difference between semi-underground and above ground placement of the storage device. If the structure, for example, is supported by a shallow foundation which is imbedded into the subsoil, it coincides with the *above ground* placement of the storage device.

6.1.4 DESIGN COMPONENTS

Before designing, it is important to know *what* components are to be included so that this can be taken into account. In this paper, the following (main) components area considered (Figure 25):

- Main container/tank
- Piston
- Pump/turbine
- Foundation
- Generator/Motor
- Return pipe
- Valve

Note that original design of the GHPS was intended for underground purposes. In this paper, the storage design is built above ground, the position of the (mechanical) system components are changed accordingly. Where in the original concept, the components were placed at the top of the structure, the components will be placed at the bottom of the structure as can be seen in Figure 25. Note that Figure 25 has not been scaled and that it does *not* represent the final situation: it is a solely an initial schematization.

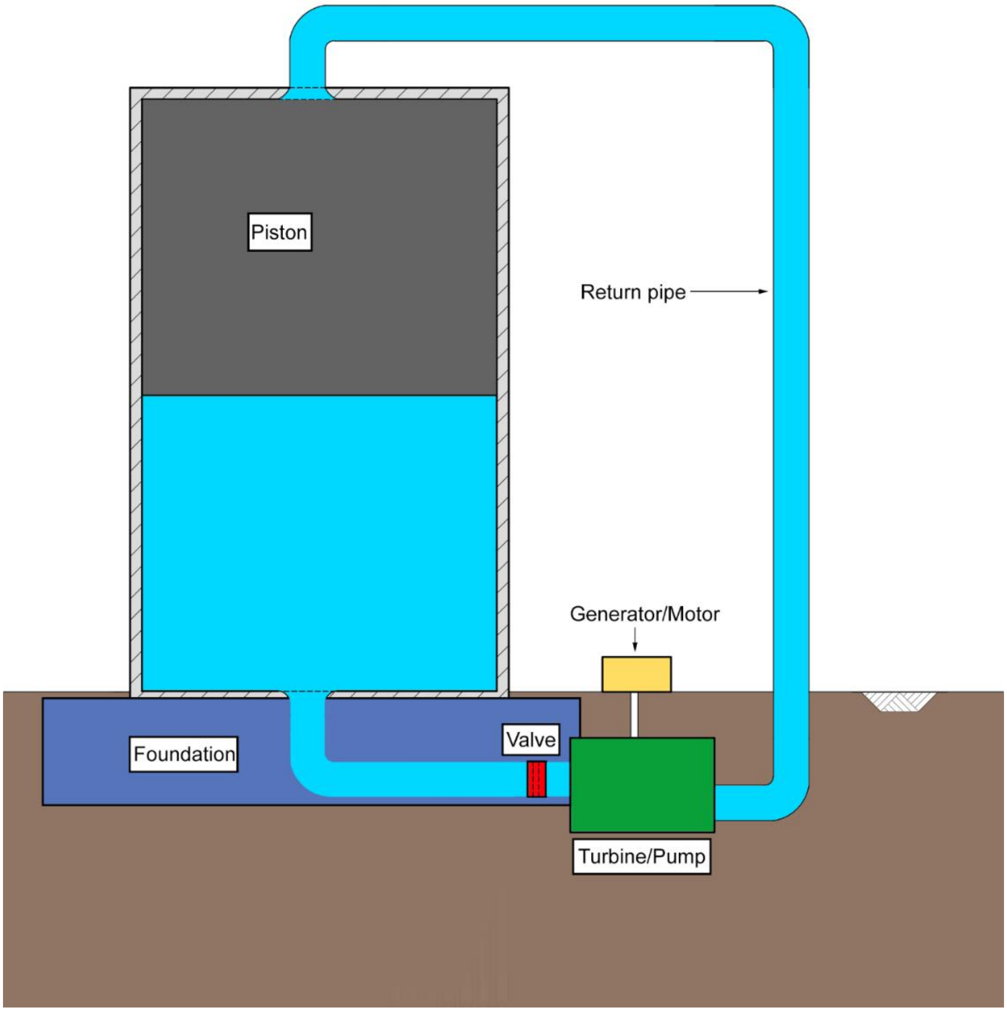


Figure 25 Component placement aboveground

Main container/tank

In the civil engineering there are three main groups of materials commonly used, that is, wood, concrete and steel. Wood is, in this case, not appropriate due to the large expected forces of the storage device. Whether concrete or steel is used, depends on the (global) *design criteria*, which are, for the body of the structure, defined as follows:

- The structure should be able to *resist large (pressure) forces (both tensile and compressive)*
- The structure is intended to have a lifetime of at least 50 years and therefore must be *robust* and *durable* (*sustainability)*
- The structure should have a certain *surface smoothness* (on the inner side of the structure) to reduce friction (for the sliding of the piston).

Concrete, is known for its long lifetime, many bridges/structures made centuries ago still standing should be adequate proof. Concrete is also relatively cheap, has large compressive resistance, but is vulnerable for tensile stresses. In order to increase the tensile resistance, concrete is often mixed with some steel known as *reinforced concrete* – or can be *pre-stressed.* The surface of concrete is naturally relative rough, and measures should be taken to ensure a smooth surface.

Steel, has relatively large tensile and compressive resistance, is light in weight, and its surface is relatively smooth. In the mechanical engineering, devices including a piston and storage devices (containers) are made of steel in general. Yet steel is more expensive than concrete. In addition, steel is highly vulnerable to corrosion and less durable than concrete.

In high pressures situations, steel is commonly more used than concrete. However due to recent developments, such as ultra-high strength concrete and developments in self-healing-concrete (Imambaks & Arfy, 2011), it is quite more interesting to design the device (mainly) in concrete. Steel will be incorporated as reinforcement, prestressing and might be involved in ensuring the surface smoothness. The tank will be calculated and designed in [6.3 Internal Stability, p40].

Piston

The piston, which is the weight in the tank, will be made of lead.

Pump/turbine

The pump/turbine is a component which in one direction acts as a pump and in another direction acts as a turbine. Such component is also known as a *(reversible) centrifugal pump/turbine* or RPT. One of those pump/turbine combination is the Francis turbine/pump as can be seen in Figure 26. The choice and specifications of the turbine will be elaborated in the [6.3.5 Turbine/Pump, p63].

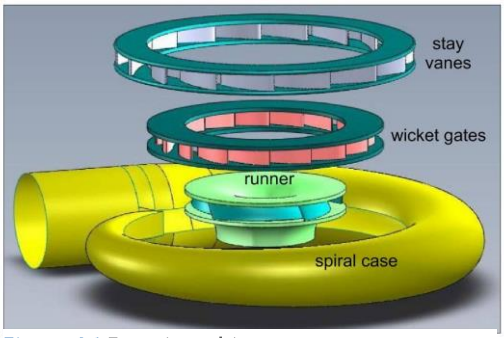


Figure 26 Francis turbine

Return pipe

The return pipe is the connection between the bottom side of the concrete tank and the top side and will be designed in [6.3.4 Return pipe, p62].

Foundation

The foundation, is the part that lies between the structure and the soil. Without a sound foundation the structure cannot remain stable. The foundation will be a shallow foundation as the soil conditions is of relatively good quality which will be clear, shortly.

Generator/Motor

An electric motor is an electromechanical device that converts electrical energy into mechanical energy. A generator converts mechanical energy into electrical energy as was clear from CHAPTER 4. This paper does not go into the detail of the different generator/motors instead one will be chosen according to the requirements of the pump/turbine.

Valves

The purpose of the valve is to control the output/input of the storage device. When the valve is closed, the piston remains at the same place and no energy is generated or stored. Whenever the valves open, the piston starts to move and energy can be stored/generated. These mechanical devices will not be further elaborated in this paper.

6.2 EXTERNAL STABILITY

6.2.1 INTRODUCTION

In this chapter, the external stability will be discussed. External stability implies that the structure as a whole must be stable, it must not rotate nor translate. One of the most important aspects involving the external stability is the *subsoil* which will be discussed firstly. Secondly, an overview of the loads will be given and finally the external stability will be checked for the most dominant *external failure modes*.

6.2.2 SOIL PROPERTIES

The Maasvlakte 2 will be reclaimed with sand particles. It is assumed that the soil is homogenous and consists of sand particles only. For reference of the soil quality, the probe curve of the current Maasvlakte is used which can be seen in [Appendix E: Soil properties, p123]. This probe curve shows that the ground level is situated at approximately NAP +5m. (Nieuw Amsterdams Pijl). The soil strength is relatively good, it follows that from NAP +4.5 m to NAP -6 m, the strength is at least 6 MPa. Due to lack of groundwater information, the groundwater level is estimated at NAP +1 m. A simplified sketch of the soil properties can be seen in Figure 27.

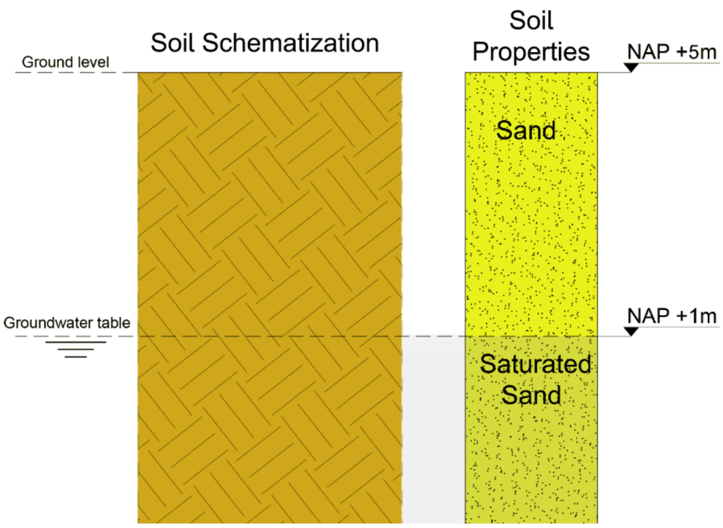


Figure 27 Soil properties

6.2.3 OVERVIEW LOADS

The most important vertical and horizontal (external) loads, in respectively blue and pink, are shown in Figure 28. These loads will be discussed shortly.

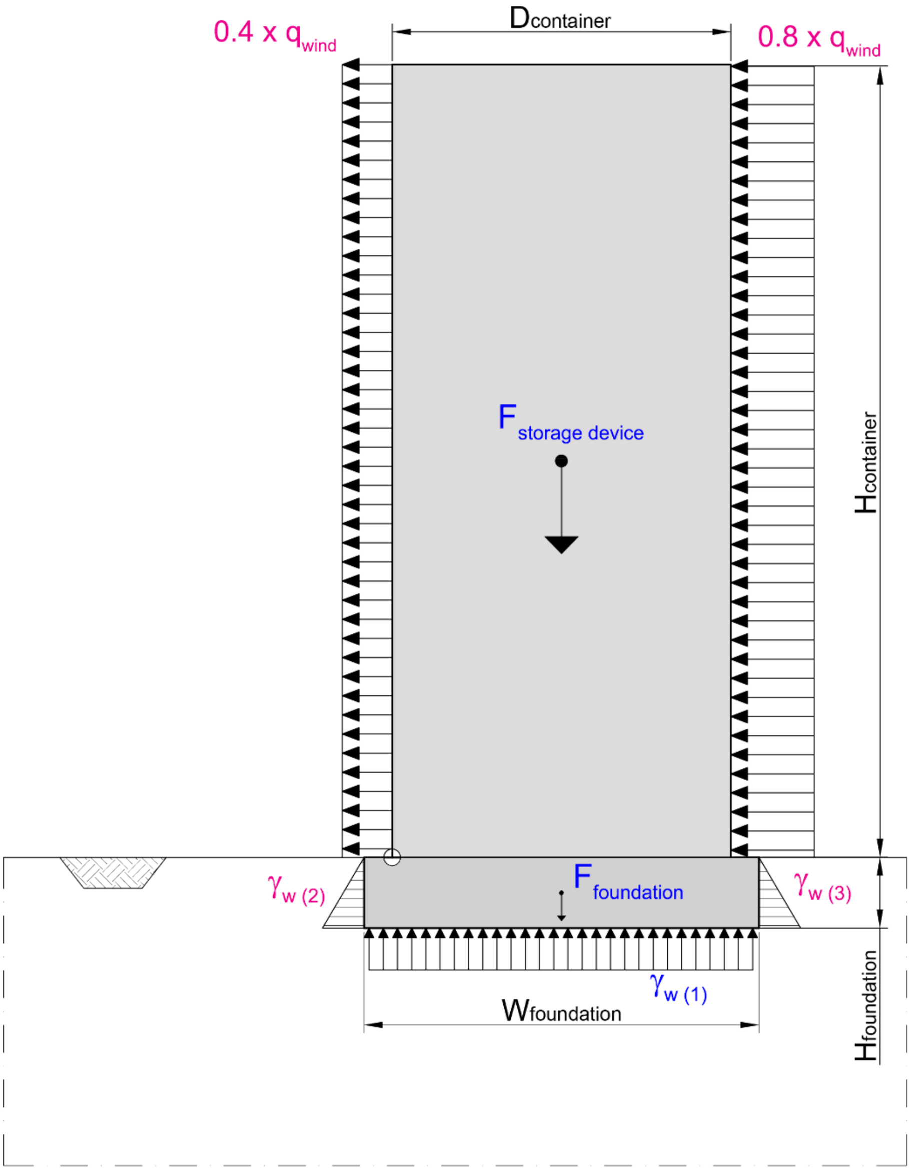


Figure 28 **Loads**

Vertical loads

The following vertical loads (blue) are defined:

- The load of *the storage device* $F_{storage-device}$, which consists primarily of (1) the weight of the piston F_{piston}, (2) the water F_{water} and (3) the cylindrical concrete wall $F_{concrete}$
- The load of the foundation $F_{foundation}$ due to its the weight
- Upwards water load from the groundwater in the soil $\gamma_{w(1)}$. Whether this load is present, depends on how deep the shallow foundation is situated.

The total vertical load is equal to the weight of the storage device and the weight of the foundation itself and can be expressed as follows:

$$\sum F_{vertical} = F_{storage-device} + F_{foundation} = F_{piston} + F_{water} + F_{wall} - \gamma_{w(1)} \cdot W_{foundation} \qquad \text{Eq. (6.1)}$$

Where:

$$F_{piston} = \underbrace{V_{piston} \cdot \rho_{piston}}_{\text{mass of the piston}} \cdot g = (\pi \cdot 12^2 \cdot 28) \cdot 12000 \cdot 9.81 = 1.5 \cdot 10^6 \text{ kN}$$

$$F_{water} = \underbrace{V_{water} \cdot \rho_{water}}_{\text{water}} \cdot g = (\pi \cdot 12^2 \cdot 28) \cdot 1000 \cdot 9.81 = 1.25 \cdot 10^5 \text{ kN}$$

The weight of the concrete cylindrical wall is estimated at 27 kN/m^2:

$$F_{wall} = \underbrace{2\pi r \cdot h_w}_{\text{Top area}} \cdot H_{container} \cdot \rho_{casing} = 2\pi \cdot 12 \cdot 1 \cdot 58 \cdot 27 = 1.18 \cdot 10^5 \text{ kN}$$

The *shallow foundation* is assumed to be a concrete block with a top area of 28 x 28m^2. For now a thickness of 3 meter (≈1/10 of the length of the foundation) and a weight of 25 kN/m³ is assumed making the vertical load of the foundation:

$$F_{foundation} = V_{foundation} \cdot \rho_{foundation} = 28 \cdot 28 \cdot 3 \cdot 25 = 5.88 \cdot 10^4 \text{ kN}$$

The total vertical equilibrium becomes:

$$\sum F_{vertical} = F_{piston} + F_{water} + F_{wall} + F_{foundation} = 1.5 \cdot 10^6 + 1.25 \cdot 10^5 + 1.18 \cdot 10^5 + 5.88 \cdot 10^4 \approx 1.8 \cdot 10^6 \text{ kN}$$

The total stress (including safety factor $\gamma_{1.2}$) on the subsoil becomes:

$$q_{subsoil} = \frac{\sum F_{vertical} \cdot \gamma_{1.2}}{A_{foundation}} = \frac{1.8 \cdot 10^6 \cdot 1.2}{28 \cdot 28} \approx 2.8 \text{ MPa}$$

Note that the vertical water load has not been taken into account, as this is expected to be small compared to the other loads. However, if for stability purposes, the foundation must be put on a lower level, the ground water load will be larger and should be taken into account.

Horizontal loads

The horizontal loads consists of the wind load q_{wind}, and the horizontal groundwater loads $\gamma_{w(2)}$ & $\gamma_{w(3)}$ (whether the groundwater load are present depends on the foundation construction depth).

The wind load can be calculated with the following formula:

$$q_w = c_{\dim} \cdot c_t \cdot p_w \qquad \text{Eq. (6.2)}$$

Where:

- q_w is the wind load [kN/m²]
- p_w is the wind-location-dependent load 1.89 [kN/m²] (Eurocode)
- c_{dim} is the shape factor (0.89)
- c_t equal to 1.2 due to pressure on both sides (0.8 on the front side and -0.4 on the back side)

Filling in these parameters in Eq. (6.2) the wind load becomes:

$$q_w = 0.89 \cdot 1.2 \cdot 1.89 \approx 2 \text{ kN/m}^2 .$$

The wind load per meter height and the total wind force becomes:

$$q_{wind} = D_{cylinder} \cdot q_w = 24 \cdot 2 = 48 \text{ kN/m}^1$$

$$F_{wind} = q_{wind} \cdot H_{container} = 48 \cdot 56 = 2688 \text{ kN}$$

The total horizontal equilibrium becomes:

$$\sum F_{horizontal} = F_{wind} + \underbrace{0.5 \cdot \gamma_3 \cdot H_{foundation}}_{\text{Horizontal water load rhs}} - \underbrace{0.5 \cdot \gamma_2 \cdot H_{foundation}}_{\text{Horizontal water load lhs}} = F_{wind} = 2688 \text{ kN}$$

Load evaluation

Clear should be that $\frac{\sum F_{vertical}}{\sum F_{horizontal}} \geq \frac{1.8 \cdot 10^6}{2688} \approx 700$ which means that the horizontal (wind) load does not play a large role.

6.2.4 FAILURE MECHANISMS

Now that the most governing loads are known, the external stability of the structure can be checked. It is important that the structure is static (it must not move), and therefore the forces on the structure should be in equilibrium. This means that the sum of all vertical and horizontal forces should be in equilibrium. In addition, the structure should not be able to rotate. This indicates that the sum of all moments should be in equilibrium.

For the storage device the following *failure mechanisms* are briefly discussed:

- **I.** Sliding stability (sliding of the structure)
- **II.** Overturning stability (rotating of the structure)
- **III.** Bearing capacity subsoil (failure of the soil)

For a more detailed discussion and calculation of these failure mechanism one is referred to [Appendix F: External Stability, p124]

I. Sliding stability

This condition requires that the horizontal friction resistance (of the subsoil) caused by the weight of the structure is larger than the friction force of the horizontal equilibrium (Figure 29). In formula:

$$\sum F_v \cdot R_{friction} \geq \sum F_h$$

The wind is only horizontal load on the structure and is a factor 1000 smaller than the weight of the structure: this device will not fail by sliding and is therefore not further elaborated.

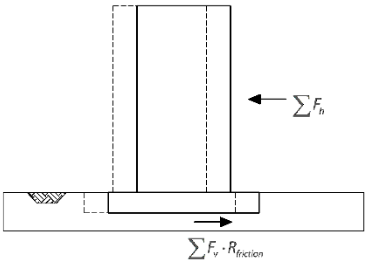


Figure 29 Sliding stability

II. Overturning stability

This condition requires that the resistance moment M_R of the soil is large enough and that no tensile stresses occur in the subsoil (Figure 30). A pressure combination due to the vertical and horizontal loads which is in tension, implies that the contact between the soil and the footing is gone which could lead to overturning.

Because $\sum F_v \gg \sum F_h$ and the largest vertical forces are applied in the center, the overturning moment will *unlikely* result in rotations of the structure. Nevertheless, a design check will be conducted.

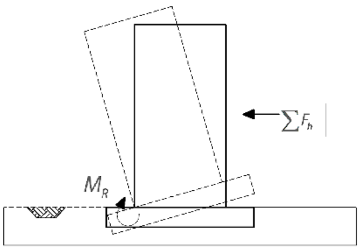


Figure 30 Overturning stability

III. Bearing capacity subsoil

This condition requires that the soil has enough resistance to carry the weight of the structure or the bearing capacity of the subsoil (Figure 31). Due to the large weight of the structure, this external failure mechanism is definitely dominant over the other mechanisms and will be further elaborated.

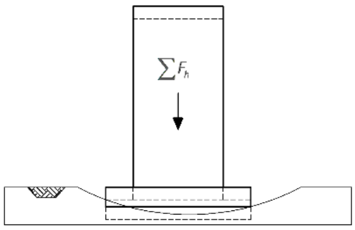


Figure 31 Bearing capacity soil

Evaluation

The structure has been checked and calculated on the above stated failure mechanism in [Appendix F: External Stability, p124], and even though the structure is quite heavy, the bearing capacity of the soil was sufficient. The structure should be placed at least a meter beneath ground level.

6.3 INTERNAL STABILITY

In this paragraph, the internal stability of the structure will be analyzed. The focus of this paper is more on the structural components rather than the mechanical components. The internal stability therefore emphasizes the (structural) internal stability of the main container. The foundation and especially the cylindrical wall are the key components in the structure, all other structural components will, if necessary indirectly be incorporated designing the foundation/wall or otherwise (briefly) mentioned. As for the mechanical aspects, the return pipe will be dimensioned (roughly) and the pump/turbine will be briefly discussed. For this paragraph, the following scheme (Figure 32) will be followed:

Figure 32 Scheme Internal stability

6.3.1 OVERVIEW LOADS

The design loads of the *internal stability* can be distinguished in *internal loads*, *external loads*, and *special loads* which are summarized in Table 10. These loads will be further discussed in this section.

Table 10 Load overview

Internal Loads	External Loads	Special Loads
Water	Temperature	Prestressing
Piston	Wind	Dynamic

Internal Loads

Water load

The water loads on the wall and bottom slab can be illustrated as a hydrostatic load (see Figure 33). The load is largest at the bottom and smallest at the intersection between the water and the piston.

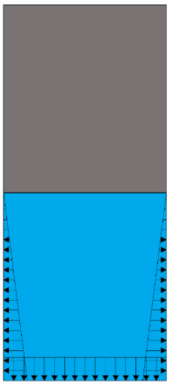


Figure 33 Water pressure load

Piston load

The piston does not *directly* load the structure. The piston *pushes* the water to all sides, creating a *vertical water pressure* on the bottom slab and the piston itself - and a *horizontal water pressure* on the walls as can be seen in Figure 34.

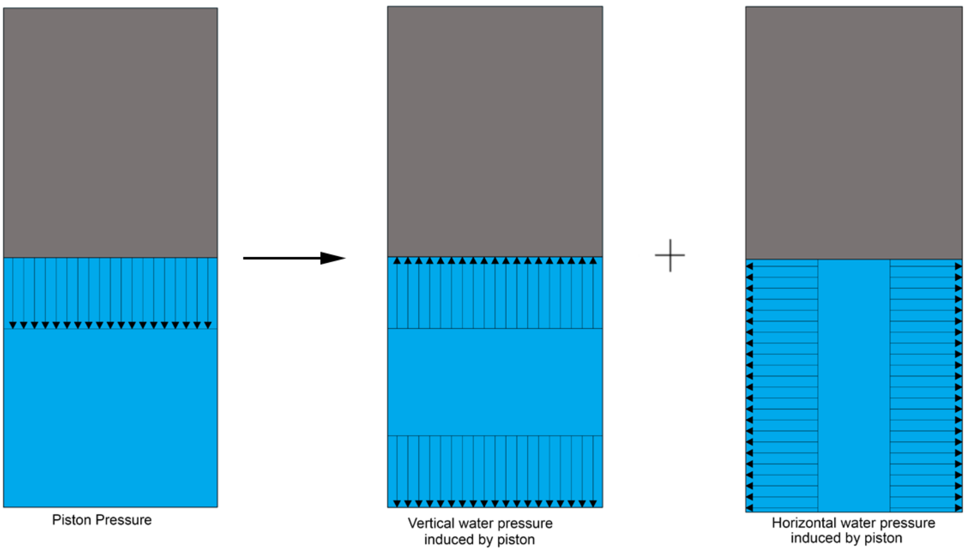


Figure 34 Piston load

Internal load 3D direction

Up to now, the loads were illustrated in 2D for simplicity. In order to explain the structural mechanisms, a necessary 3D illustration has been drawn in Figure 35 (R. Braam, 2010).

The following can be said about the *internal loads* (water + piston) denoted with $Z_l(x)$:

- Due to internal loads, the cylinder wants to expand in general, resulting in a *tensile ring force* (or *tangential forces*) in $+\theta$ direction denoted with $N_{\theta\theta,l}(x)$. An increase in $Z_l(x)$ results in an increase of the *tensile ring force*.
- In z direction the wall wants to bend due to the (large) moment forces (especially near the wall-base connection). These bending moments in the wall are denoted by M_{xx}
- Due to the internal loads, the wall wants to displace in $+z$ direction denoted as $w_l(x)$ and rotate in $+\varphi$ direction denoted as $\varphi_l(0)$

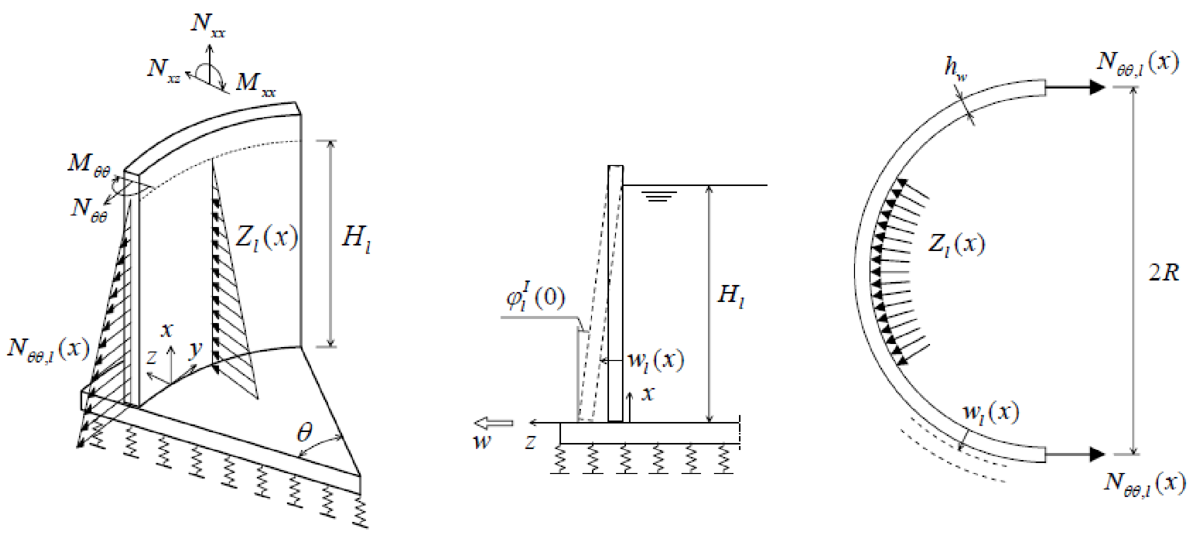


Figure 35 Load direction and deformation of a cylindrical wall subjected to internal load (R. Braam, 2010)

External loads

Temperature load

Large internal and external temperature differences can introduce so-called *temperature stresses* in the structure. When there is a *positive temperature difference* – meaning that the temperature outside > temperature inside the structure, the container wants to shrink and therefore generates compressive tangential forces. A *negative temperature difference* generates tensile tangential forces.

Wind load

The wind load is the load from the wind on the structure. In the *external stability* it became clear that the wind load is negligible in comparison to the weight of the structure (the weight of the piston in particular). As the piston generates large loading on the wall (counteracting the wind load), the wind load will be neglected.

Special loads

Prestressing load

Prestressing is nothing more than pre-loading the structure, and therefore, by definition, a load itself. This is a load which should counter balance the internal loads: this load should be slightly larger than the internal loads in order to provide compression in the concrete.

The *prestressing forces* denoted with $Z_{p0}(x)$ are of opposite sign to that of the internal forces as is illustrated in Figure 36.

- Due to the prestressing load, the cylinder wants to shrink, resulting in *compressive ring forces* in $-\theta$ direction denoted with $F_{p0}(x)$
- In z direction, the wall wants to bend at opposite direction to that of the internal loads
- Due to prestressing load, the wall wants to displace in $-z$ and rotate in $-\varphi$ direction.

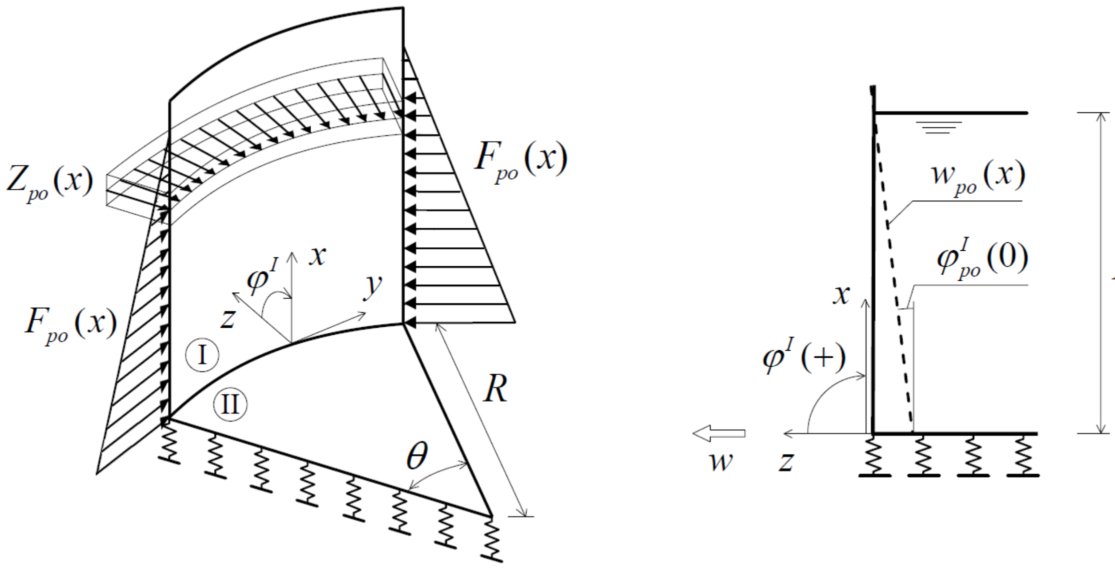


Figure 36 Load direction and deformation of a cylindrical wall subjected to prestressing load (R. Braam, 2010)

Remarks about Prestressing

For prestressing cylindrical walls, special attention has to be paid to the following requirements (R. Braam, 2010):

- Compressive *stresses* in concrete should not exceed 45% of the compressive *strength* of the concrete.
- The internal loads should be overbalanced with a small extra compressive stress of 1,0 N/mm^2.
- Vertical distance between tendons should not be more than 1000 mm or three times the wall thickness (smallest value) to prevent the occurrence of large moments.
- Crack-width limiting reinforcement should be applied to take up the temperature-induced tensile stresses.

There are two methods of prestressing:

- Prestressing conform the internal load
- Prestressing conform tangential loading a.k.a. ring force balancing

Prestressing conform the internal load states that the prestressing force follows the internal load but is slightly larger and in opposite direction. With this procedure, the internal load is balanced by the curvature pressure $Z_{p0}(x)$ generated by the prestressing cables. Slightly over prestressing results is a small residual compressive stress in the wall in tangential θ direction.

A big disadvantage of prestressing conform internal loads is that large internal bending moments occur, especially near the wall-base connection, for an *empty reservoir* as will be explained shortly.

Dynamic loads

The loads described above are all static loads. Since the piston is moving upwards and downwards, there is also a so-called dynamic load on the structure. As the piston is moving downwards from the top, the piston load on the wall shifts towards the bottom along with the piston as can be seen in Figure 37. Note that the *water load* is not illustrated in Figure 37 as the piston load is much larger than the water load as will be clear in this next paragraph. Which means that the most indicative situation is where the piston is at the top. The effects of the dynamic loading will be taken into account in this paper, but no detailed calculations will be made. Note that only the shifting of the load distribution towards the wall has been schematized.

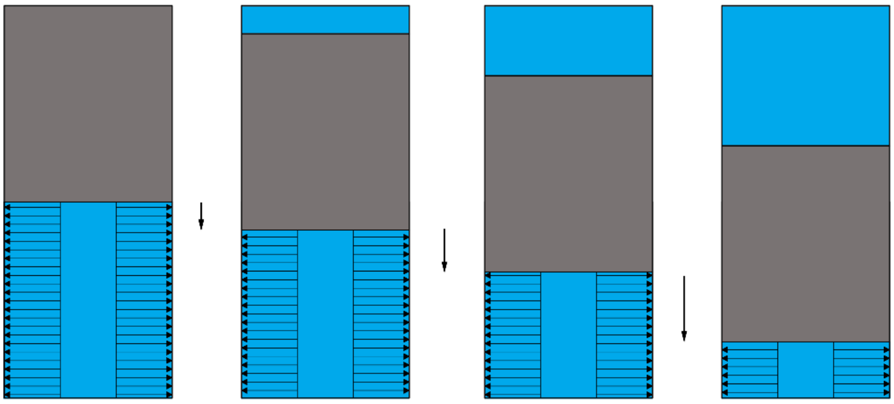


Figure 37 Dynamic piston load on the cylindrical wall

6.3.2 LOADING PHASES

Phases

Not all loads are present at all times. First comes the *initial phase* where the cylinder is empty. In this phase the container is going to be prestressed (pre-loaded) and therefore also called the *prestressed load phase* and is denoted with t_0. Second comes the *fully loaded phase* (short term) denoted with t_1, here the empty cylinder becomes saturated with water and the piston will be placed: the internal loads become active. Finally, the fully loaded phase (long term) denoted with t_∞ is defined. In this load phase the temperature load becomes active and the initial prestressing load decreases due to, for example, creep and relaxation. An overview of the load phases is given in Figure 38.

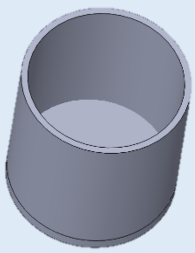
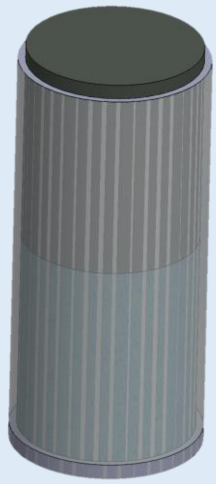
		
Initial (preloaded) load Phase t_0	**The Fully Loaded Phase t_1 (short term)**	**The Fully Loaded Phase t_∞ (long term)**
Active Loads	**Active Loads**	**Active Loads**
Prestressing F_p	Prestressing	Prestressing
	Water	Water
	Piston	Piston
		Temperature/Creep/Relaxation

Figure 38 Load Phases

Critical Design phase

The wall will be designed for the most *critical design phase*. The most critical design phase, is the phase in which the loads are the largest and will be determined as follows.

Figure 39, shows the different (time) phases in case *without* prestressing (A-C) and *with* prestressing (D-G). In case without prestressing, the most critical design phase, would be at t_1"situation (B)". In case with prestressing, the critical design phase would be at t_0 "situation (E)".

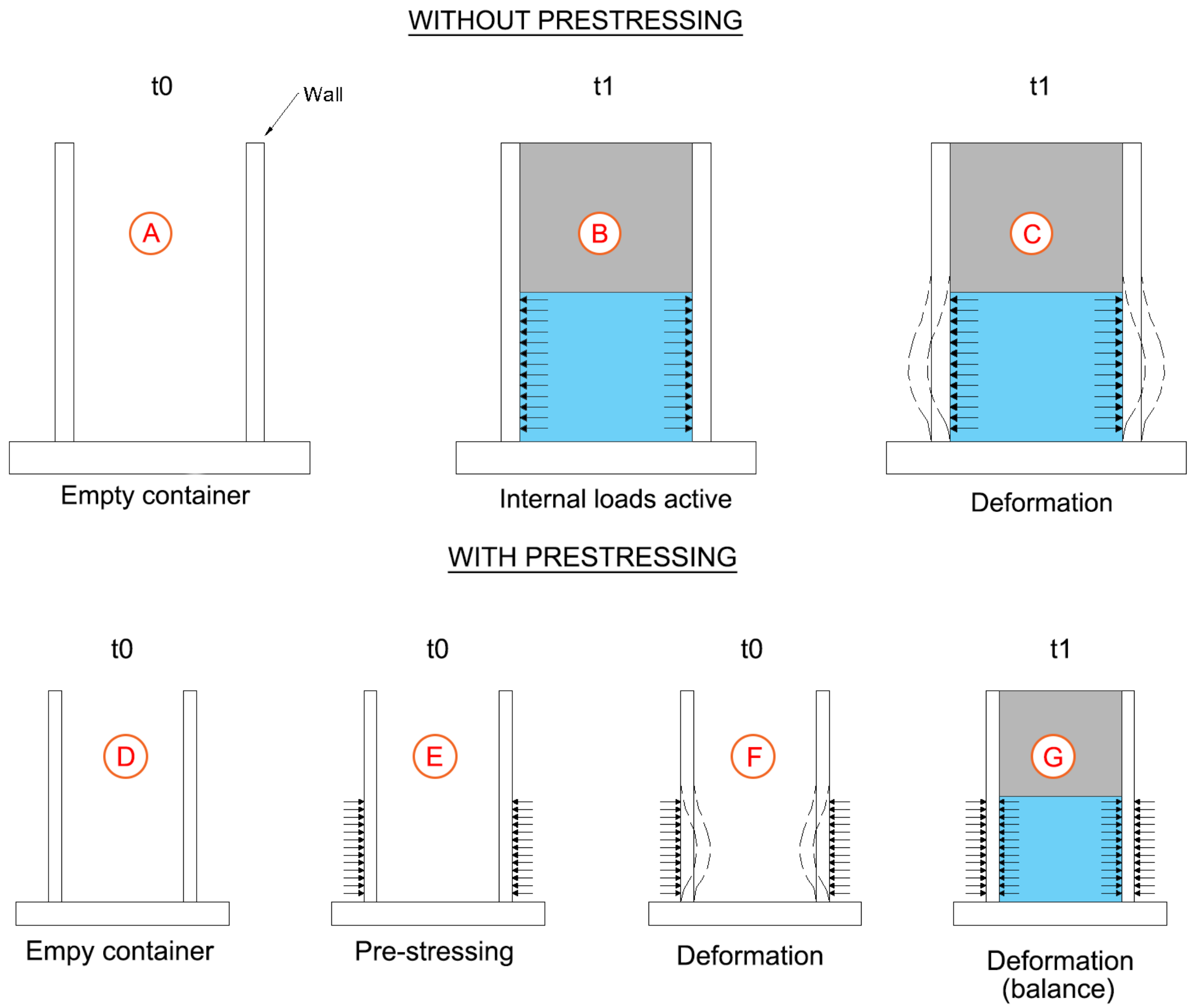


Figure 39 Deformation without/with pre-stressing

The larger a load is, the larger the occurring deformation. It has been stated before that *prestressing load* should be larger than the internal load. This means that the deformation without prestressing "situation (C)" is *smaller* than the deformation with prestressing "situation (F)". In other words, by *not* prestressing, the wall could be designed for a less severe loading, and could be designed more economically.

The question therefore is: why would one pre-stress the tank?

The real purpose of (horizontally) prestressing

The purpose of prestressing is to counter the internal loads, but in previous sub-section it became clear that by *not* prestressing the wall could be designed for a less server loading. In here, the real purpose of prestressing will be explained.

There are basically two reasons for horizontally prestressing, that is:

1. Liquid tightness
2. To prevent leakage along the wall.

Liquid tightness

It has been stated before, that concrete has low resistance against tensile forces. When the tension zone in the concrete becomes too large, the concrete starts to crack. These cracks will allow for liquid to pass through. Note that there will always be some liquid penetration, the aim is not to avoid cracks, but to limit the crack width size, which can be met providing a small tensile zone. In Figure 40 phases are shown in case *without* prestressing and in case *with* prestressing.

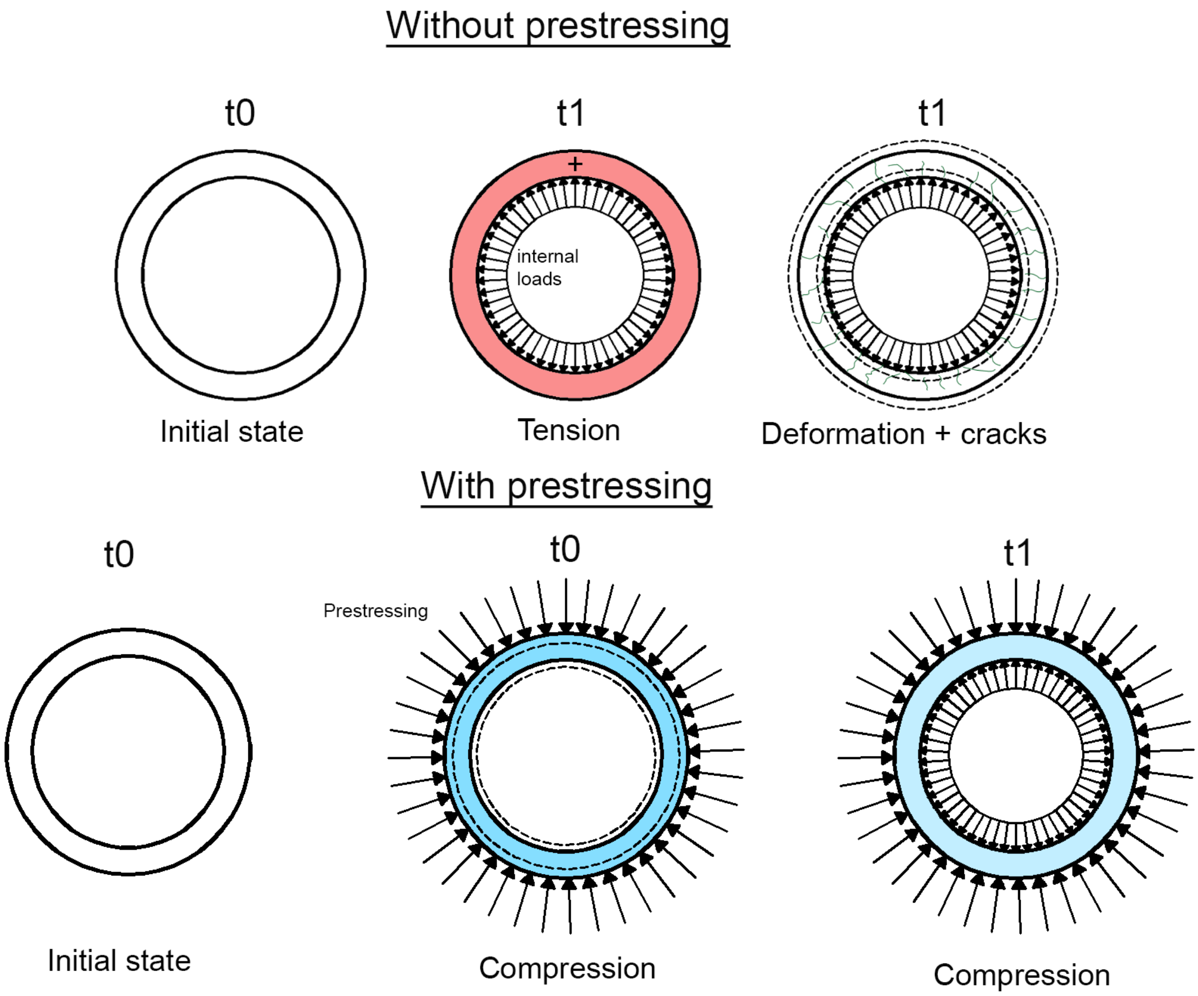


Figure 40 liquid tightness

In case without prestressing, the internal loads, will want to expand the container inducing tensile ring forces in the concrete which leads to cracking. By prestressing, the container will in *compression* at t0 and remains in compression at t1. This is also the reason why the prestressing load must be *larger* than the internal loads, in order to ensure compression in the cross section.

Leakage along the wall

To explain this, one is referred again to Figure 39. In situation (C), it can be seen that the deformation is *outer wards*. This could become a *major* problem regarding sealing the piston. Due to possible deformation, the distance between the sealing and the wall might become to large which would allow for *leakage* along the piston.

In sum, the most *critical load phase* is when the prestressing load becomes active at t_0. The cylindrical tank will therefore *not* be designed to resist the internal loads at t_1, but it is primarily designed to *resist* the *prestressing load* at t_0.

6.3.3 MAIN CONTAINER - OVERVIEW

Components

The tank consists of the following structural (design) components (Figure 41):

- The roof
- The wall
- The base slab
- The connection between the roof and the wall
- The connection base slab and the wall

The base slab is actually the foundation of the whole structure. The roof will not be exposed to large loading, and therefore has little structural relevance to the tank: it's only purpose is the closure of the structure. As stated in the introduction in this paragraph, focus will be put on the wall of the tank as these are subjected to high loads & most vulnerable. The wall-roof and wall-base connection will be incorporated in the wall design. The foundation (=base slab) will be designed briefly. In the following sub-section, the design approach of the tank will be elucidated.

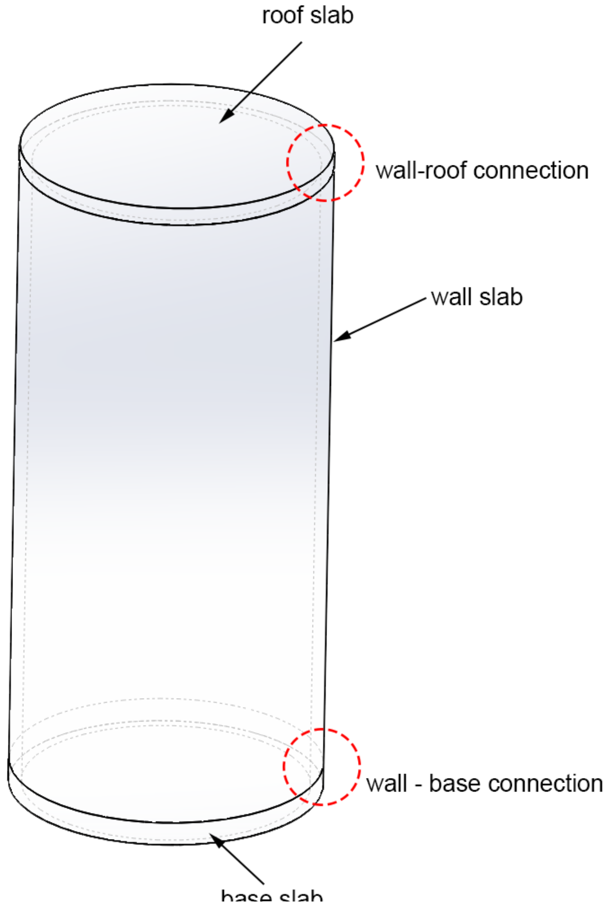


Figure 41 Design aspects main container

Design approach main container

The first design stage concerning the internal stability of the tank follows the flow chart of Figure 42.

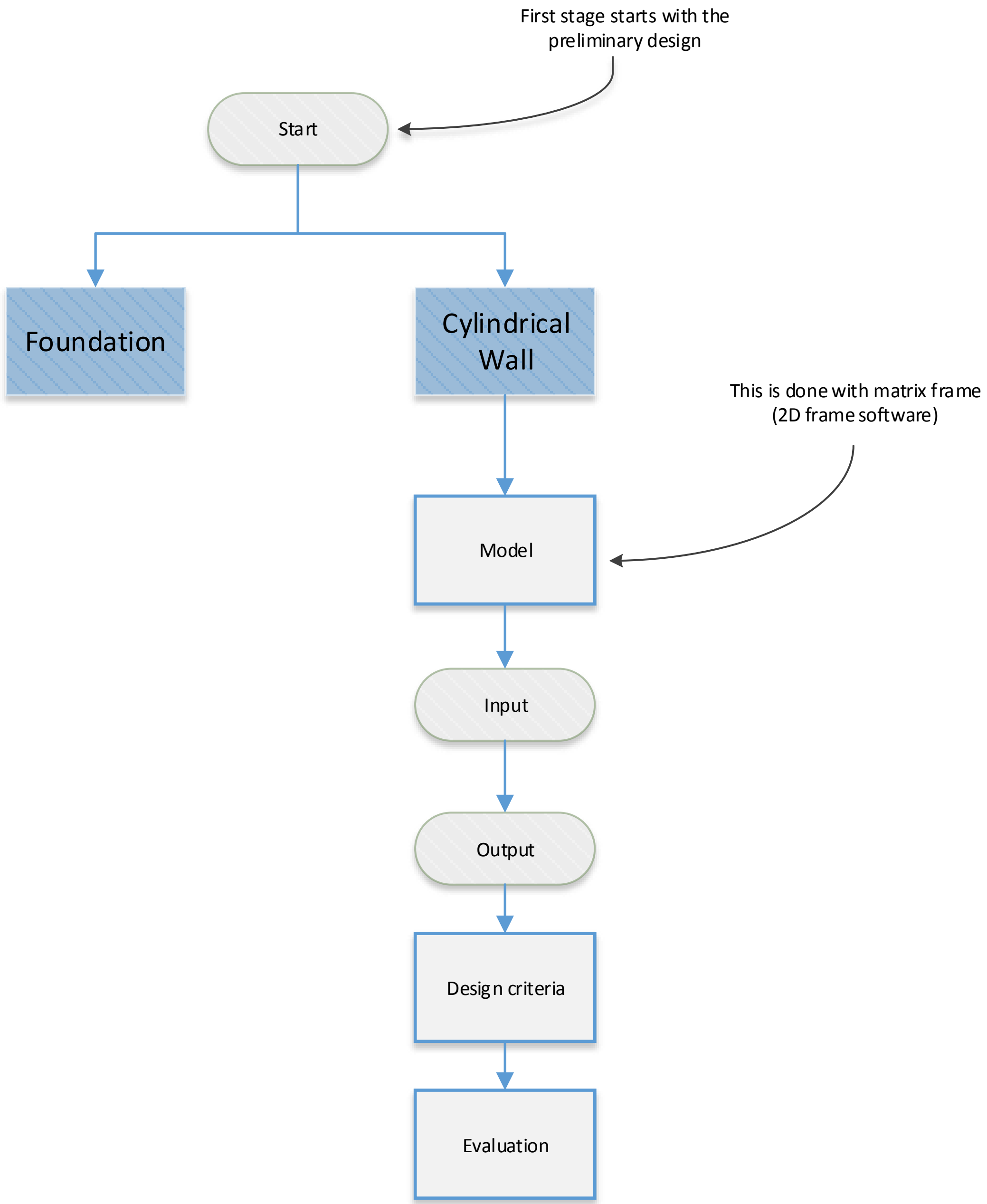


Figure 42 Flow chart wall design

Foundation

The shallow foundation slab, or *footing*, lies on the subsoil and is subjected to the following loads (see Figure 43). Note that the foundation also has a self-weight which has not been schematized.

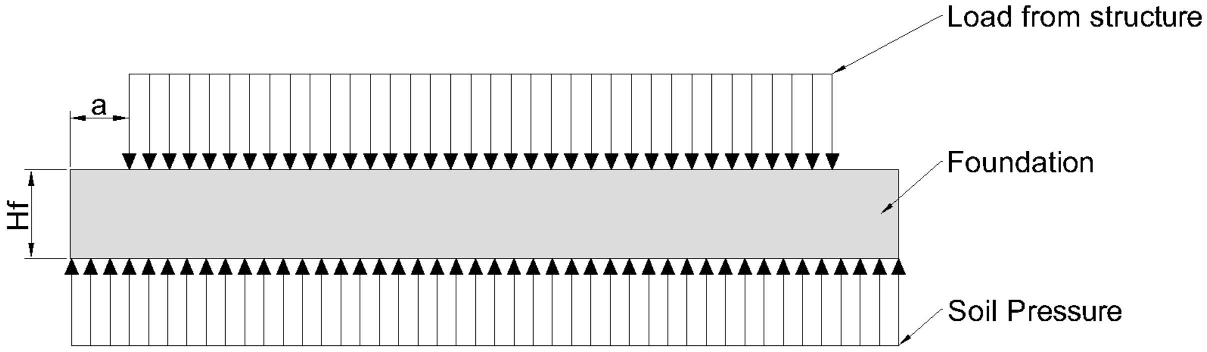


Figure 43 Load schematization on the foundation

As the distance a (Figure 43) is more or less equal to 1, the load of the soil pressure is almost equal to the load from the structure (action=reaction), meaning that the resultant moments and shear force are basically nullified in the greater part of the foundation ($\sum M \approx 0, \sum V \approx 0$). The foundation is mainly stressed in compression. Note that here, the *stiffness* of the foundation has been taken as *infinite*, hence the equal spreading of the load.

Foundation height

The foundation height H_f is to be 2 m with a reinforcement ratio ρ of 1 %. The foundation height has been calculated according to the design method in [G.2 Design in bending, p130], for the calculation, one is referred to [G.2.4 Design calculation (foundation), p134].

Wall: Model

According to (R. Braam, 2010), the cylindrical wall can be modelled as bending girder on elastic foundation. Which makes it practical as this can be used in a 2D-frame software such as Matrix Frame.

For a first iteration, a 1 by 1 meter (the wall thickness of h_w and wall width b) part of the cylinder will be modelled as a bending girder according to Figure 44.

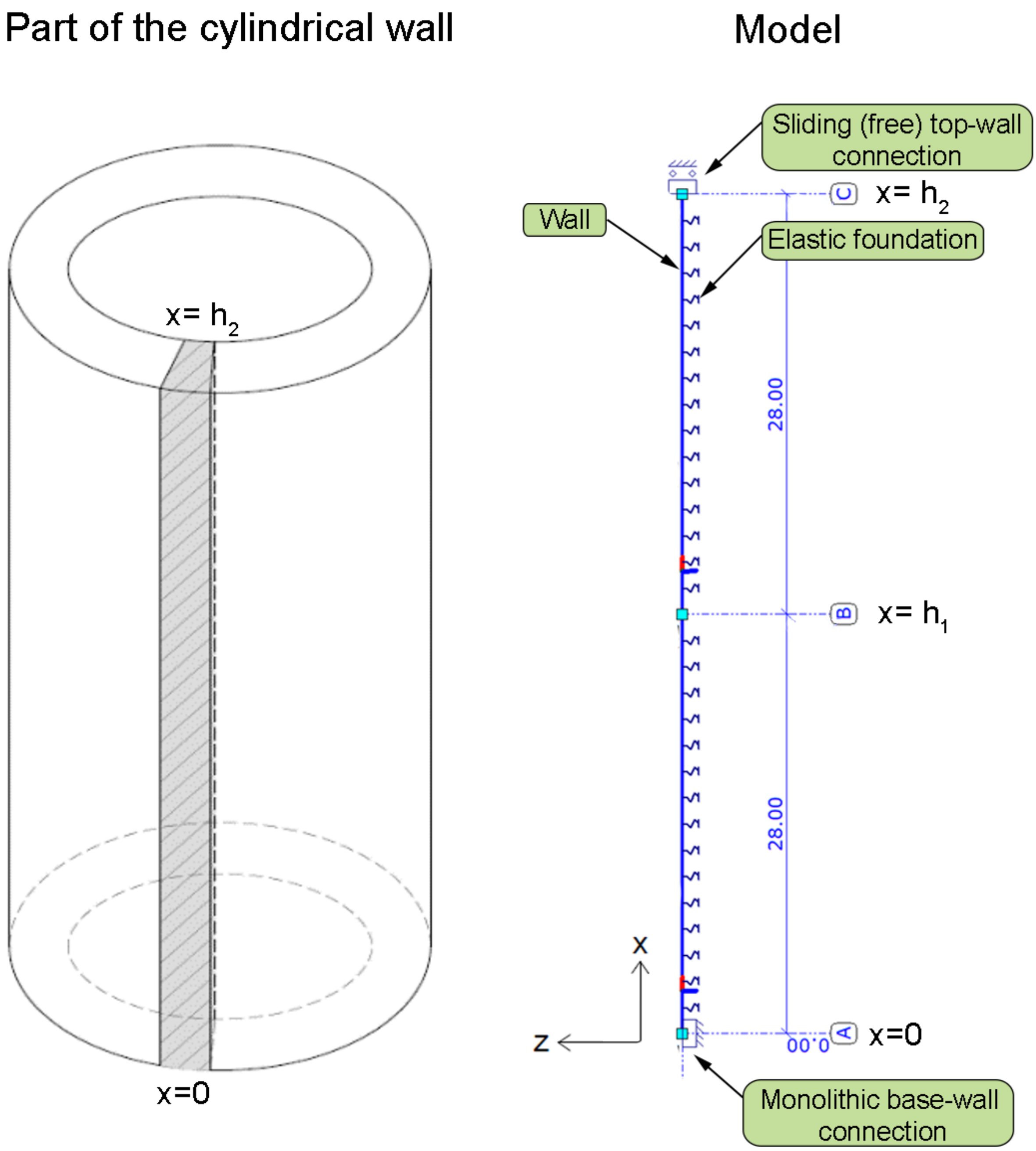


Figure 44 Model of the cylindrical wall

For illustration purposes, the wall will be rotated horizontally as a normal bending girder as can be seen in Figure 45.

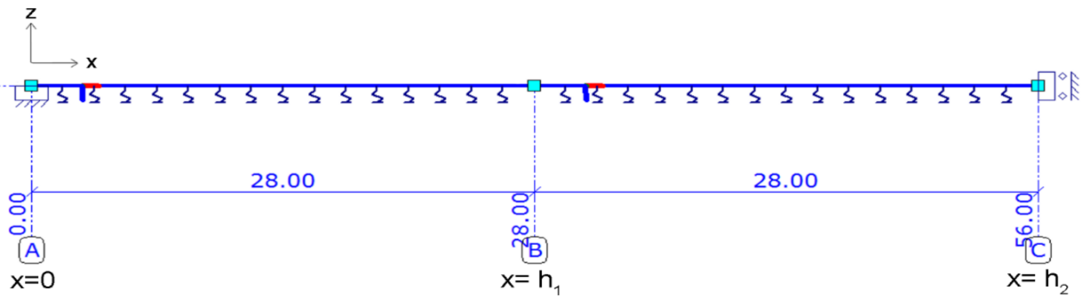


Figure 45 Horizontal rotated wall (girder on elastic foundation)

Wall: Model input

The model has the following input parameters:

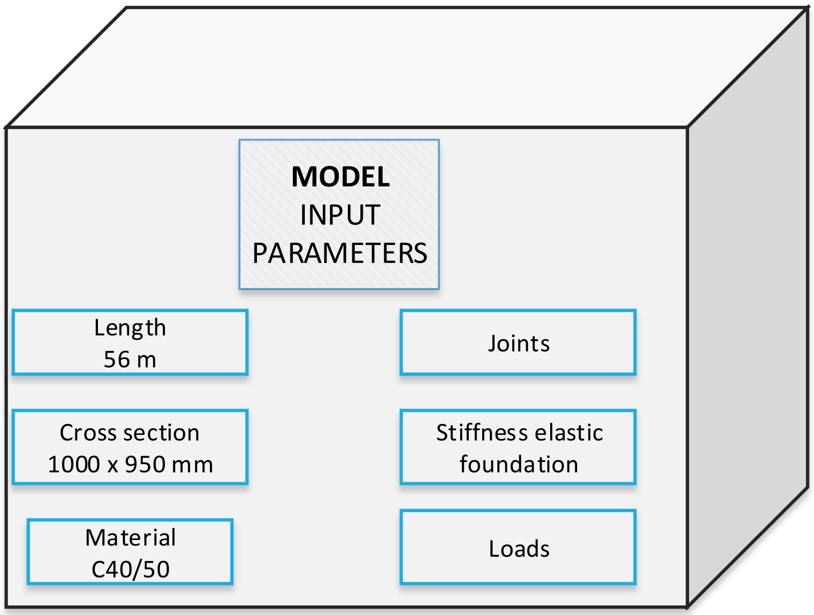


Figure 46 input parameters

Joints

There are two joints in the main container which are the: *roof-wall connection* and the *base-wall connection*. In the initial phase, there is no roof, and therefore no roof-wall connection (joint) present.

The base-wall connection of the storage connection, can be of the following main types (see Figure 47):

- Clamped (monolithic): no deformation is possible
- Hinged: is able to rotate
- Sliding: is able to freely slide and rotate

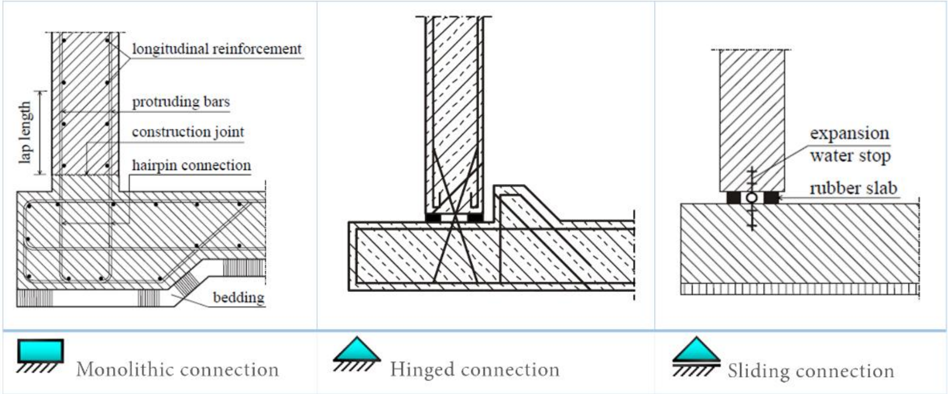


Figure 47 Connection types

According to (R. Braam, 2010), a monolithic wall-base connection with rigid clamping is the most often applied and preferred in comparison with the other connections which require more maintenance and have a lower life span of approximately 20 years. The disadvantage of a monolithic wall-base connection, in this case, are large bending moments occurring due to the piston. Nevertheless, a monolithic connection will be considered.

Note that for the determination of the force distribution in the base-wall connection, it is important to determine the so-called *rotational spring stiffness* of the base slab. In this paper, the base slab/foundation is assumed to have an infinitely large stiffness, however in reality this is not the case. In reality, the base slab does deform which affects the force distribution of the connection. By the choice of, for example, a favorable ratio between the flexural stiffness of the wall and floor slab in combination with the stiffness of the foundation, considerable reductions in the internal loads can be achieved. For a very slack floor slab, the fixing moment can even be reduced to zero (R. Braam, 2010).

Stiffness

The stiffness of the elastic foundation, c_z, can be determined by:

$$c_z = \frac{E_z \cdot A}{R^2} \qquad \text{Eq. (6.3)}$$

Where:

- E_z is the young's modulus of concrete [GPa]
- A is the area of the considered cross section [m^2]
- R is the radius of the cylinder [m]

Which leads to a stiffness value of:

$$\left.\begin{aligned} &E_z = 35 \text{ GPa} \\ &A = h_w \cdot b = 1 \cdot 0.95 \approx 1 \text{ m}^2 \\ &R = \frac{D}{2} = \frac{24}{2} = 12 \text{ m} \end{aligned}\right\} \rightarrow c_z = 2.9 \cdot 10^5 \text{ kN/m}^2$$

Loads

The input of the loads is equal to the prestressing load. Which has been taken as a factor 1.4 times the internal loads (U.L.S.). The internal loads, which consists of the water and piston load, have been defined according to t_0. The schematization of these loads can be found in [G.5.7 Loads, p143].

Wall: Model output

The forces, moments and stresses have been modelled with a 2D-frame software, Matrix Frame. In here, the most important observations of the model output are discussed. The following topics will be briefly elaborated:

- The envelope of the moment
- The shear force distribution
- The dynamic envelope of the moment
- The deformation

Envelope (moment)

Figure 48 shows the envelope. What is obvious, is that the envelop peaks only at certain locations. The first and largest peak occurs at the wall-base connection. The second peak occurs at $x = Hl$, this is where the piston meets the water. The moment at the wall-bottom slab connection as an extremely high value of 16,500 kNm (= 16500 kNm).

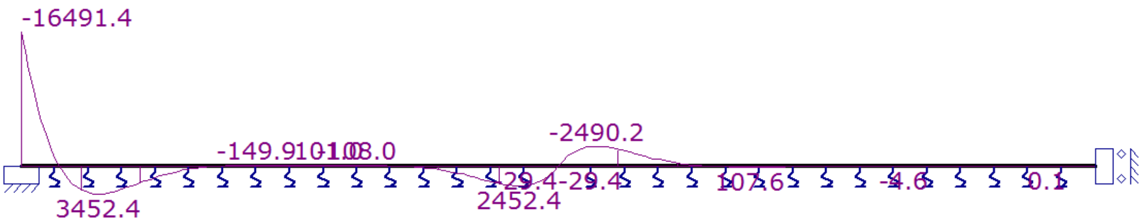


Figure 48 Envelope

Shear force

Figure 49 shows the shear force distribution. Also the shear force is highest at the wall-bottom slab connection having a value of $V_{ed,max} \approx 13000$ kN.

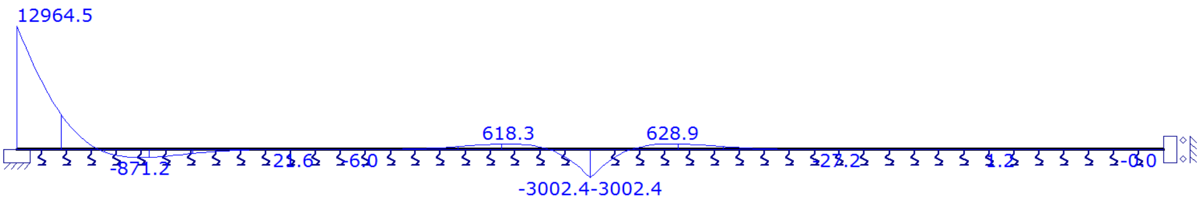


Figure 49 The shear force distribution

Envelope development during piston movement

The moment envelope and shear force distribution, shown above, are the result of a *static situation* where the piston remains at the top. The piston also moves up and down which is the *dynamic situation*.

In the dynamic situation, where the piston is moving downwards, the moment peak at $x = H_l$ moves along as can be seen in Figure 50. The envelope peak at x=HL acts as a *wave* that is going towards the base-wall slab. This peak load induces both *negative* and *positive* moments. Which means that each part of the wall between x=0 and x=H_l will undergo moment changes during piston movement. This implies that between $0 \leq x \leq H_l$ reinforcement must be applied at both sides of the wall and must be designed for the moment occurring at x=$H_l/2$. Note that the same story applies for the shear force distribution.

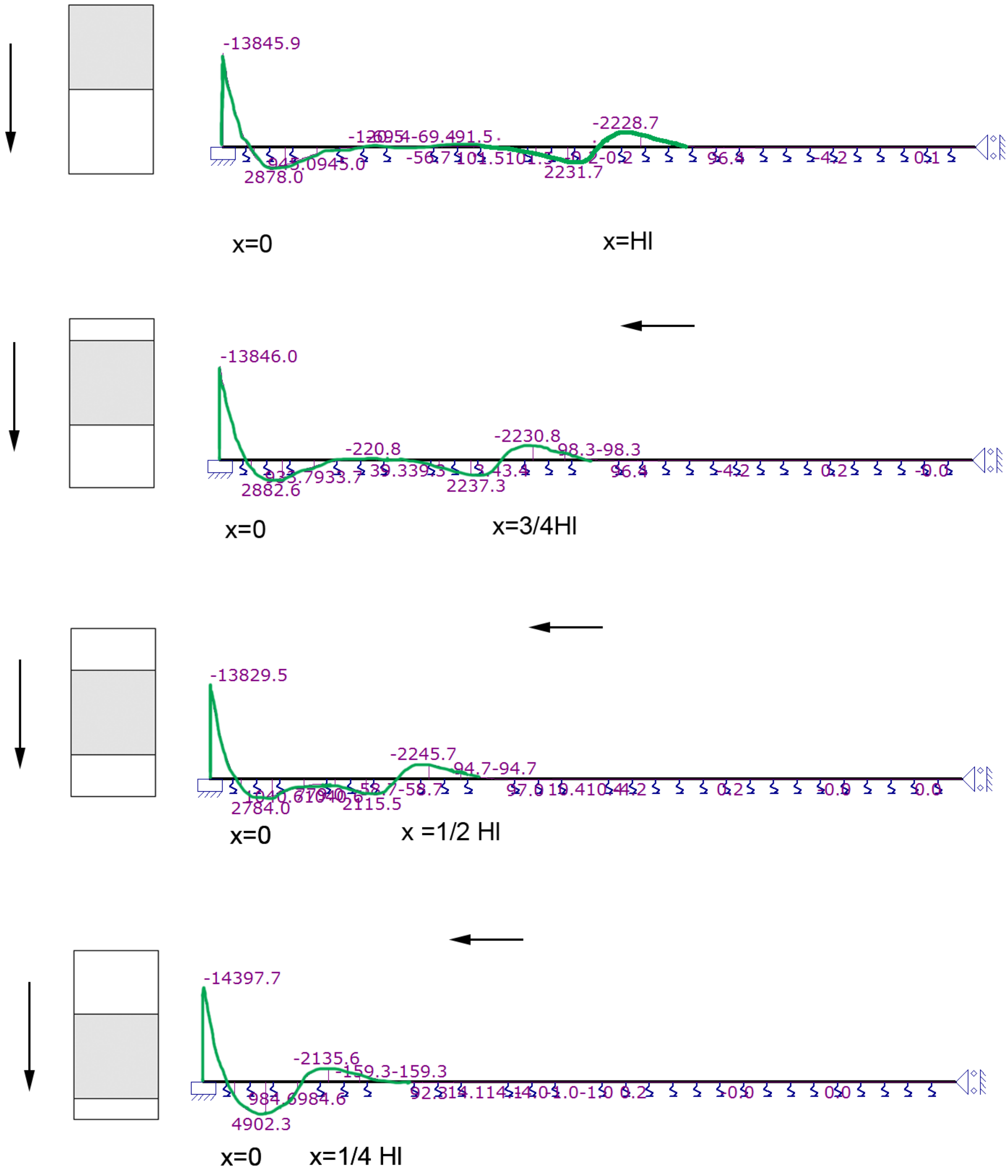


Figure 50 Effect of the Envelope on the piston movement

Wall deformation

Another interesting, and important aspect for the functionality of the structure, is the deformation of the wall. Due to the large prestressing load, the wall has a maximum deflection of 18 mm (Figure 51). This could be problematic for the *construction* of the piston.

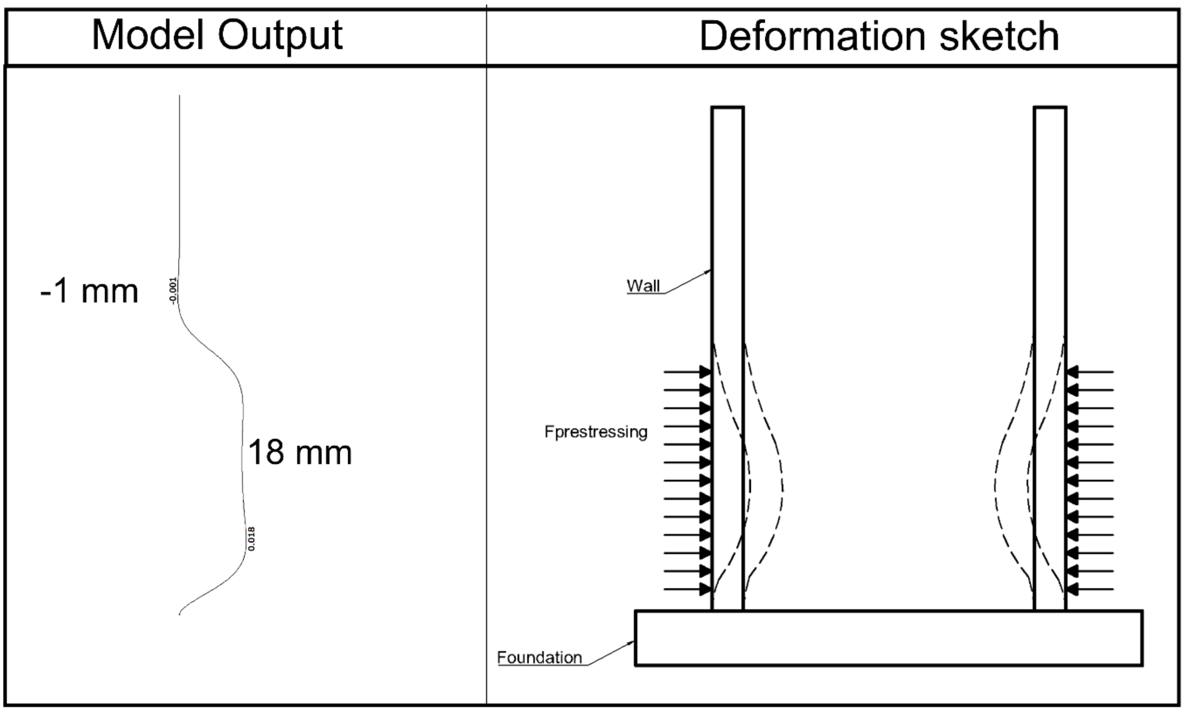


Figure 51 Wall deflection/deformation

Note that the cracks occurring due to this deformation, might still become a problem at t1, when the tank is being saturated with water and the piston is installed, regarding liquid tightness.

Wall: Design criteria

In previous sub-section, it was seen that the loads on the wall and particularly at the wall-bottom slab connection were enormous. The aim is to economically dimension the wall in such a way that it can cope with these loads. One of the main aspects for both stability and economics is the amount of reinforcement. More reinforcement results in a more stable structure, however reinforcement is much more expensive than concrete as will be clear, later in this paper. In this paper, only *the lower part of the wall is considered* (and designed), where the load is most critical. The goal of this part is to determine the required wall thickness h_w, which will be determined by design checks and will be elaborated shortly.

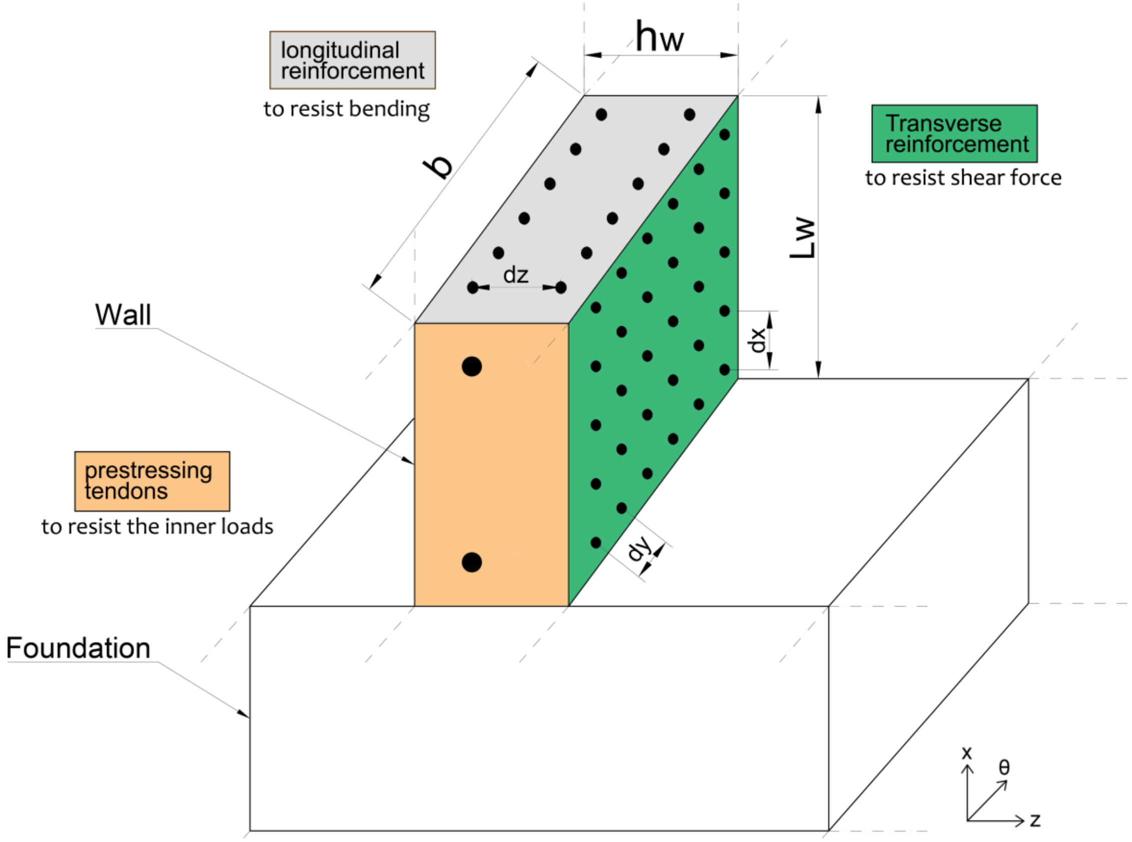


Figure 52 Schematization of the wall direction

In Figure 52, the wall-bottom slab connection has been schematized which shows rebars (reinforcement bars) facing different directions. In the orange part, the pre-stressed tendons are shown. Due to the prestressing of these tendons, forces occur in the wall which results' could be perceived in the previous subsection. Due to this forces/deformation of the wall, part of the wall is put into *compression* and another part is put into *tension*. In the *tension zone*, rebars have to be placed as concrete cannot cope with these tension zones effectively. In longitudinal direction (the grey area), rebars must be placed in order to resist bending moment. In the transverse direction (the green area), rebars must be placed in order to resist shear force. Besides resisting the force due to pre-stressing, the wall also must be liquid tight which requires a *minimum compression zone*.

In sum, the following design checks can be governed:

1) The economical (longitudinal) reinforcement ratio (design in *bending*)
2) The amount of practical shear (transverse) reinforcement (design in *shear*)
3) The minimal concrete compression zone (design in *liquid tightness*)

Based on these design checks, a suitable wall thickness h_w will be determined. These design checks will be discussed briefly as following.

1) Design in bending: the economical (longitudinal) reinforcement ratio

Due to bending moments, the wall wants to *bend*. This induces positive and negative stresses in the cross section, which are indicated with a compressive (blue) and tension (red) zone in the cross section (Figure 53). As concrete cannot cope with tension effectively, reinforcement is applied in the zones where tension is occurring. The force in the reinforcement steel $F_{s,xx}$ and the concrete force F_C is a result of bending (Figure 53).

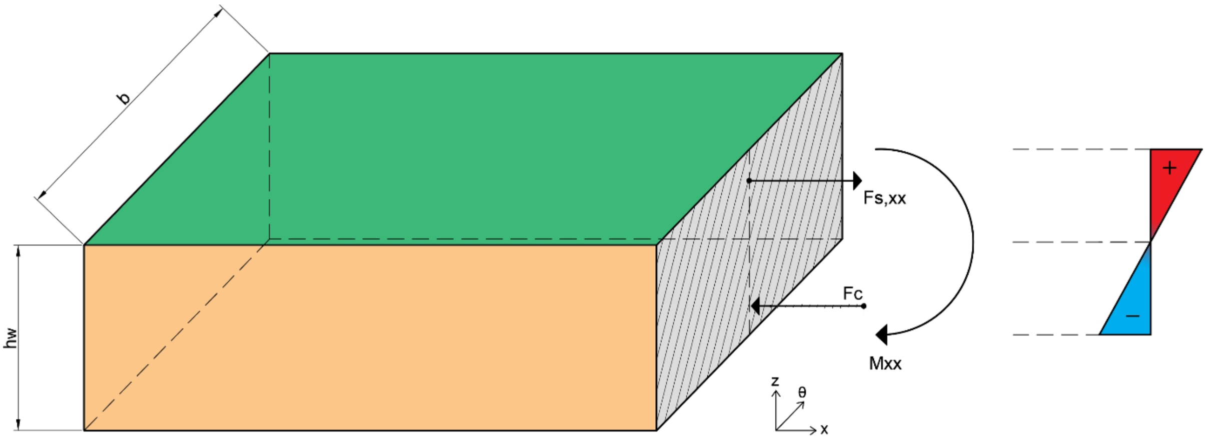


Figure 53 Part of the wall

The reinforcement ratio is the amount of reinforcement with respect to the whole concrete cross section. According to (A.Q.C. van der Horst, C.R. Braam), the economical reinforcement ratio is in the order of 1-2%. The wall will therefore be dimensioned having a reinforcement ratio between 1-2%. How one can design in bending can be explained in [G.2 Design in bending, p130].

2) Design in shear: the shear force capacity

When the shear force V_{ed} is larger than the shear resistance of concrete V_{rd}, (shear) cracks will occur in the cross section. By applying shear reinforcement, the shear force can be absorbed. Also here, the amount of (practical) shear reinforcement is fundamental for the economic feasibility. How to determine the amount of shear reinforcement can be seen in [G.3 Design in Shear, p135].

3) Design in liquid tightness: the minimum concrete compression zone

As stated earlier, due to the bending moment, one part of the cross section goes into tension and the other part goes into compression. The height of the cross section that is in compression is symbolized by x_u and also known as the *concrete compression zone* (Figure 54).

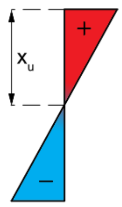


Figure 54 The concrete compression zone

One of the requirements of the container is that it must be *liquid tight* or – *minimized* at the least. This requires a *minimum* compression zone in the concrete wall. However the internal loads will not be active until t_1. At t_1 the internal loads, are already balanced by the prestressing load (which are larger) and therefore it is assumed that liquid tightness will not be a large problem. In this paper, designing in liquid tightness will not be further elaborated.

Wall: Evaluation design

The lower part of the wall at the wall-bottom slab connection have been calculated conform [G.2 Design in bending, p130] and [G.3 Design in Shear, p135]; the calculations can be found in [G.2.3 Design calculation (wall), p132] and [G.3.6 Design calculation, p139] respectively. A summary of the findings follows:

1) Bending moment design

The bending moment of 16500 kNm is a unique large loading (for prestressed concrete). It was therefore the question whether the wall would be able to resist this load. It was first found that the thickness of the wall was insufficient, and had to be increased to 1.8 m having a reinforcement ratio ρ of 1.5%. However, problems occurred when designing the rebars.

With 5 bars the required longitudinal rebar diameter was approximately Ø80 mm (Figure 55). The maximum bar size of longitudinal reinforcement is in the order of Ø40 mm (Rebar, n.d.).

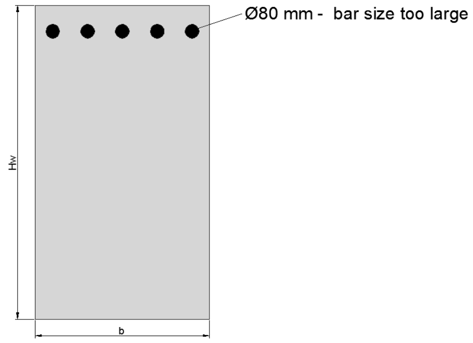


Figure 55 Rebar size too big

When designing with an Ø40 mm bar, the amount of bars that had to be placed was equal to 22. Placing all these bars within a meter length results in a center to center distance of only 45 mm which is too low (almost no concrete cover, Figure 56).

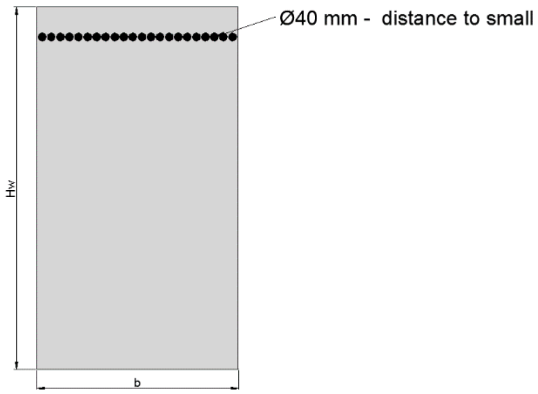


Figure 56 Mutual rebar distance to small

In order to solve this, the following can be done (Figure 57):

1) Increasing the thickness of the wall, so that the amount of reinforcement can be decreased
2) Add another row of reinforcement in order to make it fit.

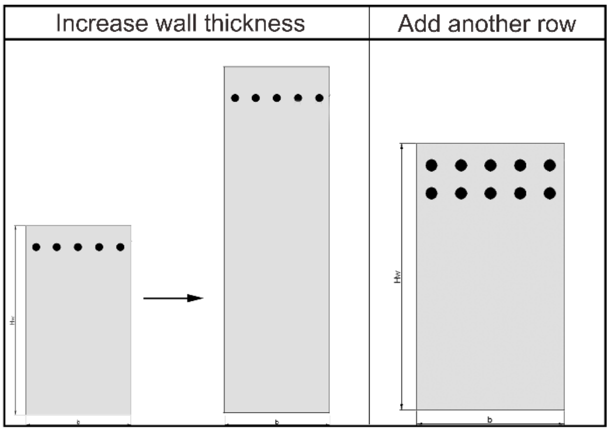


Figure 57 Rebar measures

Note that adding another row would be beneficial to the placement of the bars, but the second row would be less effective in resisting bending moment as the (moment) arm becomes less. In this paper only the effect of increasing the wall thickness has been investigated.

It was found that in order to place these bars efficiently, 10 bars of Ø40 with a center to center distance of 100 mm, the wall had to be increased to 4 meter!

2) Shear force design

Also the occurring shear force of approximately 13,000 kN is of extremely high value. In order to cope with the shear force, the wall had to be increased to 2.2 m. Also here, problems began when designing the rebars.

These transverse bars also known as *struts* need to bend around the longitudinal bars, and therefore one must make sure enough concrete coverage is available. Common strut sizes are in the order of Ø12-14 mm. However as the shear force is of extreme value, the amount of struts have been calculated with an uncommon strut diameter of Ø25 mm. The results were as follows (Figure 58):

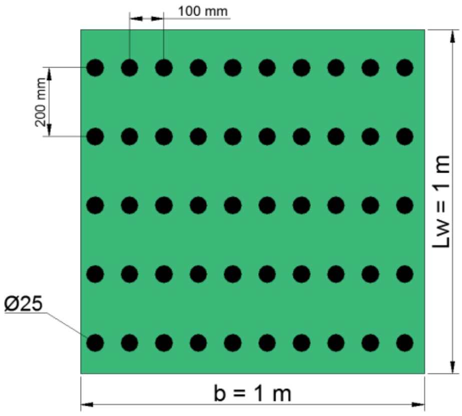


Figure 58 Shear struts

The amount of struts that have to be placed per meter width having this diameter is rather unpractical. Also here applies that in order to decrease the diameter or amount of struts, the wall thickness should be increased.

From the outcome of design in bending, a wall thickness of 4 meters followed. A wall thickness of 4 meters would result in a halve amount of transverse reinforcing steel which would make it more practical but still, likely economically insufficient.

6.3.4 RETURN PIPE

For the return pipe, the following parts will be designed:

- The diameter
- The pipe thickness

Note that the actual calculations of these parts can be found in [G.6 Return pipe, p145].

The pipe diameter

There are two formulae which can be used to estimate the diameter of the return pipe, one is based on the balance equation [A.1 Principles of fluid mechanics, p105], and one is experimentally determined for pipe return lines in hydraulic systems. First the diameter is determined by the balance equation, which states that the discharge remains constant in the system:

$$Q = v_1 \cdot A_1 = v_2 \cdot A_2 = \text{constant} \qquad \text{Eq. (6.4)}$$

Where:

- Q is the discharge in the system [m³]
- v_1 is the velocity in the main container [m/s]
- v_2 is the velocity in the return pipe [m/s]
- A_1 is the flow area of the main container [m²]
- A_2 is the flow area of the return pipe [m²]

The second formula is an experimentally derived formula (Tube Selection Chart), the pipe (inner) diameter can be calculated with:

$$D_{inner} = 4.65 \cdot \sqrt{\frac{\text{Flow in liters per minute}}{\text{Velocity in m/s}}} \qquad \text{Eq. (6.5)}$$

Both these two formulae give different pipe diameters (1100 mm vs. 620 mm). Eq. (6.5), takes in contrast to Eq. (6.4), into account phenomena such as friction losses and turbulence both resulting in pressure drops (Tube Selection Chart). The pipe (outer) diameter is therefore estimated at 700 mm.

The pipe wall thickness

The required wall thickness of the return pipe can be calculated with the Barlows formula (Tube Selection Chart):

$$P = \frac{2 \cdot S \cdot t}{D} \qquad \text{Eq. (6.6)}$$

Where:

- P is the internal pressure [kPa]
- S is the maximum allowable (design) stress in the pipe [kPa]
- t is wall thickness [mm]
- D is the diameter of the return pipe [mm]

From [G.6 Return pipe, p145] a wall thickness of 14 mm follows.

6.3.5 TURBINE/PUMP

The *reversible pump/turbine* (=RTP) is a device which should be able to move water in both directions. During *storage mode,* the pump is moving the water, this is noted as *pump mode* - and in *generation mode,* the water moves the turbine, this is noted as *turbine mode*.

There are three main (design) demands regarding a RPT (Walset, 2010):

1. Pump head should be higher than what is available in turbine mode due to the losses in the water way.
2. Stable pump
3. High efficiencies in both modes (pump & generation).

The first demand means that the pump head should be prioritized. Otherwise, the pump will not be able to pump the water back. In order to achieve a high pumping head, the blades must be longer and fewer compared to, for example, a regular Francis turbine as can be seen in Figure 59. By prolonging the blades a higher pumping head can be achieved; there are fewer blades in order to avoid the pump inlet to be too cramped. Note that the illustrations in Figure 59 are not actual designs but more schematizations

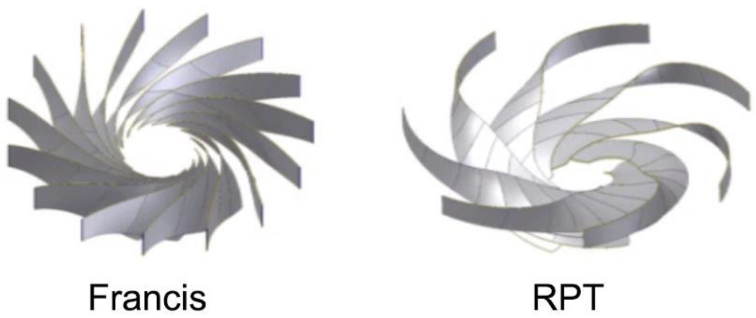


Figure 59 Francis vs. RPT

The disadvantage of prioritizing the pump head, is that the turbine is running off design which means a lower efficiency in turbine mode. To make matters worse, by prolonging the blades, the turbines will be larger which results in a more expensive turbine.

The second demand, concerning the pump stability, states that there must be no oscillations in the system. To achieve a stable pump, the blades must be bent backwards (Walset, 2010).

The third demand should be obvious. Furthermore, when designing a pump/turbine, special attention must be paid to *cavitation,* which is a phenomenon that can heavily erode the material in the turbine. This paper however, does not go into details regarding this phenomenon as it goes beyond the scope of this paper.

Design requirements

The design of the RPT is based on three main aspects:

- Total head
- Discharge
- Energy

Total head: 400 m

The head of the main container represents the head of the water and the extra head of the piston. The pressure of the water is estimated at 280 kPa meanwhile the piston has an extra load of 3,360 kPa; both of them together (including a safety factor) equals to a head of approximately 4 MPa which can be translated to a (water) head of 400 meter.

Discharge: 0.9 m³/s

The energy storage device is to supply peak load to the demand side. The peak load has a time-span of approximately 4 hours which is also the time that the piston will move from the top to the bottom of the storage. The discharge can be written as follows:

$$Q_{pump/turbine} = \frac{A_{piston} \cdot z}{t} \qquad \text{Eq. (6.7)}$$

Where:

- $Q_{pump/turbine}$ is the discharge [m³/s]
- A_{piston} is the area of the piston [m²]
- z is the potential height [m]
- t is the time [s]

Filling in these parameters in Eq. (6.7) results in a required discharge:

$$\left.\begin{array}{l} A_{piston} = \pi \cdot r^2 = \pi \cdot 12^2 = 452 \text{ m}^2 \\ z = 28 \text{ m} \\ t = 4 \text{ hours} \rightarrow 14400 \text{ s} \end{array}\right\} \rightarrow Q = 0.90 \text{ m}^3\text{/s}$$

Energy: 1250 kWh

Per cycle of 4 hours, 4850 kWh has to be generated which means that the power requirement of the turbine is $P_{turbine/pump} = \frac{4850}{4} \approx 1250$ kW.

RPT selection

Considering the requirements, a RTP can be selected via a pump characteristic curve of a RPT, doing this, goes out of the scope of this paper. Note that due to the low flow rate, the efficiency could be lower than expected as can be seen in Figure 60.

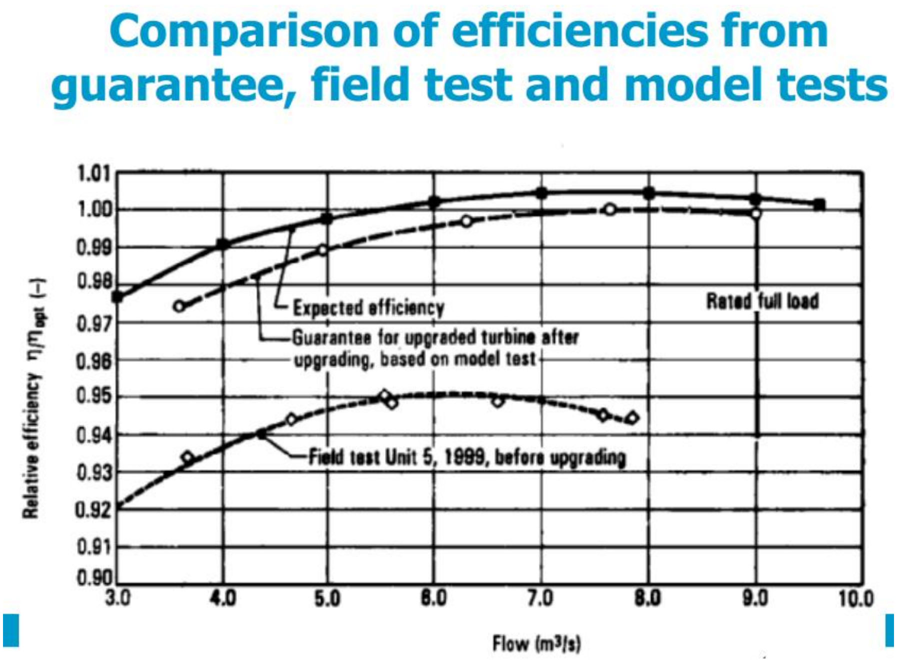


Figure 60 Turbine efficiency vs. flow rate (A. van der Toorn; W. molenaar)

6.4 CONSTRUCTION

This paragraph involves the construction of the storage device. The storage device has many similarities with a (water) storage tank. The key difference, and probably the most challenging one, is the inclusion of the piston into the storage device. Such measure, has never been dealt before in practice, and the construction method described in this paragraph might therefore miss important aspects that can only be measured/observed in practical application of the storage device. Normally, practical models will be made and measurements will be done beforehand. However, creating such a model goes beyond the scope of this paper. The construction method has therefore been described in a theoretical point of view, taking into account the expected practical problems.

6.4.1 PREPARATION

Before the storage device can be constructed, the embankments or subsoil, must be prepared. The preparation of the subsoil consist of compacting the subsoil in order to increase the bearing capacity (Figure 61).

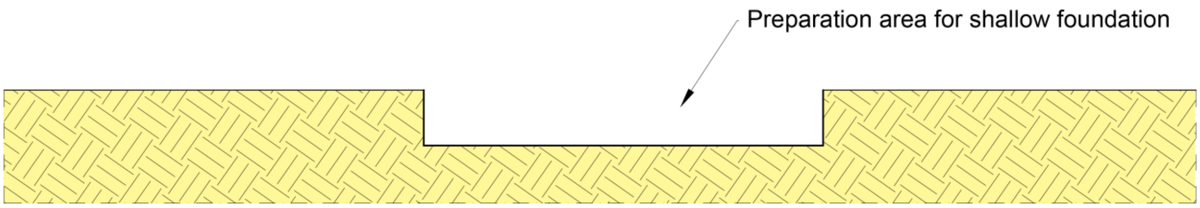


Figure 61 Preparation

6.4.2 FOUNDATION

After the preparation of the soil foundation, (common) formwork, reinforcement and part of the return pipe, is placed and the foundation will be casted (concrete) as can be seen in Figure 62.

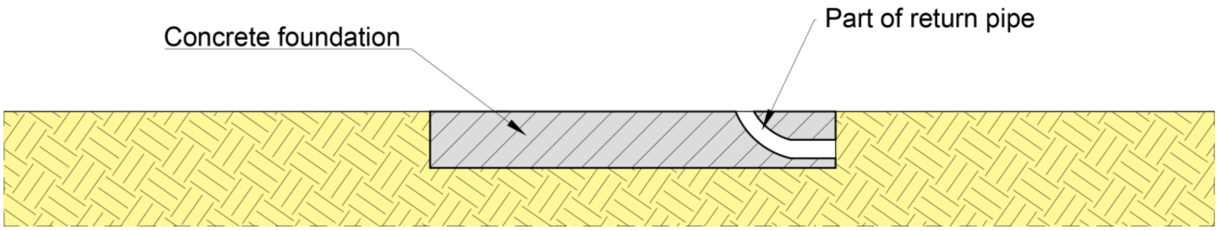


Figure 62 Foundation

The purpose of the return pipe, is to enclose the storage device. One of the key elements in the structure is the cylindrical wall, which should already cope with heavy loading from the piston. The return pipe could be connected via the wall by, for example, a gap in the wall. However as the wall is one of the key elements, decided has been to minimize/eliminate disruptions in the wall. The return pipe is integrated in the foundation instead, another advantage is that no energy height is lost: if, for instance, the return pipe was connected to the cylindrical wall, the height that would be lost, would be equal to the diameter of the return pipe. The disadvantage of this method, is that if something goes wrong with this part (fails) such as leakage or multiple large cracks, the whole structure might fail. Precautions must be taken by, for example, handling this with care and/or creating multiple integrated return pipes, if one would fail, another one could be used.

6.4.3 CYLINDRICAL WALLS

After the foundation has been casted, the cylindrical walls will be constructed with *climbing formwork*; the concrete is casted in-situ (at location), from a batch/truck.

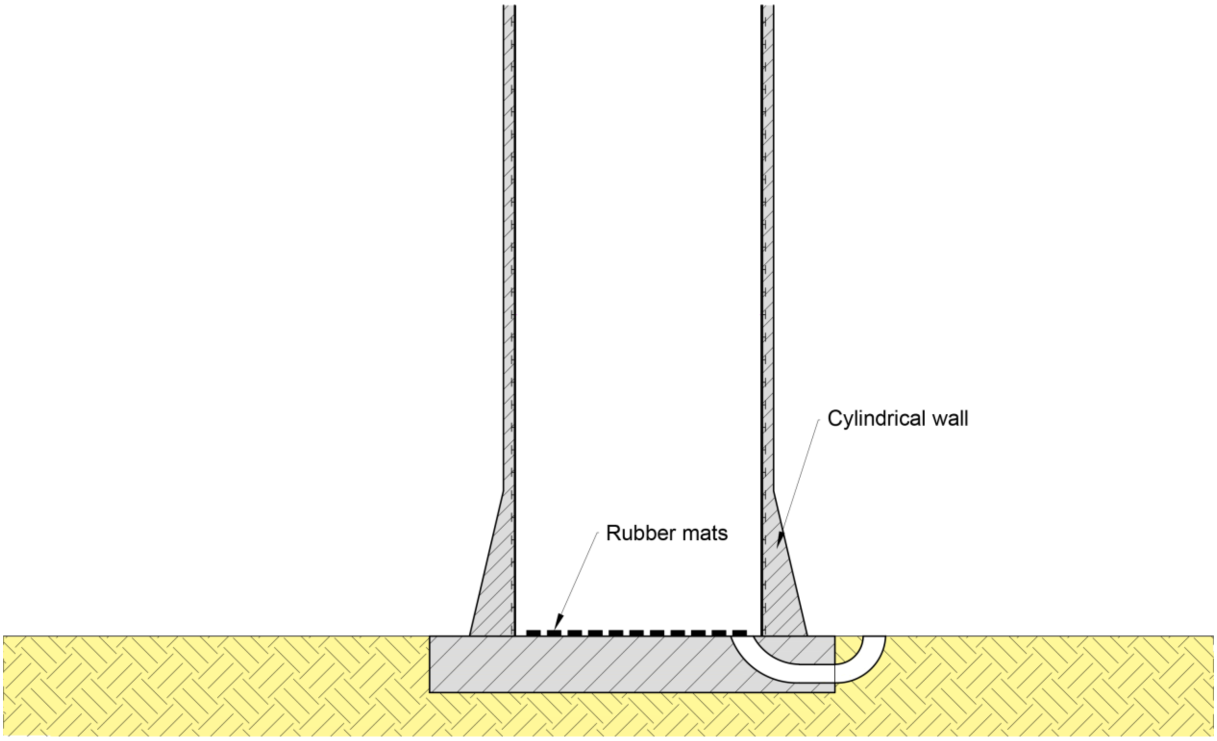


Figure 63 Constructing of the cylindrical walls

On the bottom of the structure rubber mats will be placed which have the following purposes:

1. Allowing water to reach the whole bottom area of the structure in pump mode (in order to lift more effectively).
2. Reducing the impact of the piston on the structure.

After the wall has been casted, the wall will be *horizontally* prestressed with so-called *prestressed* tendons (Figure 64).

Figure 64 Prestressing LPG Tank Terneuzen (NL) (R. Braam, 2010)

After the tank has been prestressed, the piston can be inserted into the main container (Figure 65).

6.4.4 CONSTRUCTION OF THE PISTON

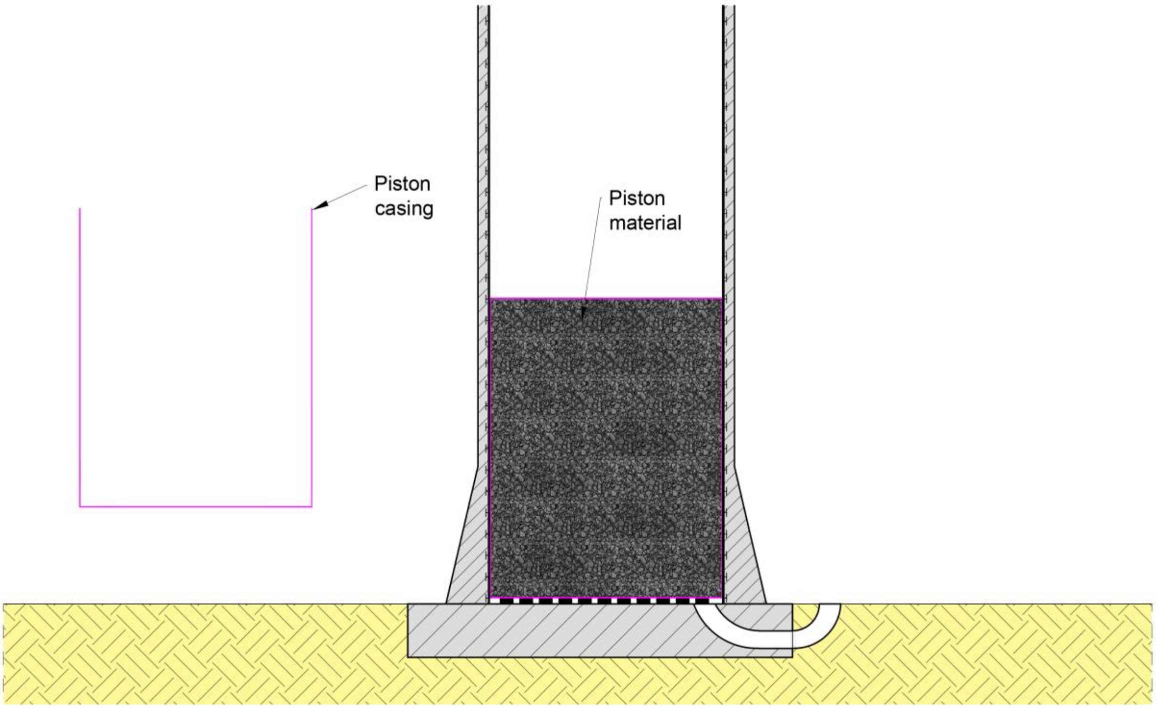


Figure 65 Construction of the piston

The piston consists of the following parts:

1. The piston casing
2. Piston sealing
3. The piston inner material

Firstly, the piston casing, made of steel, will be made outside the structure. The inner material consists of lead material. There are two requirements for the piston casing, (1) it must be water tight, otherwise it can't be lifted upwards, and (2) it must be strong enough to carry the *inner material*. Luckily, the piston casing floats on water and therefore, the effect of the load of inner material on the bottom plate of the piston casing, will be limited.

Secondly, hydraulic lip seals will be placed on the outside of the piston casing. The functional reliability and service life of a seal depends to a very great extent on the *quality* and *surface finish* of the mating surface to be sealed (Busak+Shamban, 2006).

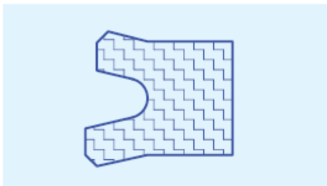


Figure 66 Piston seal (www.jameswalker.biz, n.d.)

These lips leap seals demand high requirements concerning the surface roughness. The maximum surface roughness for hydraulic seals according to (Busak+Shamban, 2006) is equal to 4 μm! Concrete can easily have a surface roughness of 20 μm (Deelman, 1984). Due to the properties of concrete this requirement cannot be met by concrete alone. Therefore either a *coating* must be applied, or some kind of *steel frame* must be placed between the concrete main container and the piston. In order to determine the roughness of the concrete and the effect of coating on the concrete, more research must be conducted. In this paper, it is assumed that by a special coating the roughness requirement of 4 μm is met. For more information about seals, one is referred to [H.1 Piston sealing, p147]. Other challenges concerning leakage along the piston may arise due the imperfections during the construction of the wall: because of the formwork, the wall will not be a perfect circle.

After the lip seals have been placed on the outside of the piston casing, the casing will be lifted with a crane and is then placed in the storage main container. When the piston casing has reached the bottom of the container, the piston inner material (lead) will be put into the casing. One aspect that may be problematic is the initial deformation due to the prestressing load. Due to prestressing the wall deforms and this should be taken into account when inserting the piston.

One of the requirements of the structure, is that it must be maintainable. Lead is of relatively high density 12000 kg/m³; if one would, for example, cast the piston full of lead (assuming that it's possible at location), the total weight of the lead would be:

$$Weight_{piston} = \underbrace{\pi \cdot r^2 \cdot H}_{\text{Volume Piston}} \cdot \rho_{lead} = \pi \cdot 12^2 \cdot 28 \cdot 12000 = 1.52 \cdot 10^5 \text{ ton}$$

A lifting crane has a lifting capacity in the order of 10-50 ton (www.alibaba.com, n.d.), which means that the piston would be too heavy to lift, when possible maintenance must be done. In order to solve this, lead could be pre-casted in smaller segments before it is put into the casing. However, assuming cylindrical segments, the thickness of such a segment would be in the order of 1 cm, (which means 2800 segments):

$$H_{segment} = \frac{Crane_{capacity}}{\pi \cdot r^2 \cdot \rho_{lead}} = \frac{50 \text{ ton}}{\pi \cdot 12^2 \cdot 12000} \approx 1 \text{ cm}$$

In other words, casting lead or using segments of pre-casted lead, is not a viable option. Instead, for practical reasons, it is chosen to fill the piston with the raw bulk material of lead: lead ore (Figure 67).


Figure 67 lead ore

Unfortunately, lead ore has a much lower density of 7500 kg/m³ instead of 12,000 kg/m³. This means a lower mass and therefore a lower energy output.

In order to avoid chemical mixing of the water with lead which might possibly result in problems, the piston casing will have a roof top.

6.4.5 INSTALLATION OF MECHANICAL COMPONENTS

After placing the piston, the turbine/pump, generator, (another) part of the return pipe and valves will be installed (Figure 68). There are two valves installed:

- Valve 1: which is used to change between pump and turbine mode.
- Valve 2: which is used for testing and maintenance purposes.

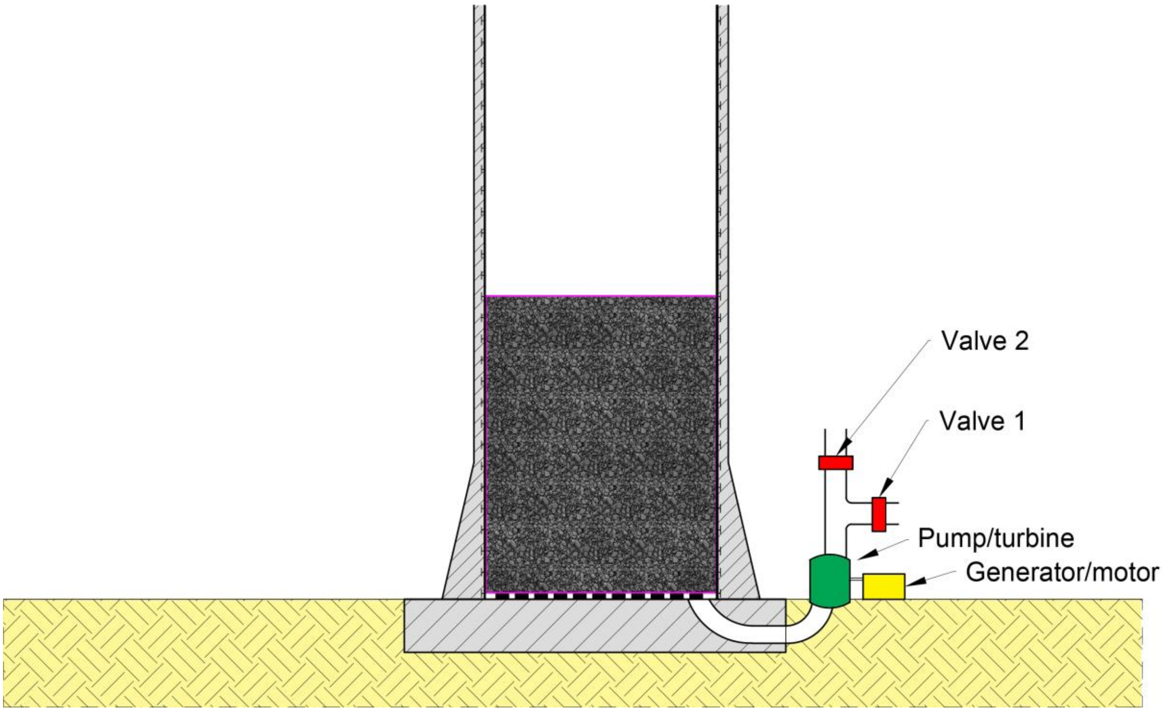


Figure 68 Installation of mechanical components

Note that special attention must be paid to the connection between the return pipe in the foundation and the pump/turbine due to differential settlement caused by not yet applied loadings on the structure such as, for example, the water load.

6.4.6 TESTING

After all key components of the structure have been placed, some actual testing must be done; the purpose of this test is to control/measure possible failures in the system such as cracks, faulty equipment, faulty connections, possible leaks in the structure, sealing, sliding of the piston, performance of the pump/turbine, etc. Does the structure operate as expected?

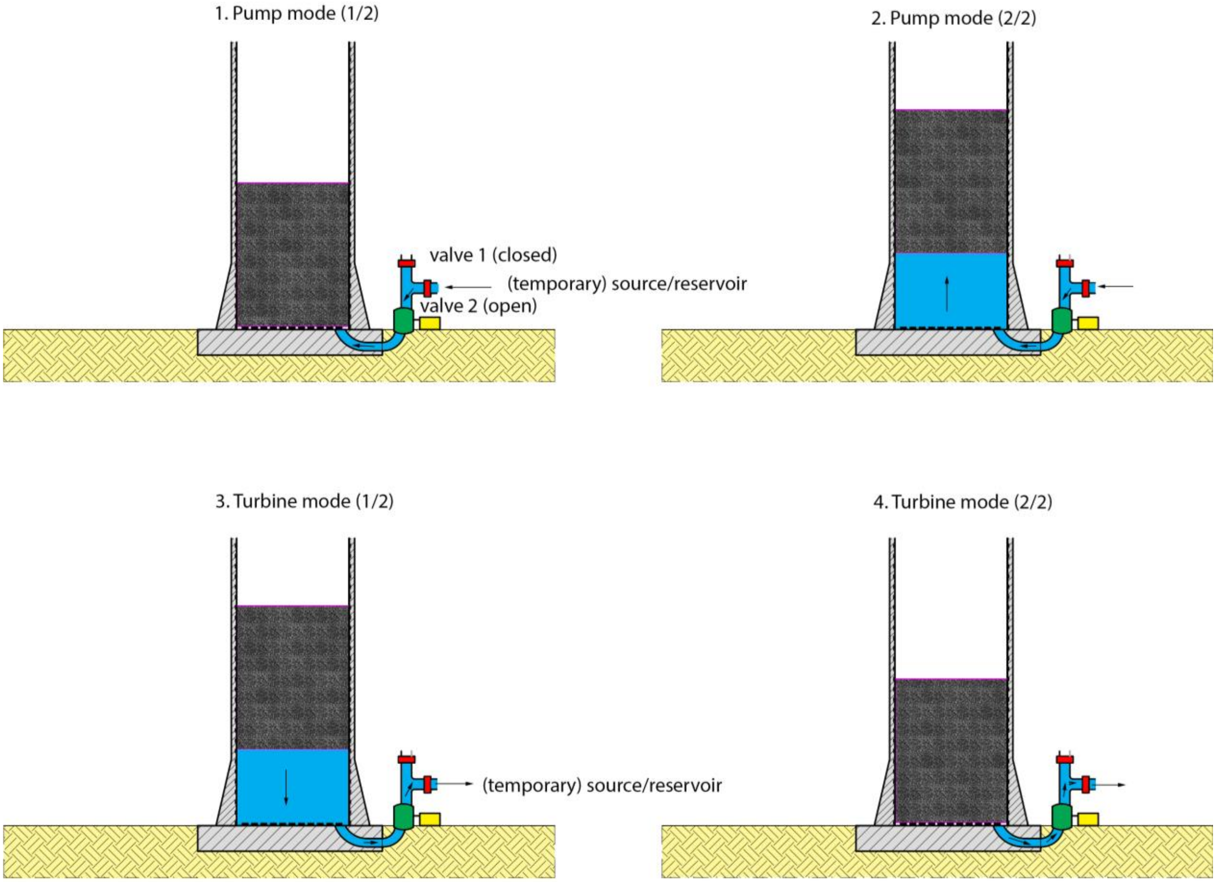


Figure 69 Testing of the structure

The testing could be done as follows (see Figure 69):

In pump mode (1/2->2/2), valve 1 is closed and valve 2, which is connected to a (temporary) reservoir or other source of water, is open. The pump/turbine goes into pump mode and uses the water from the reservoir to elevate the piston. When the piston has been elevated to a certain height, valve 2 is closed. Now the pump/turbine goes into the turbine mode (1/2->2/2) and valve 2 opens again and water is released back into the reservoir. Note that during this test phase, the water load is not yet present, however compared to the lead ore it is of relatively small significance (1000 kg/m³ vs. 7500 kg/m³); If this testing phase succeeds, there is a high probability that it also succeeds in the final phase (during operation).

6.4.7 INSTALLATION ROOF

After successful testing, the roof and the last part of the return pipe are constructed (Figure 70).

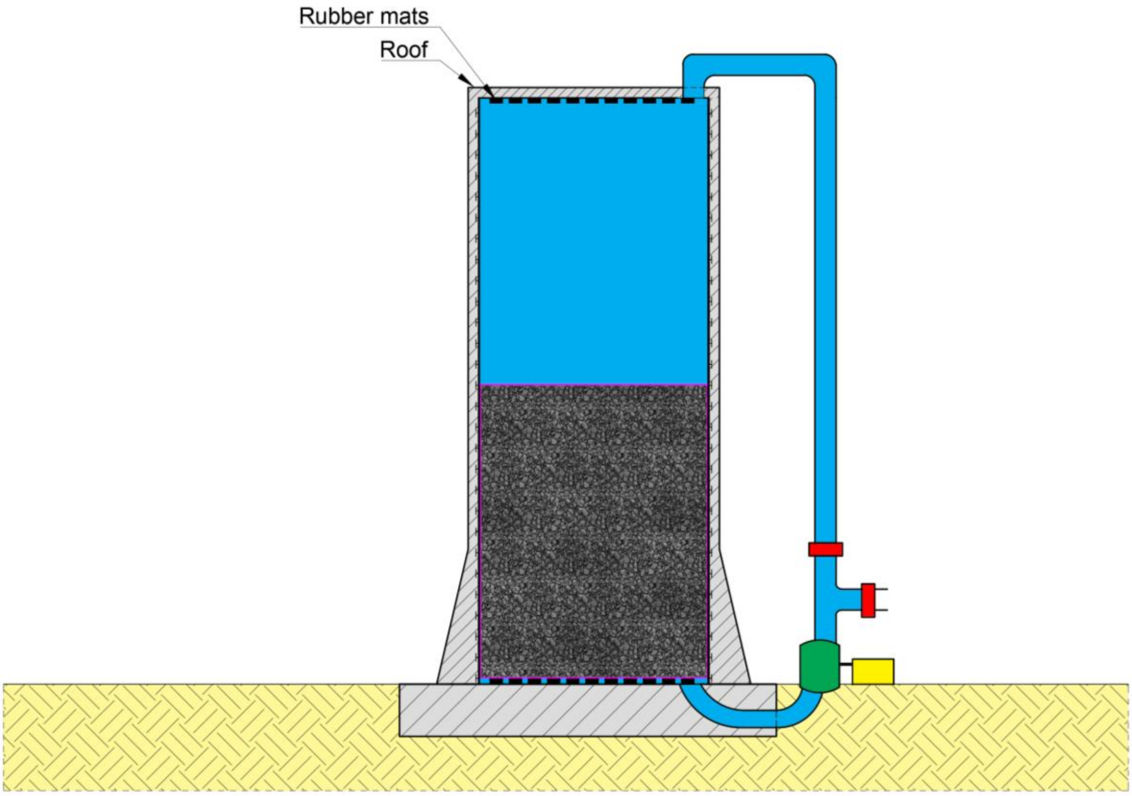


Figure 70 Installation roof

As there is low pressure expected on top, the roof can just be situated into the cylindrical walls similar to Figure 71.

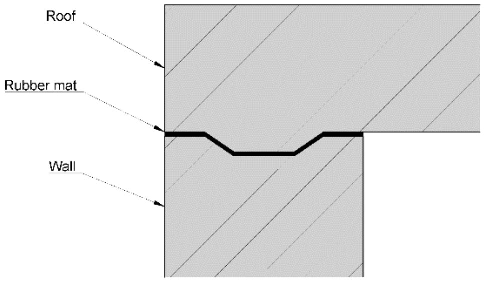


Figure 71 Roof wall connection

As no interruption is allowed in the cylindrical wall, the connection of the return pipe with the structure on top goes through the roof. Furthermore, rubber mats will be installed on the bottom of the roof to allow for shock absorption. Lastly, water will be pumped (from an external source) into the system by both opening valve 1 and valve 2, creating a saturated structure.

6.4.8 FINAL RESULT

After the main structure has been completed, a powerhouse will be built next to the structure as is schematized in Figure 72 and can be connected to the utility grid.

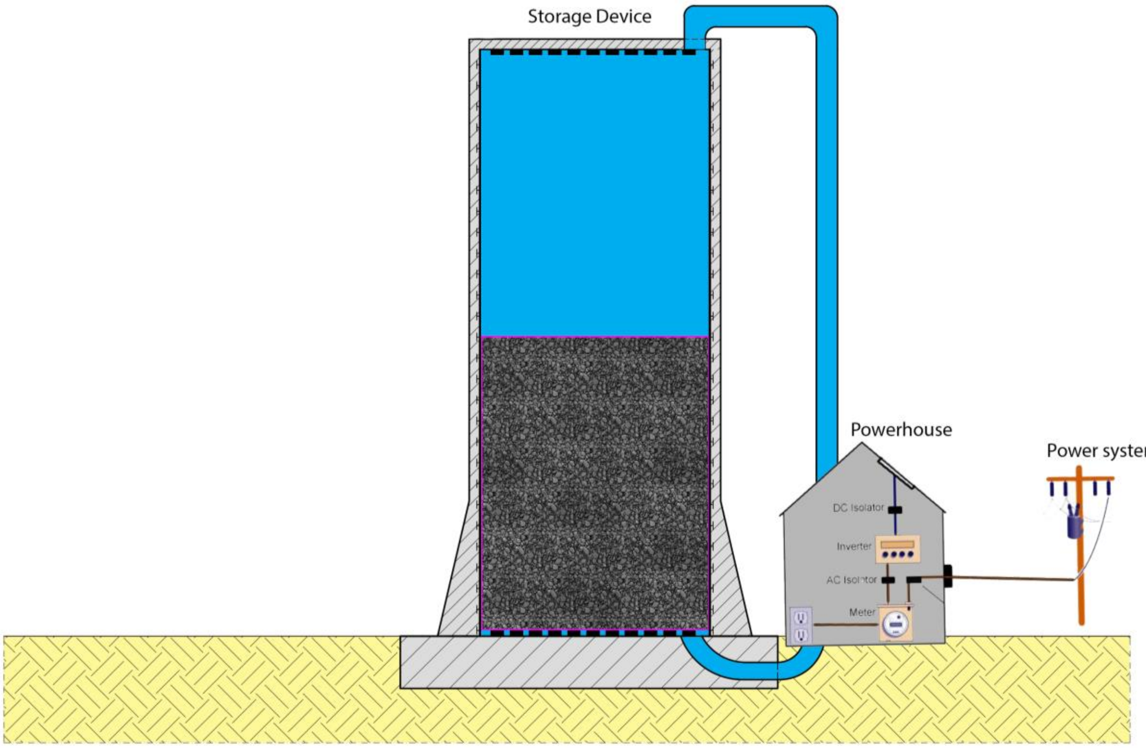


Figure 72 Final result

6.5 COSTS

6.5.1 INTRODUCTION

In this subsection, a cost overview will be given. Cost is a very general term, in a civil engineering project, or any other project different for that matter, the following facets of costs can be defined:

- **Design.** Cost of designing the project
- **Construction**. The construction costs are the costs which are required to build the structure, consisting of labor, material and equipment costs.
- **Maintenance.** The maintenance costs are the cost which is required to maintain the structure such as repairing or replacing of equipment.
- **Risk/Profit**. One can decide to use cheaper material instead of a more durable one. The probability that a cheaper material is damaged is higher than the more durable one. One can use the cheaper one, which *does* increase profit in short term, but might lead to losses in longer term. These kinds of costs can be assigned to risk/profit cost.
- **Demolition.** At the end of a structures' lifetime, the structure will be demolished: the cost of demolition.

Components

Cost is one of the most important factors which decides whether a project is feasible or not. Also in this paper, the costs will be elaborated. The purpose is not directly to determine the feasibility, but to ascertain the possibility of economic optimization. Therefore, in this paragraph, only the material cost have been included. The material cost consists of: the cost of the material concrete/steel and the cost of formwork.

The following components will be included in this subsection:

Structural	Special	Mechanical
Foundation	Piston	Pump/turbine
Cylindrical wall		Generator
Roof		
Return Pipe		

6.5.2 COST OVERVIEW

Figure 73 shows an overview of the costs of the aforementioned components. Note that the valves have not been included as their cost is assumed to be relatively small. In [Appendix I: Cost, p149], the cost of each component has been elaborated extensively.

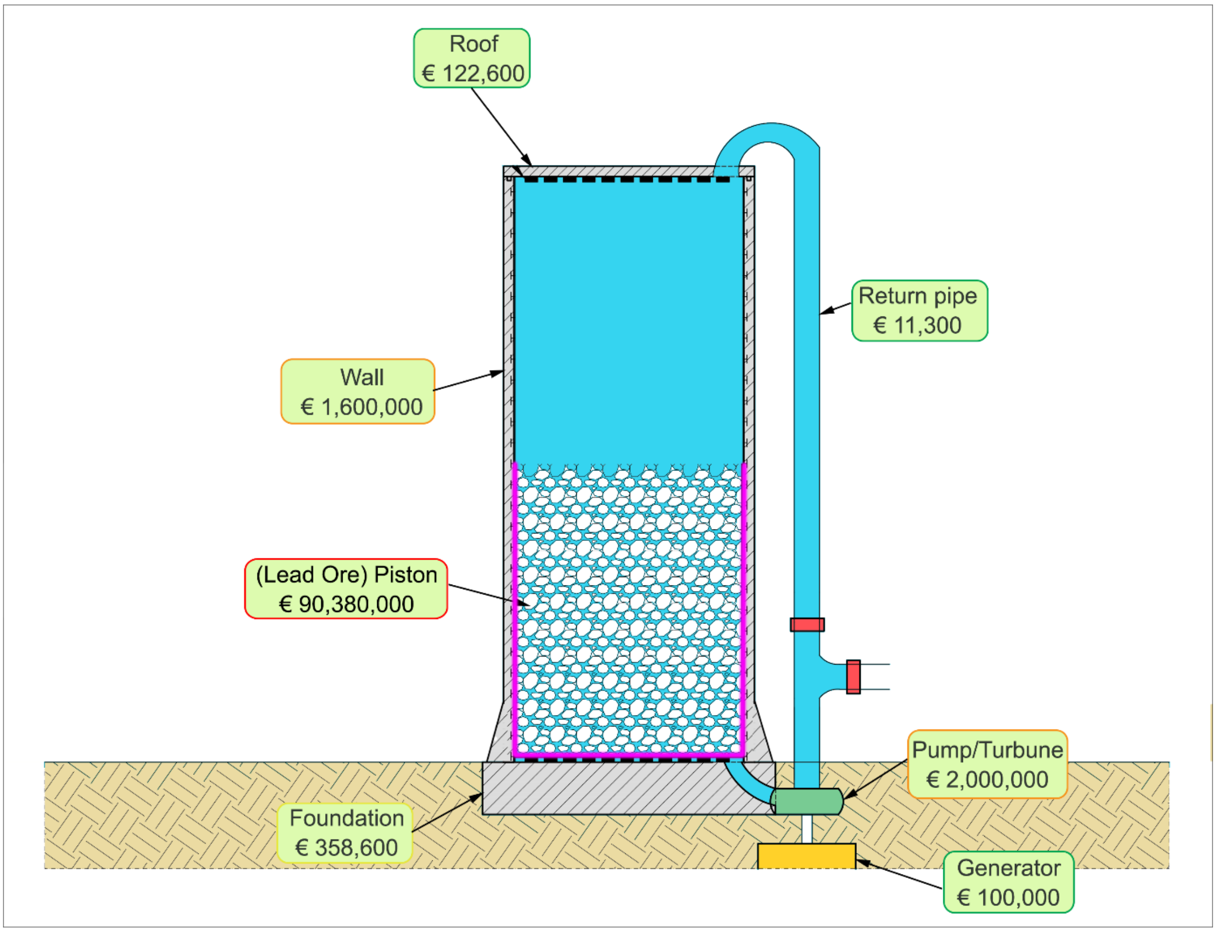


Figure 73 Cost overview

What becomes clear is that piston takes up most of the costs: the piston takes up to roughly 96% of the total material costs, meanwhile the other components together are worth for 4% of the costs as can be seen in Figure 74.

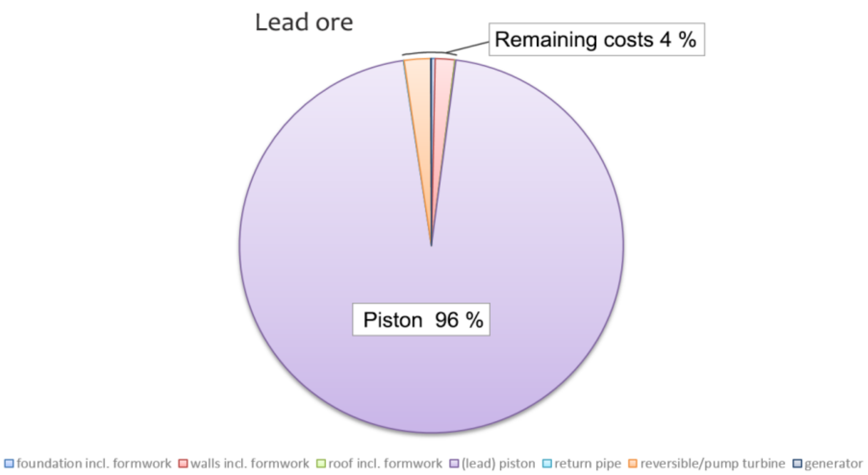


Figure 74 Cost distribution

6.6 EVALUATION

From the first stage the following becomes clear:

Externally, the structure is stable; the soil has no problems with large loading, the foundation can be situated slightly beneath ground level.

Internally, the wall component could not cope efficiently with the (extreme) large loading with the initial wall thickness. First, the wall had to be increased to 1.8 m in order to cope with the large moments in the bottom wall connection. However, it became clear that for practical reinforcement design, the wall had to be increased to 4 meters.

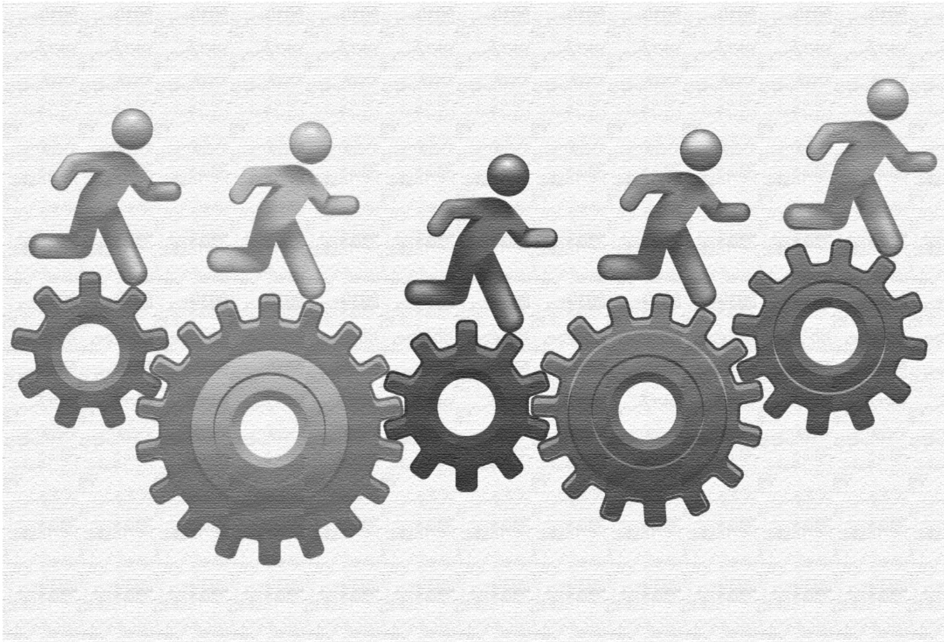
Theoretically the *construction* of the structure should not be a problem except for installing the piston and the requirement of the minimum surface roughness of the wall. Firstly, it became clear that the piston of lead could not be casted, because the structure would not be maintainable. Instead lead ore had to be used which, unfortunately, has a lower density (and results in less energy storage). Secondly, the smoothness of the wall could not be met by concrete alone. A coating might be able to solve this. However, this has not been researched any further. Also the initial deformation of the wall, due to the prestressing load, should be taken into account when inserting the piston in the main container.

In the overview of the *material cost* it could be seen that the piston alone would cost nearly 90 million euros, which would be 96% of the total costs.

Obvious is that, in order to increase the economic and technical feasibility of the structure, the piston requires a change. It should prime to a *decrease* in total loading and/or a *decrease* in the cost of the piston itself. This can either be done by (1) changing the piston material or (2) changing the dimension of the main container (an in particular the thickness of the piston).

In this paper, the effect of both optimization methods will be studied. First, the piston material will be changed and second, the dimensions of the container.

CHAPTER 7. OPTIMIZATION



Contents

7.1 INTRODUCTION

In this chapter, the production cost will be optimized by changing the piston material and the dimension of the piston/container. The total production cost is expressed in €/kWh and depends on the amount energy production for a certain period of time, and the total material cost. The *lifetime* of the structure is 50 years. Hence, the energy production will be considered for a period of 50 years.

7.2 THE PRODUCTION COST FUNCTION

The equation for the price per kWh can be written as a function of the *tank height h, the tank diameter D* and the *piston material* and can be described with:

$$\text{Production Cost}\left(h, D, \rho_{piston}, €_{material}\right) = \frac{\sum \text{Material Cost}}{\sum \text{Energy Production (during 50 years)}} \; [€/\text{kWh}] \quad \text{Eq. (7.1)}$$

7.2.1 MATERIAL COST

For the total material cost, only the most signification cost has been included, that is, the cost of the: *foundation*, *the wall*, *the piston* and *RPT* and can be formulated as follows:

$$\sum \text{Material Cost}\left(h, D, €_{material}\right) = €_{foundation} + €_{wall} + €_{piston} + €_{RPT} \quad \text{Eq. (7.2)}$$

The cost function *per* material can be seen in [J.1 Material Cost function, p155]

7.2.2 ENERGY PRODUCTION

The energy production function within a period of 50 years can be defined as follows:

$$\underbrace{E = \frac{1}{16} \cdot \pi \cdot D^2 \cdot h^2 \cdot \mu \cdot (\rho_{piston} - \rho_{water}) \cdot g}_{\text{Energy in Joules [J]}} \quad \rightarrow \quad \underbrace{\sum E = \frac{1}{16} \cdot \pi \cdot D^2 \cdot h^2 \cdot \mu \cdot (\rho_{piston} - \rho_{water}) \cdot g \cdot \langle v \rangle}_{\text{Energy in [kWh] during a period of 50 years}} \quad \text{Eq. (7.3)}$$

Where:

- $\langle v \rangle = \frac{Period}{JtoKwH} = \frac{365 \text{ days} \cdot 50 \text{ years}}{3.6 \cdot 10^6}$ is the conversion factor from J to kWh during a period of 50 years
- $\sum E$ is the total amount of energy production during a period of 50 years [kWh]
- D is the diameter of the storage device [m]
- d is the thickness/height of the piston [m]
- g is the gravitational acceleration [m/s²]
- z is the potential elevation height [m]
- μ is the system efficiency [-]
- π is constant of 3.1495 [-]
- ρ_{piston} is the density of the piston [kg/m³]
- ρ_{water} is the density of water 1000 [kg/m³]

Note that the *net constant value* has not been included in this equation, as the purpose of this optimization cycle is to see what kind of dimensions would be necessary in order to decrease the production price. Therefore, the actual price per kWh will actually be higher than shown in this paragraph.

7.3 GOAL

According to Eq. (7.1), the production cost of a storage device with a lead ore piston would come down to 1.13 €/kWh during the lifetime of 50 years. Again, these costs only involve the material cost; maintenance, demolition, risk, and the net present value are not incorporated in this production price.

The production cost of *peak hour electricity* (gas power plant) is about 0.09 €/kWh (see *part one* of this paper).

In order to compete with the production price of 0.09 €/kWh, the goal for the production cost of the storage device is estimated at 0.04 €/kWh as is illustrated in Figure 75.

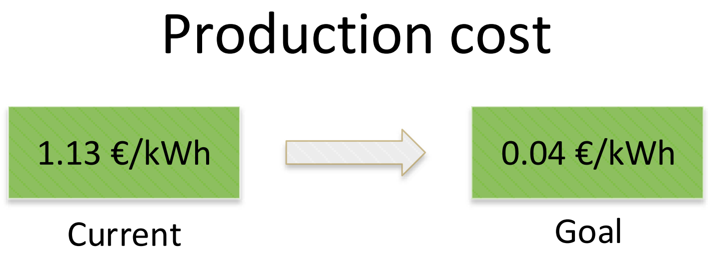


Figure 75 Goal production cost

Note that the goal of the production cost is much lower than 0.09 €/kWh as this paper only considers the cost of the material.

7.4 CHANGING PISTON MATERIAL

In this section, the structure will be (economically) analyzed by changing the piston inner material. Basically there are two significant changes involving a change of material:

- **Material density.** When the material density changes (read: decreases), the amount of energy that can be harvested automatically lowers and this would result in a decrease in energy production.
- **Material cost.** Obvious is that a higher material cost results in a higher cost of the device itself.

There are many different materials that could be used, investigating all possibilities goes out of the scope of this paper, and therefore only the following materials will be investigated:

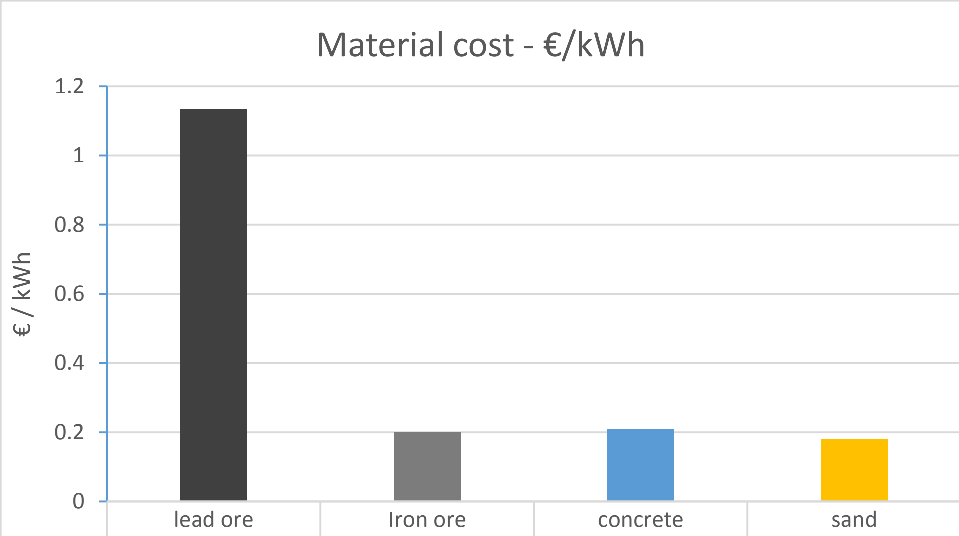
- **Iron ore.** Even though expensive, it is of relatively high density
- **Concrete.** One of the most commonly used material in the world of construction
- **Sand.** Even though relatively light, it does not come with large costs.

In Table 11, the difference in cost and theoretical output per year of these materials have been compared to lead (ore).

Table 11 Theoretical output

	Density [kg/m^3]	Theoretical output per year [kWh]	Price index	Source
Lead	12000	25x10^5	1.64 € / kg	(metal-prices-lead, n.d.)
Lead ore	7600	16x10^5	0.90 € / kg (pb=30%)	(indexmundi, 2013)
Iron ore	5100	10.7x10^5	0.105 € / kg	(indexmundi, 2013)
Concrete	2500	5.2x10^4	120 € / m^3	(A.Q.C. van der Horst, C.R. Braam)
Sand	2100	4.4x10^4	4 € / m^3	(A.Q.C. van der Horst, C.R. Braam)

In Figure 76, the price per kWh during a period of 50 years for the different piston material have been compared. Note that only the *piston material* has changed, all other parameters such as dimensions or costs of the other components (foundation, walls, return pipe) have been taken as constants.



	lead ore	Iron ore	concrete	sand
€/kwh	€ 1.13333	€ 0.20114	€ 0.20897	€ 0.18185

Figure 76 Material cost € / kWh

From Figure 76, can be observed that by changing piston material, the price can be reduced by approximately 80%. Both concrete, sand and iron ore are all in the same production cost range. Using a piston of sand would result in the least cost per kWh, unfortunately this is still too large to make the structure economically attractive.

When the piston was made of lead ore the piston was 96% of all material cost. Figure 77, which shows the material cost using a piston of sand, the piston cost has been reduced to 1 % of the total cost.

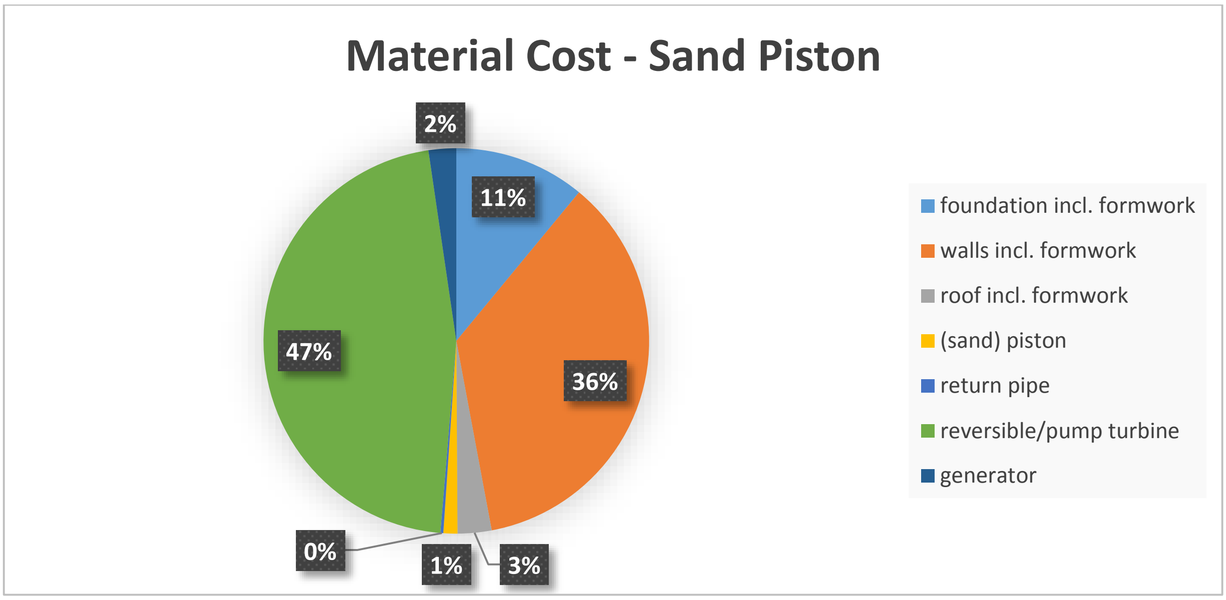


Figure 77 Material cost overview sand piston

The largest material cost components are the RPT, the walls and foundation – 47%, 36% and 2% respectively. Even though the RPT is now the largest investment of the storage device, not much (cost) optimization is expected for the RPT. It may be true, that the output/input (or storage capacity) has become lower which would lead to a smaller RPT and therefore a decrease in absolute cost; still remains that a RPT is more efficient with a larger output (pumps, n.d.). The exact dependency of the output vs. efficiency of a RPT goes out of the scope of this paper. It is assumed that the indirect cost concerning efficiency and direct cost of the RPT remains the same. The other two components: the walls and perhaps foundation are most eligible for (cost) optimization. As sand has a much lower weight than lead ore these structural components can be dimensioned more economical, but still, this would not be enough to reach the goal production price of 0.04 €/kWh. In fact, even without, for example, the walls and foundation in the cost picture, it would be difficult – or rather impossible to reach an energy production cost of 0.04 € / kWh.

To conclude, a change of material is not sufficient and therefore a change of dimensions will be investigated in the next paragraph.

7.5 CHANGING DIMENSIONS

The production price equation Eq. (7.1), is a function of the container height h, the diameter D and the piston material (and its price). Again, like in previous paragraph, the following four different materials will be considered: lead ore, iron ore, concrete and sand. The diameter will be a portion of the height. A diameter of half the height will be considered and a diameter of one third of the height will be considered, as can be seen in Figure 78. Note 1: these ratios are based on the boundary conditions of the storage device which can be found in [5.3.1 Boundary conditions, p20]. Note 2: the ratio between the piston thickness d and the height of the container h remains the same (the piston thickness is half the height of the tank).

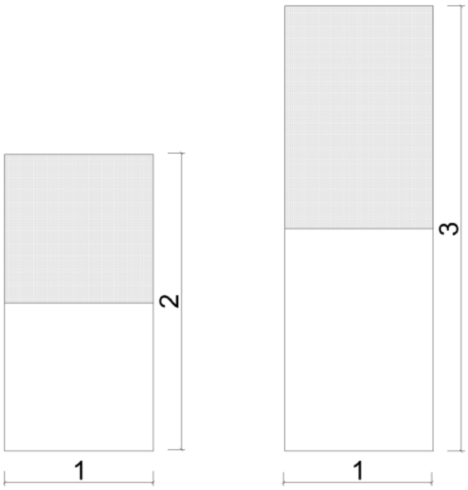


Figure 78 Ratio between the container height and the diameter

The height will be the *true variable* and is changed accordingly: from 50-200 meters for $h = 2 \cdot D$ and from 60-300 for $h = 3 \cdot D$.

7.5.1 RESULTS

In Figure 79, one can see the plot of the different materials for different height and different diameters. The pink *dash-dot line* is the target value of € 0.04 /kWh. Note that this is just only a rough estimation of production cost of the materials, as there are multiple variables which have been taken as constants such as the width of the wall (which should increase with a *larger* loading and decrease with a *smaller* loading).

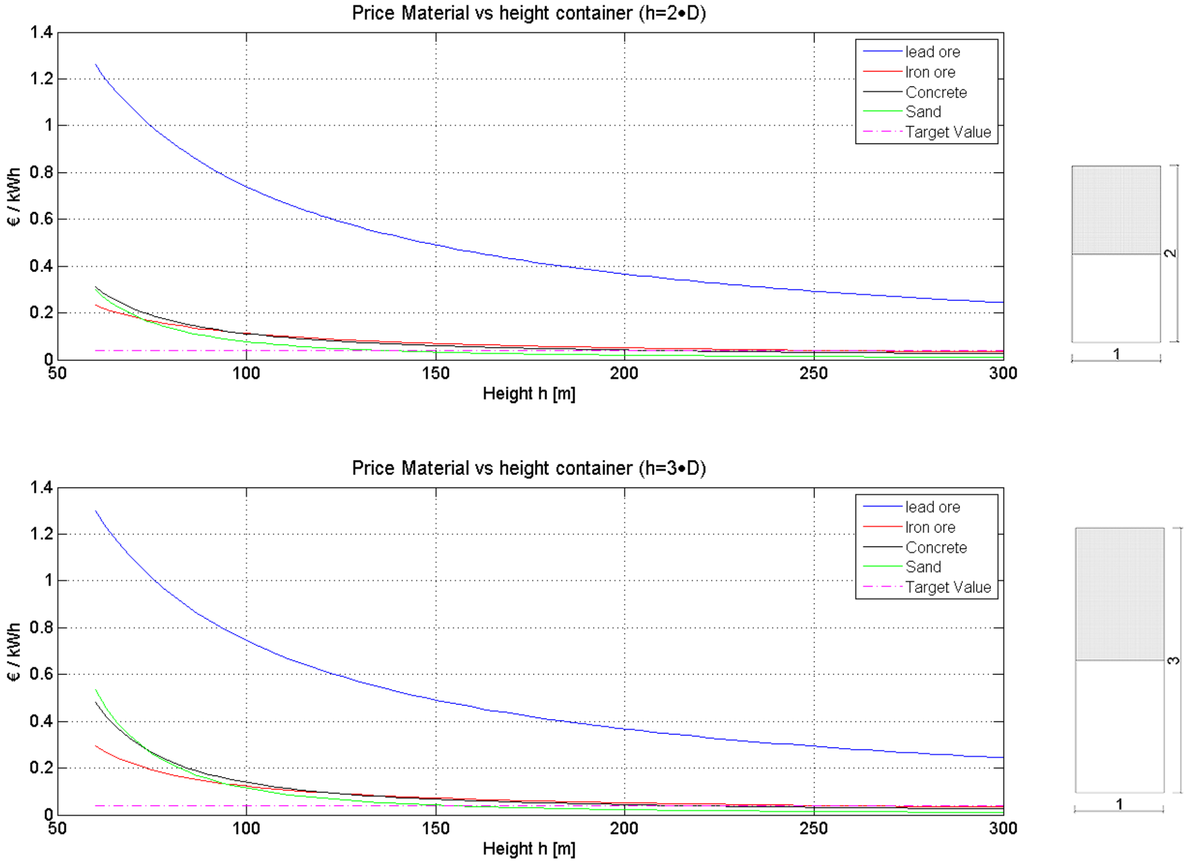


Figure 79 Plot price material vs. height container

It can be seen that from all piston materials, *sand* converges fastest to the target value of € 0.04 /kWh. Apparently, the plots also converges fastest to the target value with a smaller height/diameter ratio: for a diameter which is half the tank height, the plot converges faster than for a diameter which is only one third of the tank height. Note that all these graphs decay exponentially and that for a certain height the tangent line of this curve is almost zero, meaning that increments in size will add to a negligible decrease in cost per kWh.

Figure 80, shows the plot for only the sand piston with a tank diameter of half the height.

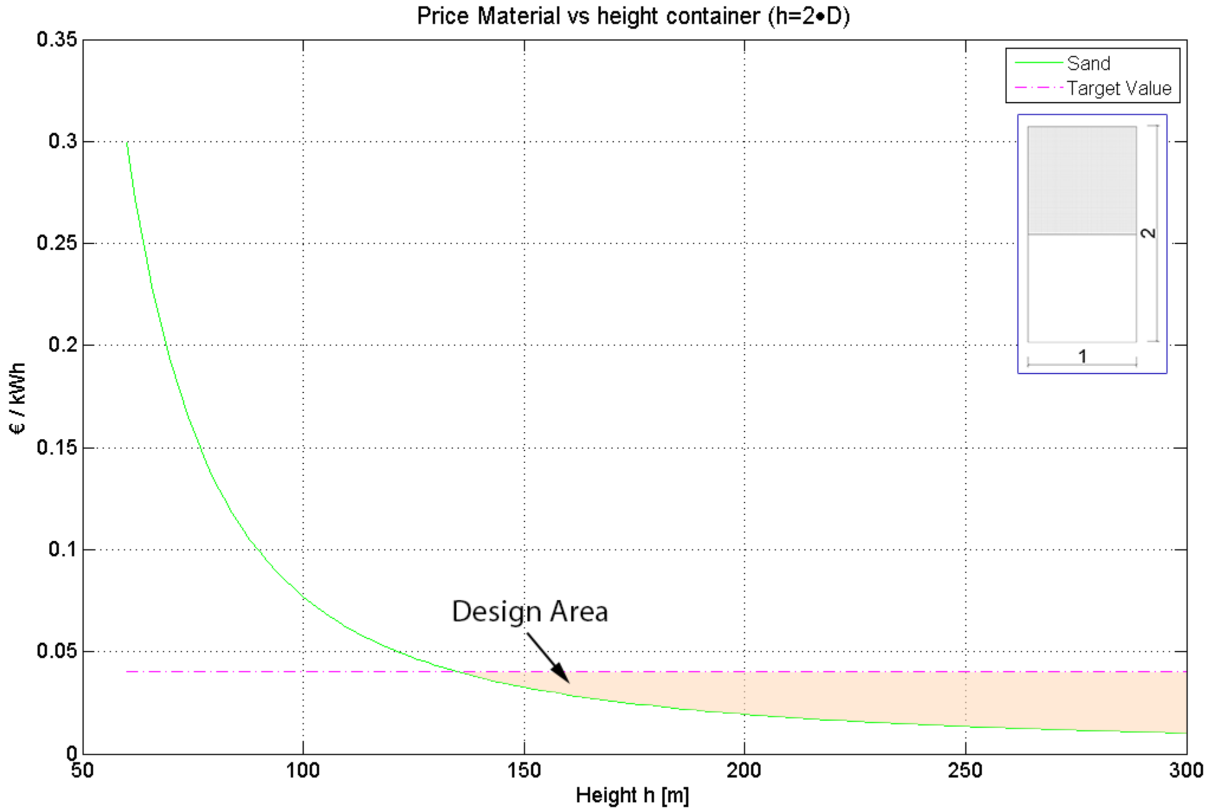


Figure 80 Design area sand piston

From this graph it follows that in order to reach a production value of 0.04 €/kWh, the height of container should be at least in the order 140 m with a diameter of $\frac{140}{2} = 70\text{ m}$ (see design area). Again, this is only a *rough estimation* of an appropriate size for which the storage device could be economically attractive. In order to get a more precise value, the following aspects should also be considered in the least:

- All other cost facets: maintenance, demolition, equipment cost, labor, risk/profit, overhead, etc.
- The net present value
- The efficiency losses due to a longer/shorter travel distance of the piston
- The efficiency of the RPT which increases/decreases with larger/smaller output.
- The wall/foundation which can be designed slimmer with a smaller loading

In addition, if one would use the minimum tank size for economic feasibility (h =140m; D= 70m), the payback period would be almost 50 years!

7.6 TANK CAPACITY

From previous paragraph it became clear that in order to be economically attractive, the tank (with a piston of sand) should have height of at least 140 m and a diameter of 70 meter. In this paragraph, the affiliated tank capacity in Mega Watt (MW) per year will be illuminated. The following formula will be used:

$$\underbrace{E = \frac{1}{16}\cdot\pi\cdot D^2\cdot h^2\cdot\mu\cdot(\rho_{piston}-\rho_{water})\cdot g}_{\text{Energy in Joules [J]}} \quad\rightarrow\quad \underbrace{\sum E = \frac{1}{16}\cdot\pi\cdot D^2\cdot h^2\cdot\mu\cdot(\rho_{piston}-\rho_{water})\cdot g\cdot\langle z\rangle}_{\text{Energy in [MW] during a year}} \qquad \text{Eq. (7.4)}$$

Where:

- $\langle z\rangle = \frac{period}{JtokWh\cdot kWhtokW\cdot kWtoMW} = \frac{365\text{ days}}{3.6\cdot 10^6\cdot 3600\cdot 1000}$ is the conversion factor from J to MW during a year

In Figure 81, Eq. (7.4) has been plotted which shows the storage in MW during a year vs. the height of the container. Note that that only heights of 140 m and more have been considered as these are required for the economic feasibility of the structure.

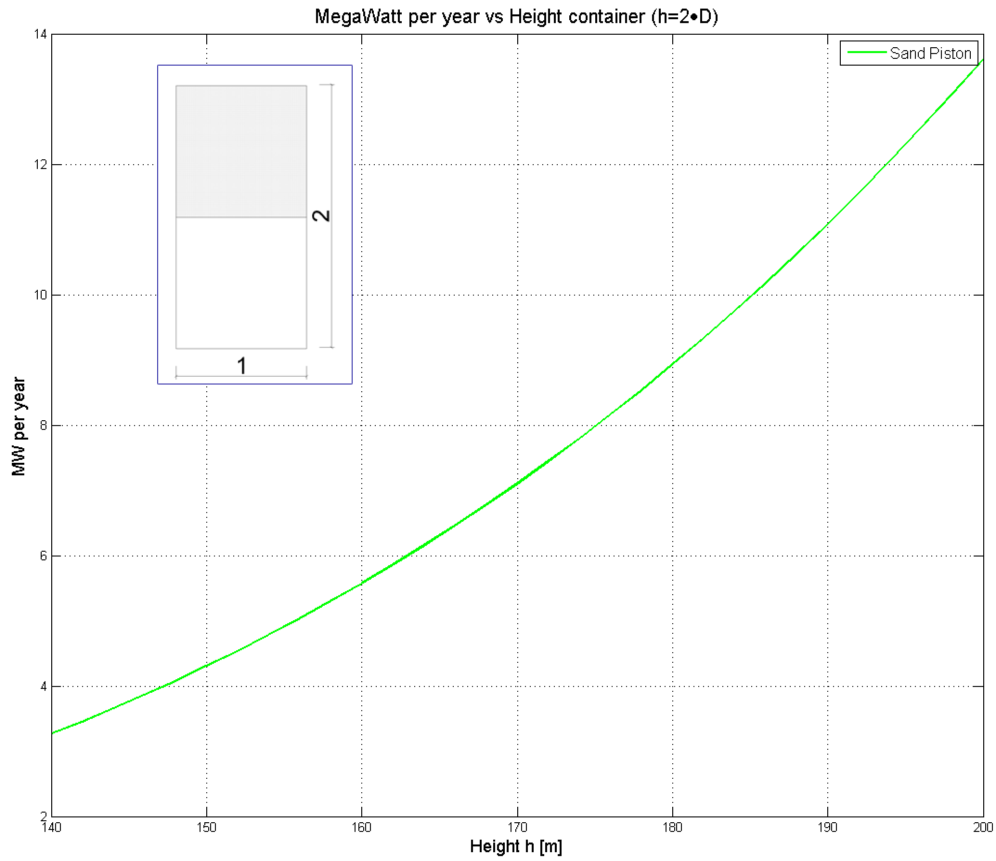


Figure 81 Capacity of the storage device

Would one design a tank with a height of 140 meter and a diameter of 70 meter, the amount of capacity of the tank would then be equal to 3.3 MW which could buffer for 3300 households (during a year). However as this storage device is being used for peak hour supply, this would be equal to:

$$\text{peak hour supply} = 3300\cdot\frac{24}{4} = 3300\cdot 6 \approx 20{,}000\text{ households}$$

In the Maasvlakte 2, the capacity of the upcoming windmills is up to 60 MW. This means that with these dimensions, $\frac{3.3}{60} \approx 5\%$ of wind power can be stored. Determining how much wind must be stored requires a probabilistic and statistical assessment which goes beyond the scope of this paper. Note that the tank has been optimized *economically*. As the dimensions have changed, the *technical* stability of the structure should be re-analyzed, this however, goes beyond the scope of this paper.

CHAPTER 8. CONCLUSIONS, RECOMMENDATIONS & EVALUATION

Contents

8.1 CONCLUSIONS

The main-question which has been formulated at the beginning of this paper is as following:

"*How can an energy storage device based on gravity power be technically realized in order to be economically competitive in the Dutch power grid?*"

With the aim of answering the main question, a design was made which has been analyzed both technically and economically. During the design of the structure, it was chosen that the structure would be built above ground and that the tank would be made of (prestressed) concrete. Initially, the tank had a height of 56 meter and a diameter of 28 meter including a piston which was made of lead.

The most important conclusions that can be drawn from this paper are as following:

- In order to become *economically competitive* in the Dutch power grid, the tank size had to be increased. It was found that the tank should be at least 140 m high having a diameter and a piston thickness which are both half the tank height (70 m). In addition the piston made of *lead* had to be changed to a piston made of *sand* in order to cut costs.
- A tank with these dimensions has an effective capacity for storing approximately 3.3 Mega Watt per year which is equivalent of supplying approximately 20,000 households during peak hours.
- In the Maasvlakte 2 (location of the storage device), the production capacity of the upcoming windmills is up to 60 MW. This means that with these dimensions approximately 5% of wind power can be stored annually.

- Increasing the size (height and/or diameter) of the tank is more effective than increasing the mass of the piston regarding *energy production* and *economic feasibility*. One should however keep in mind that increasing the height of the tank also increases the load on the wall which may put the *technical feasibility* of the structure at risk.
- Decreasing the height/diameter ratio of the tank will result in a more *economical attractive solution*. However, one should note that if the diameter is much larger than the height, piston jamming might pose a challenge.

Remarks regarding the conclusions:

- The ratio between the height and diameter of the tank is not a fixed value, this is just one of many possibilities.
- Determining the economic feasibility is primarily based on the material cost, and therefore the required minimum tank size is a rough estimation.
- The minimum tank size (for economic feasibility) corresponds to a payback period of almost 50 years.

8.2 RECOMMENDATIONS

This report has studied the economic and technical feasibility of a storage device based on gravity power. It followed that in order to make it feasible, the dimensions of the storage device had to be larger than what had been initially taken in this report. The most significant (design) recommendations are as follows:

- The minimum tank size (see conclusions) corresponds with a payback period of almost 50 years. Therefore one should construct a storage device with an even larger size in order to increase the *economic attractiveness*.
- The piston thickness should be half of the container height in order to *maximize energy storage*.
- One could do another iteration, having the acquired knowledge of this report or make different choices, for example, construct in steel.

Besides these recommendations, one could also do a follow-up study to the points listed in the grey area (see evaluation) or do it entirely different by going underground.

8.3 EVALUATION

In *part one* of this paper, it became clear why energy storage is essential, and why it becomes a necessity in the near future. In this part of the paper, a gravity storage device has been designed, analyzed and optimized in order to determine the economic and the technical feasibility of such a device. During the course of the technical part of this paper, multiple (design) decisions have been made, and every choice has a consequence. In this paragraph, the paper will be evaluated based on the choices that have been made.

The two most critical decisions that have been made in this paper, concerning the feasibility of the structure are the decision for the material of the piston (decision 1) and the decision for the material of the tank (decision 2) as can be seen in Figure 82. The amount of potential energy that can be stored is a function of height and mass. Focus had been put on the piston (mass) as this was a pioneer for hydropower storage, which resulted in a piston made of lead. The second major choice was to construct the tank in concrete. This set of choices basically determined the development of this paper as will be clear, shortly.

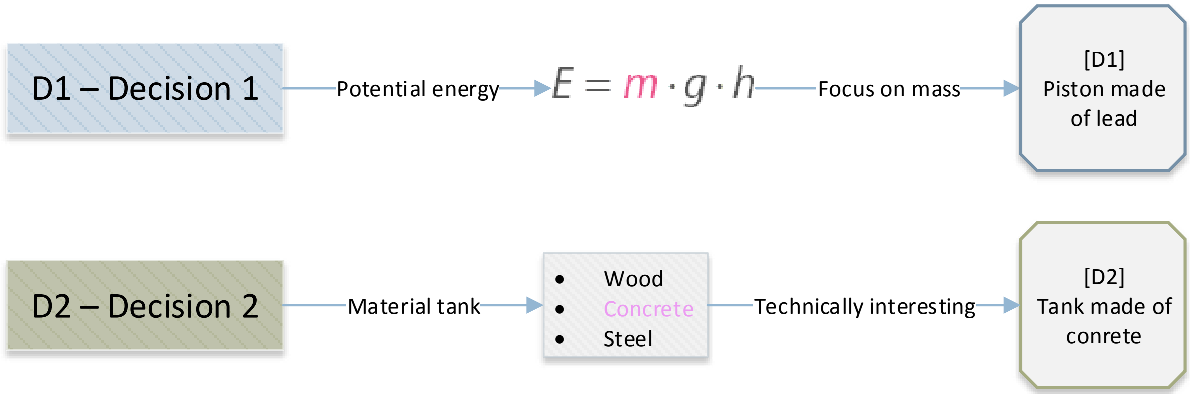


Figure 82 The two most critical decisions

In order to determine the buffer capacity and initial size of the tank [CHAPTER 5, p12], it was important to know what size was proven to be technically feasible, which was determined by the fact the tank was chosen to be made of prestressed concrete. The preliminary design was determined by the energy equation and boundary conditions, which both incorporate the material density of the piston. The consequence of these decisions on the buffer scale/preliminary design can be seen in Figure 83.

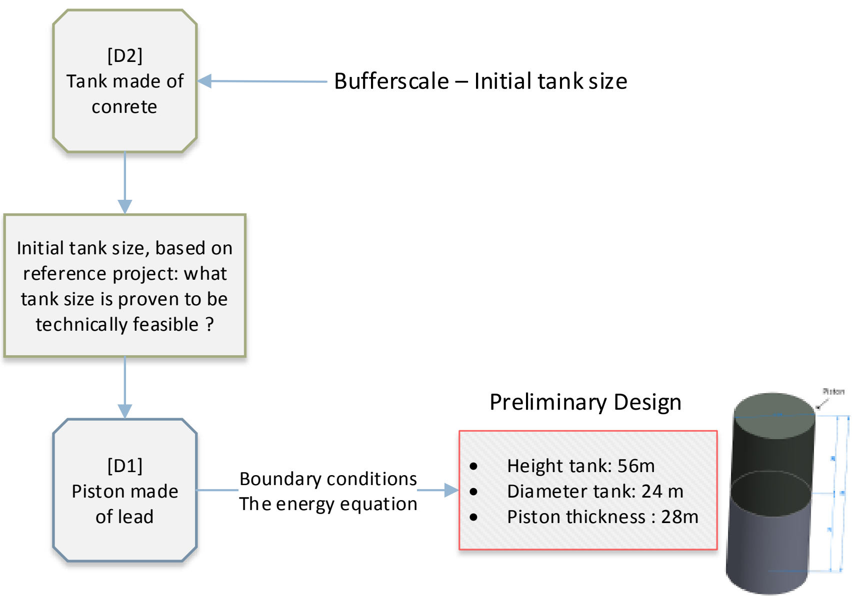


Figure 83 Buffer scale

In [CHAPTER 6, p28] the preliminary design has been analyzed, assessed and optimized with the aim of determining the technical and economic feasibility. This has been done by considering the *external stability*, *internal stability*, *construction*, and *cost* of the structure. Again these were primarily determined by the two most critical decisions. Figure 84 shows the consequences of these decisions on the technical design stage.

Legend	
O	No problem
	Not critical
X	Problem

Technical design stage	D1 (lead piston)	D2 (concrete tank)	D1+D2 (combination)
External Stability	O	O	O
Internal Stability			X
Construction	X	X	
Cost	X		

Figure 84 Consequences of the critical decisions

One of those consequences is that the mass induced large moments at the toe of the wall, which could not be effectively resisted by the wall with an initial thickness of 1 meter. It had been chosen to increase the wall thickness. The effect was that, the wall thickness (at the toe) had to be increased from 1 to 4 meters. The most technical challenge was the required smoothness of the wall which could not be met by concrete alone. In this paper, it has been assumed that this could be solved by using some sort of coating, whether this is indeed possible has not been researched any further. As far as the economics of the structure, it became clear that the price of lead was enormous: it took up 96% of all the material cost which led to an energy production cost of 1.13 €/kWh (during the course of 50 years).

An overview of the most significant consequences in the technical design stage, including the possible solutions, sub decisions and effects of each consequence, has been illustrated in Figure 85.

	(Possible) Problems	Possible solutions	Sub decision	effect
Internal stability + combination	Moment/shearforce due to mass too large for concrete wall (at the toe) Inconvenient placement reinforcement bars	Increase wall thickness Place more rows of reinforcement Vertically prestressing Change material piston/tank	Increase wall thickness	1m -> 4m
Construction + lead piston	Piston too heavy for maintenance	Use lead ore Change material piston	Use lead ore	-
Construction + Concrete tank	Surface smoothness concrete wall not sufficient	Coating Steel frame	out of scope	-
Cost + lead ore piston	Cost lead ore piston € 90 million -> 96 % of all material costs Energy Production cost 1.13 €/kWh (for only the material durin 50 years)	Change material piston		

Figure 85 Consequences technical design stage

In order to compete with other power plants, the energy production cost should be at most 0.09 €/kWh, which means that optimization was necessary. From all possible solutions, the one that occurred the most was a change of material piston (Figure 86). In order to make the structure economically (and technically) more attractive (read: feasible), it had been decided to change the piston material.

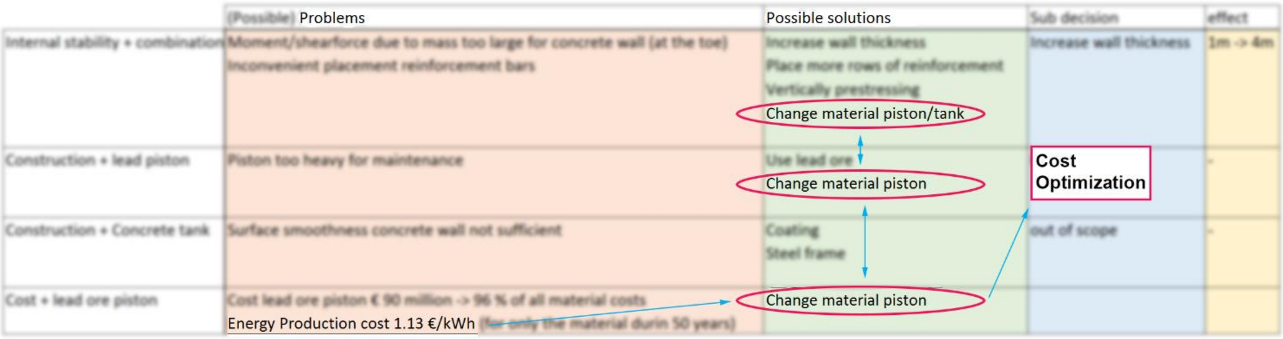


Figure 86 Change of material piston

The goal was to decrease the energy production cost (involving only the material cost) from 1.13 €/kWh to 0.04 €/kWh, which has been estimated to be sufficient to compete with other power plants. By changing the material of the piston into sand, the production cost had been decreased to 0.20 €/kWh which, unfortunately, was not sufficient. Therefore, it had been decided to (primarily) change the height of the tank. Changing the tank height results in more costs, but according to the optimal energy equation [5.3.2 The Optimal Energy equation, p23] the amount of energy increases quadratic. Finally, it was found that one of the potential options to make the structure conceivably feasible, was to increase the tank height to at least 140 m having a diameter of 70 m. The optimization process can be observed in Figure 87.

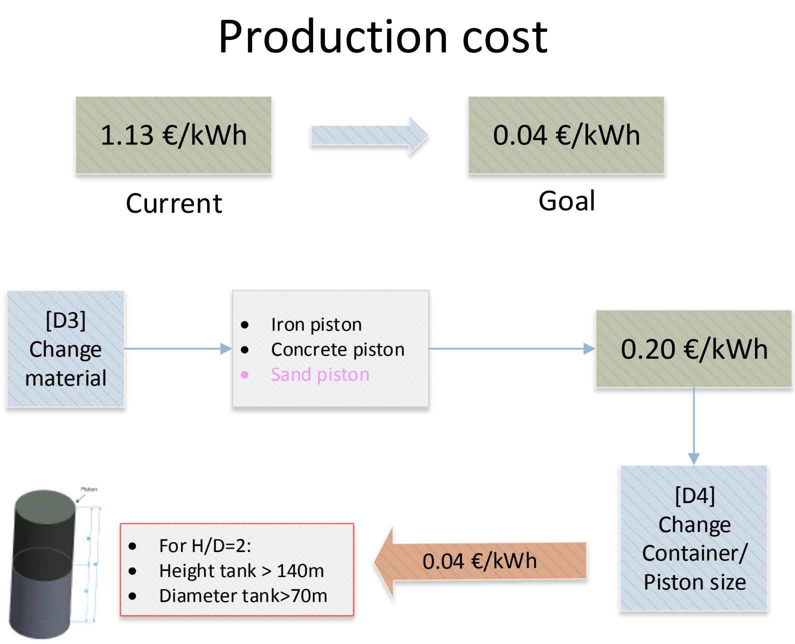


Figure 87 Optimization process

To conclude, by focusing on the mass of the piston and using prestressed concrete for the tank resulted in a multiple set of design challenges. Challenges that could have been avoided if different choices were made. If, for example, instead of focusing on the mass, focus had been put into the height of the structure, the preliminary design would have been more feasible already. Or if, for example, the cylindrical wall would have been made of steel, the internal stability would probably have had fewer problems. However, these decisions would probably lead to other sets of complications.

As far as decisions go, there are no bad decisions as the hardest thing about the road not taken is that you never know where it might have led. Who would have thought that by using a piston made of sand would lead to a more economically feasible structure? Or that the piston would induce extreme loading at the wall? The findings and results of this paper should be used as a starting point for the next iteration. Also if different decisions will be made, for example, going underground, this paper can be of great value as it considers multiple design aspects of a storage device that should be taken into account regardless the decisions made. This (part of the) paper can be considered a preliminary feasibility study to a storage device based on gravity power. It does not conclude the chapter of gravity power, but solely provides guidance and opportunity.

8.3.1 FINDINGS

The most important findings of this paper will be summed up in here.

- Gravity storage, is nothing more than power based on potential energy $E = mgh$
- The role of the piston acts as an extra pressure, which increases the amount of energy output. Therefore, the structure requires less volume in order to produce the same amount of energy as, for example, a conventional hydro pumped storage plant (having the same scale).
- Gravity storage can be applied practically everywhere, as it does not depend on natural height differences or strict soil conditions.
- The system efficiency of gravity storage device is rather low (60%)
- It is (economically) most beneficial to utilize the storage device for supplying peak load.
- The piston in the container might jam, if the diameter of the piston is much larger than its height.
- In order to produce the most amount of energy, the piston should be half of the height of the tank which results in the following *optimal energy equation*:

$$E = \left(\rho_{piston} - \rho_{water}\right) \cdot \frac{1}{16} \pi \cdot D^2 \cdot g \cdot h^2 \cdot \mu$$

Where:

- E is the amount of energy [J]
- ρ_{piston} is the density of the piston [kg/m³]
- ρ_{water} is the density of water [kg/m³]
- g is the gravitational acceleration [m/s²]
- D is the diameter of the piston [m]
- h is the height of the tank [m]
- μ is the efficiency of the storage device [-]

- From the optimal energy equation it follows that more focus should be put into the height and diameter of the tank rather than the mass of the piston.
- Large loading on the wall, will result in large tensile forces in the wall, for concrete this will be complicated to resist without prestressing.
- Horizontal prestressing is necessary, to ensure liquid tightness, and to make sure no outer deformation is possible that would allow for fluid leakage along the piston.
- The connection between the wall and the bottom slab, is a crucial element for the load distribution. In order to provide a longer lifetime, this connection is recommended to be monolithic.
- The requirement smoothness of the wall, for the considered hydraulic sealing in this paper, is 4 μm which cannot be met by concrete alone.
- The design of the pump/turbine, emphasize must be laid into pump head due to the losses in the water way
- Using a piston with lower density and lower price, decreases the *absolute* amount of energy storage, but increases the economic attractiveness of such a device.

8.3.2 GREY AREA

A report is never going to be complete, as there will always be more aspects to consider. This thesis has been written in a time-span of 6 to 8 months and therefore could not consider every aspect of the gravity storage device. It is important to, not only know what one can find in a report, but also what is missing in a report: the grey area.

The grey area for this paper (as far as known) can be summed to the following statements/questions:

- In this paper, water has been assumed as fill for the tank. What would happen if a different fluid was chosen or a gas?
- The efficiency of the storage device has been calculated at approximately 60%. The practical efficiency of a conventional pumped storage plant lies in the order of 70-80%. Where does this difference exactly come from?
- It has been stated that in order to maximum energy storage, the piston must be half of the height of the tank. Is this also the case, for minimizing the energy production cost?
- The ratio of the piston diameter and height has been based on the fact that the piston can get jammed in the container. This ratio has been determined theoretically. Can this theory be validated in practice?
- Would coating be enough to increase the smoothness of a concrete wall or must there be other measures?
- Only three basic connections for the wall/bottom slab has been considered. What would be the result if the wall and bottom slab were entirely joined like a water bottle? Would that not be more desirable regarding the moment distribution?
- In this paper it had been assumed that the storage device will be used every day: store energy during off-peak hours and generate energy during peak hours. But what happens, if there is no wind for a couple of days? How does this affect the energy production cost?
- In *part one* it became clear that wind energy is relatively unpredictable and highly variable which could result in large wind fluctuations. How does this impact the capability of storing wind energy? The generator, for example, requires a minimum startup voltage.
- It has been assumed that the RPT, could be designed for the required parameters. Based on these parameters, what would be the (true) efficiency the RPT? How large should the specific speed then become, and what diameter of the return pipe is necessary to provide this speed?
- In this paper, the goal energy production cost has been assumed to be of 0.04 €/kWh. This was estimated as this paper only considered the material cost. What would be the true energy production cost and how would the recommended height/diameter of the tank change, if one would also take into account the following aspects:

    - All other cost facets: maintenance, demolition, equipment cost, labor, risk/profit, overhead, etc.
    - The net present value
    - The efficiency losses due to a longer/shorter travel distance of the piston
    - The efficiency of the RPT which increases/decreases with larger/smaller output
    - The wall/foundation which can be designed slimmer with a smaller loading

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LIST OF FIGURES AND TABLES

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APPENDICES

Contents

APPENDIX A: PRINCIPLES OF FLUID MECHANICS

A.1 PRINCIPLES OF FLUID MECHANICS

The (fluid) mechanical aspects of hydro storage systems can be described with following three basic laws/principles:

- Conservation of mass
- Conservation of momentum (Newton's second law of motion)
- Conservation of energy

In order to explain these principles, *a system* must be defined. A system is a fixed quantity of matter, everything external to the system is separated by system boundary conditions which may be fixed, movable, real or imagined (Potter, 2006).

A.1.1 CONSERVATION OF MASS

The first law states that *mass* is indestructible; it can neither be created nor destroyed. Basically, it says that the mass of a system remains constant during a process and is expressed as $m_{sys} = \text{constant}$ or $\frac{dm_{sys}}{dt} = 0$.

For a volume (V) or a *system*, the *mass balance* in the rate form – or the *continuity equation* is expressed as:

$$\dot{m}_{in} - \dot{m}_{out} = \frac{dm_v}{dt} \qquad \text{Eq. (A.1)}$$

Where:

- $\dot{m}_{in}$ is the mass flow rate into a volume or system[kg/s]
- $\dot{m}_{out}$ is the mass flow rate out of a volume or system [kg/s]
- $\frac{dm_v}{dt}$ is the rate of change of mass within a volume or system

For a *steady flow* ($\frac{dm_{sys}}{dt} = 0$) this means that $\dot{m}_{in} = \dot{m}_{out}$ – or $\rho_1 V_1 A_1 = \rho_2 V_2 A_2$. The subscripts (1) and (2) refer to the place in the system, where number (1) is referred to a place near the entrance of the system and number (2) is referred to a place near the exit of a system.

A.1.2 CONSERVATION OF MOMENTUM

The second principle is the conservation of *momentum (mass x velocity)*. The conservation of momentum states the momentum of a system remains constant provided that *no external forces* are acting of the system. A more specific law based on this principle is *Newton's second law of motion*: The sum of all external forces acting on a system is equal to the time rate of change of linear momentum of the system – or:

$$F = m \cdot a = \frac{dmv_2 - dmv_1}{t} \qquad \text{Eq. (A.2)}$$

A.1.3 CONSERVATION OF ENERGY

The third law involves the conservation of energy. As stated many times before, energy cannot be created nor destroyed. It can only be transferred to other kinds of energy. The conservation of energy can be expressed by $E_{in} - E_{out} = \Delta E$. According to (Cengel, 2006), the energy content of a closed system can be changed by two mechanisms: *heat transfer* Q and *work transfer* W. In this paper only the latter is of importance. By introducing this aspect into the conservation equation the following is obtained:

$$\dot{W}_{net,in} = \frac{dE_{system}}{dt} \qquad \text{Eq. (A.3)}$$

Work transfer is energy transfer through distance, such as a rotating shaft or a rising piston, virtually any device that rotates/translates produces work. The rate of change of energy over a time interval is called *power* and denoted by $\dot{W}$. *Turbines* and *pumps* produce work, but also piston *produces* work. A system can contain multiple forms of work and the total work can be expressed as:

$$W_{total} = W_{shaft} + W_{pressure} + W_{viscous} + W_{other} \qquad \text{Eq. (A.4)}$$

All hydro storage devices contain a turbine and pump which means that in their energy balance equation W_{pump} and $W_{turbine}$ will be present. In addition, the gravity-power storage device includes a piston which also produces work (pressure) and therefore its energy equation includes W_{piston}.

In *part one* the term *energy losses* has been briefly explained, but for recollection: when one type of energy converts into another type of energy, for example, *work* is converted to *electricity* via a turbine, not all the energy is converted to electrical energy as some energy is *lost* because it is converted into *unwanted heat energy*. The energy equation therefore includes so-called *energy loss* E_{losses}.

A.2 BERNOULLI

Bernoulli is an important formula which is often used to describe hydraulic engineering problems and can be derived from the aforementioned principles/laws[1]; the Bernoulli equation is defined as follows:

$$\frac{p_1}{\rho g} + \frac{v_1^{\,2}}{2g} + z_1 = \frac{p_2}{\rho g} + \frac{v_2^{\,2}}{2g} + z_2 = \text{constant} \qquad \text{Eq. (A.5)}$$

The Bernoulli equation states that the sum of kinetic, potential and flow energies of a fluid particle is constant along a streamline during steady flow (Cengel, 2006) and is an important formula for describing the system of a hydro storage device.

The first term $\frac{p1}{\rho g}$ represents the *pressure head* from the flow energy, the second term $\frac{v_1^2}{2g}$ represents the *velocity head* from the kinetic energy and the last term z_1 represents the *elevation head* which comes from the potential energy. The sum of these terms represents the *total head* H (Figure A-1). Note that all these terms are in units of meters.

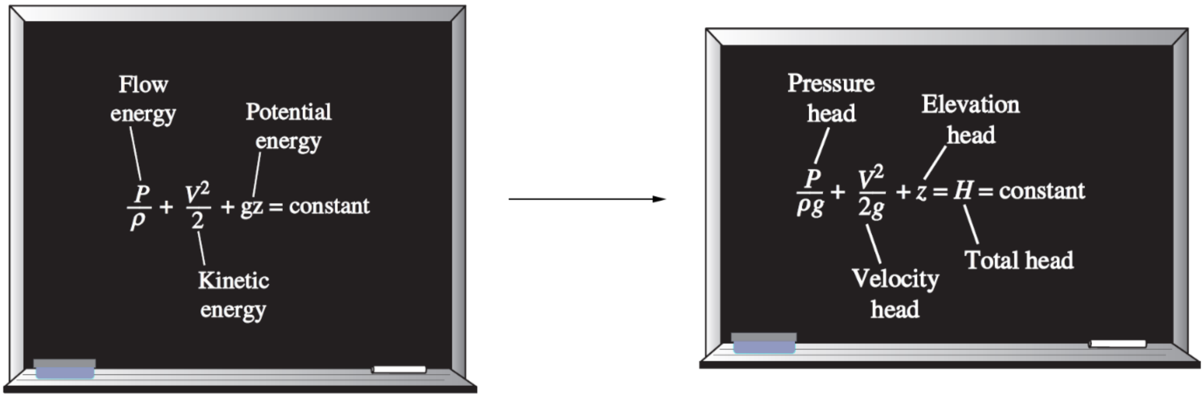


Figure A-1 Bernoulli equation (Cengel, 2006)

A.2.4 BERNOULLI EQUATION DERIVATION

There are some downsides though within this equation, in which the most important ones are enlightened. Firstly, it is only meant for *steady flow* which means it cannot be used where flow accelerates, changes in density or compressibility (in which the last two conditions do not matter for the hydro storage systems). Secondly, Bernoulli is not valid for *frictional effects*, this means that it cannot be applied to, for example, sudden contractions in a pipe. Thirdly, this equation is *not* valid in flow sections that involve a pump, turbine or other machine since such devices interrupt the streamline on which the Bernoulli equation is derived from. Simply put: Bernoulli is *not* valid in non-steady flow which involves accelerations and decelerations, meaning that Bernoulli cannot be used in parts of the system involving turbines and pumps.

On the bright side, the Bernoulli equation can still be applied to a flow section prior to or past a machine (assuming that the other restrictions of the equation are satisfied). In such cases, the Bernoulli constant changes from upstream to downstream. What follows the derivation of the Bernoulli equation.

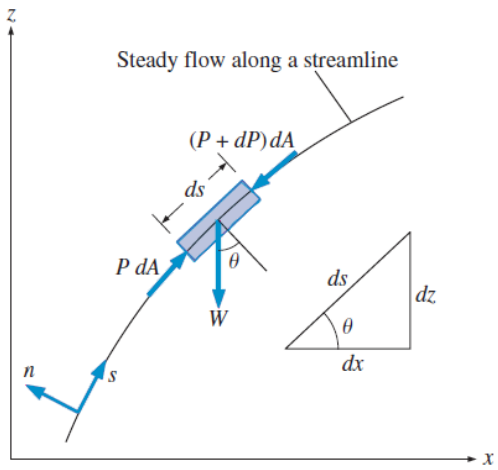


Figure A-2 fluid particle (Cengel, 2006)

Figure A-2, shows the forces on a fluid particle. When applying newton's law in *s* direction on a fluid particle along the streamline gives:

$$\sum F_s = m \cdot a_s \qquad \text{Eq. (A.6)}$$

The most significant forces on the particle (Figure A-2) are the pressure forces (on both sides) and the weight W of the particle. Therefore Eq. (A.6) becomes:

$$P\ dA-(P+dP)dA-W\sin(\theta)=mv\frac{dv}{ds} \qquad \text{Eq. (A.7)}$$

Where:

- θ is the angle between the normal of the streamline and the vertical z −axis $\frac{dz}{ds}=\sin\theta$
- $m=\rho V=\rho\ dA\ ds$ which is the mass [kg]
- $W=mg=\rho g\ dA\ ds$ which is the weight of the fluid particle [N]

Substituting gives:

$$\left.\begin{array}{l} m=\rho V=\rho\ dA\ ds \\ W=mg=\rho g\ dA\ ds \end{array}\right\}\rightarrow -dP\ dA-\rho g\ dA\ ds\frac{dz}{ds}=\rho\ dA\ ds\ v\frac{dv}{ds} \qquad \text{Eq. (A.8)}$$

Or

$$-dP-\rho g\cdot dz=\rho v\cdot dv \qquad \text{Eq. (A.9)}$$

As $vdv=\frac{1}{2}d\left(v^2\right)$, Eq. (A.9) can be written as:

$$\frac{dP}{\rho}=\frac{1}{2}d\left(v^2\right)+g\cdot dz=0 \qquad \text{Eq. (A.10)}$$

Integrating Eq. 7.8 and dividing by g gives (for a steady, incompressible flow along a streamline):

$$\frac{P}{\rho g}+\frac{v^2}{2g}+z=\text{constant} \qquad \text{Eq. (A.11)}$$

Which is the famous **Bernoulli** equation.

A.2.5 HYDRAULIC GRADE LINE/ENERGY GRADE LINE

The total head H may differ along the stream line, due to external influences, and can be distinguished into the following lines:

- *Hydraulic grade line (HGL)* which consists of the pressure and elevation head $\frac{P}{\rho g}+z$
- *Energy grade line (EGL)* which consists of the velocity, pressure and elevation head $\frac{P}{\rho g}+\frac{v^2}{2g}+z$

The difference in these hydraulic gradient lines is the velocity head $\frac{v^2}{2g}$ as can be seen in Figure A-3.

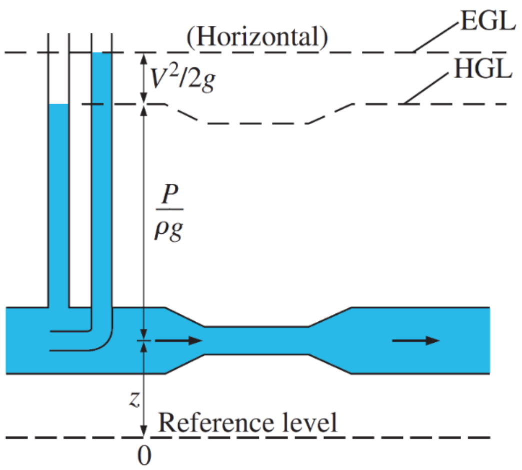


Figure A-3 Hydraulic gradient lines (Cengel, 2006)

The hydraulic gradient line may change due to external influences. Each hydro storage concept includes a *pump* and *turbine* which are in fact external influences. A pump is an *input* of energy in the system, which means that the EGL/HGL *increases*. A turbine *extract* energy from the system and therefore acts as an *output* on the system, the effect on the EGL/HGL is that these lines *decreases* as can be seen in Figure A-4. The reason to use these lines is to visually describe the system, which makes it often easier to understand. Note that the notation $\dot{W}$ stands for power [joule/seconds].

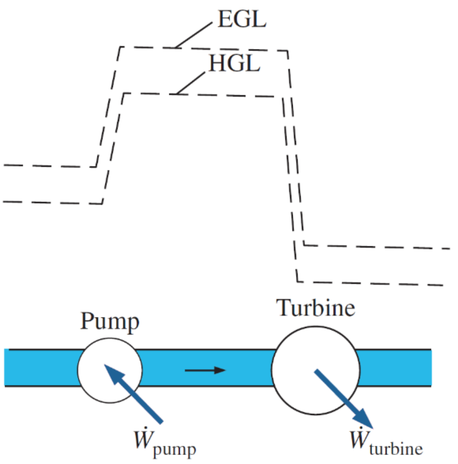


Figure A-4 EGL/HGL increases/decreases due to a pump/turbine

A.3 HYDRO STORAGE ANALYSIS

A.3.6 THE ENERGY EQUATION: PHS & UPHS

Applying the principle of energy conservation the following energy (power) balance for a PHS & UPHS can be described with:

$$P_{flow,in} + \dot{W}_{mechanical;pump,in} = P_{flow,out} + \dot{W}_{mechanical;turbine,out} + \dot{E}_{mechanical;losses} \qquad \text{Eq. (A.12)}$$

Due to the presence of a turbine/pump, *work transfer* is to be expected. In addition *energy losses* are expected. When applying Bernoulli the following balance can be acquired:

$$\sum_{in} \rho g Q + \left(\frac{P_1}{\rho g} + \frac{v_1^2}{2g} + z_1\right) + \dot{W}_{pump} = \sum_{out} \rho g Q + \left(\frac{P_2}{\rho g} + \frac{v_2^2}{2g} + z_2\right) + \dot{W}_{turbine} + \dot{E}_{losses} \qquad \text{Eq. (A.13)}$$

Note that $\rho Q = \dot{m}$. Figure A-5 illustrates this energy power balance.

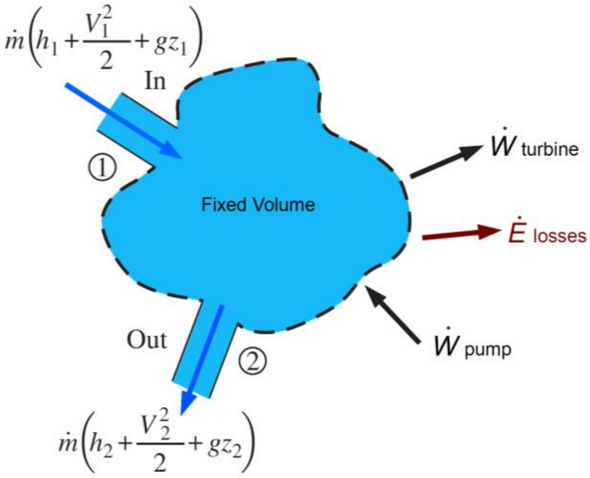


Figure A-5 Energy balance for PHS and UPHS

The following example explains how the system works in fluid mechanical perspective. This example considers the *power generation mode* which means that water is flowing from higher elevated reservoir to the lower elevated reservoir and refers to Figure A-6.

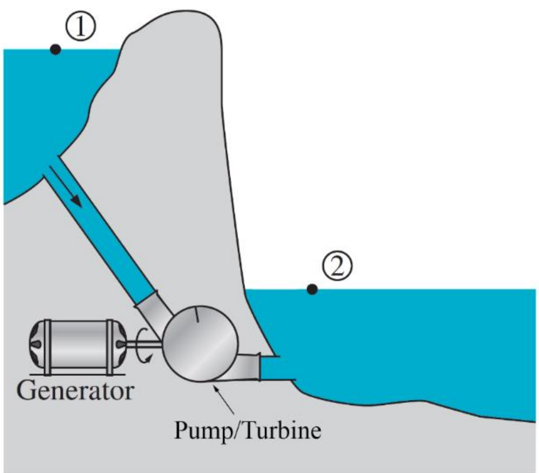


Figure A-6 PHS: Hydro storage

Assumptions: it is assumed that the flow is steady and the discharge Q and water levels remains constant.

The elevation z1 and z2 are at position (1) and (2) respectively; the reference level is taken at point (2), which means that z2 = 0. As both points are at the top of the reservoir both P_1 and P_2 have atmospheric pressure (=0). Also both velocity heads are 0 as the water levels at the reservoirs remain constant. Which means that the power generated is only due to (potential) elevation height. In the power generation mode, the pump is inactive and can be left out of the equation.

With the abovementioned information, Eq. (A.13) can be simplified to:

$$\sum_{in} \rho g Q \cdot \left(\cancel{\frac{P_1}{\rho g}} + \cancel{\frac{v_1^2}{2g}} + z_1 \right) + \cancel{\dot{W}_{pump}} = \sum_{out} \rho g Q \cdot \left(\cancel{\frac{P_2}{\rho g}} + \cancel{\frac{v_2^2}{2g}} + \underset{0}{z_2} \right) + \dot{W}_{turbine} + \dot{E}_{losses}$$

$$Power = \mu \rho g h H_{turbine} \qquad \text{Eq. (A.14)}$$

Note 1: $\dot{W}_{turbine}$ has been denoted as $Power$; note 2: H is coming from $z1 - z2$ (the elevation height); note 3: $\dot{E}_{losses}$ has been integrated into the equations as μ which, instead of losses representing the efficiency.

Eq. (A.14) Has not been written in the form where it indicates that the generated power is nothing else than power due to potential energy ($E = m \cdot g \cdot z$) as was clear from the *potential energy* section. In order to write it in this form the following can be done:

As $\rho Q = \dot{m}$, the equation can be written as $P = \mu \dot{m} g H$. The potential energy formula follows by replacing $\dot{m}$ with m resulting in

$$Power = \mu \rho g h H_{turbine} \rightarrow \{pQ = \dot{m}\} \rightarrow E = \mu m g H \qquad \text{Eq. (A.15)}$$

A.3.7 THE ENERGY EQUATION: GRAVITY POWER

Due to piston an additional component is added to the power (energy) balance:

$$P_{flow,in} + \dot{W}_{mechanical;pump,in} + \dot{W}_{mechanical:piston,in}$$
$$=$$
$$P_{flow,out} + \dot{W}_{mechanical;turbine,out} + \dot{E}_{mechanical;losses} + \dot{W}_{mechanical:\,piston,out}$$

Or

$$\sum_{in} \rho g Q \cdot H_1 + \dot{W}_{pump} + \sum_{in} \dot{W}_{piston} = \sum_{out} \rho g Q \cdot H_2 + \dot{W}_{turbine} + \sum_{out} \dot{W}_{piston} + \dot{E}_{losses} \qquad \text{Eq. (A.16)}$$

Note that the piston has been added to both sides of the energy balance, as the piston puts in (pressure) energy in the system and extracts energy out of the system in generation- and storage mode respectively.

The following example shows that power generation is due to potential energy; it involves water that is *about to* flow counter clockwise (*generation mode)* which considers the following components: piston, water head, and the turbine. The reference line and both reference point's z1 & z2 can be seen in Figure A-7.

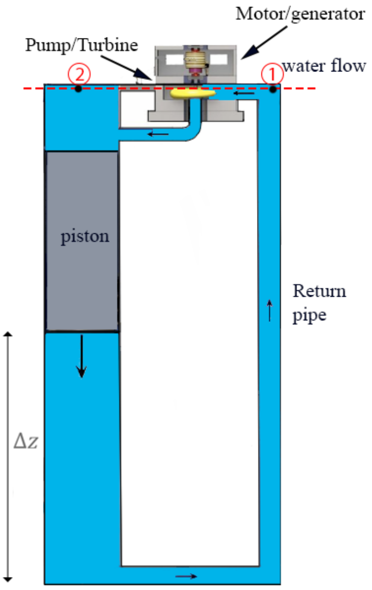


Figure A-7 Gravity power

Remarks: water is not flowing and it involves a static situation

In this situation (generation mode) Eq. (A.16) can be written as:

$$\sum_{in} \dot{m}_{water} g \cdot H_1 + \sum_{in} \dot{W}_{piston} = \sum_{out} \dot{m}_{water} g \cdot H_2 + \dot{W}_{turbine} + \dot{E}_{losses}$$

→

$$\dot{W}_{turbine} = \dot{W}_{piston} - \rho g Q \cdot (H_1 - H_2) - \dot{E}_{losses} \qquad \text{Eq. (A.17)}$$

As the water is not flowing, the velocity head is equal to 0. Both reference points are at the same height meaning that the elevation head (1) and elevation head (2) cancel out each other. The only difference between those reference points is the pressure height, which is equal to $P_1 = \rho_{water} g \Delta z$ at point (1) and zero in point (2) meaning that:

$$(H_1 - H_2) = \left(\frac{P_1}{\rho g} + \cancel{\frac{v_1^2}{2g}} + \cancel{z_1}\right) - \left(\cancel{\frac{P_2}{\rho g}} + \cancel{\frac{v_2^2}{2g}} + \cancel{z_2}\right) = \Delta z \qquad \text{Eq. (A.18)}$$

From the *work equation* it follows that:

$$W_{piston} = F \cdot ds = mg\Delta z \longrightarrow \dot{W}_{piston} = m_{piston} \cdot g \cdot \Delta z \qquad \text{Eq. (A.19)}$$

Substituting Eq. (A.18) & Eq. (A.19) in Eq. (A.16) and rewriting the losses as a coefficient μ in the formula, the following power formula for the gravity storage device is acquired:

$$Power = \mu \cdot \dot{m}_{rel} \cdot g \cdot \Delta z \tag{A.20}$$

Where

- $\dot{m}_{rel} = \dot{m}_{piston} - \dot{m}_{water}$

Rewriting gives:

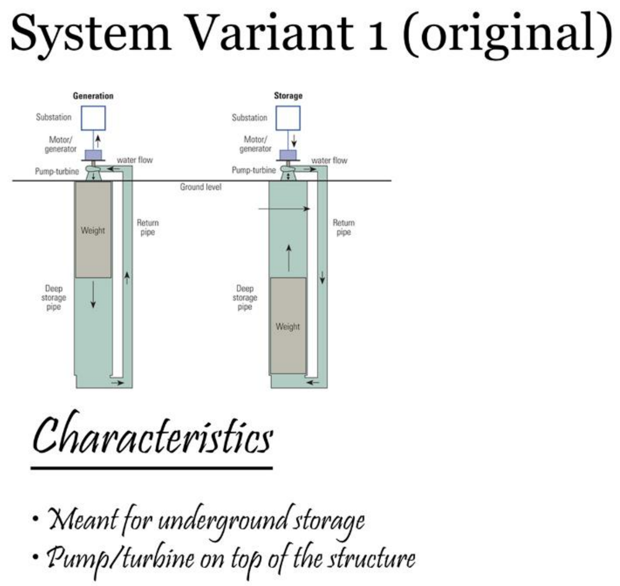
$$E = \mu \cdot m_{rel} \cdot g \cdot \Delta z \tag{A.21}$$

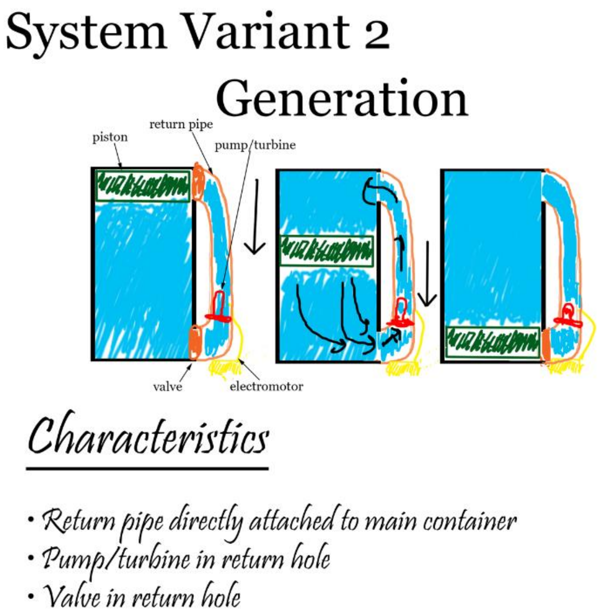
In other words, also gravity power is nothing more than power from potential energy.

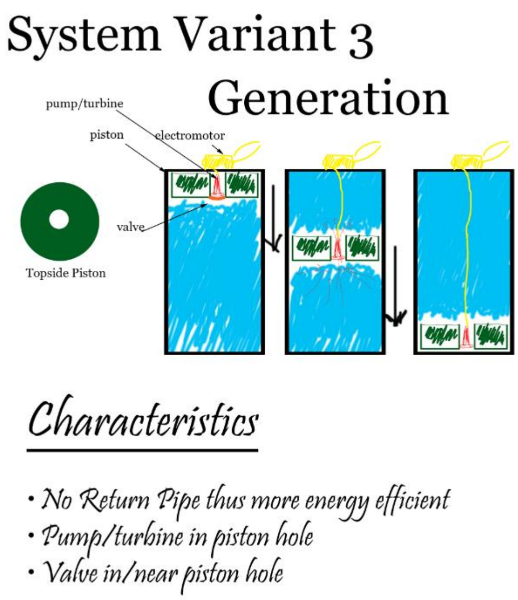
APPENDIX B: DESIGN SKETCHES/IDEAS

In this appendix, some pre-preliminary sketches design have been made prior the preliminary design. This was done in the brainstorm phase.

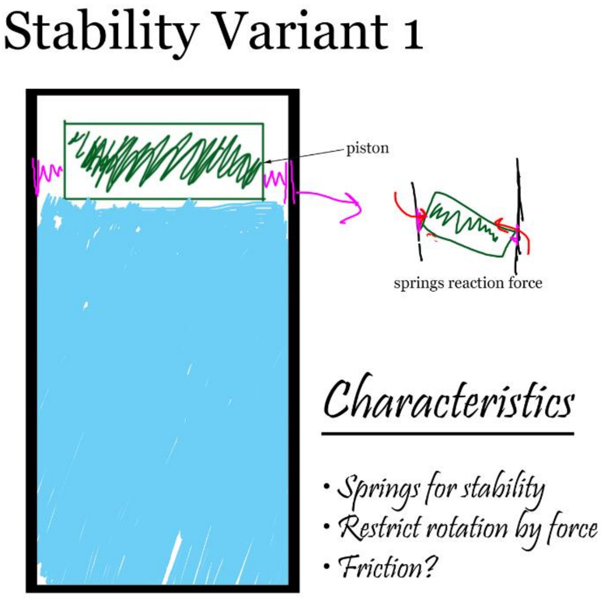
B.1 SYSTEM SKETCHES

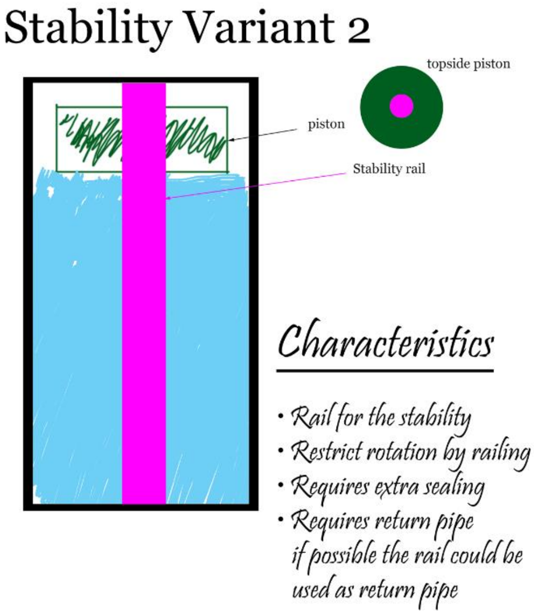


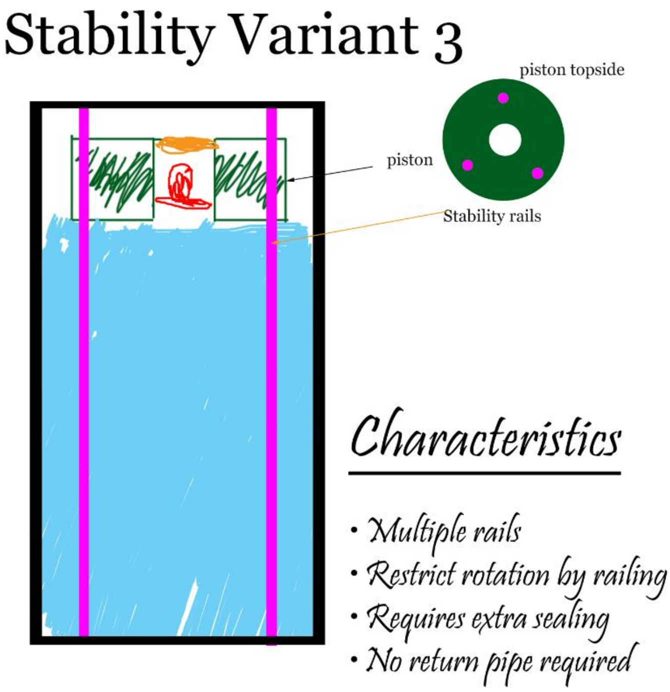




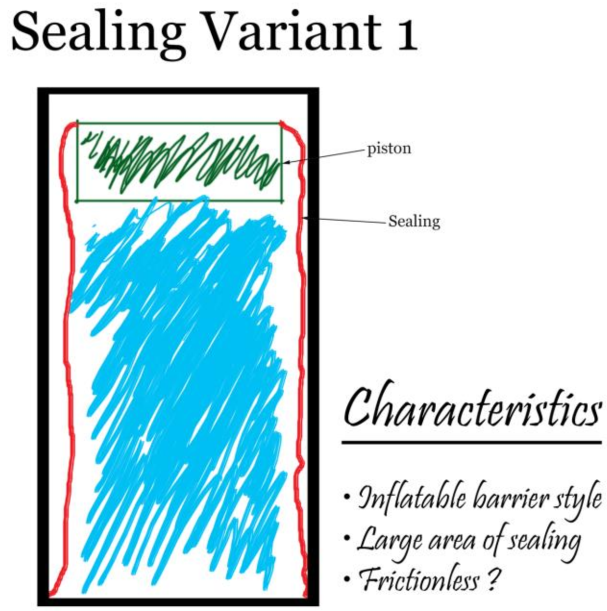
B.2 STABILITY SKETCHES

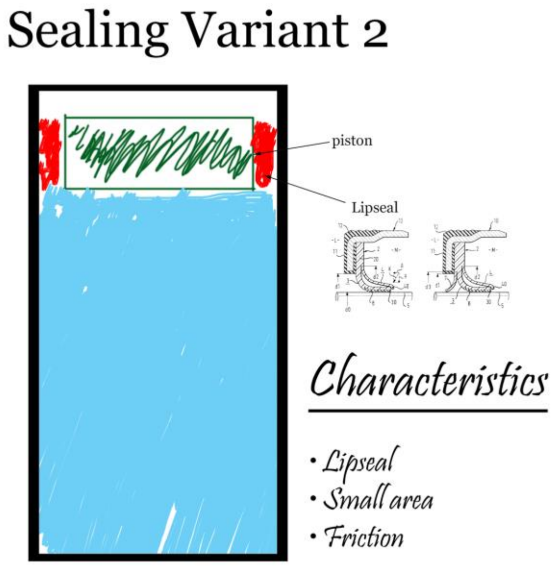






B.3 SEALING SKETCHES





APPENDIX C: THE ENERGY EQUATION

C.1 INITIAL ENERGY EQUATION

From [Appendix A: Principles of fluid mechanics, p105], it became clear that the energy storage of a gravity storage device, could be described with the following equation:

$$E = m_{rel} \cdot g \cdot z \cdot \mu \qquad \text{Eq. (C.1)}$$

According to Eq. (C.1), the amount of energy E (in joules) that can be stored in the container, depends on the relative mass m_{rel} which is the mass of the piston relative to the water, the gravity g, the elevation height z and the efficiency μ. In this appendix, the energy equation will be rewritten in terms of dimensions of a gravity power storage tank.

In order to rewrite the energy equation in terms of dimensions of the tank and piston, the relative mass m_{rel} must be further elaborated. The relative mass depends on the shape of the main container (and therefor the shape of the piston) and will be discussed shortly after determining the shape the tank.

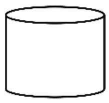
C.1.1 SHAPE MAIN CONTAINER

A size or volume can be defined by the multiplication of an area times a length or height:

$$V_{container} = A \cdot h \qquad \text{Eq. (C.2)}$$

An area could have the following shapes:

- square
- rectangle
- triangle
- circle



Most of the storage (compressed gas) containers are of cylindrical shape, in which the area is a circle as can be perceived from Figure C-1.

Figure C-1 Cylinder

A circle shaped area has several advantages over the other shapes:

- **No corners.** A round shape has no corners, meanwhile a rectangle, for instance, has corners which is often the weakest spot. Also corners make it technically more challenging for sealing purposes
- **Strength.** The least material is required for a given strength and is equally strong among both axes.

The disadvantage of a round shape, is that these devices are often more difficult to build than, for example, a block which has a square or rectangle area. Nevertheless, in this paper, the main container will be of cylindrical shape.

The volume or size V of the cylindrical container can be described with (Figure C-2):

$$V_{container} = A \cdot h = \frac{1}{4}\pi D^2 \cdot (z+d)$$ Eq. (C.3)

Where:

- h is the height of the container [m]
  - $h = z + d$
    - z is the potential height [m]
    - d is the piston thickness [m]
- A is the area is [m^2]
  - $A = \frac{1}{4}\pi D^2$
    - D is the diameter [m]
    - π is a constant 3.1415 [-]

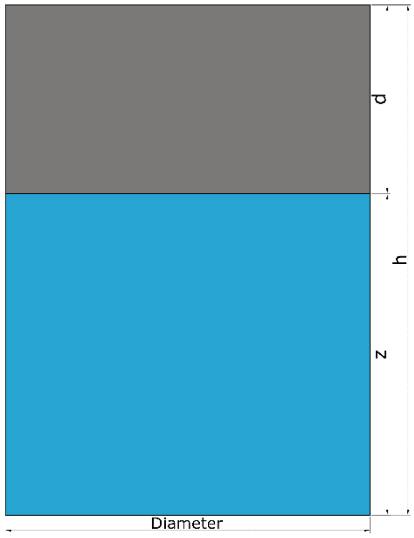


Figure C-2 Container size specifics

C.1.2 THE RELATIVE MASS m_{rel}

The greater the mass, the more potential energy can be stored. In order to explain the *relative* mass, the density ρ must be introduced. The density, denoted with the Greek symbol ρ, is defined as its mass per unit volume and is typically used to characterize the mass of a fluid system (D. Young, 2011). In other words: multiplying a density ρ with a volume V would result in a mass. In formula form:

$$m = \rho \cdot V$$ Eq. (C.4)

The *relative mass* is in this case defined as the mass of the piston compared to that of the water. The relative mass depends on: 1) the relative specific material density ρ_{rel} which is the difference between the density material of the piston and the water, and 2) the volume of the piston V_{piston} which mainly depends on the diameter D and piston thickness d. Note that for simplification, the diameter D of the piston has been taken equal to that of the container.

$$m_{rel} = \rho_{rel} \cdot V_{piston}$$ Eq. (C.5)

Where:

- $\rho_{rel} = \rho_{piston} - \rho_{water}$ [kg/m^3]
- $V_{piston} = A \cdot d$ [m^3]
  - $A = \frac{1}{4}\pi D^2$ [m^2]
  - d the piston thickness [m]

Or

$$m_{rel} = (\rho_{piston} - \rho_{water}) \cdot \frac{1}{4}\pi D^2 \cdot d$$ Eq. (C.6)

Now that the relative mass has been expressed in terms of dimensions of the container/piston, the energy equation of the tank can be derived.

C.2 THE ENERGY EQUATION (GPHS)

Combining Eq. (C.1) and Eq. (C.6) the following energy equation is acquired:

$$E = (\rho_{piston} - \rho_{water}) \cdot \frac{1}{4}\pi D^2 \cdot d \cdot g \cdot z \cdot \mu \qquad \text{Eq. (C.7)}$$

Where:

- E is the total amount of energy that can be stored [J]
- D is the diameter of the storage device [m]
- d is the thickness/height of the piston [m]
- g is the gravitational acceleration [m/s^2]
- z is the potential elevation height [m]
- μ is the system efficiency [-]
- π is a constant of 3.1415 [-]
- ρ_{piston} is the density of the piston [kg/m^3]
- ρ_{water} is the density of water [kg/m^3]

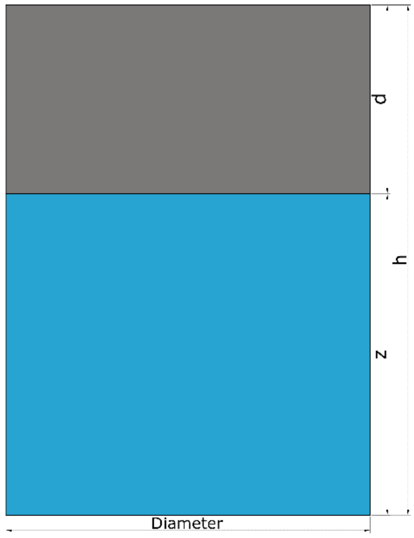


Figure C-3 Tank dimensions

APPENDIX D: EFFICIENCY

The efficiency μ of the system is probably one of the most important parameter: it determines how much energy is lost. The following losses, according to Figure D-1, can be expected:

- Conversion losses
- Local losses
- External losses

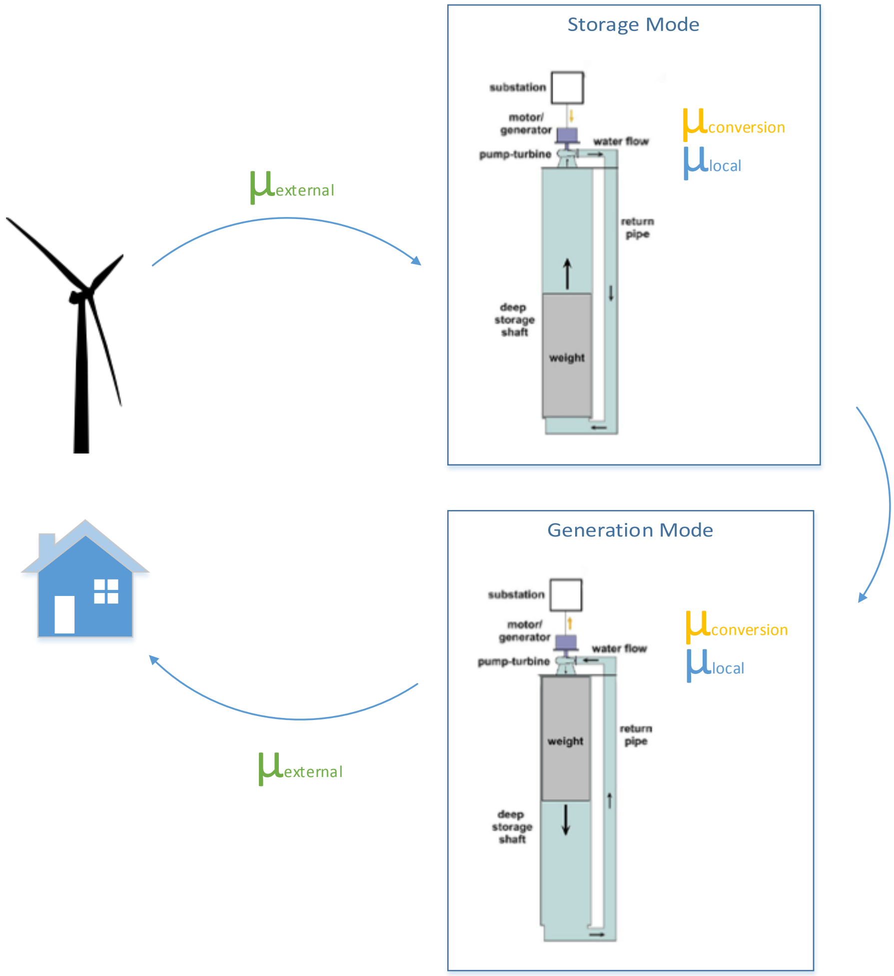


Figure D-1 System Efficiency

Conversion efficiency

The *conversion efficiency* depends the energy losses during conversions of one kind of energy to another kind and has been discussed in [4.4 Hydro storage analysis, p6] and is shown in Table D-1. The components subject to these conversions will be discussed briefly.

Table D-1 Quick overview energy conversion

Storage mode $\mu_{conversion;storage}$	Generation mode $\mu_{conversion;generation}$
Wind mill → Electricity → motor → pump → flow	Flow → turbine → generator → electricity → transformer (from DC to AC) → homes

One of those components is the pump/turbine which is going to be a hydraulic reversible pump/turbine, these turbines can be of quit high efficiency up to 95% (Huggins, 2010). The Motor/generator in general have high efficiencies of 90%/85% (Demirel, 2012). Before the electricity reaches the harbor, it (might) go through so-called *transformers* which converts *electrical energy* to *electrical energy* (from *DC* to *AC* as is explained *Part One*. The efficiency of a transformer can be up to 99% (Energy-Efficient-Distribution-Transformers, n.d.). The estimated component efficiencies have been stated in Table D-2

Table D-2 Component efficiencies

Component	Efficiency
Turbine	90%
Generator	85%
Transformer	98%
Motor	90%
Pump	90%

Now that all the component efficiencies are known, the total (roundabout) conversion efficiency can be calculated as follows:

$$\underbrace{\begin{aligned}\mu_{conversion-storage} &= \mu_{motor} \cdot \mu_{pump} = 0.9 \cdot 0.9 = 0.81 \\ \mu_{conversion-generation} &= \mu_{turbine} \cdot \mu_{generator} \cdot \mu_{transformer} = 0.9 \cdot 0.85 \cdot 0.98\end{aligned}}$$

$$\downarrow$$

$$\mathbf{\mu_{conversion}} = \mu_{conversion-storage} \cdot \mu_{conversion-generation} = 0.81 \cdot 0.75 \approx 0.61$$

Local efficiency

Local efficiency involve losses due contraction/expansions in the system and friction losses due to, for example, turbulent flow. For now the total local losses (for both during storage- and generation mode) is assumed to be $\mu_{local} = 0.95$.

External efficiency

Aside from local- and conversion efficiency, there is also a so-called *external efficiency*. External losses involve transmission losses through cables. The external losses is assumed to be (for both receiving and supplying electricity) approximately $\mu_{external} = 0.98$.

Total (system) efficiency

The *total losses* or *system efficiency* are defined by the aforementioned losses. The total system efficiency can be calculated according the following formula:

$$\mu_{system} = \mu_{conversion} \cdot \mu_{local} \cdot \mu_{external} \qquad \text{Eq. (D.1)}$$

Following from Eq. (D.1) follows that the total system efficiency $\mu_{system} = 0.61 \cdot 0.95 \cdot 0.98 \approx 0.57$
The efficiencies have been summarized in Table D-3.

Table D-3 Summary efficiency

Efficiency	Aspect	Efficiency parameter	losses	Efficiency
Conversion		$\mu_{conversion}$	Conversion	0.61
	Pump/Turbine	$\mu_{pump/turbine}$	*mechanical energy* to *kinetic energy (vice versa)*	0.90
	Motor/Generator	$\mu_{motor/generator}$	*electrical energy* to *mechanical energy (vice versa)*	0.90/0.85
	Transformer	$\mu_{transformer}$	*Electrical energy to electrical energy*	0.98
Local		μ_{local}	Friction	0.95
External		$\mu_{external}$	Transmission	0.98
System				**0.57**

APPENDIX E: SOIL PROPERTIES

Figure E-1 shows a probe curve graph originating from the Maasvlakte.

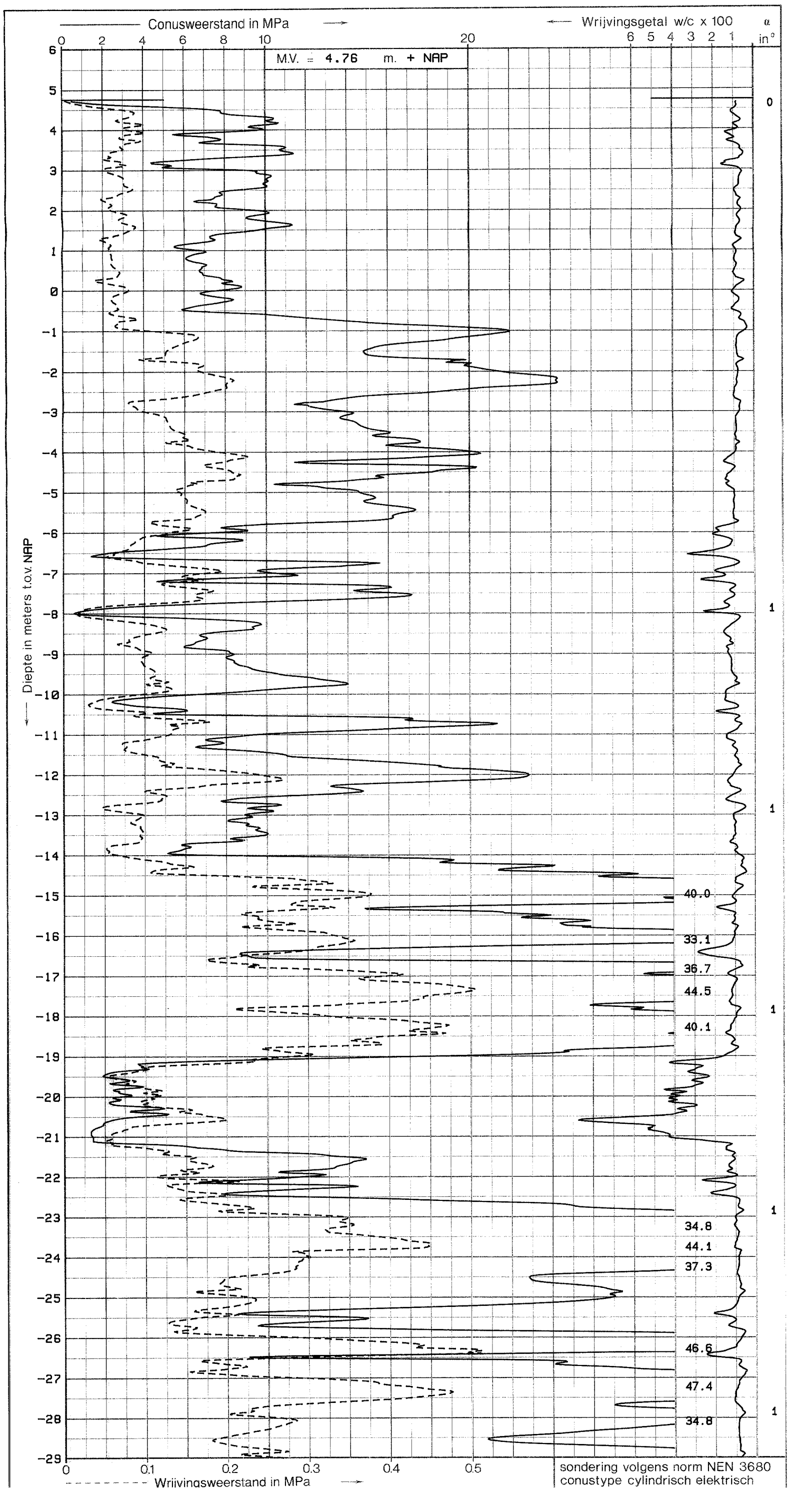


Figure E-1 Probe curve Maasvlakte (ondergrondgegevens, n.d.)

APPENDIX F: EXTERNAL STABILITY

F.1 GENERAL INFORMATION

F.1.1 LIMIT STATES & LOAD FACTORS

During designing some safety factors will be used. These *safety* or *load* factors depend on the *limit state*. Two types of limit states can be distinguished:

- The service limit state
- The ultimate limit state

The serviceability limit state (S.L.S.) is the point where a structure can no longer be used for its intended purpose but would still be structurally sound such as bending of a book shelf. The ultimate limit state (U.L.S.) is reached when the applied stresses actually exceed the strength of the structure or structural elements causing it to fail or collapse (SBDW1, n.d.).

In U.L.S. a load has a different (read: higher) design value which is governed by so-called *load factors*. In formula form:

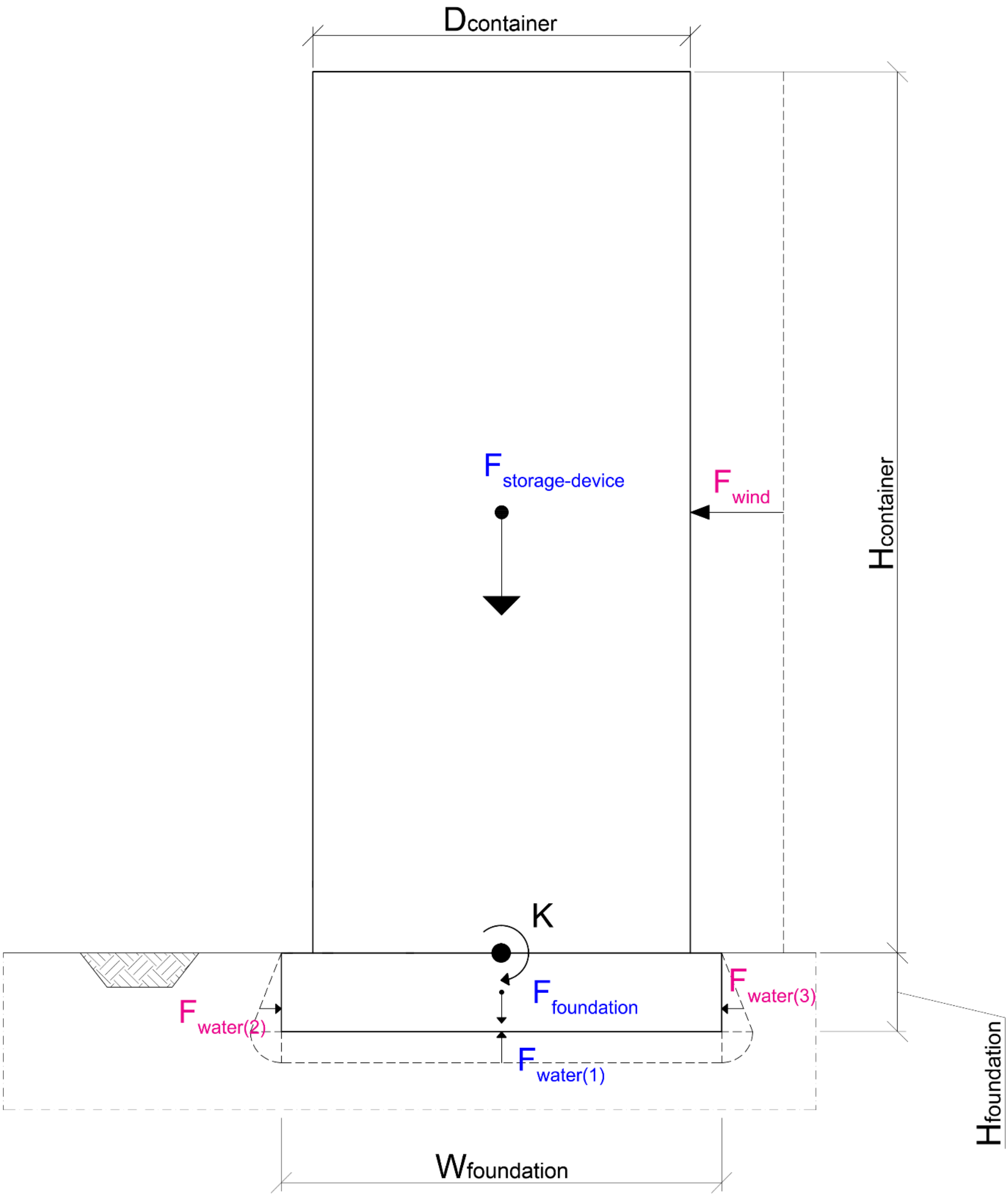
$$U.L.S = \underbrace{\gamma_x}_{\text{load factor}} \cdot S.L.S.$$

In this paper, the following load factors are used:

Table F-1 Load factors

Load	Factor [-]
General	
Static loads	1.2
Dynamic loads	1.5
Specific	
(internal) Water load	1.35
(internal) Piston Load	1.35
Prestressing Load	1.4

F.2 OVERTURNING STABILITY



For the overturning stability the following check must be met:

$$|\sigma_{horizontal}| \ll |\sigma_{vertical}| \qquad \text{Eq. (F.1)}$$

The overturning stability will be determined at point "K".

$$\sum F_{vertical} = F_{piston} + F_{water} + F_{wall} + F_{foundation} + F_{water(1)} = 1.5 \cdot 10^6 + 1.25 \cdot 10^5 + 1.18 \cdot 10^5 + 5.88 \cdot 10^4 \approx 1.8 \cdot 10^6 \text{ kN}$$

The stress of the structure on the soil (assuming an infinite stiff foundation), is equal to:

$$\sigma_{vertical} = \frac{\sum F_{vertical} \cdot \gamma_{1.2}}{A_{foundation}} = \frac{1.8 \cdot 10^6 \cdot 1.2}{28 \cdot 28} \approx -2.8 \text{ MPa}$$

Note that the '-' sign indicates compression.

The total moment at point "K" is:

$$\sum M_k = \sum F_{horizontal} \cdot \left(\frac{H_{foundation}}{2} \right) = F_{wind} \cdot \left(\frac{56}{2} \right) = 2688 \cdot \left(\frac{56}{2} \right) = 75264 \text{ kNm}$$

The resistance moment is equal to:

$$W_r = \frac{1}{6} \cdot W_{foundation} \cdot L^2_{foundation} = \frac{1}{6} \cdot 28 \cdot 28^2 = 3658 \text{ m}^4$$

The stress on the subsoil due to the wind load becomes:

$$\sigma_{horizontal} = \frac{\sum M_k}{W_r} = \frac{75264}{3658} = 20.5 \text{ kN/m}^2$$

The absolute value of the stress due to wind is so much smaller than the absolute value of the weight of the storage device, that overturning should not be a problem. In sum:

$$\left|\sigma_{horizontal}\right| \ll \left|\sigma_{vertical}\right| \rightarrow \text{ Overturning condition satisfied!}$$

F.3 BEARING CAPACITY OF THE SUBSOIL

As the subsoil is of relatively good quality (sand), a shallow foundation will be used to support the storage device. The deeper the shallow foundation is situated, the more resistance the soil can offer. Here, a rough calculation is done to investigate the required depth of the shallow foundation for which it is able to support the structure and will be done by the following equation:

$$\frac{(q_{ult})}{\gamma_{[3]}} \geq q_{subsoil} \qquad \text{Eq. (F.2)}$$

Where:

- q_{ul} is the bearing capacity of the subsoil (Brinch Hansen) [kPa]
- $q_{subsoil}$ is the load on the subsoil [kPa]
- $\gamma_{[3]}$ is the safety factor [-]

Basically, Eq. (F.2) says that the bearing capacity of the subsoil, must be larger than the total load on the subsoil. What follows is the determinations of both parameters.

F.3.2 LOAD ON THE SUBSOIL $q_{subsoil}$

The total load on the sub soils follows from previous section:

$$q_{subsoil} = \frac{\sum F_{vertical} \cdot \gamma_{[1.2]}}{A_{foundation}} + \frac{\sum M}{W} = \frac{1.8 \cdot 10^6 \cdot 1.2}{28 \cdot 28} + \frac{75264}{3658} \approx 2.8 \text{ MPa}$$

F.3.3 CAPACITY SUBSOIL q_{ult}

Whether the soil is capable to carry the load depends on the *bearing capacity* of the subsoil which can be calculated with Brinch Hansen:

$$q_{ult} = \underbrace{c \cdot N_c \cdot s_c}_{\text{Cohesion}} + \underbrace{q \cdot N_q}_{\text{Surcharge}} + \underbrace{0.5 \cdot B \cdot N_\gamma \cdot \gamma \cdot s_\gamma}_{\text{Density}} \qquad \text{Eq. (F.3)}$$

Where:

- c is the cohesion coefficient [$0\ kPa$] (Verruijt, 2005)
- N_x are the Brinch Hansen coefficients, in case of sand (35°) the following coefficients are found:
  - $N_c = 46.124$
  - $N_q = 33.296$
  - $N_\gamma = 45.228$
- s_x are shape factors, in case of a square footing, the following factors can be found:
  - $s_c = 1 + 0.2 \cdot \frac{B}{L} = 1.2$
  - $s_q = 1 + \frac{B}{L} \sin \phi = 1$
  - $s_\gamma = 1 - 0.3 \cdot \frac{B}{L} = 0.7$
    - B is the width of the foundation
    - L is the length of the foundation
- γ is the density of the soil 21 [kN/m²]
- The (surcharge) bearing capacity q [kN/m²] can be calculated with:

$$q = \gamma(D_f - D) + \gamma' D \qquad \text{Eq. (F.4)}$$

Where:

- D_f is the distance between the bottom of the structure and ground level or *the foundation depth* (Figure F-1)
- D is the distance between the bottom of the structure and the groundwater table
- $\gamma' = 21 - 10 = 11\ \text{kN/m}^3$
- $D_f - D = 4\ \text{m}$
- $\left.\begin{matrix} \gamma' = 21 - 10 = 11\ \text{kN/m}^2 \\ D_f - D = 4\ \text{m} \end{matrix}\right\} \rightarrow q = 21 \cdot 4 + 11 \cdot (D - 4)$

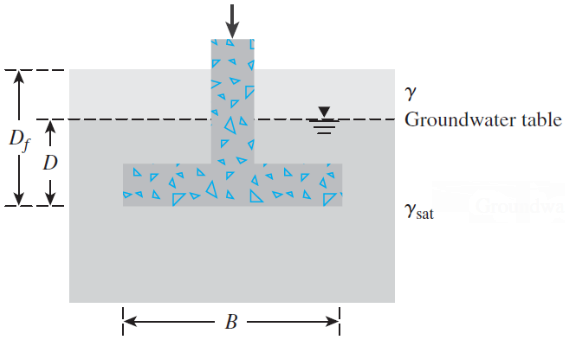


Figure F-1 Bearing capacity factor (B.Das, 2010)

F.3.4 BEARING CAPACITY CHECK

Substituting Eq. (F.3) including parameters, in Eq. (F.2) results in the following:

$$q_{ult} = \frac{\left[0 \cdot 46.124 \cdot 1.2 + \left[48 + 11 \cdot (D_f - 4)\right] \cdot 33.296 \cdot 1 + 0.5 \cdot 28 \cdot 45.228 \cdot 21 \cdot 0.7\right]}{3} \geq 2.8\ \text{MPa} \qquad \text{Eq. (F.5)}$$

When inserting $D_f = 0\ \text{m}$ (which is on ground level) in Eq. (F.5), it is found that $q_{ult} \geq 2.8\ \text{MPa}$. The structure could therefore be put on ground level. Note that the first 1 m of the subsoil, is relatively weak and the structure should therefore be put at least a meter into the subsoil.

APPENDIX G: INTERNAL STABILITY

G.1 GENERAL INFORMATION

G.1.1 MATERIAL PROPERTIES

Below one can find the material properties used in this paper.

Table G-1 Piston properties

Piston made of lead		
Density	γ_p	120 kN/m³

Table G-2 Concrete properties

Concrete C40/50		
Density	γ_c	25 kN/m³
Young's Modulus	E_c	35 GPa
Characteristic yield stress of steel	f_{yk}	500 N/mm²
Design yield stress of steel	f_{yd}	435 N/mm²
Characteristic cubic compressive strength	f_{ck}	50 MPa
Characteristic cubic tensile strength	$f_{ctk,0.05}$	2.9 MPa
Mean compressive strength	f_{cm}	40+8 = 48 MPa
Mean tensile strength	f_{ctm}	1+0.05 · 48 = 2.4 MPa
Design compressive strength	f_{cd}	$\alpha_{cc} \cdot f_{ck}/\gamma_c$
Design tensile strength	f_{ctd}	$\alpha_{ct} \cdot f_{tk,0.05}/\gamma_c$

Table G-3 Reinforcement steel

Reinforcement steel FeB500		
Young's Modulus	E_s	200 GPa

Table G-4 Prestressing steel

Prestressing steel Fep 1860		
Young's Modulus	E_p	205 GPa

G.2 DESIGN IN BENDING

G.2.2 DESIGN METHODOLOGY

The reinforcement for bending can be calculated with the following steps[2]:

I. Determine the force in the steel due to the occurring moment

$$F_{s,xx} = \frac{M_{xx}}{0.75 \cdot h_w} \qquad \text{Eq. (G.1)}$$

Where:

- $F_{s,xx}$ is the force in the steel [kN]
- M_{xx} is the occurring moment [kNm]
- h_w is the wall thickness [m]

II. Determine the required reinforcement

$$A_s = \frac{F_{s,xx}}{f_{yd}} \qquad \text{Eq. (G.2)}$$

Where:

- A_s The amount of steel reinforcement [m^2]
- f_{yd} the yield design stress of the steel, which has assumed to be 435 N/mm² (B500, $\frac{f_{yk}}{1.15}$)

III. Determine the reinforcement ratio

$$\rho = \frac{A_s}{h_w \cdot b} \cdot 100\% \qquad \text{Eq. (G.3)}$$

Where:

- b is de width of the wall (per running meter wall) [m]

According to Eq. (G.1) and Eq. (G.2): for larger bending moments, larger cross sectional area (larger wall thickness per meter) is necessary in order to maintain an economical reinforcement ratio. For a reinforcement ratio ρ of 1.80 %, for example, the max moment that may occur, with a wall thickness of one meter is 6000 kNm.

This can also be perceived in Figure G-1 , in which the reinforcement ratio ρ has been plotted against the occurring bending moment M_{xx} for different thicknesses of the wall h_w. The initial dimensions of the wall, due to bending, will be determined by Figure G-1.

[2] Note that these are formulae are only valid for *uncracked* concrete

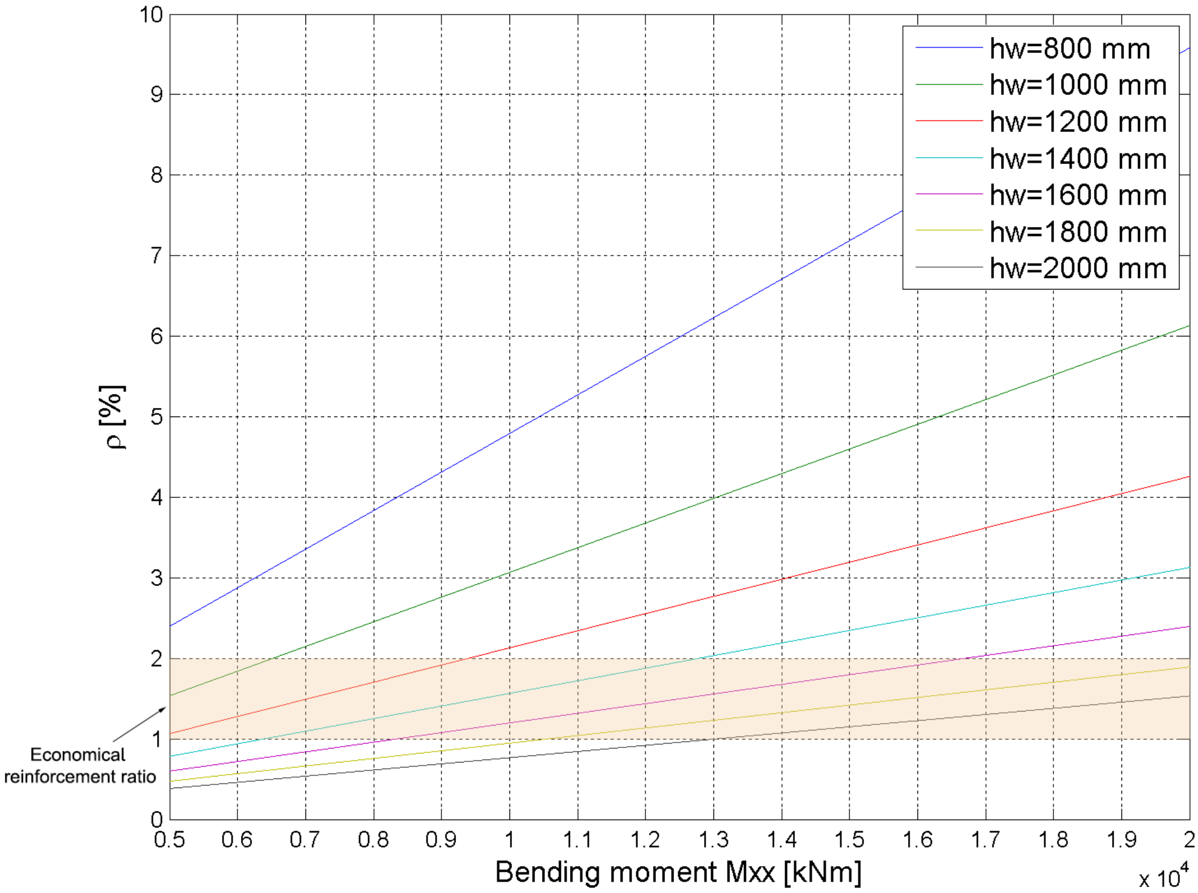


Figure G-1 Reinforcement ratio vs. bending moment

G.2.3 DESIGN CALCULATION (WALL)

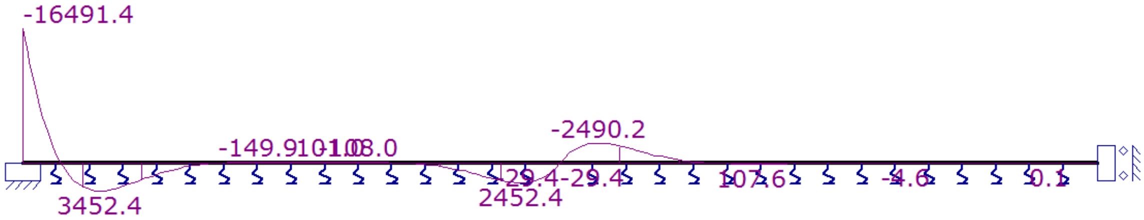


Figure G-2 Envelope

The occurring maximum moment at the monolithic connection is equal to approximately 16,500 kNm for a 1 meter thick wall (Figure G-2). From Figure G-1, it follows that for this occurring moment, a (local) wall thickness of 1.8 m with a reinforcement ratio ρ of 1.5% is necessary to cope with this moment.

Reinforcement design

Consider a part of the wall having a width b of 1000 mm. The amount of reinforcement is then equal to:

$$A_c = b \cdot h_w = 1000 \cdot 1800 = 1.8 \cdot 10^6 \text{ mm}^2 \rightarrow A_s = \rho \cdot A_c = 0.015 \cdot 1.8 \cdot 10^6 = 27000 \text{ mm}^2$$

Amount of bars

If the center to center distance between the cables is equal to 200 mm, the amount of bars that can be placed per 1 meter is equal to:

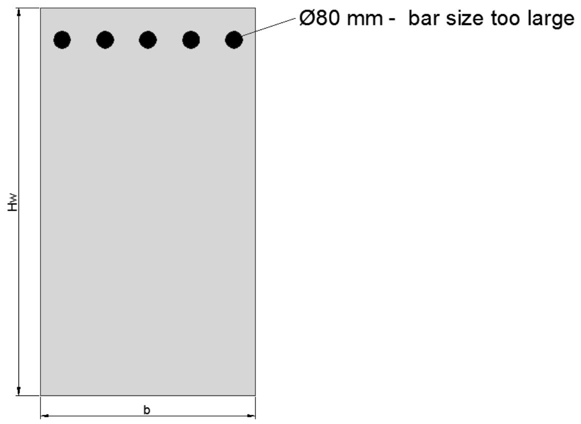
$$n = \frac{1000}{200} = 5 \text{ bars}$$

The area & diameter of *one* bar

The area and diameter Ø of one bar is equal to:

$$A_{bar} = \frac{A_c}{n} = \frac{27000}{5} = 5400 \text{ mm}^2$$

$$\phi = \sqrt{\frac{A_{bar} \cdot 4}{\pi}} = \sqrt{\frac{5400 \cdot 4}{\pi}} \approx 80 \text{ mm}$$

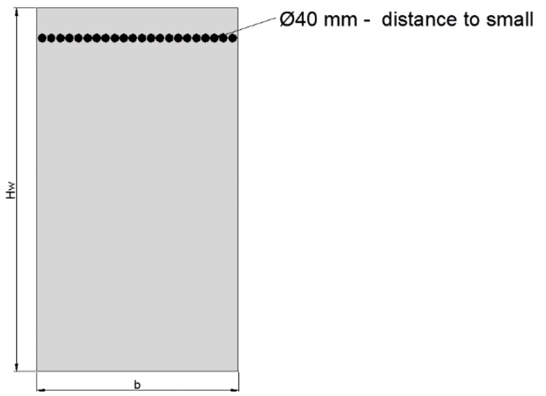


Rebars (reinforcement bars) with this size are not the common and therefore probably not economical. The maximum nominal rebar diameter is in the order of 40 mm².

In order to use these rebar sizes per 1 meter, the amount of bars must be increased and center to center distance between the bars must be decreased:

$$\left.\begin{array}{l}\phi = 40 \text{ mm} \\ A_{bar} = \frac{1}{4}\pi D^2 = \frac{1}{4}\cdot\pi\cdot 40^2 = 1256 \text{ mm}^2\end{array}\right\} \rightarrow n = \frac{A_s}{A_{bar}} = \frac{27000}{1256} = 22 \text{ bars}$$

Which comes down to a *center to center* distance of 45 mm which means a mutual distance of 5 mm per bar which is too low.



Redesign

In order to solve this problem, the amount of steel reinforcementA_s, per meter width, must be reduced, which can only be done by increasing the wall thickness h_w (according to Eq. (G.1) and Eq. (G.2)). Assuming a center-to-center distance of 100 mm (10 bars) having a diameter of Ø 40 mm, the total amount of reinforcement is then equal to:

$$A_s = A_{bar}\cdot n = 1256\cdot 10 = 12560 \text{ mm}^2$$

According to Eq. (G.1) and Eq. (G.2), the wall thickness becomes:

$$h_w = \frac{M_{xx}}{0.75\cdot A_s\cdot f_{yd}} = \frac{16.5E9}{0.75\cdot 12560\cdot 435} \approx 4 \text{ m!!!}$$

Evaluation

Locally, the wall has to be increased to at least 4 meters, in order to cope with the large occurring moment. The wall can be dimensioned slimmer by: increasing the diameter of the rebar, but as already stated this would lead to an uncommon size.

Another method is to use more rows of rebars which would lead to an increase of the reinforcement and a possibly slimmer wall or one could pre-stress *vertically*. Calculating the effect of these measures, goes out of the scope of this paper.

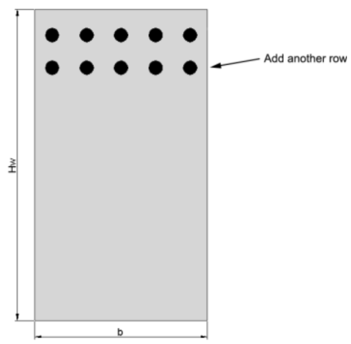


Figure G-3 add another row

G.2.4 DESIGN CALCULATION (FOUNDATION)

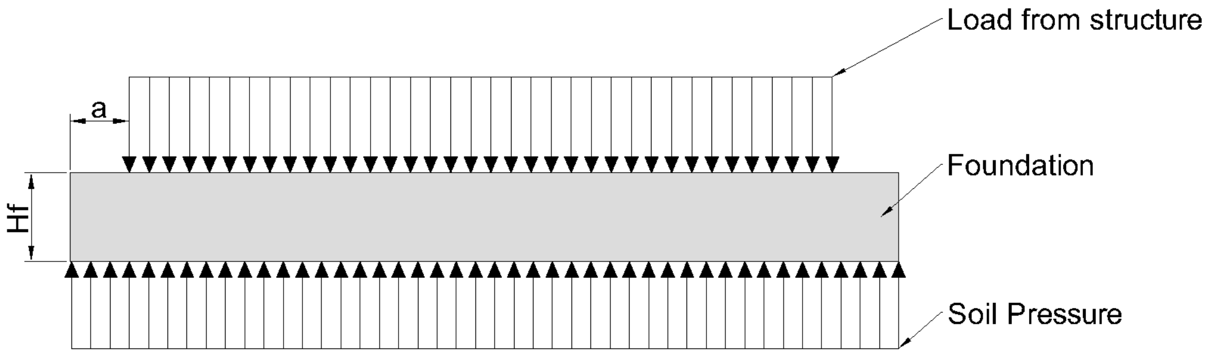


Figure G-4 Load schematization on foundation

The maximum moment occurring in the foundation is at a distance a (see Figure G-4).

Assuming that the soil pressure is equal to the load of the structure 2.8 MPa, the following reinforcement ratio can be calculated:

$$q_{soil} \approx q_{load} = 2.8 \cdot 10^3 \text{ kN/m}$$

$$M_{ax} = \frac{1}{2} \cdot q_{soil} \cdot a^2 = \frac{1}{2} \cdot 1.8 \cdot 10^3 \cdot 1^2 = 1.4 \cdot 10^3 \text{ kNm}$$

$$F_{s,xx} = \frac{M_{ax}}{0.75 \cdot H_f} = \frac{1400}{0.75 \cdot 3} = 622 \text{ kN}$$

$$A_s = \frac{F_s}{f_{yd}} = \frac{622 \cdot 10^3}{435} = 1430 \text{ mm}^2$$

$$\rho = \frac{A_s}{h_w \cdot b} \cdot 100\% = \frac{1430}{3000 \cdot 1000} \cdot 100\% = 0.05\%$$

Eurocode 2 prescribes a minimum reinforcement ratio ρ of 0.20 %, the foundation can therefore be designed much slimmer. However, as the wall-base connection is exposed to *major loading*, this part will require more reinforcement. The foundation height H_f is assumed to be 2 m with a reinforcement ratio ρ of 1 %.

G.3 DESIGN IN SHEAR

G.3.5 DESIGN METHODOLOGY

For designing in shear, the following scheme, which is based on Eurocode 2, will be followed through:

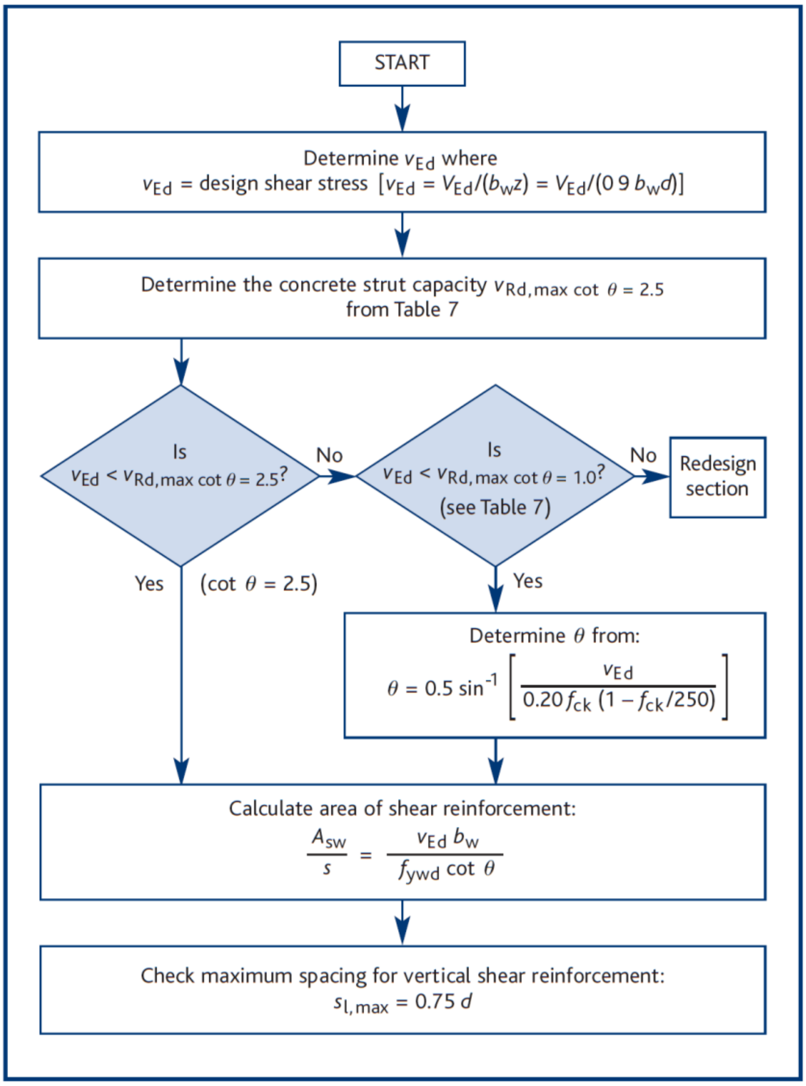


Figure G-5 Scheme shear reinforcement (Bond, 2006)

The corresponding steps are explained as follows:

I. Check if the shear force is smaller than the shear resistance of concrete: $V_{ed} \leq V_{rd,c}$
   - Determine the shear force V_{ed}
   - Determine $V_{rd,c}$

The shear resistance of concrete can be calculated with the following equation:

$$V_{rd,c} = 0.12 \cdot k \cdot (100 \cdot \rho \cdot f_{ck})^{\frac{1}{3}} \cdot b \cdot d \qquad \text{Eq. (G.4)}$$

Where:

- d is the effective height $\approx 0.75 \cdot h_w$ [-]
- $k = 1 + \sqrt{\frac{200}{d}}$ [-]
- f_{ck} is the characteristic cylinder strength - 50 [N/mm²]
- ρ is the reinforcement ratio ≤0.02 [-]
- b is the width of the wall – 1000 [mm]

In Figure G-6, the effective wall height d against the resistance shear force of the concrete $V_{rd,c}$ has been plotted for multiple reinforcement ratio ρ according to Eq. (G.4).

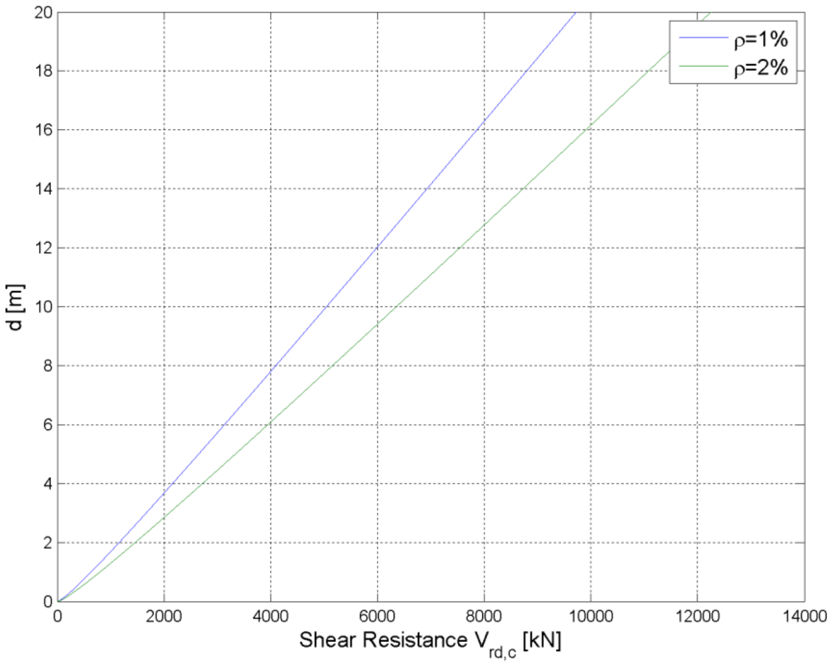


Figure G-6 Effective wall thickness vs. Shear resistance

It can be seen that in order to resist, for example, 2000 kN, the effective wall thickness must be in the order of 3-4 meters. If the shear force is larger than the shear resistance of concrete (which is the case), stirrups (vertical shear reinforcement) must be applied.

II. Check if the *shear stress* is smaller than the *max strut capacity*: $v_{ed} \leq v_{rd,\max}$

According to Eurocode 2, Table 7:

$v_{rd,\max} = 8$ MPa for C40/50, rewriting gives:

$V_{rd,\max} = v_{rd,\max} \cdot b \cdot d = 6000 \cdot h_w$

If $V_{ed} \geq V_{rd,\max}$ see step III.

III. Increase the effective wall thickness h_w so that co-tan of the strut angle (see Figure A-6) lies between 1 and 2.5.

The $\cot\theta$ can be calculated with the following equation:

$$1 \leq \cot\theta = 0.5 \cdot \sin^{-1}\left[\frac{\frac{V_{ed}}{b \cdot d}}{0.2 \cdot f_{ck}\left(1 - \frac{f_{ck}}{250}\right)}\right] \leq 2.5 \qquad \text{Eq. (G.5)}$$

Where:

- d is the effective height $\approx 0.75 \cdot h_w$ [mm]
- f_{ck} is the characteristic cubic compressive strength 50 [N/mm^2]
- θ is the strut angle [rad]
- V_{ed} is the shear force [N]
- b is the width (1000 mm)

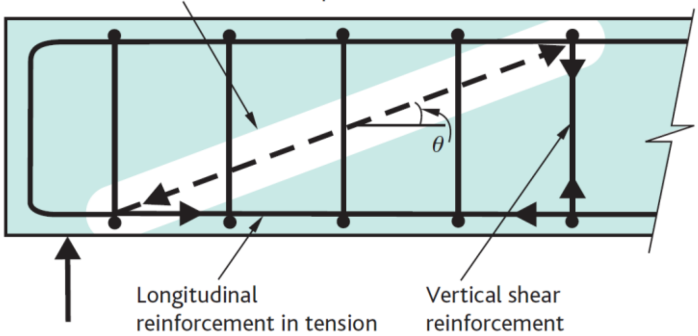


Figure G-7 Schematization shear reinforcement and struts (Bond, 2006)

In order to simplify the calculation, co-tan of the strut angle $\cot\theta$ has been plotted against the shear force V_{ed} for different effective wall thicknesses d according to Eq. (G.5) in Figure G-8. From this figure, an appropriate *effective* wall thickness d can be chosen for an occurring shear force V_{ed}. The next step shows then how the shear reinforcement can be calculated.

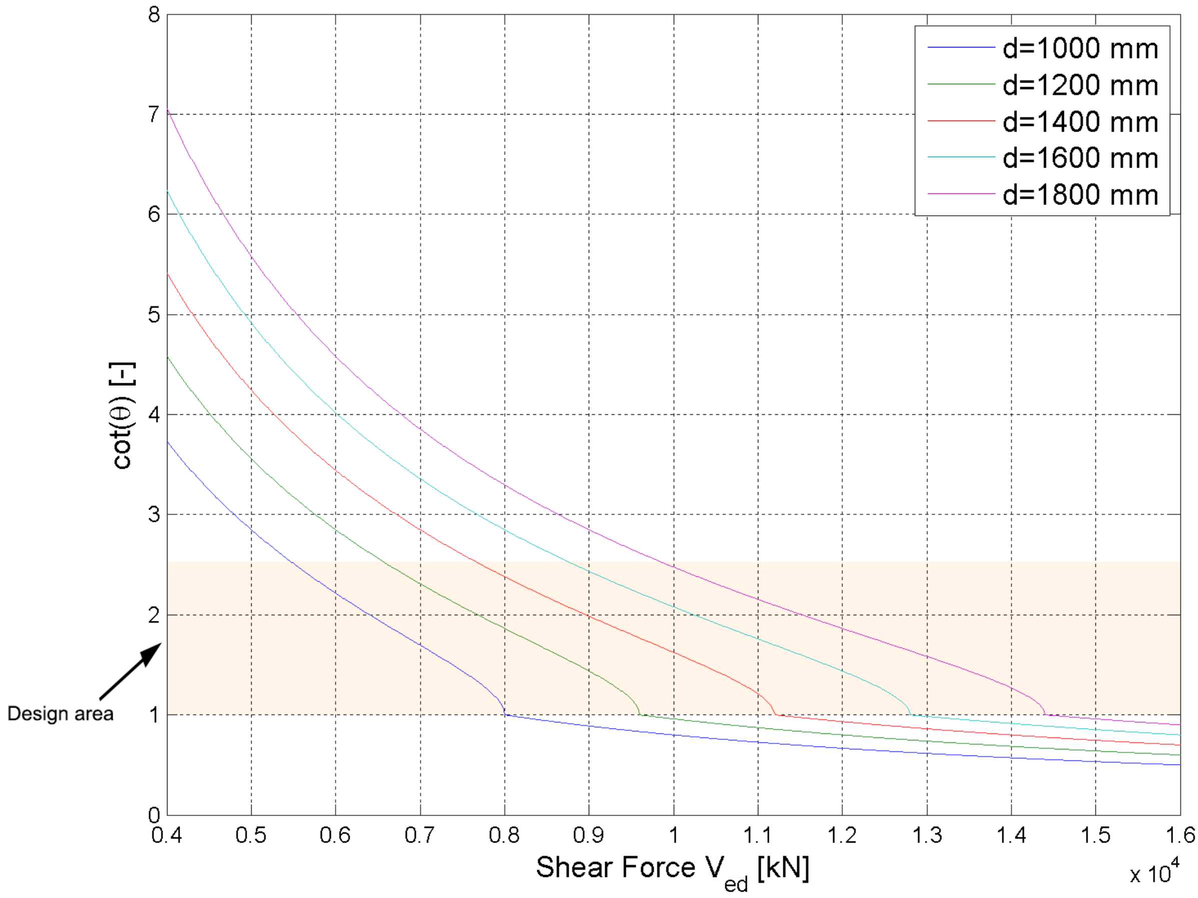


Figure G-8 Cot θ vs. Shear force

IV. Determine the shear reinforcement

When the effective wall thickness is known, the shear reinforcement A_{sw} can be determined with the following equation:

$$\frac{A_{sw}}{s} = \frac{V_{ed}}{0.78 \cdot d \cdot f_{yk} \cdot \cot\theta} \qquad \text{Eq. (G.6)}$$

Where:

- A_{sw} is the shear reinforcement [mm^2]
- s is the distance between the struts [mm]
- V_{ed} is the shear force [N]
- f_{yk} is the characteristic yield stress of steel 500 [N/mm^2]
- $\cot\theta$ is the strut angle [-]

V. Check for the practical amount of shear reinforcement

The amount of shear reinforcement will be checked, if this is too much, the wall thickness should be increased or vertical prestressed.

G.3.6 DESIGN CALCULATION

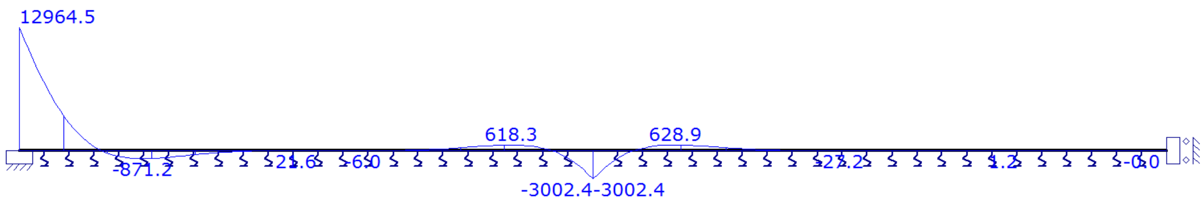


Figure G-9 Shear force distribution

The greatest amount of shear reinforcement must be applied at the monolithic connection. The wall will be dimensioned according to:

I. Check if the shear force is smaller than the concrete resistance $V_{ed} \leq V_{rd,c}$

The shear force is $V_{ed} \approx 13000 \text{ kN}$ and the resistance of the concrete is, according to Figure G-6, equal to $V_{rd,c} \approx 700 \text{ kN}$. This means that shear reinforcement must be applied

II. Check if the shear stress is smaller than the max strut capacity:

The maximum strut capacity is $V_{rd,\max} = v_{rd,\max} \cdot b \cdot d = 6000 \cdot h_w = 6000 \text{ kN} < 13000 \text{ kN} = V_{ed}$

III. Increase the effective wall height/thickness so that co-tan of the strut angle lies between 1 and 2.5.

For a shear force of V_{ed} of 13000 kN, the effective thickness should be approximately 1650 mm for $\cot\theta = 1$

IV. Determine the shear reinforcement

$$\frac{A_{sw}}{s} = \frac{V_{ed}}{0.78 \cdot d \cdot f_{yk} \cdot \cot\theta} = \frac{13E6}{0.78 \cdot 1650 \cdot 500 \cdot 1} = 20000 \text{ mm}^2/\text{m}$$

V. Check if the reinforcement is practical

Here is checked how many struts must be applied for an: $\frac{A_{sw}}{s} = 20000 \text{ mm}^2/\text{m}$? In this section, a part of the wall having a width b of 1 meter and a height h_l of 1 meter, is considered.

<u>Reinforcement design</u>

The amount of bars

The *horizontal* center-to-center distance has been taken equal to that of the longitudinal reinforcement which is 100 mm; the *vertical* center to center distance of 200 mm.

In horizontal direction $\frac{1000}{100} = 10$ bars will be applied and in vertical direction $\frac{1000}{200} = 5$ bars. This would be equal to $5 \cdot 10 = 50$ bars.

<u>Diameter of “one” bar:</u>

The average diameter is approximately:

$$\left.\begin{aligned} \frac{20000}{50} &= 400 \text{ mm}^2 \\ \frac{1}{4}\pi \cdot D^2 &= 400 \text{ mm}^2 \end{aligned}\right\} \rightarrow D = 23 \text{ mm} \approx \phi\, 25 \text{ mm}$$

Design

In Figure G-10, one can see an example of how this would look like. One can imagine that using this many struts is highly unpractical, especially when these walls are to be prestressed with tendons. Note that these bars have to bend along the longitudinal reinforcement, and therefore it is not practical to design with a larger rebar size (common struts are in the order of $\phi 12-14$ mm, compared to that, even a diameter of $\phi 25$ mm would be considered unpractical).

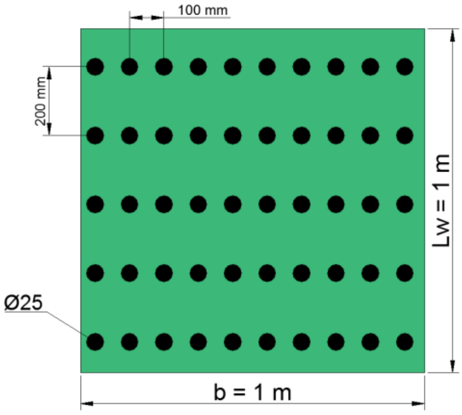


Figure G-10 Shear reinforcement design

For this calculation, the wall width has to be increased to $\frac{1650}{0.75} = 2200$ mm. In order to decrease the diameter or amount of bars, the wall thickness would need to be increased even further.

G.4 THE EFFECT OF REDUCING PRESTRESSING

It becomes clear that the moment due to prestressing becomes extremely large. One of the counter methods is to remove some of the prestressing cables in the lower part of the wall. What follows is an indication of what happens if one would do that.

A first estimation is to decreasing the prestressing in the first 5 meters, which results in the following structural and loading changes (Figure G-11, Figure G-12 and Figure G-13):

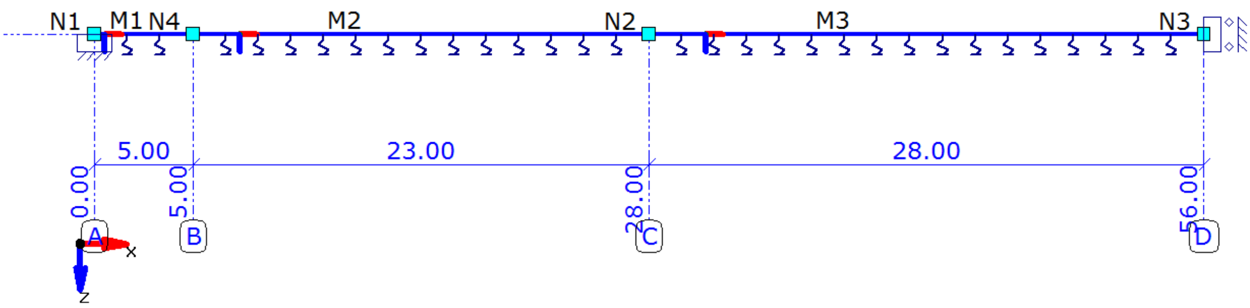


Figure G-11 Model

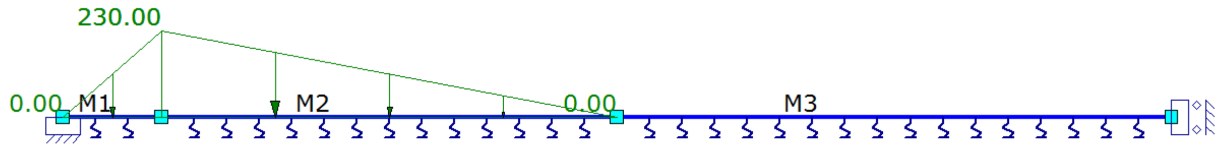


Figure G-12 Water load — prestressing (input)

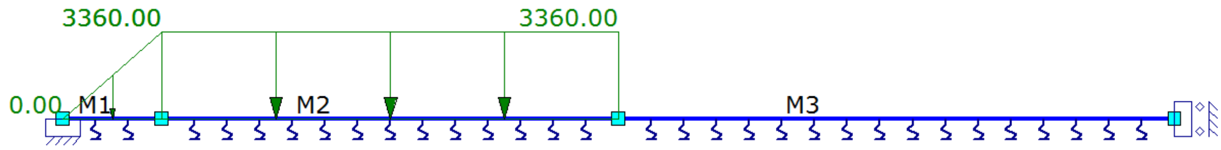


Figure G-13 Piston load — prestressing (input)

In (Figure G-14) the envelope is shown of lowering the prestressing.

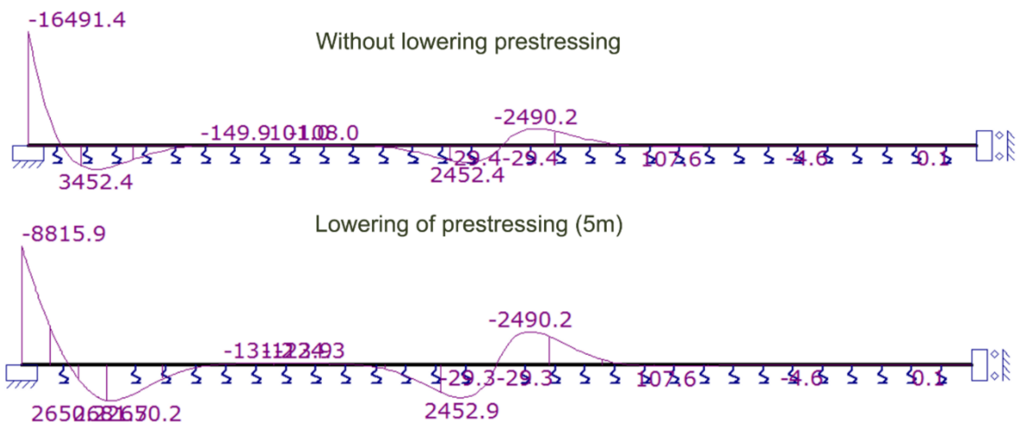


Figure G-14 Envelope (output)

It can be seen that the moment has been reduced by a half at t_0. However, at t_1, the internal loads induces a large opposite bending moment (Figure G-15).

This method would therefore require a large amount of longitudinal reinforcement at both sides of the wall near the wall-base connection and is therefore not that effective with extremely large loading.

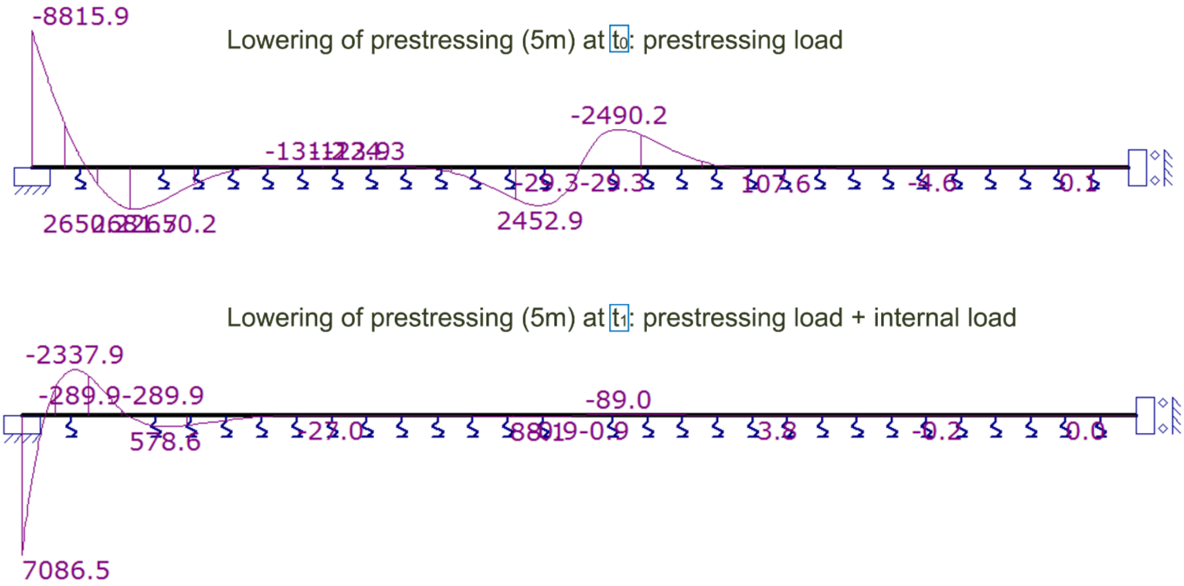


Figure G-15 Envelope t_0 *and* t_1

G.5 MODEL INPUTS

G.5.7 LOADS

The storage container has a total height of 56 meters. The piston thickness is 28 meters. De diameter of the piston/container is 24 meters.

The bottom part is saturated with water which has a weight of γ_w = 10 kN/m^3. The total water head is 28 meters resulting in a pressure of 280 kN/m^2 (S.L.S.) at x=0 and a water pressure of 0 kN/m^2 at x= H_l (which at half of the height of the tank).

The piston is assumed to be of lead, which has a weight of approximately 120 kN/m^3. The thickness of the piston is 28 meters; the total pressure of the piston is equal to 28m · 120 kN/m^3 = 3360 kN/m^2 (S.L.S.).

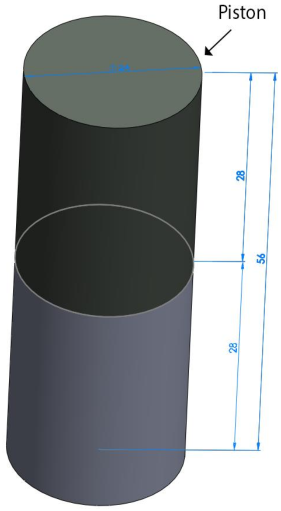


Figure G-16 Preliminary dimensions

The loads that will be implemented in this models are <u>not</u> the internal loads, but the prestressing load! Both of the internal loads have a safety factor of 1.35, the prestressing load has a safety factor of 1.4.

In the ultimate limit state (U.L.S) the prestressed water load becomes 1.4· 280 = 392 kN/m^2 and the prestressed piston load becomes 1.4 · 3360 =4536 kN/m^2. These loads are illustrated, both S.L.S. and U.L.S., in Figure G-17.

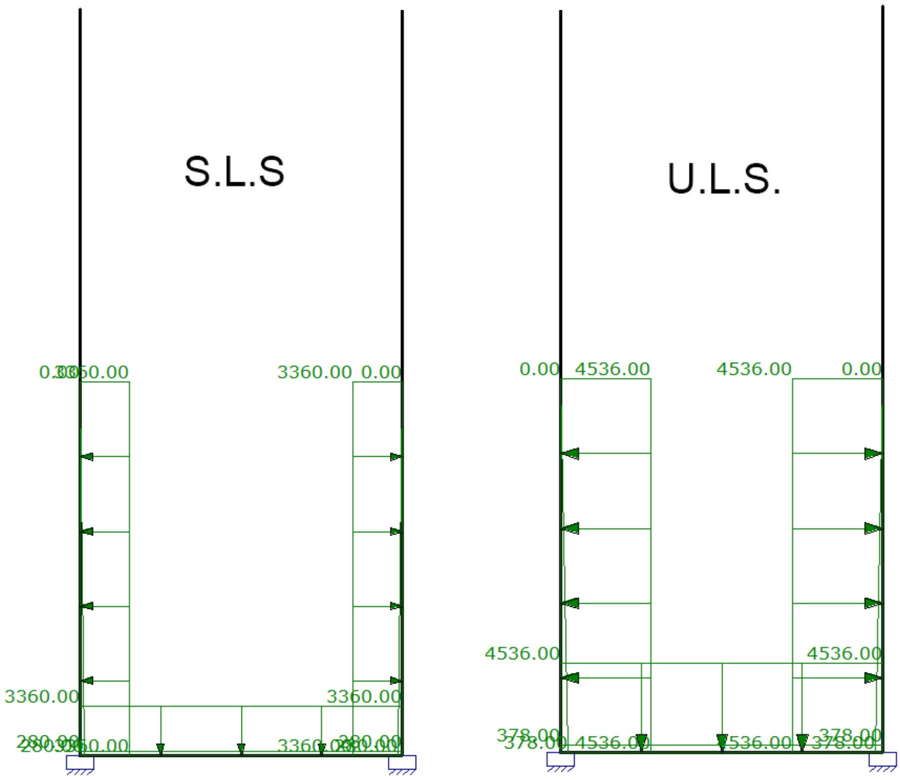


Figure G-17 Load schematization S.L.S. and U.L.S.

It becomes clear that the water load does not do much, if anything at all, compared to the piston load. Note that the roof of the main container will be constructed *after* the final load phase. Meaning that the roof slab and the connection between the roof and the wall are not present until the final load phase is finished.

Figure G-18 illustrates the water load in S.L.S. on the wall, which is 280 kN/m^2 at the wall – bottom slab connection and 0 at x=Hl (where the water, meets the piston).

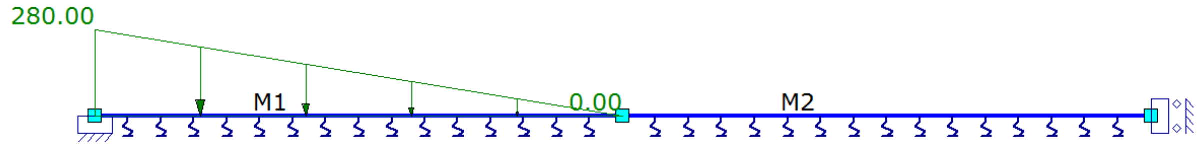


Figure G-18 Water load

Figure G-19 illustrates the piston load in S.L.S. on the wall, which is a constant of 3360 kN/m^2.

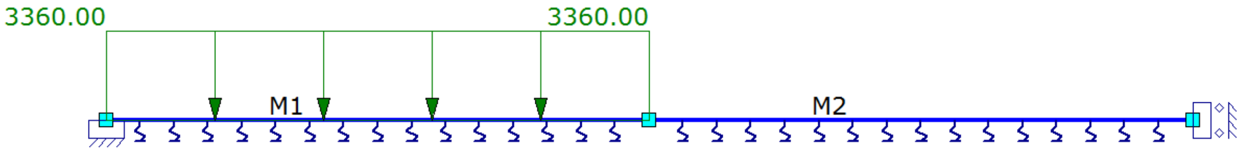


Figure G-19 Piston load

G.6 RETURN PIPE

In this section, the return pipe is designed. There are two formulae which can be used to estimate the diameter of the return pipe, one is based on the balance equation (A.1.2 Conservation of momentum, p105), and one is experimentally determined for pipe return lines in hydraulic systems.

G.6.8 DIAMETER PIPE

First the diameter is determined by the balance equation, which states that the discharge remains constant in the system:

$$Q = v_1 \cdot A_1 = v_2 \cdot A_2 = \text{constant} \qquad \text{Eq. (G.7)}$$

Where:

- Q is the discharge in the system [m³]
- v_1 is the velocity in the main container [m/s]
- v_2 is the velocity in the return pipe [m/s]
- A_1 is the flow area of the main container [m²]
- A_2 is the flow area of the return pipe [m²]

The piston moves down from the top to bottom and moves 28 meters in 4 hours. The velocity of piston in the main container is equal to:

$$v_1 = \frac{28 \text{ m}}{4 \text{ hours} \cdot 3600 \text{ s}} \approx 2 \text{ mm/s}$$

The discharge in the system (assumed that it is constant) is equal to:

$$Q = v_1 \cdot A_1 = 0.02 \cdot [\pi \cdot R^2] = 0.02 \cdot [\pi \cdot 12^2] \approx 0.9 \text{ m/s}$$

According to (Tube Selection Chart), a return pipe in a hydraulic system has an optimum velocity of $v_2 =$ 3.05 m/s. Applying Eq. (G.7) the diameter of the return pipe becomes:

$$A_2 = \frac{Q}{v_2} = \frac{0.9}{3.05} = 0.3 \text{ m}^2$$

$$D_{inner} = \sqrt{4 \cdot A_2} = \sqrt{4 \cdot 0.3} = 1100 \text{ mm}$$

According to an experimentally derived formula (Tube Selection Chart), the pipe (inner) diameter can be calculated with:

$$D_{inner} = 4.65 \cdot \sqrt{\frac{\text{Flow in liters per minute}}{\text{Velocity in m/s}}} \qquad \text{Eq. (G.8)}$$

Where:

- D_{inner} is the inner diameter of the pipe [mm]
- v is the required velocity 3.05 [m/s]

The flow in liters per minute is equal to:

$$Q = 0.9 \text{ m/s}^3 == 0.9 \cdot 60 \cdot 1000 = 54000 \frac{\text{Liters}}{\text{Minute}}$$

Filling these parameters in Eq. (G.8) results in:

$$D_{inner} = 4.65 \cdot \sqrt{\frac{54000}{3.05}} \approx 620 \text{ mm}$$

Both these two formulae give different pipe diameters (1100 mm vs. 620 mm). Formula Eq. (6.5), in contrast to Eq. (6.4), takes into account phenomena such as friction losses and turbulence both resulting in pressure drops (Tube Selection Chart). The pipe (outer) diameter is therefore estimated at 700 mm.

G.6.9 THICKNESS PIPE

The required wall thickness of the return pipe can be calculated with the Barlows formula (Tube Selection Chart):

$$P = \frac{2 \cdot S \cdot t}{D} \qquad \text{Eq. (G.9)}$$

Where:

- P is the internal pressure [kPa]
- S is the maximum allowable (design) stress in the pipe [kPa]
- t is wall thickness [mm]
- D is the diameter of the return pipe [mm]

The maximum internal pressure P is equal to the pressure on the bottom of the of the storage container which is approximately 4000 kPa. The pipe is made of steel C-1021 which has an allowable design stress S = 103000 kPa, filling in formula Eq. (G.9) results in:

$$t = \frac{P \cdot D}{2 \cdot S} = \frac{4000 \cdot 700}{2 \cdot 103000} \approx 14 \text{ mm}$$

APPENDIX H: CONSTRUCTION

H.1 PISTON SEALING

One of the main technical challenges in of the storage device, is sealing the piston, especially due to the pistons large size and weight. Sealing of the piston can be done with hydraulic seals (Figure H-1). The performance of such a seal depends on the occurring *pressure*, the *temperature*, the elevation *speed* of the piston, and the last and probability most challenging within this project is, the *surface finish*.

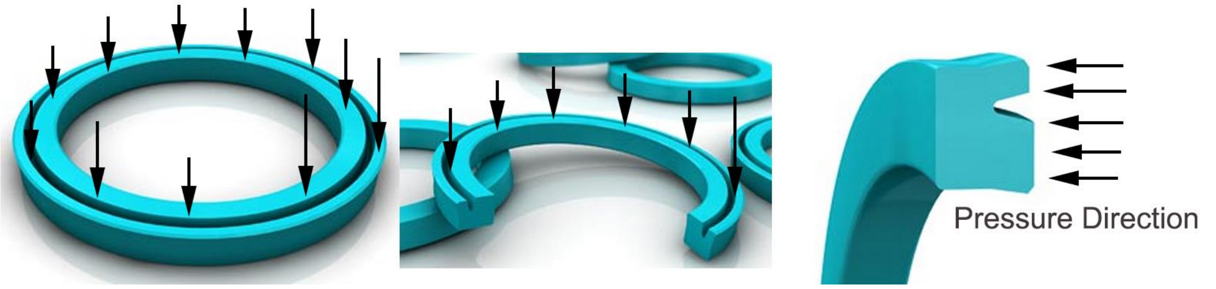


Figure H-1 Hydraulic seals

H.1.1 PRESSURE PARAMETER

How the pressure affects the seal is basically determined by the *extrusion resistance* of the seal material and the extrusion gap which the seal must passage without extruding (see Figure H-2 and Figure H-3). If the extrusion gap is too large for a certain pressure, the seal will flow into it (see Figure H-2). As the pressure increases, the extrusion gap must become smaller (Tran Seals), an alternative is another design in which this gap is being blocked by so called anti-extrusion devices (Figure H-3).

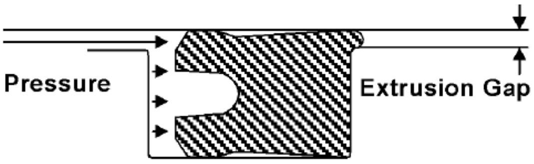


Figure H-2 Seal passage through extrusion gap

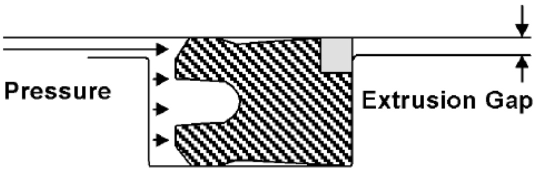


Figure H-3 Anti-extrusion device (Tran Seals)

H.1.2 TEMPERATURE PARAMETER

If the temperature in the system becomes too low, the seal will become brittle. If the temperature in the system becomes too high, the seal becomes more vulnerable to extrusion, which leads to an increasing friction and therefore a reduction in lifetime.

H.1.3 SPEED PARAMETER

The speed relates to the friction generated at the sealing surface which at too high speeds decreases the seals functionality.

H.1.4 SURFACE FINISH PARAMETER

One of the most challenging is the surface finish. The lifetime and functionality of the seal is greatly influenced by the properties of the sealing surfaces against which it operates (Tran Seals). The surface values can only be determined by a comparison of the average surface roughness R_a. The purpose of the surface finish is to provide a surface which causes the least wear to the seal. However prior comes the maximum surface roughness R_{max} of the piston seal in order to operate efficiently. (Busak+Shamban, 2006) Recommend the following surface finish (or roughness):

Surface Roughness µm			
Parameter	Mating Surface		Groove Surface
	Turcon® Materials	Zurcon® and Rubber	
R_{max}	0.63 - 2.50	1.00 - 4.00	< 16.0
$R_{z\ DIN}$	0.40 - 1.60	0.63 - 2.50	< 10.0
R_a	0.05 - 0.20	0.10 - 0.40	< 1.6

Figure H-4 Surface roughness (Busak+Shamban, 2006)

APPENDIX I: COST

This appendix discusses the following aspects:

- Pricing rates
- Cost of the structural and mechanical components

I.1 PRICING RATES

The pricing rates used in this subsection, have been summarized in Table I-1.

Table I-1 Pricing rates

Material	Pricing	Source
Lead ore	0.90 € / kg	(indexmundi, 2013)
Concrete	120 € / m³	(A.Q.C. van der Horst, C.R. Braam)
Reinforcement steel	800 € / m³	(A.Q.C. van der Horst, C.R. Braam)
Prestressing steel	800 € / m³	(A.Q.C. van der Horst, C.R. Braam)
Formwork (normal)	50 € /m³	(A.Q.C. van der Horst, C.R. Braam)
Formwork (climbing)	450 € / m³	(A.Q.C. van der Horst, C.R. Braam)

I.2 STRUCTURAL COMPONENTS

I.2.1 FOUNDATION

The foundation is a shallow in-situ poured, reinforced concrete. The total volume of the foundation (Figure I-1) can be expressed by: $V_{foundation} = L_{foundation} \cdot W_{foundation} \cdot H_{foundation}$

The length and width of the foundation are estimated at 28 meters; the height is 2 meters for now. With these parameters, the total volume of the foundation:

$$V_{foundation} = 28 \cdot 28 \cdot 2 = 1568\ \text{m}^3$$

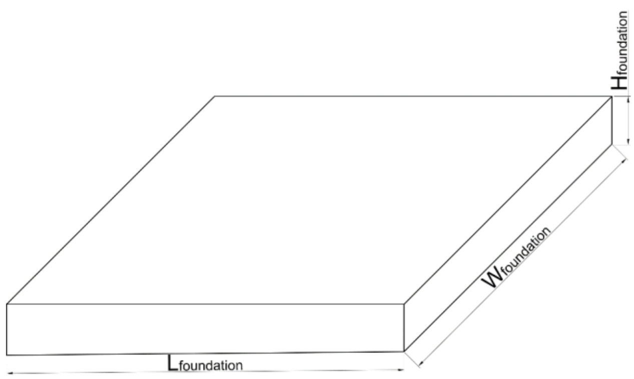


Figure I-1 Foundation

The total area of formwork (FWA=Formwork area) can be expressed by:

$FWA_{foundation} = \underbrace{L_{foundation} \cdot W_{foundation}}_{\text{Bottom}} + 2 \cdot \underbrace{L_{foundation} \cdot H_{foundation}}_{\text{Length side}} + 2 \cdot \underbrace{W_{foundation} \cdot H_{foundation}}_{\text{Width side}}$. Note that the top side does not require formwork. Filling in the parameters, the FWA of the foundation:

$FWA_{foundation} = 28 \cdot 28 + 2 \cdot 28 \cdot 2 = 896 \text{ m}^2$

The amount of reinforcement is estimated at 1% (see *internal stability*). In Table I-2 the costs for the foundation are shown.

Table I-2 Foundation costs

Foundation	Amount	Costs [€]
Total volume	2352 m^3	
Concrete (99%)	2328 m^3	279,400
Reinforcement (1%)	24 m^3	146,800
Formwork	896 m^2	47,600
Total		**328,900 €**

I.2.2 CYLINDRICAL WALL

Also the wall will be casted at location. The wall is made of concrete, the thickness is assumed to be 1 meter. The wall is both reinforced (2%) and prestressed (1%). Note that these numbers are estimates and not the actual percentages of steel in concrete.

The total volume of the cylindrical wall (Figure I-2) can be expressed by:

$V_{wall} = \pi D_{inner} \cdot W_{wall} \cdot H_{wall}$. The inner radius is equal to 12 m, the width of the wall is 1 m and the height is equal to 56 meter. Filling in these parameters results in a total volume of the wall of: $V_{wall} = \pi \cdot 24 \cdot 1 \cdot 56 = 4222 \text{ m}^3$

The wall will be poured by *climbing formwork*, the big advantage is that it can be reused. The maximum height of one piece of formwork is equal to 3.5 m (A.Q.C. van der Horst, C.R. Braam). By including the fact, that formwork can be reused for the wall, the amount of formwork can be expressed by:

$$FWA_{wall} = 2 \cdot \underbrace{\pi D_{inner} \cdot 3.5}_{\text{Inner/Outer side of the wall}} + 2 \cdot \underbrace{W_{wall} \cdot 3.5}_{\text{Cross section}} + \underbrace{\pi D_{inner} \cdot W_{wall}}_{\text{Bottom}} \cdot$$

Where the outer diameter is the sum of the width of the wall and the inner diameter. The total formwork area becomes:

$$FWA_{wall} = 2 \cdot [\pi \cdot 24 \cdot 3.5] + 2 \cdot [1 \cdot 3.5] + \pi \cdot 24 \cdot 1 = 610 \text{ m}^2$$

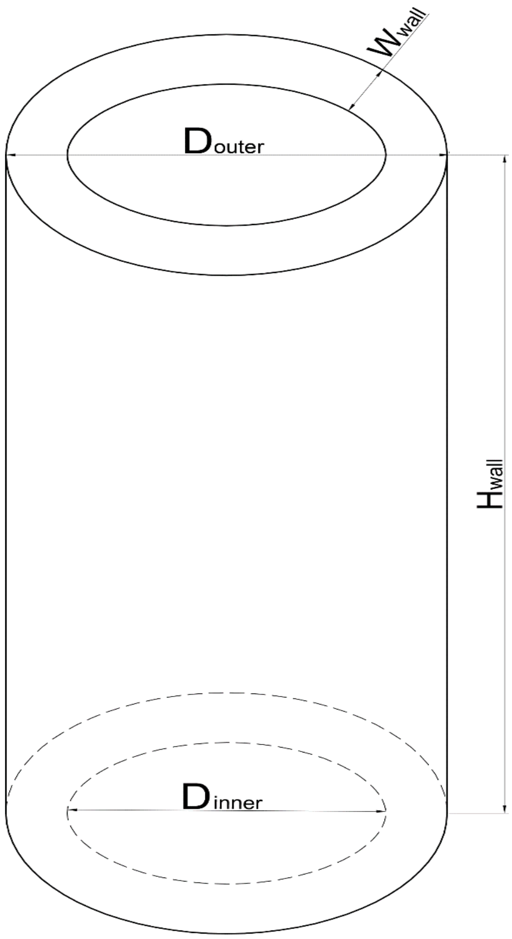


Figure I-2 Wall

In Table I-3, the costs of the wall are shown.

Table I-3 Wall costs

Wall	Amount	Costs [€]
Total volume	4222 m^3	
Concrete (97%)	4095 m^3	491,500
Reinforcement (2%)	84 m^3	526,900
Prestressing tendons (1%)	42 m^3	263,500
Formwork	610 m^2	274,600
Total		**€ 1,600,000**

I.2.3 ROOF

The roof is just like the foundation made of reinforced concrete. The height of the roof is estimated at 1 meter. The total volume (Figure I-3) becomes:

$$V_{roof} = \frac{1}{4}\pi D_{outer}^2 \cdot H_{roof} = \frac{1}{4}\pi \cdot 26^2 \cdot 1 = 531\,m^3$$

The amount of form work equal to:

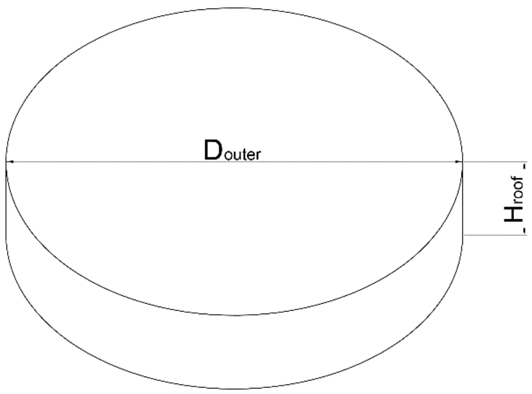


Figure I-3 Roof

$$FWA_{roof} = \underbrace{\frac{1}{4}\pi D_{outer}^2}_{\text{Bottom}} + \underbrace{\pi D_{outer} \cdot H_{roof}}_{\text{Side}} = \frac{1}{4}\pi \cdot 26^2 + \pi \cdot 26 \cdot 1 = 528\ m^2$$

With a reinforcement (1%), the costs of the roof are shown in Table I-4.

Table I-4 Roof Costs

Roof	Amount	Costs [€]
Total volume	531 m^3	
Concrete (99%)	525 m^3	63,100
Reinforcement (1%)	5.3 m^3	33,100
Formwork	610 m^2	26,400
Total		**€ 122,600**

I.2.4 RETURN PIPE

The return pipe has a length of roughly 70 m. The total volume therefore becomes:

$$V_{returnpipe} = \pi \cdot D_{inner} \cdot d_{returnpipe} \cdot L_{returnpipe} = \pi \cdot (\frac{700-12}{1000}) \cdot \frac{12}{1000} \cdot 70 = 1.8 \text{ m}^3$$

Total cost of the return pipe has been estimated in Table I-5.

Table I-5 Return pipe costs

Return pipe	Amount	Costs [€]
Total volume	1.8 m^3	**€ 11,300**

I.2.5 THE PISTON

Piston casing will be filled up with lead ore. For now only the material of the piston will be taken into account in the total cost of the piston. The volume of the piston is:

$V_{piston} = \pi R_{piston}^2 \cdot H_{piston} = \pi \cdot 12^2 \cdot 28 = 12667 \text{ m}^3$, the total cost of the piston can be seen in Table I-6.

Table I-6 Piston costs

Piston	Amount	Costs [€]
Total volume	12667 m^3	**€ 90,380,000**

With the price of lead ore, the total cost of the piston (only material) becomes approximately 90 million euro!

I.3 MECHANICAL COMPONENTS

I.3.6 PUMP/TURBINE

Pump requirement equals to 1250 kW. According to Figure I-4, a single regulated costs, by extrapolating the graph, approximately 800 €/kWh, the total cost of the turbine is equal:

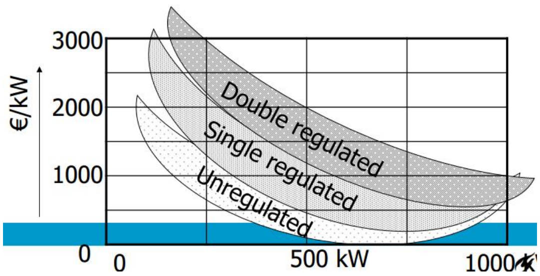


Figure I-4 Cost turbine (A. van der Toorn; W. molenaar)

$$Cost_{turbine} = 1250 \text{ kW} \cdot 800 \text{ €/kW} = 1{,}000{,}000 \text{ €}$$

As the reversible pump/turbine includes not only a turbine but also a pump, the total cost of this device is assumed to be twice as large (see Table I-7)

Table I-7 Pump/turbine costs

Pump/Turbine	Amount	Costs [€]
	1	**€ 2,000,000**

I.3.7 GENERATOR

The price of the generator with a power output of 1250 kW is estimated according to (KTA50-G3-1250kW-generator, n.d.) as can be seen in Table I-8.

Table I-8 Generator costs

Generator	Amount	Costs [€]
	1	**€ 100,000**

APPENDIX J: COST OPTIMIZATION

J.1 THE PRODUCTION COST FUNCTION

$$\text{Production Cost}\left(h, D, \rho_{piston}, €_{material}\right) = \frac{\sum \text{Material Cost}}{\sum \text{Energy Production (during 50 years)}} \quad [€/kWh]$$

The cost parameters can be found in Table J-1.

Table J-1 Cost parameters

Parameter	Unit	Description	Type	Value
ρ_{piston}	[kg/m³]	The density of the piston depending on material	*constant*	lead ore, iron ore, concrete, sand
$€_{material}$	[euro]	The price of the material used for the piston	*constant*	lead ore, iron ore, concrete, sand
h	[m]	This is the height of the container	*variable*	1:200
D	[m]	Is the diameter of the container	*variable*	h/2,h/3

General remarks:

- The thickness of the piston remains half of the height of the container ($d_{piston} = \frac{h}{2}$)
- The wall thickness has been taken as a constant (1 m)
- Only material cost have been included; other cost facets: maintenance, demolition, equipment cost, labor, risk/profit, overhead, etc. are *not* included

J.1.1 ENERGY FUNCTION

$$\underbrace{E = \frac{1}{16} \cdot \pi \cdot D^2 \cdot h^2 \cdot \mu \cdot (\rho_{piston} - \rho_{water}) \cdot g}_{\text{Energy in Joules [J]}} \quad \rightarrow \quad \underbrace{\sum E = \frac{1}{16} \cdot \pi \cdot D^2 \cdot h^2 \cdot \mu \cdot (\rho_{piston} - \rho_{water}) \cdot g \cdot \nu}_{\text{Energy in [kWh] during a period of 50 years}} \qquad \text{Eq. (J.1)}$$

Where:

- $\nu = \frac{Period}{JtoKwH} = \frac{365 \text{ days} \cdot 50 \text{ years}}{3.6 \cdot 10^6}$ is the conversion factor from J to kWh during a period of 50
- $\sum E$ is the total amount of energy production during a period of 50 years [kWh]
- D is the diameter of the storage device [m]
- d is the thickness/height of the piston [m]
- g is the gravitational acceleration [m/s²]
- z is the potential elevation height [m]
- μ is the system efficiency [-]
- π is constant of 3.1495 [-]
- ρ_{piston} is the density of the piston [kg/m³]
- ρ_{water} is the density of water 1000 [kg/m³]

J.1.2 MATERIAL COST FUNCTION

In here, only the most crucial components have been taken into account. The material cost function can be described as following:

$$\sum Cost(h,D,€_{material}) = €_{foundation} + €_{wall} + €_{piston} + €_{RPT} \qquad \text{Eq. (J.2)}$$

In which the cost parameters are defined as follows:

Foundation - (D)

$$€_{Foundation} = \overbrace{0.99 \cdot \left[\underbrace{(2+2\cdot W_{wall}+D)^2}_{\text{Area of the foundation}} + \underbrace{\frac{1}{10}(2+2\cdot W_{wall}+D)}_{\text{Height of the foundation}} \right] \cdot €_{concrete}}^{\text{Cost concrete}} +$$

$$\overbrace{\left[4\cdot \left(\underbrace{\frac{1}{10}(2+2\cdot W_{wall}+D)}_{\text{Height of the foundation}} \cdot (2+2\cdot W_{wall}+D) \right) \right] \cdot €_{formwork}}^{\text{Cost formwork}} +$$

$$\overbrace{0.01\cdot \left[\underbrace{(2+2\cdot W_{wall}+D)^2}_{\text{Area of the foundation}} + \underbrace{\frac{1}{10}(2+2\cdot W_{wall}+D)}_{\text{Height of the foundation}} \right] \cdot €_{steel}}^{\text{Cost steel}}$$

Piston - (h, D)

$$€_{piston} = \underbrace{\frac{1}{4}\cdot \pi \cdot D^2 \cdot (\frac{h}{2})}_{\text{Volume of piston}} \cdot €_{material}$$

Wall - (h, D)

$$€_{wall} = \overbrace{\underbrace{0.97}_{\text{Concrete/Total volume ratio}} \cdot \underbrace{(\pi \cdot D \cdot W_{wall} \cdot h)}_{\text{Total volume}} \cdot €_{concrete}}^{\text{Concrete cost}} + \overbrace{\underbrace{(2\cdot \pi \cdot D \cdot 3.5 + 2\cdot W_{wall} \cdot 3.5 + \pi \cdot D \cdot W_{wall})}_{\text{Total formwork}} \cdot €_{climbing\_formwork}}^{\text{Formwork cost}}$$

$$+ \overbrace{\underbrace{0.03}_{\text{Concrete/Total volume ratio}} \cdot \underbrace{(\pi \cdot D \cdot W_{wall} \cdot h)}_{\text{Total volume}} \cdot €_{steel}}^{\text{reinforcement/prestressing cost}}$$

RPT – constant

The absolute cost of the RPT increases, with a larger power-output, however the efficiency of the RPT also increases with a larger power-output. The cost here is assumed to be a constant of 3 million euro.

$$€_{RPT} = €\ 3{,}000{,}000$$

APPENDIX K: SOFTWARE CODES

K.1 MATLAB

K.1.1 BENDING MOMENT

```
%% bending moment wall thickness/reinforcement
clear;
clc;
Mxx=[5E9:1E5:20E9]';
fyd=435;
b=1000;
%% hw = 800 mm
hw = 800;

F=Mxx/(0.75*hw);
As=F/fyd;
rho8=100*As/(hw*b);

%% hw = 1000 mm;
hw = 1000;
F=Mxx/(0.75*hw);
As=F/fyd;
rho10=100*As/(hw*b);
%% hw = 1200 mm;
hw = 1200;
F=Mxx/(0.75*hw);
As=F/fyd;
rho12=100*As/(hw*b);
%% hw = 1400 mm;
hw = 1400;
F=Mxx/(0.75*hw);
As=F/fyd;
rho14=100*As/(hw*b);
%% hw = 1600 mm;
hw = 1600;
F=Mxx/(0.75*hw);
As=F/fyd;
rho16=100*As/(hw*b);
%% hw = 1800 mm;
hw = 1800
F=Mxx/(0.75*hw);
As=F/fyd;
rho18=100*As/(hw*b);


%% hw = 2000 mm;
hw = 2000
F=Mxx/(0.75*hw);
As=F/fyd;
rho20=100*As/(hw*b);
%%
rho=[rho8 rho10 rho12 rho14 rho16 rho18 rho20];

plot(Mxx/1E6,rho); grid;
xlabel('Bending moment Mxx [kNm]','FontSize',13);
ylabel('\rho [%]','FontSize',13);
h_legend=legend('hw=800 mm','hw=1000 mm', 'hw=1200 mm','hw=1400 mm','hw=1600 mm','hw=1800 mm','hw=2000 mm');
set(h_legend,'FontSize',13);
set(gca,'XTick',[5E3:1E3:20E3])
```

K.1.2 SHEAR FORCE RESISTANCE CONCRETE

```
%%
%*shear force  STRUTTZ*
clear;
clc;

d(:,1)=[1:20000];
% parameters
fck = 50;
bw = 1000;

%% rho =0.01
rho=0.01;
k1=1+(sqrt(200./d));
Vrdc1=0.12.*k1*(100*rho*fck)^(1/3)*bw.*d;

%% rho =0.02
rho=0.02;
k2=1+(sqrt(200./d));
Vrdc2(:,1)=0.12.*k2*(100*rho*fck)^(1/3)*bw.*d;

%% plots
Vrdc=[Vrdc1 Vrdc2];
plot(Vrdc/1E3,d/1E3); grid
xlabel('Shear Resistance V_r_d_,_c
[kN]','FontSize',13);
ylabel('d [m]','FontSize',13);
h_legend=legend('\rho=1%','\rho=2%');
set(h_legend,'FontSize',13);
```

K.1.3 SHEAR FORCE VS. COT THETA

```
%%
%*shear force  STRUTTZ*
clear;
clc;

vEd(:,1)=[4E6:1E4:16E6];

fck = 50;
b = 1000;

%% d=1000

d=1000;

ved = (vEd./(b*d));

x=ved/(0.2*fck*(1-(1/250)*fck));

g0=0.5*asin(x);
b0=cot(g0);

%% d=1200
d=1200;

ved = (vEd./(b*d));

x=ved/(0.2*fck*(1-(1/250)*fck));

g2=0.5*asin(x);
b2=cot(g2);

%% d=1400
d=1400;

ved = (vEd./(b*d));

x=ved/(0.2*fck*(1-(1/250)*fck));

g4=0.5*asin(x);
b4=cot(g4);

%% d=1600
d=1600;

ved = (vEd./(b*d));

x=ved/(0.2*fck*(1-(1/250)*fck));

g6=0.5*asin(x);
b6=cot(g6);

%% d=1800
d=1800;

ved = (vEd./(b*d));

x=ved/(0.2*fck*(1-(1/250)*fck));

g6=0.5*asin(x);
b8=cot(g6);
%%

b=[b0 b2 b4 b6 b8]

plot(vEd(:,1)/1E3,b); grid
xlabel('Shear Force V_e_d [kN]','FontSize',13);
ylabel('cot(\theta) [-]','FontSize',13);
h_legend=legend('d=1000 mm', 'd=1200 mm','d=1400 mm','d=1600 mm','d=1800 mm');
set(h_legend,'FontSize',13);
set(gca,'XTick',[4E3:1E3:20E3])
```

K.1.4 COST OPTIMIZATION

Function file

```
function europkwh = europerkwh(D,h,rho_piston,piston_price)
%% energy function
rho_water=1000;
g=9.81;
mu=0.57;
jtokwh=3.6E6;
pvj=365*50;     %totale kwh in 50 jaar
kwh=((((1/16).*(rho_piston-rho_water).*mu.*D.^2*pi*g.*h.^2))./jtokwh).*pvj; %.*pvj
%% the foundation
n=0.99; %reinforcement ratio
cost_concrete= 120; % cost per m3
cost_formwork= 50;% in €/m3
cost_reinforcement=6240;
w_wallz=1;% wall width
ftot_vol_concrete=(2+2*w_wallz+D).^3/10;
ftot_vol_formwork=(2+2*w_wallz+D).^2+4*(1/10).*(2+2*w_wallz+D).*(2+2*w_wallz+D);
costf=n.*cost_concrete*ftot_vol_concrete+(1-
n).*cost_reinforcement.*ftot_vol_concrete+cost_formwork.*ftot_vol_formwork; %total cost in euros
%% wall
% overview
n_w=0.97; % reinforcement ratio
cost_concrete= 120; % cost per m3
cost_climbing_formwork= 450;% in €/m3
cost_reinforcement=6240;
w_wallz=1; % thickness of the wall (1 m)
vol_wall=pi.*D*w_wallz.*h;
form_wall=2*pi.*D*3.5+2*w_wallz*3.5+pi.*D*w_wallz;
costw=(n_w).*vol_wall.*cost_concrete+(1-
n_w).*vol_wall.*cost_reinforcement+form_wall.*cost_climbing_formwork;
%% pistons
V_piston=(1/4)*pi*D.^2.*(h/2); %
costp=V_piston*piston_price;
%% Cost mechanical components
RPT=3E6;

%% europerkwh
europkwh= (costf+costw+costp+RPT)./kwh
```

Plot file

```
%% In this file, the energy/kwh will be determined
clear;
clc;

%% priston prices
price_sand=4;
price_concrete=120;
price_ironore=535.5;
price_leadore=6799;
%% piston densities
rho_sand=2100;
rho_concrete=2500;
rho_ironore=5100;
rho_leadore=7600;


%% Plot of D and h 2/1
D=[30:100]';
h=[2*D];

% lead ore piston
ppkwh_lead=europerkwh(D,h,rho_leadore,price_leadore);
% iron
ppkwh_iron=europerkwh(D,h,rho_ironore,price_ironore);
% concrete
ppkwh_concrete=europerkwh(D,h,rho_concrete,price_concrete);
% concrete
ppkwh_sand=europerkwh(D,h,rho_sand,price_sand);

% subplot(2,1,1)
% plot(h,ppkwh_lead,'b'); xlabel('Height h [m]','Fontsize',13);
% ylabel('€ / kWh','Fontsize',13); title('Price Material vs height container (h=2\bulletD)','FontSize', 15); hold on
% plot(h,ppkwh_iron,'r'); hold on
% plot(h,ppkwh_concrete,'black'); hold on
% plot(h,ppkwh_sand,'g'); hold on
% plot([h(1) h(end)],[0.04 0.04], '-.m'); hold off
% h_legend=legend('lead ore','Iron ore','Concrete','Sand','Target Value');
% set(h_legend,'FontSize',12);


plot(h,ppkwh_sand,'g'); title('Price Material vs height container (h=2\bulletD)','FontSize', 15); hold on
xlabel('Height h [m]','Fontsize',13);
ylabel('€ / kWh','Fontsize',13);
plot([h(1) h(end)],[0.04 0.04], '-.m');
axes1=gca;
set(axes1, 'XAxisLocation',  'bottom');
h_legend=legend('Sand','Target Value');
set(h_legend,'FontSize',12);
hold off;


%% Plot of D and h 3/1
D=[20:100]';
h=[3*D];

% lead ore piston
ppkwh_lead=europerkwh(D,h,rho_leadore,price_leadore);
% iron
ppkwh_iron=europerkwh(D,h,rho_ironore,price_ironore);
% concrete
ppkwh_concrete=europerkwh(D,h,rho_concrete,price_concrete);
% concrete
ppkwh_sand=europerkwh(D,h,rho_sand,price_sand);

% subplot(2,1,2)
% plot(h,ppkwh_lead,'b'); xlabel('Height h [m]','Fontsize',13);
% ylabel('€ / kWh','Fontsize',13); title('Price Material vs height container (h=3\bulletD)','FontSize', 15); hold on
% plot(h,ppkwh_iron,'r'); hold on
% plot(h,ppkwh_concrete,'black'); hold on
% plot(h,ppkwh_sand,'g'); hold on
% plot([h(1) h(end)],[0.04 0.04], '-.m'); hold off
% h_legend=legend('lead ore','Iron ore','Concrete','Sand','Target Value');
% set(h_legend,'FontSize',12);



% subplot(2,1,2)
% plot(h,ppkwh_sand,'g');  title('Price envelope sand piston vs Dimensions {D=h/3}','FontSize', 15);
% xlabel('Height h [m]','Fontsize',13);
% ylabel('€ / kWh','Fontsize',13);
% axes1=gca;
% set(axes1, 'XAxisLocation',  'bottom');
% hold off;
```

K.2 MAPLE

K.2.5 PRELIMINARY DESIGN

```
restart; with(plots);
print(`output redirected...`); # input placeholder

print(??); # input placeholder
rho[piston] := 12250; rho[water] := 1000; E := 148500000000*(1/6); g := 9.81; mu := .57;
print(`output redirected...`); # input placeholder


print(`output redirected...`); # input placeholder


h := proc (Dm) options operator, arrow; sqrt(E/(((1/16)*rho[piston]-(1/16)*rho[water])*g*mu*Pi*Dm^2)) end proc;
print(`output redirected...`); # input placeholder



y := proc (x) options operator, arrow; x*1.6 end proc;
print(`output redirected...`); # input placeholder
gg := plot(y, 0 .. 100, linestyle = dot, color = green);
print(`output redirected...`); # input placeholder
zz := plot(80, 0 .. 100, linestyle = dash, color = red);
%;


hh := plot(h, 0 .. 1000, view = [0 .. 100, 0 .. 100], labels = [Diameter*D, Height*h], color = blue, gridlines =
true, labelfont = [Arial, roman, 14], labeldirections = [horizontal, vertical]);
print(`output redirected...`); # input placeholder

display(hh, gg, zz);
%;



evalf(h(50));
print(`output redirected...`); # input placeholder



Buffering
yearly := 1000*(4000*3600)*1.5;
print(`output redirected...`); # input placeholder
daily := (1/365)*yearly; daily2 := 2*daily; daily3 := 3*daily;
print(`output redirected...`); # input placeholder
weekly := 7*daily;
print(`output redirected...`); # input placeholder
monthly := 4*weekly;
print(`output redirected...`); # input placeholder
seasonaly := 3*monthly;
print(`output redirected...`); # input placeholder
print(??); # input placeholder



rho[piston] := 12250; rho[water] := 1000; g := 9.81; mu := .57;
print(`output redirected...`); # input placeholder
d := 20; h := 50; households := 10000;
print(`output redirected...`); # input placeholder

hzz := evalf(17800000000/(((rho[piston]-rho[water])*(1/4))*Pi*Dmz^2*d*g*mu)+d);
print(`output redirected...`); # input placeholder


Dm := evalf(sqrt(daily*households/(((rho[piston]-rho[water])*(1/4))*Pi*h*d*g*mu*(1-d/h))));
print(`output redirected...`); # input placeholder




Dm := evalf(sqrt(weekly*households/(((rho[piston]-rho[water])*(1/4))*Pi*h*d*g*mu*(1-d/h))));
print(`output redirected...`); # input placeholder



Dm := evalf(sqrt(monthly*households/(((rho[piston]-rho[water])*(1/4))*Pi*h*d*g*mu*(1-d/h))));
print(`output redirected...`); # input placeholder



Dm := evalf(sqrt(seasonaly*households/(((rho[piston]-rho[water])*(1/4))*Pi*h*d*g*mu*(1-d/h))));
print(`output redirected...`); # input placeholder


Dm := evalf(sqrt(yearly*households/(((rho[piston]-rho[water])*(1/4))*Pi*h*d*g*mu*(1-d/h))));
print(`output redirected...`); # input placeholder
```

APPENDIX LIST OF FIGURES AND TABLES