Delft University of Technology, MSc. Thesis Civil Engineering

# Pumped hydropower storage in the Netherlands

## *APPENDICES*


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*These appendices are to be used in accordance with the main document titled similarly.*

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# Appendix A Part A further reading

## 1. ***Past and future wind***

Already before the windmill, the wind's power was used for sailing to undiscovered continents, while the first application of wind as a power source was as a grinding mill or water pump.

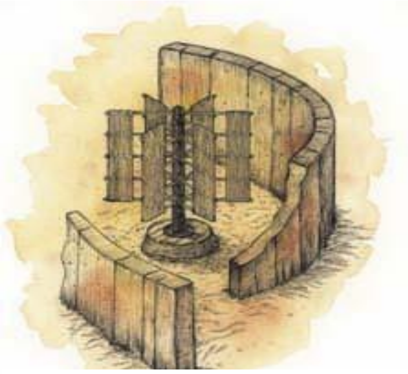

*Figure 1 … Earliest designs of windmills from Persia ([WebEcoist](), 2009)*

The first windmills date back to 4$^{th}$ century B.C. in either ancient Babylonia (or possibly Arthasastra).[1] The Babylonian emperor Hammurabi utilized wind power for his massive irrigation projects. The first design sketches (see Figure 1) date back to early Persian empires around 200 B.C., using a rotating vertical axis attached with wicks made from bundles of reeds and wood. The development made a large leap in the early medieval Europe, who transformed the mill into one with a horizontal axis, which resembles modern style windmills. Especially the Dutch developed new types of mills, e.g. using airfoil in their wicks to increase efficiency. They were now used for applications such as draining marshland in Holland. Early Dutch settlers brought the mill technology along to America along 1700-1800 and continued development.

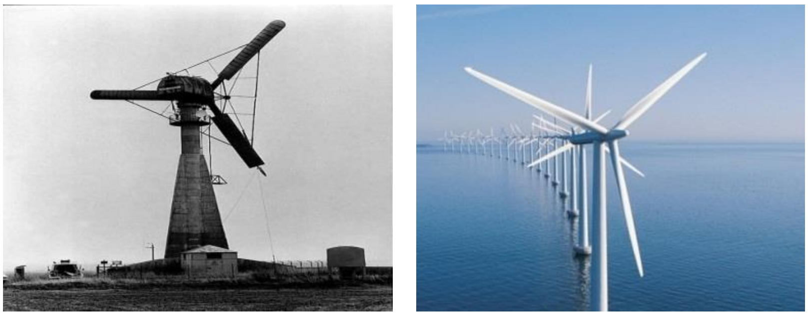

*Figure 2 ... (left) Danish concept of Gedser wind turbine designed (AE3W02TU Introduction to Wind Energy, 2013) and right (Currently most used wind turbine (VOZT, http://www.vozt.nl/2010/nieuws/offshore-windenergie/, 2010)*

The current concept of wind turbine (see Figure 2 right) finds its origins in the plans of Johannes Juul of Denmark designed in 1956 what is now known as the 'Danish wind turbine concept', designed based upon the aerodynamic principles using smaller wicks; rotors (see Figure 2 left).

In early 20$^{th}$ century, the cost for wind power was about 12-30 cents/kWh, while fossil fueled costs ranged from 3-6 cents/kWh. Along the years, the price of power from fossil sources continued to drop while development of wind energy was almost put to a halt.[2] With respect to prices, a turning point has past now that wind power is getting cheaper as fossil power costs rise.

With more installments and the lowering price for wind power, wind power development is increasing. The turbines are expanding especially in terms of power capacity and size with rotor lengths of up to 80m

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[1] *Sathyajith Mathew, Wind Energy, 2006*
[2] *E.H. Lysen, Introduction to wind energy, 1982*

Whereas 3 MW turbines are common today, future planned wind farms already incorporate future development and assume 8 MW plants for their wind farm. [3,4]

Due to the size of these windmills, they are preferably used for offshore purposes. Offshore, much greater wind speeds, capacity factors and less visual blockage is experienced.

Maintenance is a large portion of the costs of offshore wind farms. With larger capacity windmills, fewer numbers will be required, lowering the maintenance costs.

# 2. *Wind power fundamentals*

Due to the imbalance of sun's radiation, some parts of the globe heat up more than others. This is affected by time of day, adsorption rate of the specific soil and the earth's natural rotation. Because of this, some areas heat up and the air rises and becomes less dense than other areas. Since also air flows from dense areas to less dense areas; airflow is started which we name wind. Although not very dense, air does have mass. This means that if air is in motions, it contains kinetic energy. With this understanding, the definition of wind energy can be given: wind energy is the transfer of the kinetic energy in moving air to electrical energy or mechanical energy.[5]

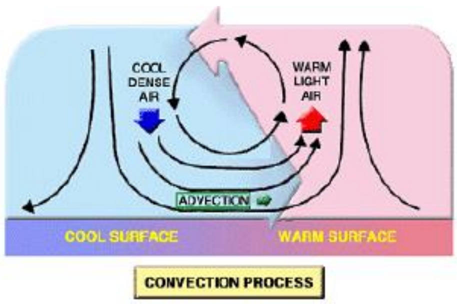
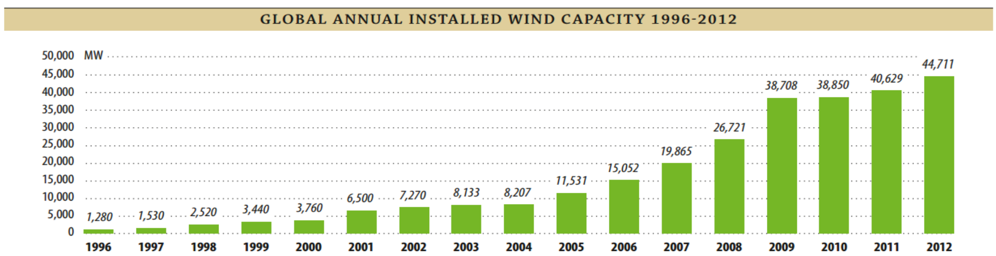



*Figure 3 … Convection process explained (NASA, 2009)*

# 3. *Global and European wind power*

Currently covering 7% of global power demand, wind power is the fastest rising energy source in the world. Both the cumulative installed wind power and the growth are rising. The total installed capacity in 2012 was equal to 282.482 MW (*see Figure 4*), of which China has the largest share with 75.564 MW. These numbers indicate that the potential for wind power is increasingly utilized and the power source is attractive for investment. Estimations consider a global installed capacity of 1.2 million MW by 2020.[6]

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[3] *Vesta, 2013*
[4] *Windpark Noordoostpolder, 2013*
[5] *Wind Energy, Encyclopedia Britannica*
[6] *GWEC, Global wind statistics, 2012*

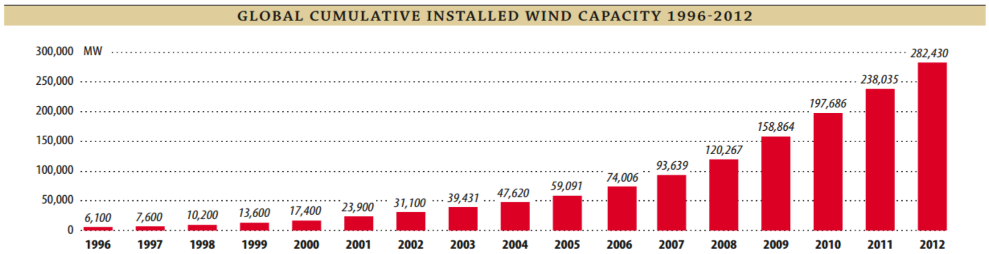



*Figure 4 … (Top) Global annual installed wind capacity and (bottom) global cumulative installed wind capacity 1996-2012 (GWEC, 'Global wind statistics', 2012)*

Out of the modern RES (geothermal, wind, solar, tidal, biofuel), wind power is the most mature technology and already a lot of experience is acquired with wind power. In Europe the application of wind power is led by Germany with a total installed capacity of 29060 MW in 2011, followed by Spain with 21674 MW (*see Figure 5*). Especially in Eastern Europe the installed capacity is relatively low.

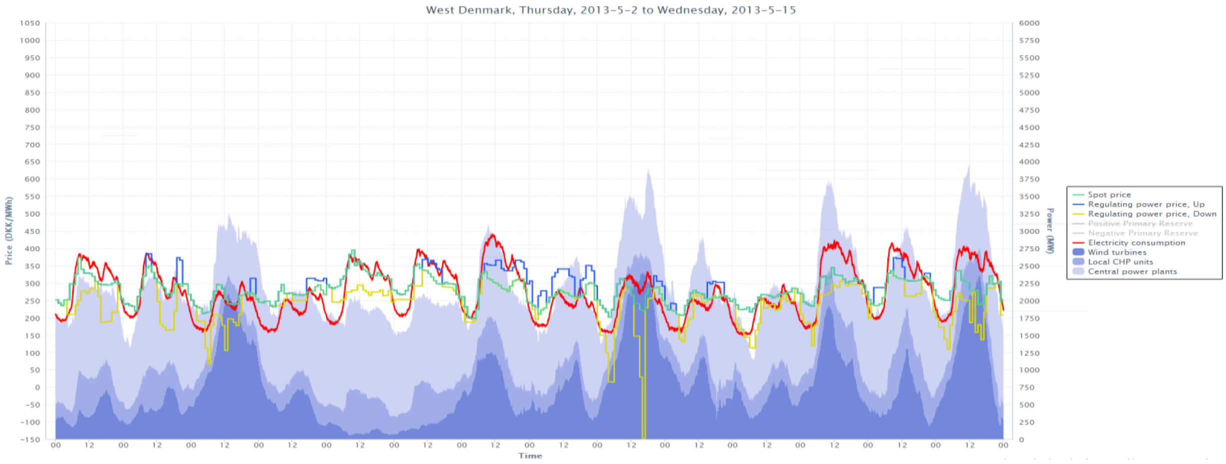

*Figure 5 … Wind power installed (MW) in Europe by the end of 2011 (EWEA, Annual Report 2011, 2012)*

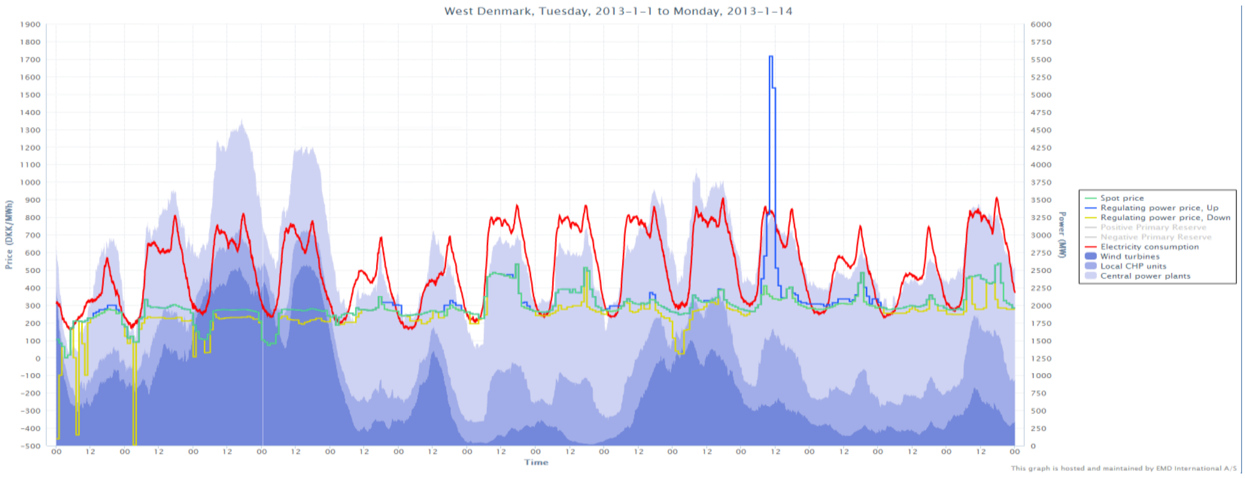
# Appendix B Wind data

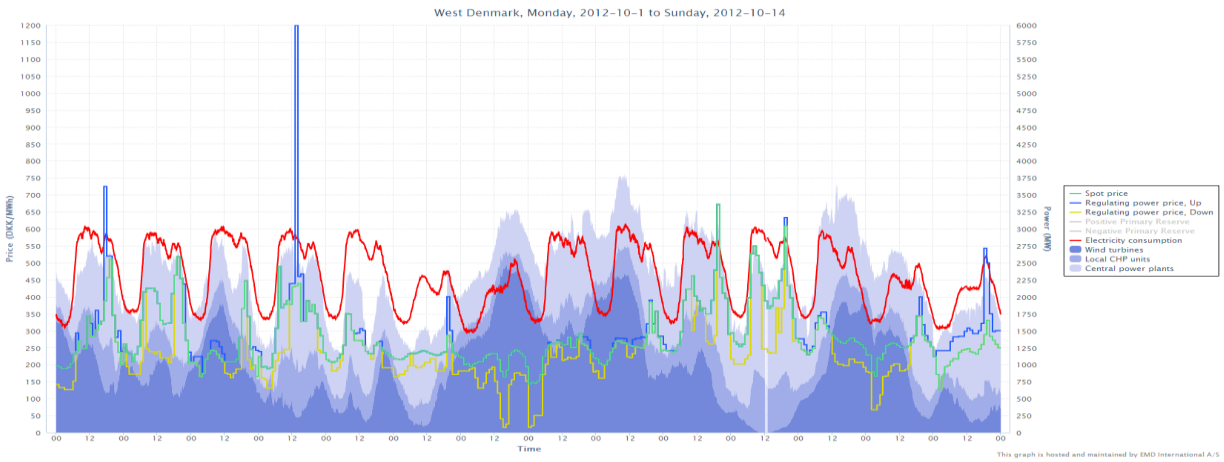
## 1. ***Danish wind power output data***

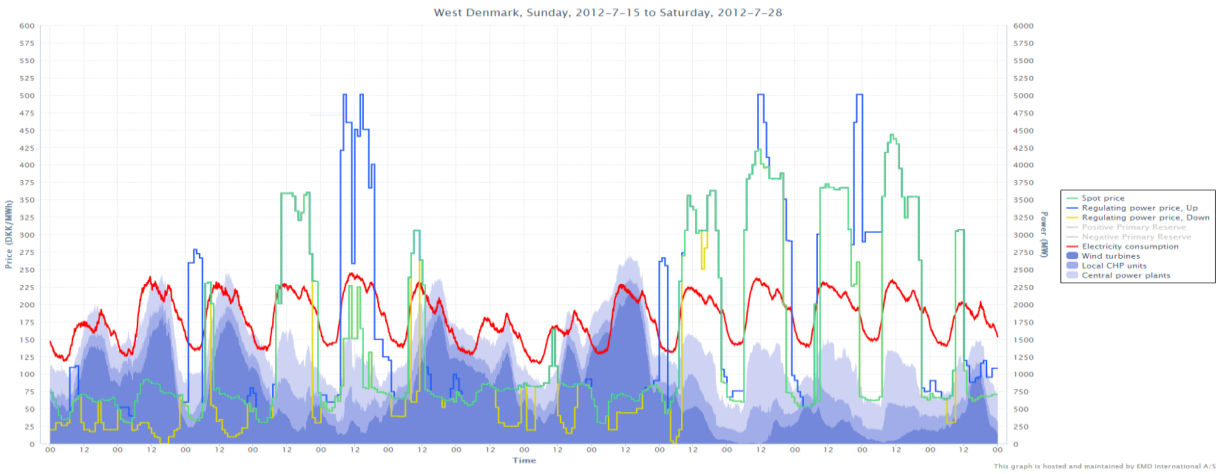
Here are some snapshots of different data around the year of the Western Danish daily load curves displaying supply of wind, CHP, central power plants in relation to the demand and energy prices.

Analysis from the data shows some interesting trends in the wind power output. Western Denmark has enough installed wind power capacity to supply (nearly) the full demand with wind energy.






## 2. *Wind data Hoek van Holland: wind directions*


***Table 1 ... Wind direction distribution over the year 2012***

# Appendix C Description storage techs

The storage systems can be divided into three categories:

- Mechanical systems (PHS, CAES, flywheels)
- Electrical systems ((super)capacitors, superconducting magnetic energy storage (SMES)
- Chemical/electrochemical (flow-, Li-ion-, NaS batteries, hydrogen fuel cells)

## 1. *Pumped hydro-electricity storage (PHS)*

Traditionally used with two reservoirs, one upper and one lower, filled with water. The water is pumped from the lower one into the upper reservoir during low demand. During high demand, the water is released using gravity to pass through a turbine to generate energy. PHS is suited for large-scale solutions and the system can be operating in a matter of minutes. The system is very dependent on geographical conditions as the energy capacity is dependent on a height of the free fall and the size of the reservoirs. Depending on geographical situation, high primary investment is required, after which operating costs are small. PHS is suitable for long-term or short-term storage and can thus be used to either balance out the daily fluctuations as well as the seasonal variations. Long experience has led to optimized turbines with high efficiencies, ranging from 75% to 85%. The concept dates back to early 20th century during which the first PHS systems were built.

There is wide variety of possible design alternatives, e.g. using an elevated reservoir, an underground reservoir, natural reservoirs (the sea, a river) and large surface PHS.

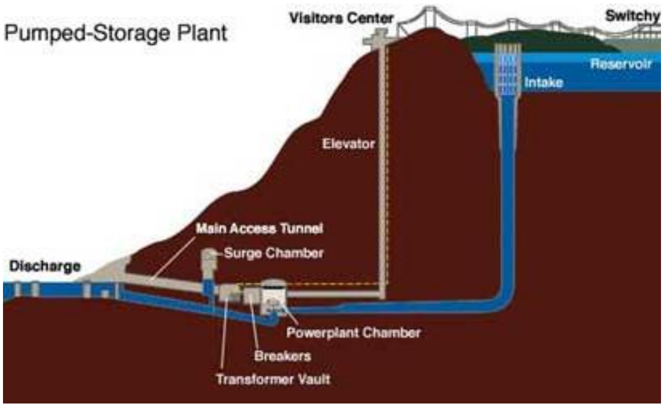



*Figure 6 ... Schematization PHS (bravenewclimate.com)*

## 2. *Compressed air energy storage (CAES)*

Compressed air energy storage (CAES) uses underground holes, cavities and empty mines to pump compressed air inside them during low demand. This air is then used to fire a gas-fired turbine to generate electricity during high demand. CAES is suitable for large-scale storage and is a system with a quick response time. While there are only two major CAES systems working right now, their big disadvantage is their efficiency of 42%.[7] Like PHS, also CAES is suitable for either long- or short-term fluctuations.

[7] *The Economist, Energy storage packing some power, 2012*

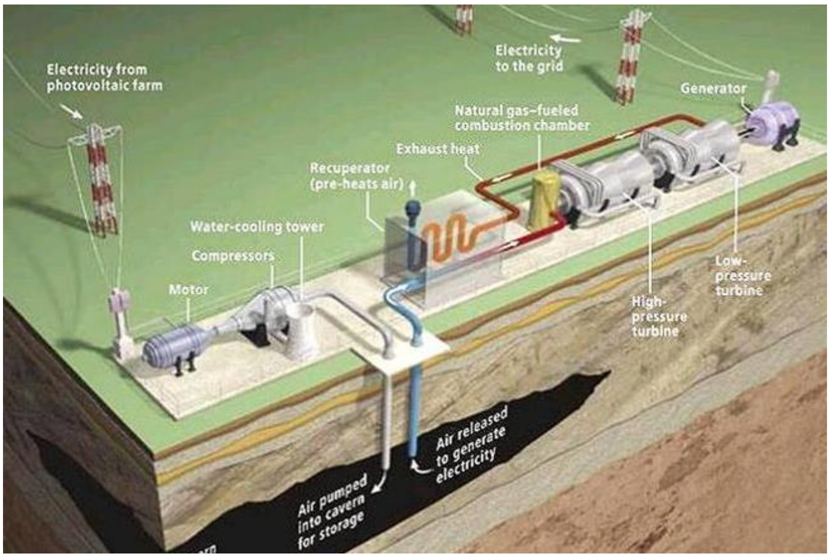



*Figure 7 ... Schematization of CAES (climatetechwiki.org)*

# 3. *Flywheels and other mechanical storage*

Flywheels are heavy symmetrical masses that are charged by rotation around an axis. Making direct use of Newton's 2nd law $F = m * a$, this system works by accelerating the heavy mass and making it spin around an axis with a turbine. Flywheels are mainly used for small-scale and short-term energy storage, for example in vehicles. The solution is restricted in energy capacity, since the creation of a large flywheel is very expensive. Overall, flywheels perform well for systems that require very quick response, quick charging, high power density and high efficiency.

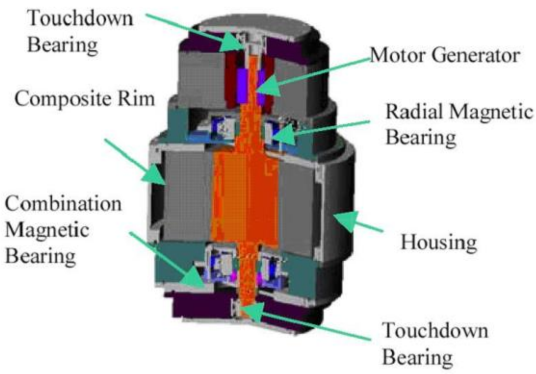



*Figure 8 ... Schematization of a flywheel (climatetechwiki.org)*

# 4. *Chemical storage alternatives*

Batteries are widely represented in this category, divided into electrochemical and thermo-chemicals.

Lead-acid (Pb-acid) batteries are the most conventional ones. Using a lead anode and lead acid cathode inside a dilute sulfuric acid electrolyte, energy is generated by running a current. Most used way of small-scale energy storage, they offer low cost with high availability. However using acid makes it dangerous, it requires high maintenance and it has a low cycle life.

Sodium-sulfur (Na-S) batteries utilize a high temperature reaction between sodium and sulfur. The benefits are excellent life cycle, high energy density and experience has proven them working well at peak balancing energy demand.[8] However they are expensive and require high temperature to operate.[9]

Flow batteries use electro-active materials to store and convert chemical energy into electricity. They are divided into redox and hybrid. They can be used for large-scale, however they not as developed enough to be competitive with the other storage solutions.

Nickel metal hybrid (Ni-MH) batteries are the follow up of the well-known nickel cadmium batteries. Using nickel oxyhydroxide as cathode, a potassium hydroxide electrolyte and a hydrogen-absorbing alloy serving as a source of reduced hydrogen, which can be oxidized to form protons. In almost all field do they beat the lead-acid batteries, except that they are expensive and also contain toxic material, i.e. cadmium.


*Figure 9 ... An example of a chemical storage alternative: the battery*

The last type that is discussed is the lithium-ion (Li-ion) battery. They work through the transfer of ions from the cathode to the anode to generate electricity. This type of battery performs well with high density of energy, however is quite expensive and lithium is hard to get by.

# 5. ***Hydrogen fuel cells***

Fuel cells generate and store electricity when the anode (the fuel) and cathode (the oxidant) react with one another inside an electrolyte. With a constant inflow of reactants and products the energy production will be continuous. The reverse reaction is possible with the input of electricity. This sounds like a battery; however the reactants in a fuel cell are consumed and must be replenished. In hydrogen fuel cells, hydrogen is used as a reactant and oxygen as an oxidant to form water and electricity. They pack in very high-density energy. Fuel cells are suitable for both large-scale as well as small-scale systems. For hydrogen fuel cells the output is water when producing energy and hydrogen and oxygen when storing energy. However the technology hasn't matured yet as the efficiency is low and costs are high.[10]

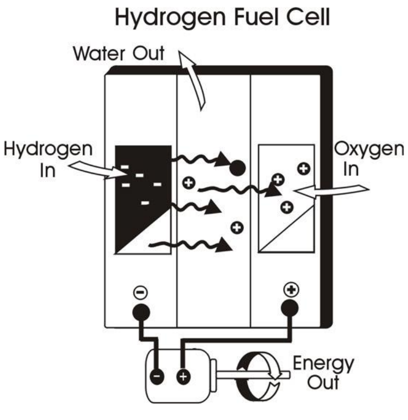



*Figure 10 ... Workings of a hydrogen fuel cell*

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[8] *Chen HS et al., Progress in electrical storage system: a critical review. Prog Nat Sci 2009;19:291–312, 2013*
[9] *Walawalkar R, Apt J. Market analysis of emerging electric energy storage systems, Carnegie Mellon Electricity Industry Center, National Energy Technology Laboratory; 2008*
[10] *Chen HS et al, Progress in electrical storage system: a critical review. Prog Nat Sci 2009;19:291–312, 2013*

# 6. *Electrical systems*

Capacitors work by saving the energy between two electrodes separated by an insulating material. They are no longer a popular energy storage solution as they offer low energy capacity and energy density and super capacitors are largely taking over.

Supercapacitors or ultracapacitors that utilize double layer of capacitors are a kind of advanced capacitors. They have a large energy density, offer quick recharges, but are rather expensive. Examples with wind turbines have shown that they decrease voltage and power fluctuations.

Superconducting magnetic energy storage (SMES) uses a superconducting coil to store the energy inside applying a magnetic field. It has a very balancing characteristic, offering voltage and other dynamic stability. There are very low energy losses, with an efficiency of up to 95%, however it's a very expensive system.[11]

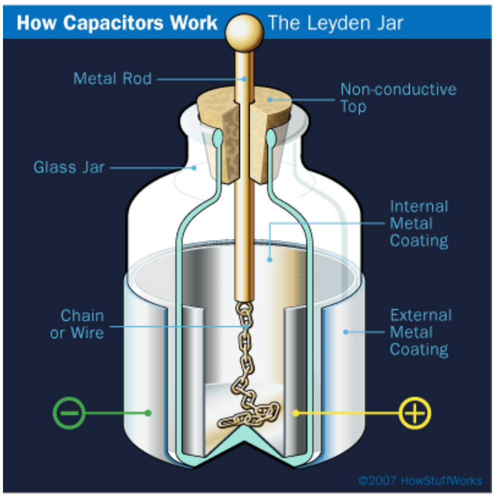


*Figure 11 ... How capacitors work (Howstuffworks.com)*

# 7. *Thermal storage*

Thermal energy is divided into high temperature and low temperature, which is again divided into aquifer low temperature energy storage (AL-TES) and cryogenic energy storage (CES). Only CES is applicable for storage through electricity, making use of energy to create a cryogenic fluid, which can be used in a cryogenic heat engine to generate energy. Still a developing technology, its expectation are high energy density, long term use, low cost per kWh, however the downside is its low efficiency around 40-50%.[12]

High temperature storage is divided into latent and sensible. Sensible heat storage uses heat of media such as steam, hot water, graphite, concrete and hard rock to store energy. The heat is acquired when required. Benefits are mainly centered on low investment costs, because the energy density is quite low. Lastly latent heat systems use high temperature phase changing, e.g. metals, paraffin and inorganic salts to store energy. The system uses transformations of the material at steady temperature. The heat is then transferred through a fluid. The result is a way higher energy density with respect to sensible storage.

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[11] *Honghai K and Zhengqiu W, Research of super capacitor energy storage system based on DG connected to power grid, In: International Conference on Sustainable, Power Generation and Supply, 2009. SUPERGEN '09. IEEE. 2009. p. 1–6*
[12] *Chen HS et al, Progress in electrical storage system: a critical review. Prog Nat Sci 2009;19:291–312, 2013*

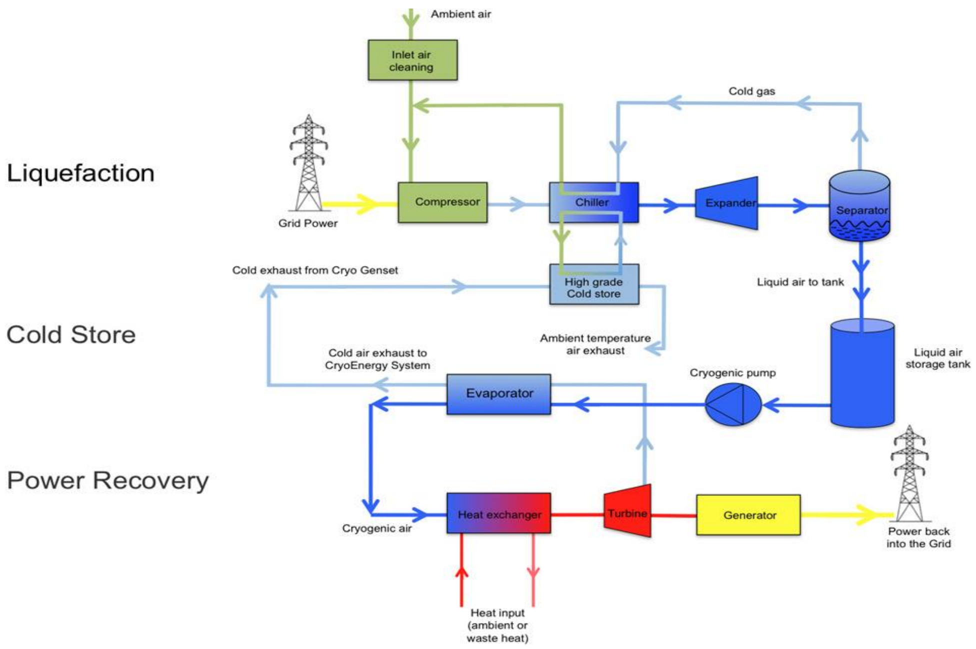



*Figure 12 ... Cryogenic Utility-Scale Power Storage for Load Leveling 50% Efficient, [Afin2300.com](Afin2300.com)*

# 8. *'Energy storage' by European market transfer*

The functioning of the European market is discussed previously an option to put excess power inside the grid and collecting it from the grid. The hypothesis is that there is always a need for energy somewhere in Europe, to which it can be sent through the grid when demand is low at this particular region. According to the theory, there will always be a balance with this transfer of energy. The advantages and disadvantages have been discussed largely. The operating areas of the top electricity companies have been put forward already. These areas comprise most of Europe. It is therefore not unimaginable that these companies should vow for increased transmission of electricity in between regions in which they operate, e.g. supplying their customers in the Netherlands of excess energy produced in Germany. This option however is not a technical solution, but rather a political and socio-economic one. Since the operation of this alternative is neither a technical question, nor one of engineering, this option is not considered in the selection procedure.

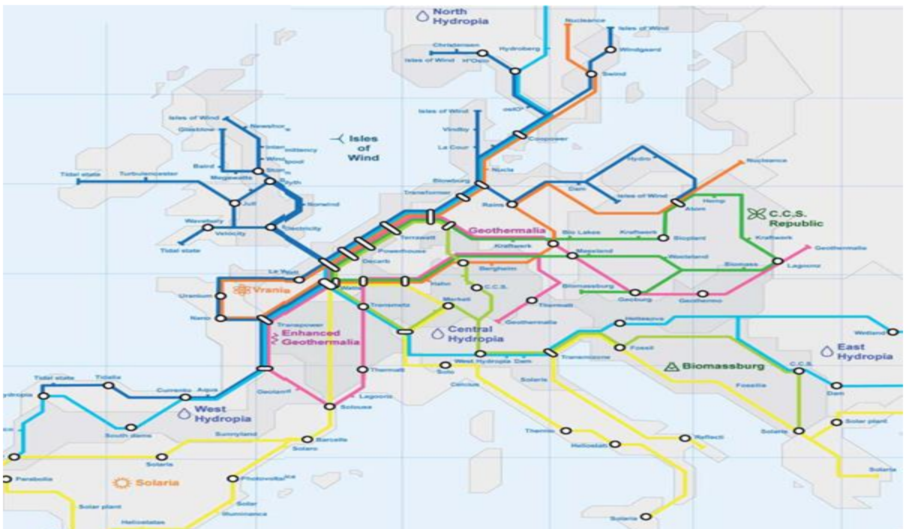



*Figure 13 ... European energy trade (OMA, Roadmap 2050, 2012)*

# Appendix D MAPLE Models

## 1. *Gravity power*

Displayed with the variables for the BEST CASE situation:

> $restart;$

> $E_{cap} := \mathrm{A}\cdot\left(\rho_{piston} - \rho_{water}\right)\cdot t\cdot z\cdot g\cdot \mathrm{eta};$

> $g := 9.8; \rho_{piston} := 3200; \rho_{water} := 1000; A := \frac{1}{4}\cdot evalf(\mathrm{Pi})\cdot d^2; h := 1058; t := 500; z := h - t; \mathrm{eta} := 0.7; d := 6.7; V_{sand} := A\cdot t;$

> $E_{joule} := evalf\left(E_{cap}\right);$

> $E_{GWh} := \frac{E_{joule}}{3.6\cdot 10^{12}};$

## 2. *Energy Island*

> $restart;$

> $E_{cap} := \frac{1}{2}\cdot \mathrm{rho}\cdot g\cdot A\cdot\left(h_0^2 - h_1^2\right)\cdot \mathrm{eta};$

> $A := 100\cdot 10^6; g := 9.8; \mathrm{rho} := 1025; h_0 := -40; h_1 := -32; \mathrm{eta} := 0.7;$

> $E_{joule} := evalf\left(E_{cap}\right);$

> $E_{GWh} := \frac{E_{joule}}{3.6\cdot 10^{12}};$

## 3. *Slufter alternatives*

> $E_{cap} := \frac{1}{2}\cdot \mathrm{rho}\cdot g\cdot A\cdot\left(h_0^2 - h_1^2\right);$

> $A := 2.8\cdot 10^6 : g := 9.8 : \mathrm{rho} := 1025 : h_0 := 28 : h_1 := 0 : E_{joule} := evalf\left(E_{cap}\right); E_{GWh} := \frac{E_{joule}}{3.6\cdot 10^{12}};$

> #power capacity

> $X := 1 : \mathrm{eta} := 0.8 : Q := 230 : P_{maximum} := X\cdot\frac{\left(\mathrm{rho}\cdot g\cdot h_0\cdot Q\cdot \mathrm{eta}\right)}{10^6};$

> $T_{hours} := \frac{E_{joule}}{P_{maximum}\cdot 10^6\cdot 3600};$

> $restart;$ #Energy capacity with dam and turbine in middle

> $E_{cap2} := \frac{1}{2}\mathrm{rho}\cdot g\cdot A\cdot\left(\left(h_0^2 - h_1^2\right) - \left(h_0 - h_1\right)^2\right)\cdot \mathrm{eta};$

> $\mathrm{eta} := 0.8; A := 1.2\cdot 10^6 : g := 9.8 : \mathrm{rho} := 1025 : h_0 := 70 : h_1 := 56 : E_{joule2} := evalf\left(E_{cap2}\right); E_{GWh2} := \frac{E_{cap2}}{3.6\cdot 10^{12}};$

> $Q := 465 : \mathrm{eta} := 0.8 : X := 1 : P_{maximum} := X\frac{\left(\mathrm{rho}\cdot g\cdot Q\cdot h_0\cdot \mathrm{eta}\right)}{10^6};$

> $P_{power} := 4 \cdot 125$; $Q_{real} := \dfrac{P_{power} \cdot 10^6}{\text{rho} \cdot g \cdot (h_0) \cdot \text{eta}}$;

> $V := A \cdot h_0$; $T := \dfrac{V}{Q_{real} \cdot 3600}$

> *restart*; **#formule vdToorn komt hetzelfde uit!**

> $E_{cap3} := \frac{1}{2} \text{rho} \cdot A \cdot g \cdot H_1^2 + \frac{1}{2} \cdot \text{rho} \cdot g \cdot A \cdot H_2^2$;

> $A := 1.4 \cdot 10^6 : g := 9.8 : \text{rho} := 1025 : H_1 := \frac{51}{2} : H_2 := \frac{51}{2} : E_{joule3} := evalf(E_{cap3})$;

$E_{GWh3} := \dfrac{E_{cap3}}{3.6 \cdot 10^{12}}$;

> *restart*; **#Energy capacity with dam in middle and turbines on the sides**

> $E_{cap} := \frac{1}{2} \cdot \text{rho} \cdot g \cdot A \cdot (h_0^2 - h_1^2) + \frac{1}{2} \cdot \text{rho} \cdot g \cdot A \cdot (h_2^2 - h_3^2)$;

> $A := 1.4 \cdot 10^6 : g := 9.8 : \text{rho} := 1025 : h_0 := 23 : h_1 := 0 : \text{h}_2 := 28 : h_3 := 0 : E_{joule}$

$:= evalf(E_{cap})$; $E_{GWh} := \dfrac{E_{joule}}{3.6 \cdot 10^{12}}$;

> $Q_1 := 200 : Q_2 := 250 : \text{eta} := 0.8 : X := 1 : P_{left} := X \cdot \left( \dfrac{(\text{rho} \cdot g \cdot h_0 \cdot Q_1 \cdot \eta)}{10^6} \right)$; $P_{right} := X$

$\cdot \left( \dfrac{(\text{rho} \cdot g \cdot h_2 \cdot Q_2 \cdot \eta)}{10^6} \right)$; $P_{maximum} := P_{left} + P_{right}$

> *restart*; **# expansion of reservoir**

> $E_{cap2} := \frac{1}{2} \text{rho} \cdot g \cdot A \cdot \left( (h_0^2 - h_1^2) - (h_0 - h_1)^2 \right)$;

> $A := 1.4 \cdot 10^6 : g := 9.8 : \text{rho} := 1025 : h_0 := 58 : h_1 := \frac{51}{2} : E_{joule2} := evalf(E_{cap2})$; $E_{GWh2}$

$:= \dfrac{E_{cap2}}{3.6 \cdot 10^{12}}$;

> **#power capacity**

> $X := 1 : \text{eta} := 0.8 : Q := 501 : P_{maximum} := X \cdot \dfrac{(\text{rho} \cdot g \cdot h_0 \cdot Q \cdot \text{eta})}{10^6}$;

# Appendix E MCA

## 1. *Introduction*

A *Multi Criteria Analysis* (MCA) will be used to determine the value of the different alternatives. An MCA is a scientific method to attempt to determine the value of different alternatives in a rational and objective way. The objectives of an MCA are organizing, increasing the transparency of decision making and supporting decision makers in their choice. The analysis is based upon different criteria, which are determined based upon the stakeholder's analysis and value-variables. These criteria have unequal importance and thus have a different influence on the final solution. This factor is called the weight factor and is determined with a *Weight Matrix* (*see* Table 49).

## 2. *Primary MCA*

### Criteria

The different criteria that have an influence on the solution are explained here. These criteria have been based on the characteristics of the alternatives, problems and desired situation for the area. Many aspects are very subjective and educated guesses are needed here to determine their value.

The following criteria will be taken into account here (with their abbreviation between brackets) and are explained below:

- *Compactness (COMP)*
- *Constructability & construction time (CONSTR)*
- *Costs (COST)*
- *Durability, reliability & proven technology (DURA)*
- *Economic benefits & added value (BENEF)*
- *Esthetics & visual/physical obstruction (ESTH)*
- *Extensibility (EXTEN)*
- *Geographical dependency (GEODEP)*
- *Large Scale applicability (LSCALE)*
- *Power generating capacity (POWER)*
- *Risks & safety feeling (RISK)*
- *Sustainability & Ecology (SUSTAIN)*

***Compactness***

Since the reservoirs require a lot of space to store large amounts of energy, this is a rather important aspect. Land space is scarce for the Netherlands and therefore a solution which is compact and utilizes water space of a subsoil space has the preference.

***Constructability & construction Time***

It is preferable that an alternative is easily constructed. The amount of works that need to be done as well as how complicated these works are, determine to a large degree whether an alternative easily constructed. The construction time is the time required to realize the alternative from start to end of construction. The correlation that the construction time has with the total costs is disregarded here.
E.g. If alternative 2 takes 10 months longer to build than alternative 1, then this extra construction time influences the costs (like more rent of equipment, etc.). This influence is already taken into account under

construction costs and doesn't need to be taken into account here again. Instead, construction time affects aspects like nuisance and availability of space, with the lost function value.

***Costs***

The cost of a solution is one of the most important criteria considered in this initial stage. Since the alternatives are still in conceptual phase, their costs can only be assessed in respect to each other. With more detail, the costs can be regarded separate from the MCA.

***Durability, reliability & proven technology***

The solution has to function as a robust system for many years. Alternatives that consist of many dynamic parts have a higher chance of failure and are therefore less durable.
Reliability stands for the guarantee the system can give to function when required. In this initial stage, this means that prior experience with a similar system has the preference since the practical application is proven. This is in contrast to a rather experimental solution which is solid in theory, but is never shown to work in practice.

***Economic benefit and added value***

With respect to costs, this is rather important criteria. Consider for example are solution which costs a lot. It may be so that this costs offer many other benefits such as large yearly savings or the creation of added recreational space. Aspects like these justify the costs and could make the alternative worth the money.

***Esthetics and visual/physical obstruction***

How appealing a structure is, the esthetics, plays a role in the total value of solution. The creation of a masterpiece in architecture is surely to be more likely to be realized than an uninteresting solution.
Visual obstruction is the degree of how much the solution blocks of view, e.g. the creation of high upper reservoir is blocking the landscape and also a physical hindrance. People, cars or ships will have to perform extra effort because the solution is in the way.

***Extensibility***

In regard to future plans and future expectations of increase in variable output, it is rather important to create easily upgradable system. The available space for this has to be taken into account, as well as the extra costs this upgrade will require

***Geographical dependence***

Since the alternatives are still in the conceptual phase, it is important to consider the availability of the required geographical situation. For example: traditional PHS scores low, because it requires high elevations (specifically shaped mountains or hills) which are not present in the Netherlands.

***Large scale applicability***

Some solutions are more optimal as a small-scale solution and when wanted to apply for large-scale use, they perform very bad, either in terms of efficiency, costs, upgradability etc. The system should be sufficient to supply the energy storing capacity which is needed.

***Power generation capacity***

While there are requirement defined earlier in this report of how much power generation capacity is wanted in the solution, with some alternatives it may be easier to create more power capacity with less capital and effort.

***Risks and safety feeling***

The risks considered here are mostly in the operational phase. The solution may fail in so many ways, for example due to technical problems, efficiency problems or acts of terrorism.

A structure can be designed and constructed to withhold huge deflections, however, when the building starts to shake back and forth, people will get afraid. Therefore, apart from functional requirement, a structure which puts peoples mind at ease is preferable.

***Sustainability & ecology***

Sustainability is a very extensive term. There are many definitions for sustainability and the word is coined in various situations. The following definition is used here: "Sustainability integrates natural systems with human patterns and celebrates continuity, uniqueness and place making", (Early, 1993). This means that the structures have to be built with respect to their environment, without straining the resources much and without causing too much damage to the environment. Ecology is the specific aspect with regard to nature. For example, a traditional hydropower which requires the flood of huge pieces of land is very destructive for the local ecology.

## Weight Matrix and MCA Results

The amount of influence each of the criteria is supposed to have on the choice of alternative is dependent on the weight factor assigned to each criterion. This will be done using a Weight Matrix, also known as the Relation Matrix. In this matrix each criterion is compared to one another in terms of importance (e.g. costs is appointed 1 and construction time 0 because costs are more important than ecology). After all comparisons are made, the totals are summed up and divided by the total amount of points.

The values in Table 2 are mainly determined based upon factors that may influence the problem characteristics and the desired situation.

The totals clearly show that the importance of some criteria above others. Criteria like esthetics, sustainability, geographic dependence, constructability and large-scale applicability are of lower importance, while particularly costs, economic benefits and added value, durability and risk are considered highly important and their score has a large influence on the total value of the alternatives.

| | COMP | CONSTR | COST | DURA | BENEF | ESTH | EXTEN | GEODEP | LSCALE | POWER | RISK | SUSTAIN | Subtotal | Weight |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **COMP** | | 1 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 0 | 1 | 1 | 6 | **9%** |
| **CONSTR** | 0 | | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 3 | **5%** |
| **COST** | 1 | 1 | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 11 | **17%** |
| **DURA** | 1 | 1 | 0 | | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 8 | **12%** |
| **BENEF** | 1 | 1 | 0 | 1 | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 10 | **15%** |
| **ESTH** | 0 | 1 | 0 | 0 | 0 | | 0 | 0 | 0 | 0 | 0 | 0 | 1 | **2%** |
| **EXTEN** | 0 | 0 | 0 | 0 | 0 | 1 | | 1 | 1 | 0 | 0 | 1 | 4 | **6%** |
| **GEODEP** | 1 | 0 | 0 | 0 | 0 | 1 | 0 | | 1 | 0 | 0 | 0 | 3 | **5%** |
| **LSCALE** | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | | 1 | 0 | 1 | 3 | **5%** |
| **POWER** | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | | 0 | 0 | 5 | **8%** |
| **RISK** | 0 | 1 | 0 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | | 1 | 8 | **12%** |
| **SUSTAIN** | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | | 4 | **6%** |
| | | | | | | | | | | | | Total | 66 | **100%** |

*Table 2 ... Weight matrix*

| Alternative name | NO | PHS | EEM | LIEVE | EI | SLUF | UPHS | OPAC | GP | scaled | NO | PHS | EEM | LIEVE | EI | SLUF | UPHS | OPAC | GP |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Criterion/alternative nr. | 0.1 | 0.2 | 0.3 | 1.1 | 1.2 | 1.3 | 2.1 | 2.2 | 2.3 | weight | 0.1 | 0.2 | 0.3 | 1.1 | 1.2 | 1.3 | 2.1 | 2.2 | 2.3 |
| Compactness | 10 | 3 | 8 | 3 | 2 | 4 | 5 | 5 | 9 | 9% | 0,91 | 0,27 | 0,73 | 0,27 | 0,18 | 0,36 | 0,45 | 0,45 | 0,82 |
| Constructability and construction time | 10 | 5 | 7 | 4 | 4 | 8 | 3 | 3 | 6 | 5% | 0,45 | 0,23 | 0,32 | 0,18 | 0,18 | 0,36 | 0,14 | 0,14 | 0,27 |
| Costs | 10 | 5 | 8 | 4 | 1 | 9 | 4 | 4 | 5 | 17% | 1,67 | 0,83 | 1,33 | 0,67 | 0,17 | 1,50 | 0,67 | 0,67 | 0,83 |
| Durability, reliability & proven tech | 1 | 8 | 4 | 7 | 8 | 7 | 5 | 4 | 4 | 12% | 0,12 | 0,97 | 0,48 | 0,85 | 0,97 | 0,85 | 0,61 | 0,48 | 0,48 |
| Economic benefits & added value | 1 | 4 | 5 | 5 | 9 | 5 | 5 | 5 | 5 | 15% | 0,15 | 0,61 | 0,76 | 0,76 | 1,36 | 0,76 | 0,76 | 0,76 | 0,76 |
| Esthetics, visual & physical obstruction | 10 | 4 | 6 | 3 | 4 | 6 | 4 | 4 | 8 | 2% | 0,15 | 0,06 | 0,09 | 0,05 | 0,06 | 0,09 | 0,06 | 0,06 | 0,12 |
| Extensibility | 1 | 3 | 5 | 8 | 8 | 6 | 2 | 2 | 2 | 6% | 0,06 | 0,18 | 0,30 | 0,48 | 0,48 | 0,36 | 0,12 | 0,12 | 0,12 |
| Geographic dependency | 10 | 1 | 5 | 8 | 8 | 8 | 3 | 4 | 5 | 5% | 0,45 | 0,05 | 0,23 | 0,36 | 0,36 | 0,36 | 0,14 | 0,18 | 0,23 |
| Large-scale applicability | 1 | 2 | 5 | 8 | 8 | 3 | 6 | 7 | 7 | 5% | 0,05 | 0,09 | 0,23 | 0,36 | 0,36 | 0,14 | 0,27 | 0,32 | 0,32 |
| Power generation capacity | 1 | 2 | 5 | 8 | 8 | 3 | 5 | 5 | 6 | 8% | 0,08 | 0,15 | 0,38 | 0,61 | 0,61 | 0,23 | 0,38 | 0,38 | 0,45 |
| Risks & safety feeling | 1 | 4 | 2 | 3 | 6 | 5 | 5 | 5 | 6 | 12% | 0,12 | 0,48 | 0,24 | 0,36 | 0,73 | 0,61 | 0,61 | 0,61 | 0,73 |
| Sustainability & ecology | 1 | 3 | 5 | 4 | 5 | 4 | 5 | 5 | 5 | 6% | 0,06 | 0,18 | 0,30 | 0,24 | 0,30 | 0,24 | 0,30 | 0,30 | 0,30 |
| Total | 57 | 44 | 65 | 65 | 71 | 68 | 52 | 53 | 68 | 1 | 4,3 | 4,1 | 5,4 | 5,2 | 5,8 | 5,9 | 4,5 | 4,5 | 5,4 |

*Table 3 ... MCA results*

# 3. *Extended Multi Criteria analyses*

## Criteria

Most of the criteria are similar to the ones used in the previous MCA. They are detailed more and the joined criteria are split into separate criteria. Below one can find the list of criteria used (*see Table 4*). For the description, one is directed to the description in *paragraph 2*.

## Weight matrix

| Criterion | Constructability | Construction time | Ecology | Environmental integrat | Extensebility | Originality/Prestige | Physical blockage | Power output potential | Risks | Silt solution | Storage capacity | Sustainability | Visual blockage | Subtotal | Weight |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Constructability** | | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 3 | **4%** |
| **Construction time** | 1 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | **1%** |
| **Ecology** | 0 | 1 | | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 1 | 7 | **9%** |
| **Environmental integration** | 1 | 1 | 1 | | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 5 | **6%** |
| **Extensebility** | 1 | 1 | 0 | 1 | | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 6 | **7%** |
| **Originality/Prestige** | 1 | 1 | 0 | 1 | 1 | | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 5 | **6%** |
| **Physical blockage** | 0 | 1 | 0 | 0 | 1 | 1 | | 0 | 0 | 0 | 0 | 0 | 0 | 3 | **4%** |
| **Power output potential** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | | 1 | 1 | 1 | 1 | 1 | 12 | **15%** |
| **Risks** | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | | 1 | 0 | 1 | 1 | 10 | **12%** |
| **Silt solution** | 1 | 1 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | | 0 | 0 | 1 | 7 | **9%** |
| **Storage capacity** | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | | 1 | 1 | 9 | **11%** |
| **Sustainability** | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 1 | 1 | 1 | | 1 | 8 | **10%** |
| **Visual blockage** | 0 | 1 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 0 | 1 | | 6 | **7%** |
| **TOTAL** | | | | | | | | | | | | | | 82 | **100%** |

*Table 4 ... Weight matrix extended MCA*

# Appendix F Reference projects

## 1. *Reference project: Ludington, USA*

*Figure 14 ... Aerial view of the Ludington PHS in the Michigan, USA (http://www.northlightlc.com)*

The Ludington PHS plant in Michigan USA is a relevant reference project which is operating cost-efficiently since its construction in 1973. It underwent a major update in 2008, giving it the present form. The PHS plant makes use of Lake Michigan as a lower reservoir combined with an artificial upper reservoir. This upper reservoir has an average depth of 33.5 m and a surface of 3.4 km$^2$. The reservoir height is 290 m above sea level, which is the hydraulic head used for the capacity. Six turbines of each 312 MW generate the required power. With a response time of two minutes, a power capacity of 1872 MW can be generated, enough for 1.4 million people. This power output corresponds with a flow rate of 120 thousand m$^3$ per minute. The main goal of the plant is to offer power during peak load, while storing during nightly hours. The primary investments needed for the construction (which is mainly the upper reservoir) were $327 million with a construction time of nearly 7 years. A new upgrade is planned to expand the power capacity to 2172 MW.

### Evaluation

PHS in its traditional requires large height elevations from which it extracts its power. Since large height elevations are not to be found in the Netherlands, this alternative is not really feasible. However, working out this alternative has shown the potential of PHS projects and the order of power generations that can be realized. Therefore, this alternative fulfills its role as a reference.

## 2. *Costs of turbines for reference dams*

| Reference project | Head difference (m) | Power output (MW) | Flow through turbine (m$^3$/s) | Efficiency | Costs in million |
|---|---|---|---|---|---|
| **Alqueva dam** | 76 | 4 x 129.6 | 208.6 | 80% | €1300 for total project<br>€47 million per turbine[13] |
| **Phase 2 Markermeer** | 21.95-29.45 (25.8) | 31 x 52 | 306 | | €60 per turbine |
| **Phase 2 Noord-zee** | 37-50 (43.5) | 31 x 80 | 230 | | €90 per turbine |
| **Energy Island** | 32-40 | 16 x 125 | 230-345 | | € 70 per turbine |
| **Nant de Drance** | 52 | 6 x 150 | | 80% | €1457 total project |

*Table 5 ... Costs of turbines in reference projects*

[13] *Portugal utility awards equipment contract for 260 MW Alqueva-2, Hydroworld.com, 2008*

# 3. *Alqueva Pumped hydropower dam*

*Figure 15 ... Alqueva Power Dam in Portugal*

The Alqueva power dam is an arch dam built in 2004 comprising a head difference of 75.8m. This head is used to generate 129.6 MW per turbine. A total of 4 reversible Francis turbines are used to reach maximum output of 518 MW. With these numbers, it is one of the largest hydropower dams in Western-Europe. Runner diameter is 6.01m and the ring gate diameter is 7.85m. The total construction of the dam has been $1.7 billion. When pumping the water back up, the pump needs to cover a net delivery head of 72.3m and 208.6 $m^3$/s flows through each turbine. The main characteristics are

- Turbine mode
  - Range of net heads: 44.7 to 75.8m
  - 129.6 MW with 71.1m net head
- Pump mode
  - Range of delivery heads: 45.9 to 72.3m
  - 170 $m^3$/s with 64m gross head

# 4. *Torrao Pumped Storage Power Plant*

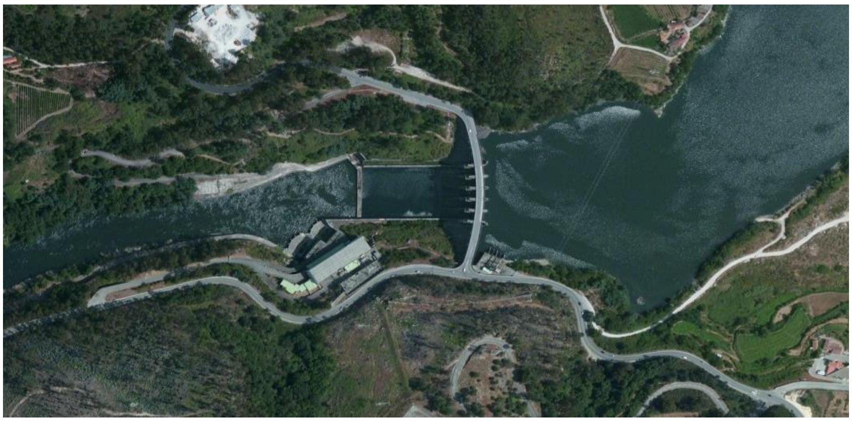


*Figure 16 ... Top view of Torrao Pumped Storage Plant (Bing Maps, 2013)*

The dam is located close to Porto in Portugal and has been commissioned in 1988. The plant has reversible turbines and is used as a peak-unit plant. The dam has a capacity of 146 MW, which is built up from two units with each 73 MW capacity. The effective head difference is around 50m.

# 5. *Reference project: IJsseloog*

The IJsseloog is a dredged island in the Ketelmeer Lake, built as a depot for heavy contaminated silt coming from the bottom of the Ketelmeer Lake. This lake is heavily contaminated because of the outflow of the rivers the Rhine and the IJssel. The island has a diameter of 1 km which means the reservoir surface of 0.785 $km^2$ and the surround dam has a length of 3 km. Constructed in 1998, the project has cost 250 million Dutch guilders, which translated to €152 million in today's money.[14]

*Figure 17 ... Aerial view on the IJsseloog*

# 6. *Plan Lievense specifications*

## Phase 1

Three different alternatives are considered in the first phase.

| Characteristic data | high head | medium head | low head |
|---|---|---|---|
| **Water level [m]** | 80-100 | 56-70 | 32-40 |
| **# turbines** | 9 | 13 | 23 |
| **Foundation depth [m]** | -37.3 | -34.3 | -29.5 |
| **Diameter reservoir [km]** | 2.5 | 3.5 | 6 |
| **Surface area ($km^2$)** | 4.9 | 9.6 | 28.3 |
| **Dike height [m]** | 100 | 70 | 40 |
| **Flow pump ($m^3/s$)** | 296 | 322 | 271 |
| **Flow turbine ($m^3/s$)** | 346 | 329 | 319 |
| **Total turbine [$m^3/s$)** | 3114 | 4277 | 7337 |
| **Net guaranteed capacity (MW)** | 233 | 156 | 89 |
| **Total capacity (MW)** | 2097 | 2028 | 2047 |

[14] *Internationale instituut voor sociele geschieden, De waarde van de gulden/euro, iigs.nl, 2013*

## Phase 2

| Characteristic data | Markermeer | | | Coast | | North Sea |
|---|---|---|---|---|---|---|
| **Surface area [km$^2$]** | 30 | 55 | 165 | 55 | 30 | 40 |
| **Dike height [m]** | 35 | 27-30 | 27-30 | 27.5 | 33.5 | 55 |
| **Water level [m]** | 21.95-29.45 | 17.3-23.3 | 17.3-23.3 | 17.3-23.3 | 20-29.5 | 37-50 |
| **- Average [m]** | 25.8 | 20.3 | 20.3 | 20.3 | 25.7 | 43.5 |
| **Average depth [m]** | -8 | -5 | -5 | -8 | -8 | -20 |
| **Clay layer depth [m]** | -40 | -40 | -40 | -40 | -40 | -40 |
| **Outer slope [-]** | 1:3 | 1:3.5 | 1:3.5 | 1:3 | 1:3 | 1:4 |
| **Inner slope [-]** | 1:6 | 1:6 | 1:6 | 1:6 | 1:6 | 1:4 |
| **Outer beach width – high water [m]** | - | - | - | 10 | 10 | 10 |
| **Outer beach width – low water [m]** | - | - | - | 250 | 250 | 250 |
| **Flow through central – max hour value [m$^3$/s]** | 4800-9600 | 4750-9500 | 14260 | 4800-9600 | 4800-9600 | 2300-6900 |
| **Daily average flow [m$^3$/s]** | 1000-2000 | 1000-2000 | 3000 | 1000-2000 | 1000-2000 | 500-1500 |
| **Net capacity [MW]** | 800-1600 | 800-1600 | 2400 | 1000-2000 | 1000-2000 | 800-2400 |
| **Amount of turbines [#]** | 17-35 | 15-31 | 45-93 | 15-31 | 17-35 | 10-31 |
| **Cost in millions €** | | | | | | |
| **Dunes** | 980 | 1420 | 4260 | 1420 | 980 | 2715 |
| **Pump turbines** | 650-1295 | 605-1210 | 1815-3640 | 605-1210 | 650-1295 | 500-1490 |
| **Turbine housing** | 460-975 | 470-975 | 1410-2925 | 470-975 | 460-975 | 510-1420 |
| **Building pit and supporting structures** | 315 | 310-495 | 930-1485 | 310-495 | 315 | 800-885 |
| **Connections to grid** | 35-70 | 35-70 | 105-270 | 35-70 | 35-70 | 450-850 |
| **Total** | 2370-3635 | 2830-4170 | 8490-12510 | 2830-4170 | 2370-3635 | 5095-7360 |
| **Costs /turbine (millions)** | **€60** | | | | | **€84** |

*Table 6 ... Plan Lievense worked out alternatives and their characteristics*

# 7. *Pedreira PHS plant*

Built in 1988, this PHS plant is the first PHS in Brazil and has been placed in the state of Rio de Janeiro.

With a range of head varying from 20 to 30 meters, it supports a maximum flow of 90 m$^3$/s while creating 20 MW power. These turbines have cost around 50 million per turbine. [15]

[15] *Alstom, PAC presentation Alstom, 2006*

# Appendix G Derivations formulas

## 1. *Derivation $E_{cap}$ Valmeer*

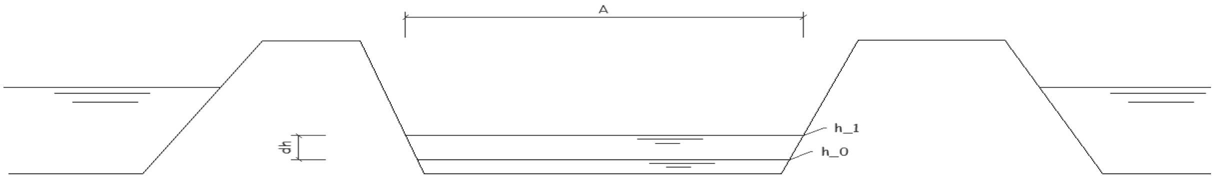



***Figure 18 ... scheme used for derivation***

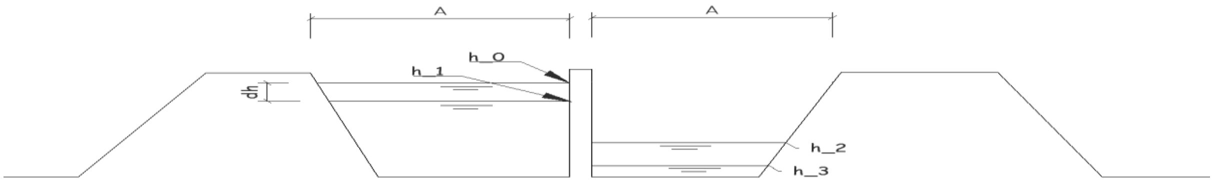
The principal equation of any hydropower solution is the benefitting from the potential energy of the elevated water relative to the lower level water. The elemental potential energy equation can be substitutes and re-written to obtain a formula that is dependent only on the desired parameters:

$$E = mgh = \rho V gh = \rho A gh\, dh$$

The total energy which is stored can be calculated as the sum of all the little layers of water on top of each other from h_0 to h_1 (*see Figure 18*). This is the energy capacity equation for the Valmeer.

$$E_{cap} = \int_{h_1}^{h_0} \rho A gh\, dh = \left[\frac{1}{2}\rho A g h^2\right]_{h_1}^{h_0} = \frac{1}{2}\rho g A\,(h_0^2 - h_1^2)$$

## 2. *Derivation $E_{cap}$ Split reservoir*




The same principal equation steps are taken for the derivation of the split reservoir. From the previous derivation the energy capacity using a steady lower reservoir was obtained, so

$$E_{cap} = \frac{1}{2}\rho g A\,(h_0^2 - h_1^2)$$

Similarly, the equation of the capacity with a steady upper reservoir but varying lower reservoir is derived. The reservoir levels are linked, meaning that there is a relation between h_0 and h_2 and h_3.

$$E_{cap} = \frac{1}{2}\rho g A\,(h_2^2 - h_3^2)$$

$$h_2 = h_0 - h_1 \text{ and } h_3 = 0$$

$$E_{cap} = \frac{1}{2}\rho g A\,(h_0 - h_1)^2$$

Now the energy capacity loss derived from a varying lower level is subtracted from the steady upper level given the expression for the energy capacity for the split reservoir.

$$E_{cap} = \frac{1}{2}\rho g A(h_0^2 - h_1^2) - \frac{1}{2}\rho g A\,(h_0 - h_1)^2$$

$$= \frac{1}{2}\rho g A\,(h_0^2 - h_1^2) - (h_0 - h_1)^2$$

# Appendix H Ideas

## 1. *Optimization ideas for the Slufter*

These are the ideas that have been considered and analyzed

- Construction of a dam inside the Slufter
    - Orientation of the separating dam
    - Storing the silt in the upper reservoir
    - Making the upper reservoir larger
- Lowering the depth of the Slufter
- Expansion of the reservoir
- Increasing the height of the surrounding dams
- The upper and lower limit of the water level

## 2. *Considerations & Ideas*

The calculation and full argumentation are displayed here, for a summary of the results, see the report.

### Consideration 1: Increasing the height of the surrounding dams

Increasing the height of the surrounding dams is something that can be easily done to raise the hydraulic head and thus the power output.
There is balance between the costs and risks for the heightening and the extra power gained from it. This analysis has shown that the height of the dams could be improved to +40m NAP.

### Consideration 2: Increasing the depth even further

The subsoil analysis has shown some potential for further enlarging the depth so to create an even higher hydraulic head. Practical considerations should be considered as currently there is a 30m thick layer of silt on top.
Analyzing the subsoil and the danger for bursting because of the water pressures has shown that the depth could be further increased from -28m to -31.5m NAP, an increase of 3.5 meter.

### Consideration 3: Damming the reservoir

Damming the Slufter and thus creating two reservoirs, one higher rand one lower one, can have benefits because this way both the depth and the height can be utilized.
The analysis resulted in a clear preference of height over surface area. This is because the height leads to a quadratic growth in power generation while surface area has a linear relation. Even though the reservoir will be split in half, the loss of energy storing capacity is outweighed by the exponential growth in power output capacity.

#### *Consideration 3.1: orientation of the dam*

When designing the dam, it should be considered which way it is turning. An important aspect in this consideration has been choosing an orientation that reduces the risk of dam failure.
As the chances for a dam failure are the same regardless of the orientation, the consequences are certainly not. There is a clear preference for a higher reservoir to be on the southern side of the Slufter.

#### *Consideration 3.2: storing the silt inside the upper reservoirs*

The Slufter is now filled up to NAP with contaminated silt. When seeking to utilize the depth of the Slufter, the silt is preventing this.

A solution to utilize the depth of the Slufter is to place all the silt in the created upper reservoir. The hydraulic head is the important parameter for power output; since only the top layer of water is required for power generation, the lower layers can be filled with the silt inside the Slufter.

***Consideration 3.3: Making the upper reservoir larger***

Since the top layer is the essential part in generating power, it could be beneficial to make the upper reservoir as wide as possible, so more water particles depart from this high position.
But the analysis showed that the idea doesn't consider the reservoirs being linked. A larger upper reservoir means a reduction of the lower reservoir. So despite there being more water on a higher level, thus having more potential energy, the water level in the lower reservoir is also rising higher due to the smaller size. Instead of offering a benefit, the quick rise of the lower level reduces the hydraulic head faster than the higher water level can compensate.
It is therefore preferable to split the reservoir into two pieces with exactly the same size.

## Consideration 4: Creating a new reservoir (see results ideas 3.2 and 3.3)

The possible options are analyzed for the case that the higher storage capacity is desired to serve a larger area of the Netherlands.
The analysis presents a possibility for expansion at the east-side of the Slufter. The results of the analysis can be found in the description of Alternative 3.

## Consideration 5: Choosing the right slice of fluctuating water

A high hydraulic head leads to a high power output. As more power is generated and the hydraulic drops, the power output will decrease. At a certain point, the hydraulic head will be so low, that the turbine will not work in an efficient matter and the power generation will simply be too low. So to guarantee a certain power output, the minimal hydraulic head must be kept high.
On the other side, the bigger the difference between high level and low water level, the more energy can be stored in the system; more volume of water will be fluctuating back and forth that will store more energy. So basically, this is a balance between energy storage capacity and guaranteed power generation capacity. This balance is essential in the determination of the upper and lower limit of the water level. Raising the lower limit of the water level results in a lower energy storing capacity while lowering it, lowers the guaranteed power output and the efficiency of the system (see Figure 19).

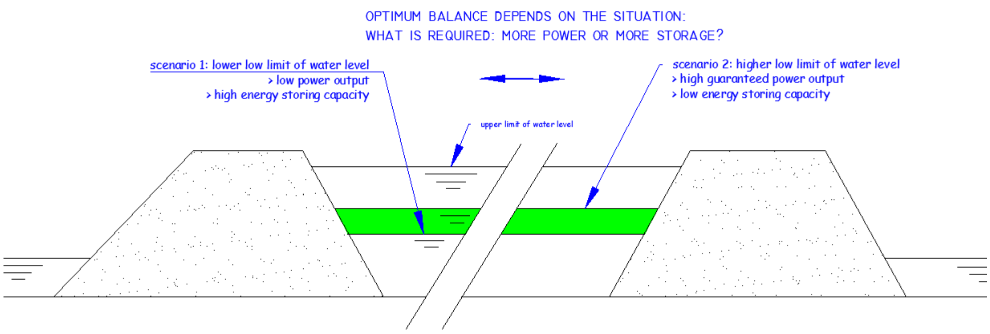



*Figure 19 ... Balance between guaranteed power output vs. more storage capacity*

## Consideration 6: Wind setup in the reservoir

Because the reservoir stretches some kilometers, it should be analyzed whether the top of the dam should be raised significantly higher than the upper water level. This is calculated using the following formula:

$$s = \frac{\gamma_a}{\gamma_w} * \frac{c_f}{2} * \frac{U^2}{gD} * F$$

- $\gamma_a$ and $\gamma_w$= density air and water [kN/m$^3$]
- F = fetch length (in the direction of the wind) [m]
- U = wind velocity [m/s]
- D = reservoir depth [m]
- $c_f$ = friction coefficient at water surface [-]
- g = gravitational acceleration [m/s$^2$]

The analysis shows that the fetch length is relatively small and that when considering the longest span of the reservoir, the total setup because of (extreme) winds is only 2.5 cm, which is insignificant.

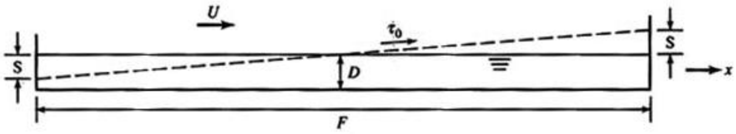



*Figure 20 ... scheme for wind setup calculation*

## Consideration 7: Solving the double functionality

***Consideration 7.1: Storing the silt inside the upper reservoirs (see above: Consideration 3.2)***

***Consideration 7.2: Using the silt for the current dams***

Using the silt in the construction of the dam is a way to make the dam impervious to water. With the water flow restricted, the dam's stability will improve as will the total efficiency of the system. The constructability remains as the main issue in this consideration. Due to the difficulties in the implementation of the current dams, this option is rather costly.

***Consideration 7.3: Using the silt as filling in the water enclosing slurry walls***

The application of silt as filling instead of the slurry has some clear benefits. The silt is free while the slurry costs money. The silt is contaminated and by putting the contaminants deep in the soil, it won't be causing a problem for the environment. There is a lot of silt inside the Slufter and ideally, this silt is removed as much as possible. This consideration offers a way to solve this issue, albeit on a very small scale, as the amount that would be implemented is in the order of 0.5 million m$^3$ of silt.

***Consideration 7.4: Transferring the silt to other locations or recycling***

The possibilities for this have been discussed before. The findings were that there is some possibility for the transfer as well as recycling, however only for a small portion of the silt. The capacities of the other depot are small or nearly full and cannot take a lot. Therefore, this option should only be considered when there is no good solution within the system boundaries. If this option is considered, it is assumed that up to 20% of the silt, so 15 million m$^3$ of silt can be handled in this way.

***Consideration 7.5: Aligning the silt on the sides***

Opening up the Slufter to increase the hydraulic head is wished for. However, when the silt cannot be moved, there is still the possibility to stack the silt on the sides. However, due to the low internal angle of repose, the silt will stack at a slope of 1:10, occupying a lot of the depth that is wished to be cleared.

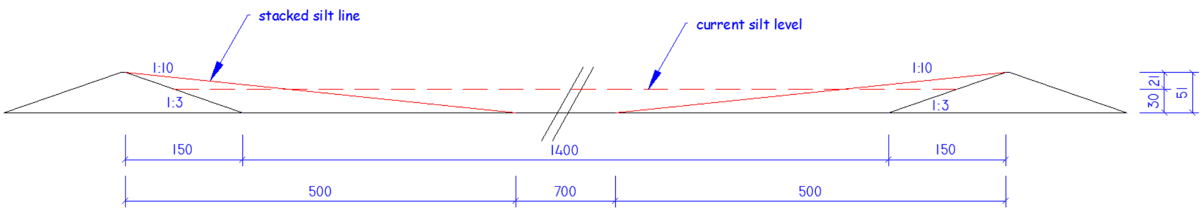



*Figure 21 ... Silt slope at 1:10 stacked to the sides relative to the old silt level*

This way, up to 70 million m$^3$ silt can be stored, a little less than required. This small amount can be accounted for in the other possible strategies (*see other considerations above*). And once the bottom layers are filled, the reduction of surface area is increasing fast which reduces the energy storing capacity.

# 3. *Creating a dam inside the Slufter*

***General***

By constructing a dam inside the Slufter, the water level can be raised to a higher level than the surrounding sea level. There are two possibilities of how such a system can work.

With the construction of the dam, the system can operate using:

1.1 The high head difference to generate and store power, thus using effectively only half of the reservoir.

1.2 Using a dual system; a Valmeer on one side and a traditional hydropower concept on the other side.

Since both ideas utilize the same design, there is no difference in material amount, costs etc. Since the sizes are the same, both systems will also have the same energy capacity. The main difference will be the power output capacity.

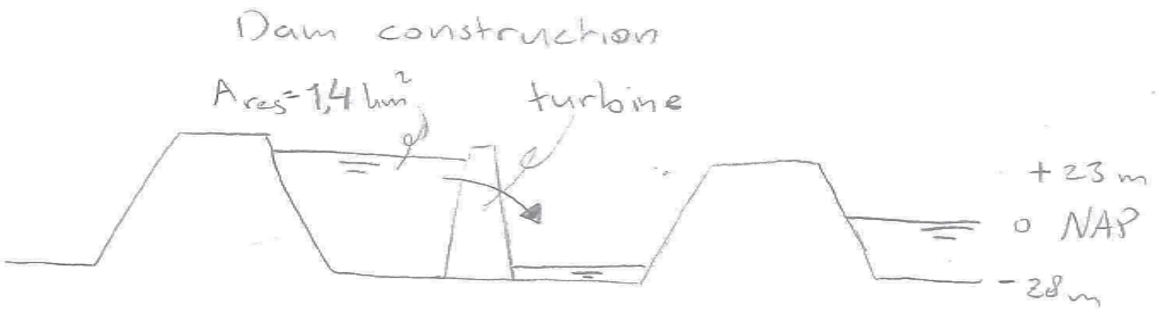



*Figure 22 ... Sketch of the Slufter with a dam inside idea 1.1*

For idea 1.1, the total energy storage capacity is given by

$$E = \frac{1}{2}\rho g A\left((h_0^2 - h_1^2) - (h_0 - h_1)^2\right) = 8.9 * 10^{12}\, J \sim 2.5\, GWh$$

The maximum power generation capacity is given by

$$P_{max} = \rho g Q h_0 \eta = 176\ MW\ per\ turbine$$

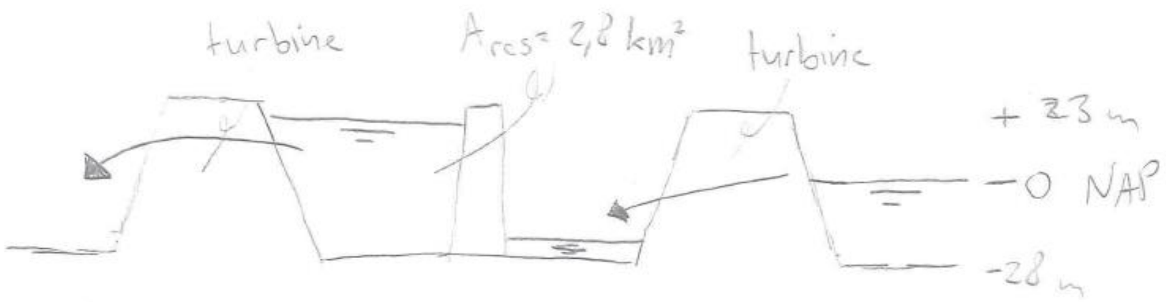



***Figure 23 … Sketch of the Slufter with a dam inside idea 1.2***

For idea 1.2, the energy capacity is given by

$$E = \frac{1}{2}\rho g A(h_0^2 - h_1^2) + \frac{1}{2}\rho g A(h_2^2 - h_3^2) = 2.5\ GWh$$

This confirms the previous thought that the energy capacities were in fact the same. The maximum power capacity is given by

$$P_{left} = \rho g Q_{left} h_0 \eta = 37\ MW\ per\ turbine$$

$$P_{right} = \rho g Q_{right} h_2 \eta = 56\ MW\ per\ turbine$$

$$P_{maximum} = P_{right} + P_{left} = 93\ MW\ per\ two\ turbines$$

And the maximum power capacity will be a function of:

$$P = \rho g Q \eta \big(h_0 - (h_0 - h_1)\big)$$

With a Q,h-relation flowing from the pump characteristics.

The dam design is dependent on the forces acting on it. For a primary guess, the thickness will be estimated using a rule of thumb, which states that. The dam will be 2 km long with thickness of XX m

The construction costs of a dam of 2 km will be estimated using the reference project IJsseloog). In this plan, the construction of 3.5 km dam has cost €150 million, which means the construction of half of this length will cost about €100 million (taking into account fixed costs, the costs aren't halved).

***Orientation of the dam***

The reservoir has a size of 2.6 km$^2$ and in the consideration above, it is the discussed that it's preferable to have equal sized reservoirs. However, it remains a design choice what the specific orientation of the dam will be. Considerations that have to be taken into account are the currently placed windmills and the risk that the upper reservoir may form. As for the windmills, it is rather costly to remove and replace them, so therefore is it preferable that they remain at their place. Another point is that the dam is not blocking the wind so that their efficiency is lowered.


*Figure 24 ... Birds eye overview of the Slufter (Bing Maps, 2003)*

As for the risk, the possibility of a dike breach is considered. The high water level in the upper reservoir is causing a risk in this respect. A quick overview of the consequences in each direction will lead to favorable orientation of the dam for this aspect. The sections defined in Figure 24 are used for this explanation.

If the upper reservoir is placed at the western or south-western section, a dam breach will cause a direct flooding of the new Maasvlakte 2 area. Likewise, an upper reservoir at the northern section will directly flood the Maasvlakte and the port area. A north-eastern breach will partially affect the Maasvlakte but will largely be buffered by the Oost-Voornse Meer. A south-eastern breach will largely be buffered by the sea, the beach and the nature area in between the Slufter and West-Voorne. A southern breach will be to open sea (see Figure 25).

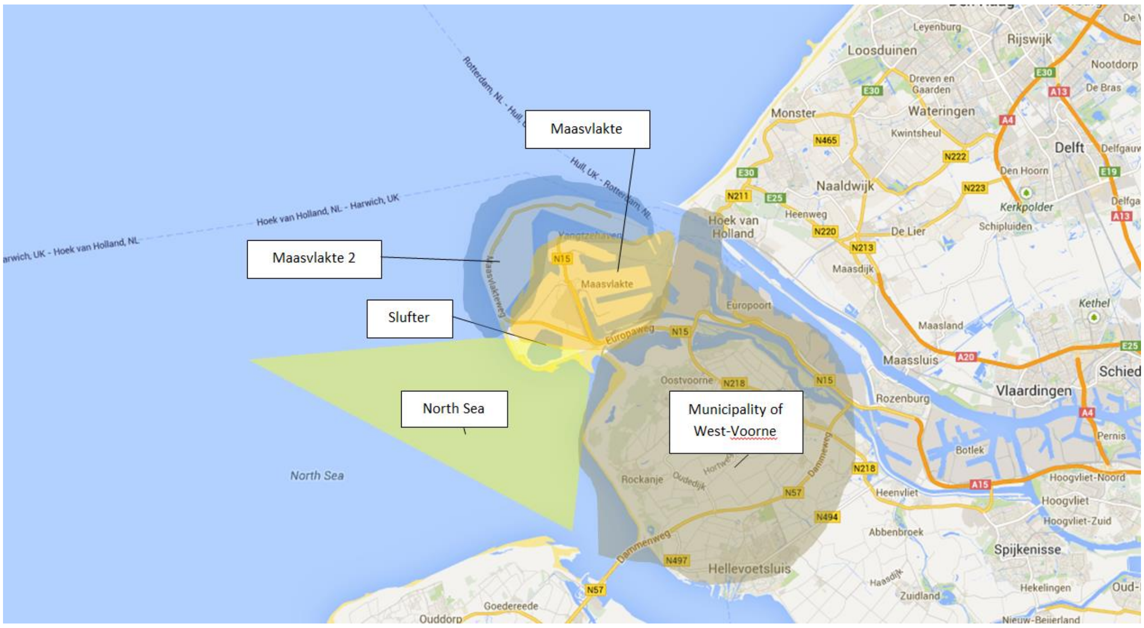



*Figure 25 ... Top view of the area split into section (Google Maps, 2013)*

Therefore, from all of the options considered, a southern and somewhat south-eastern orientation of the upper reservoir is favorable considering the consequences in case of a dike breach. Since this orientation is in accordance with the first consideration regarding the windmill positioning, this is the preferable orientation overall.

***Storing the silt in the upper reservoir***

Storing the silt in the upper reservoirs solves the problem of where to keep 70 million $m^3$ of silt. The silt will not interfere with the energy storing function of the reservoir as only the top layer of water is effective in the generation of power. In the designs, the water level is never let to approach this height. Depending on the size of the reservoir, the silt will occupy the lower part of the height. If the reservoir remains unchanged, the silt can be left at is right now. Currently the thickness of this layer is 30 meters. If the reservoir is split in two sections, the upper reservoir will have less than half of the original size to occupy. With 70 million $m^3$ of silt and 1.3 $km^2$ of surface area, the silt will have a thickness of

$$\frac{70 * 10^6}{1.3 * 10^6} = 54\ meters$$

Starting at -28m NAP, the layer will reach up to +26m NAP. If this is too high, the layer thickness can be reduced by a number of ways.

***Creating a larger upper reservoir***

Choosing unequal sizes for the reservoir may have some benefits, as it may increase the storing capacity of the system. Whether this is true will be explored in this paragraph.

Since only a disk of water is used to generate power, it is favorable for the average power generation to utilize different reservoir sizes. In this way, the upper reservoir can be chosen to have a higher surface area so that a larger portion of the water will have a higher potential energy.

However, in this alternative the energy capacity is dependent on both reservoir sizes. Both reservoirs are linked in a way that lowering the water level in the upper reservoir, leads to an equal rise in the water level of the lower reservoir. However, the reason why creating a larger reservoir is not beneficial here, is that the reservoir are also linked in size, meaning that increasing the size of the upper reservoir, lowers the size of the lower reservoir, decreasing its capacity. So with a large upper reservoir, there will be more water at a higher point, but this effect is countered by the relatively quickly rising water level in the smaller lower reservoir, leading to an smaller effective head difference. Calculations show that the higher average generation is small compared to the decrease in energy storing capacity.

***Blocking of the wind leading to lower efficiency Windpark Slufter***

Could the construction of a high dam on the southern side block the wind flow and decrease the efficiency of the windmills? This can be answered by a simple review of the numbers. The dams that may block wind flow are 16 meters higher than the dam on which the windmills currently stand (the northern section, see Figure 24). The heights are +39m versus +23m NAP. The distance between the new dam and the northern section is 1 km. Furthermore, the axis height of the mills is 67 m so the mills still reach out 41m higher than the separating dam (see Figure 26)

Without further analysis, it can be concluded that it is considered highly unlikely that the dam will block the wind flowing to the windmills. In fact, it may even be so that the dam narrows the wind flow, causing a local acceleration of the wind speed (see Figure 26). Since this is not the main topic of this report, no further analysis will be done for the possible local wind flow improvements.

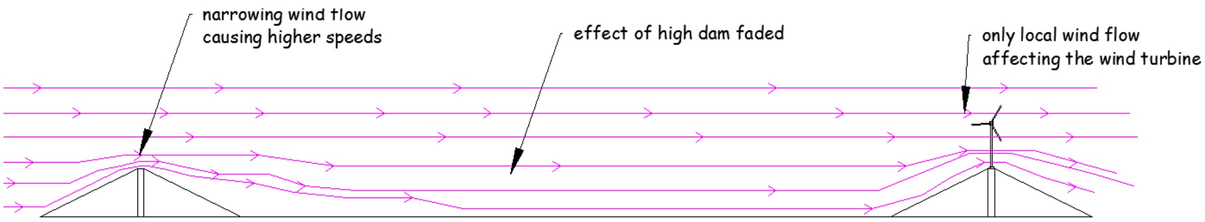



*Figure 26 ... Affected wind flow caused by high dam*

# 4. *Lowering the depth of the Slufter*

The depth of the Slufter can be further lowered to increase the hydraulic head. The feasible depth is dependent on the thickness of the water enclosing clay layer at the bottom. As previously mentioned, this layer can be found at a depth of 45m (see Figure 27). Here, a soil formation Pieze-Waalre (indicated in yellow) can be found. This profile shows that there is a thick clay layer starting at 50 meters which is quite thick.

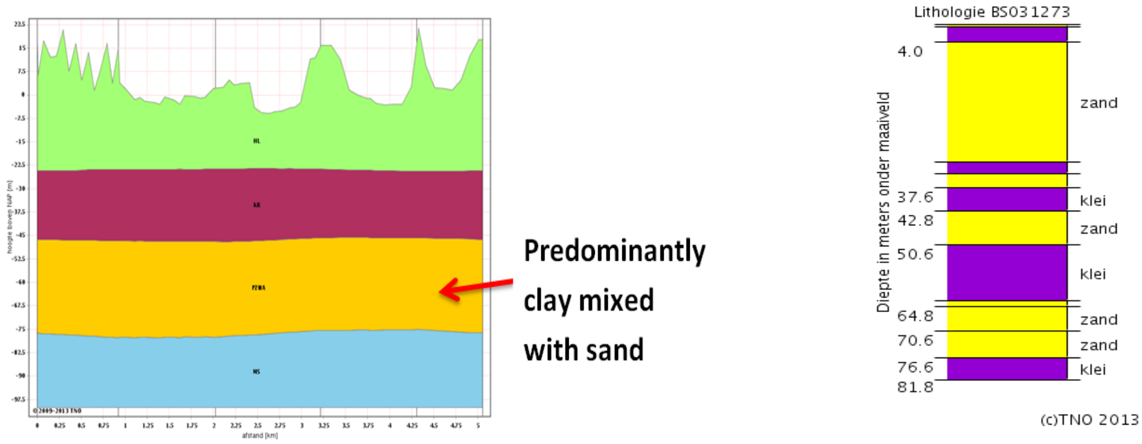



*Figure 27 ... (left( Bottom profile underneath the Slufter until a 60m depth (TNO, DinoLoket.nl, 2009-2013) and (right) Bottom profile near Slufter (TNO, 2013)*

According to the bottom profile, the extra depth which can be reached is 3.5 meters. This requires a dredging of 10 million $m^3$ of sand. The dredging will increase the depth to -31.5 m NAP, which will increase the maximum power generation of a turbine to 200 MW and the energy holding capacity to 2.9 GWh. With a dredging cost of €18/$m^3$,[16] the total dredging costs are €180 million.

# 5. *Increasing the size of the reservoir*

Increasing the size of the reservoir will definitely have a beneficial effect on the energy storing capacity. The Slufter is restricted in the northern and western side by respectively Maasvlakte 1 and 2. Any expansion must therefore be either in the east and/or south.

[16] *Dredging costs Project IJsseloog & Masterproject Brazil, Solving the coast of Recife, 2010*

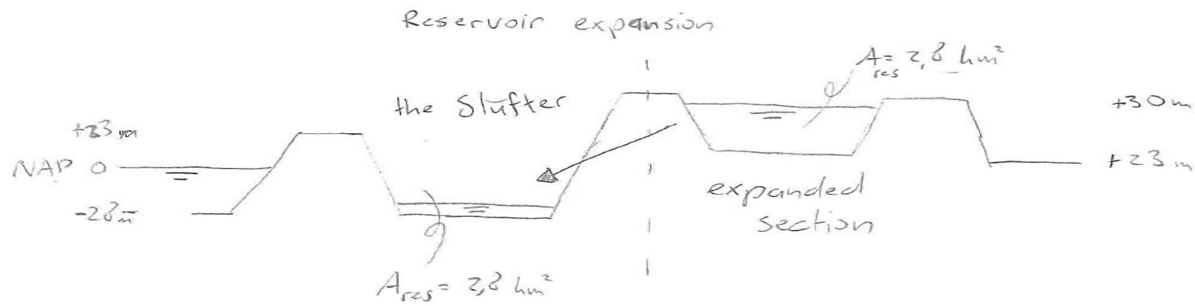



***Figure 28 ... Sketch of the cross section with the expansion of the reservoir***

The expansion isn't dependent on technical restrictions, but on restrictions of land space usage, prior functions and costs. The current function of this area is predominantly recreational with the presence of a beach and natural environment that attracts wild life.

With this expansion, a balance between two reservoirs defines the energy capacity. With the given characteristics, the storage capacity is raised to 3.3 GWh, with a maximum power capacity of 233 MW per turbine.

The costs for this expansion consists of buying these pieces of land and the civil engineering works that are required to realize this. To minimize the construction costs, the area bordering the eastward site of the Slufter is closed off for this purpose. With this expansion, a doubling of the reservoir size is idealized, an added reservoir size of 2.6 km$^2$, which a total size of 5.2 km$^2$.

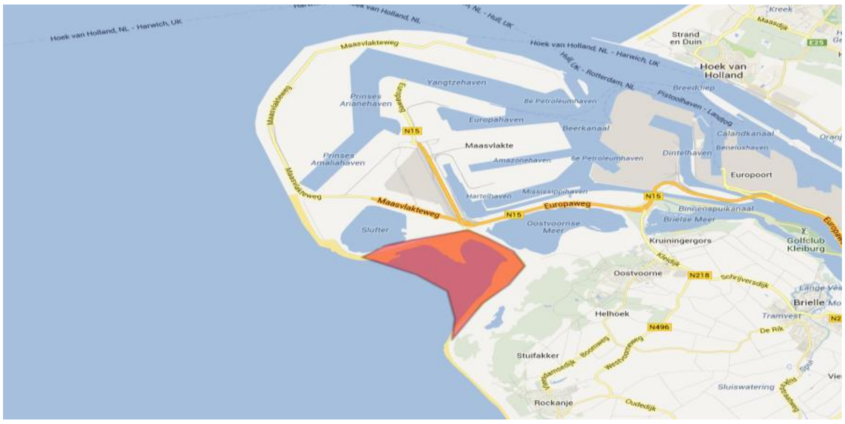



***Figure 29 ... The expansion of the Slufter indicated by a red overlay (Google Maps, 2013)***

The construction of this expanded reservoir consists of a dam that stretches 3.5 km. The reference project IJsseloog required the construction of a dam of 3 km, which is similar for the situation here. The costs for the dredging works thus are estimated to be around €150 million.

However, the newly created reservoir must have higher elevation surroundings to support the water height. The thickness of the dams is about 100 m average, the total perimeter is about 7000 m and a heightening is required of 15 m, which requires 20 million m$^3$ of soil replacement, which will cost about €360 million.

The total dredging works required for the expansion of the reservoir is estimated €510 million.

# 6. *Solving the problem of double functionality*

## Introduction

The Slufter is currently used as silt depot. Even though the amount of silt in the depot is not growing a lot, there is still 73-million $m^3$ silt stored. To enable a function as energy storage solution, the problem regarding this double functionality has to be solved. This can be done in two ways, which will both be analyzed:

1. Transferring the silt to another location or recycling the silt
2. Leave the silt and create a design with double functionality

Joining the silt storage functionality is a possibility, but comes at the expense of either one function or the other, since both functions mainly require space. Because a large height difference is important for the power output, the following ideas offer a compromise:

2.1 Aligning the silt <u>on the sides of the reservoir</u> along the height
2.2 Transferring all the silt <u>inside the upper reservoir</u>
2.3 Transfer the silt inside the surrounding dams
2.4 Transfer the silt inside the dams in the expanded sections

## Idea 1: Transferring to another location or recycling the silt

Considering first the silt storage functionality to another location, this must be a location with similar conditions. The location must close off the contaminated silt from the surrounding environment.

By cleaning the material, it can reach a lower classification, so that it needs less care. An example of this can be found close to the Slufter; at the Papegaaienbek depot in the Maasvlakte, which contains silt of class 4. When the Papegaaienbek had to be demolished for the construction of a container terminal, the highly contaminated material was somewhat cleaned and mixed with the material inside the Slufter of class 3.[17]

Another recycling option is to use the silt for construction of new dikes (expanded in Idea 2.4) or the creation of bricks out of this material. However, these ideas have a lot of uncertainty and their practical application is arbitrary. Therefore, these ideas will only be mentioned as an option.

The costs of moving all of the 73 million $m^3$ silt, with an estimated €18/$m^3$ will be €1.3 billion.[18] This number is highly unrealistic and makes this alternative very unattractive. However, it is possible to apply both methods on a smaller scale, meaning a combination with other ideas can be beneficial.

## Idea 2.1: Aligning the silt on the sides of the reservoir along the height

Putting a volume of 78 $m^3$ of silt on the sides along the full height will require a silt layer thickness of 258 m stretching along the entire perimeter, reducing the surface of the reservoir from 2.6 $km^2$ to 1.02 $km^2$. This reduced surface area has only an energy storing capacity of 0.54 GWh and therefore is deemed to be too low to be considered a feasible option.

## Storing the silt inside the upper reservoir

The silt can be transferred inside the upper reservoir. The system effectively benefits the most from the highest slice of water in generating power. By moving the silt into the upper reservoir, the head difference is maintained while the solution of dual functionality is somewhat solved (see Figure 30).

[17] *Wikipedia, Maasvlakte, Wikipedia.com, 2013*
[18] *Dredging costs Project IJsseloog & Masterproject Brazil, Solving the coast of Recife, 2010*

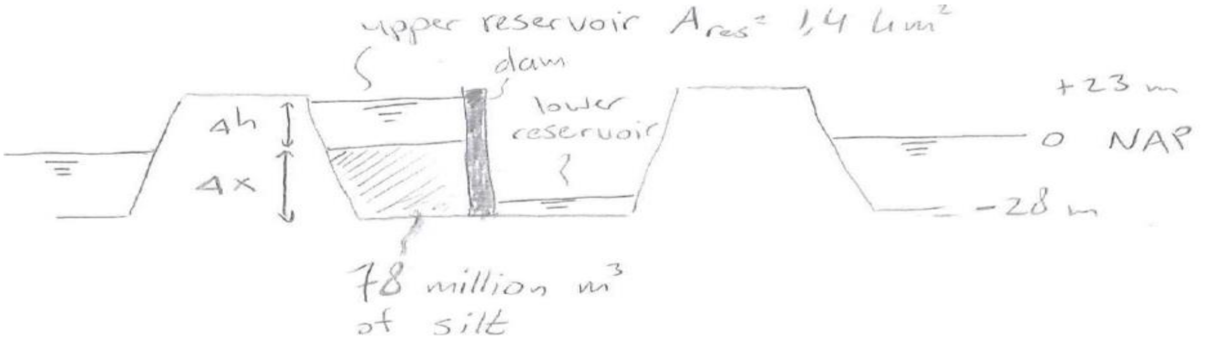



*Figure 30 ... Sketch of the idea of joining the two functions*

When all of the silt is stored in the upper reservoir, this layer of silt will have a height of 52 meters, higher than the top of the supposed dam. By storing silt up to half of the upper reservoir, an amount of 35.7 million $m^3$ can be stored. This will reduce the volume to 42.3 million $m^3$. Using half of the upper reservoir means that the energy storage capacity as well as the power generation capacity will not affected.

## Using of silt for the current dams

Storing the silt inside the dams is another option. However in a practical sense, this is rather difficult, since one needs to replace the current dams with the partially silt dams. Due to the practical issues and the problems concerning the constructability, this idea is dismissed.

## Using the silt for the construction of the dams or implementation inside new reservoir.

The expansion of the reservoir was previously proposed under increasing size of the reservoir. For the creation of the new section, dams are needed. For the construction of these dams, the material inside the Slufter may be used. To make sure that the silt doesn’t access the outer waters, the silt can only be implemented inside the reservoir. In a practical sense, this means that the new dams can be raised to above sea level with non-contaminated soil so that a barrier between both water levels is created. At this point the contaminated soil can be used to heighten the rest of the height, covered with a clean layer.

If the energy storage area of the Slufter is to be enlarged, the silt can be transferred in the new upper reservoir. This is dependent on which reservoir will be used as an upper reservoir. Currently, there is 73 million $m^3$ inside the reservoir. This brings the silt to NAP-level. By filling the rest with water, so up to +23 m NAP, the reservoir can very well be used as the upper one without the need to transfer 73 million $m^3$ of contaminated soil. In this case however, the newly created reservoir will have to be dredged to a significant depth, say 30 m, which means a displacement of 84-million $m^3$ soil. In this case, there is no need to raise dam levels on the landside. The dredging will cost up to €672 million.

The other option is to transfer all of this contaminated soil to the newly constructed reservoir. By emptying the Slufter, it can be used as the lower reservoir and there is no need for the dredging of the new reservoir. The new reservoir can be raised significantly or let to remain around NAP.

# 7. *Wind setup inside the reservoir*

Both the upper reservoir and lower reservoir are closed off from the surrounding sea. There will therefore be no external factors affecting the water level such tides and short waves. Since the reservoir has a large size, wind setup may be an important issue to consider. Since the lower reservoir dam is very high compared to the water level, this will be no issue there. However for the upper reservoir, the same doesn’t go, and therefore the expected wind setup is calculated using formulas for a closed lake:

$$dh_1 = 0.5\kappa \frac{u^2}{gh} F\cos\phi$$

In which u is the wind velocity, g the gravitational acceleration, h the water depth, F the Fetch length, $\phi$ the approach angle to the coast and $\kappa$ is a friction factor that can be calculated using:

$$\kappa = c_w * \frac{\rho_{air}}{\rho_{water}}$$

The value for $\kappa$ is very dependent on the friction coefficient $c_w$ which is a varying value. The Netherlands Delta Committee (Part IV) suggested a value of $\kappa = 3.4 * 10^{-6}$. Due to the similarity of the conditions here, this value is used. The water depth in the upper reservoir depends on the decision regarding the silt storing function. Even though an assumption is made about this, the water depth will be chosen 14m only, which is necessary as the disk varies from +39m to +25m NAP height.

Historical wind data shows that wind speeds of 32 m/s are very rare, but are occurring in this part of the Netherlands.[19] With the values filled in, the wind setup becomes:

$$dh_1 = 0.5 * 3.4 * 10^{-6} * \frac{30^2}{9.8 * 14} * 1650 = 0.025\, m$$

Meaning that wind setup is negligibly low even in extreme situations and will have no significant influence on the water levels. This is largely due to the low fetch length.

# 8. *Consideration of an earth dam for Alternative 2: Split*

## General

The current dams are of the earth dam type. Earth dams are mostly preferred because of their low costs to build up and their high strength. The upper reservoir has a level of +40 m NAP, which is 35 meters above ground level. The outer dams of the upper reservoir can be upgraded by an expansion on top and on the outer edge. The separating wall will have to be constructed entirely from the ground up. The bottom of the Slufter will be at -31m NAP, meaning a dam height of 70m. To make the dam impervious, the silt material inside the Slufter can be used. Especially the bottom layers of this silt are largely consolidated and suitable because of its low permeability.

To minimize the slope angle of the dam and thus the volume that it occupies, a material with a high angle of friction is preferable. Slope angles of 1:2 are possible for rock-fill dams as proven for the Oroville Dam in Canada.[20] However, for the Netherlands, as the material rock is not widely available and to import a volume of rock of that magnitude will be too expensive, this is a problematic option. Materials that are widely available are sand and silt. When constructing dams with sand, one has to account for a best case scenario of a slope of 1:3. This makes the width of the dam 210 meter at the bottom on one edge, width a total width of 427 meter, a massive structure. However, this does not have a big effect on the energy storing capacity because in the design the water level is only ranging in between 70m and 56m. Earth dams of this size are rare but feasible.[21]

The real problem lies in the realization of this alternative. Since the depot is already filled with silt and the dam cannot be built on top of the silt, the construction of a dam with 427 meter width at bottom is

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[19] *KNMI, Zware stormen sinds 1910, 2013*
[20] *Paul D.K., Seismic safety analysis of a high rock-fill dam subjected to severe earthquake motion, 2010*
[21] *NASA, Earth Sciences Web Team Tarbela dam, NASA, 2010*

impossible. Ideally, all the silt would be removed, the dam would be built and the silt would be pumped back into the upper reservoir. However, where does one leave a silt volume of that magnitude?

## Dam orientation

The following orientation is chosen based upon the above considerations.

*Figure 31 ... Overview showing orientation of the dam (Google Earth, 2013)*

The creating of the arch is beneficial because the less windmills that have to be displaced. Despite the consideration of the wind mill positions in the orientation, three wind mills will need to be removed at the western section. A breach in the northern side of the dam will cause no large problems for the port area, since it will simply fill up the empty reservoir in front of it. The flood waves caused by this breach will cause a high setup at the northern dams of the Slufter. Because these dams are already +23m NAP, this will not cause any problems. Dam design

Three different dams are distinguished in the project (see Figure 32):

1. Lower reservoir dams (indicated in yellow)
2. Upper reservoir dams (indicated in green)
3. Separation dam housing the turbines (indicated in red)

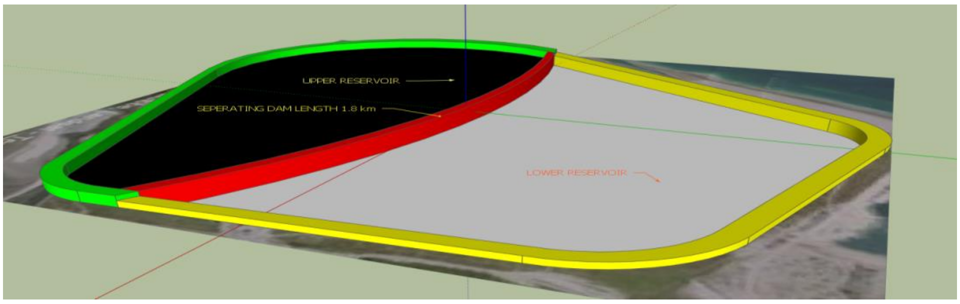


*Figure 32 ... View on the Slufter showing a the dam from a different perspective*

The lower reservoir dam (in yellow) has a height of +23m NAP and will remain the same as it is now, with the windmills on top. Lowering this dam is simply unnecessary and will be a waste of capital, especially because in this case the wind mills on top will have to be removed. Therefore, this dam is unchanged.

The upper reservoir dam (in green) is +23m NAP at the moment. This dam will need to be heightened to +40m NAP, a rise of 17m.

The separation dam (in red) is a completely new structure that will have to be raised from the current bottom of the reservoir, -28m NAP, to the height of the upper dam, +40m NAP, meaning that the height of the dam is 70m. To make sure the water level is not exactly at the top of the dam, the height of the dam is set 0.5m higher than the water level, at 70.5m, i.e. +40m NAP.

This 1m buffer is enough to account for wind setup and waves created inside the reservoir.

## Material

The dam must have an impervious core so that the water inside doesn't simply flow away through the pores or worse, may lead to instability of the dam. Therefore, the core of the dam needs to be impervious, namely built up from clay. This clay is covered by sand and silt. Since the top layers of the surrounding areas are sand, the availability of sand is quite large. The bottom of the reservoir will be dredged 3 meters, which creates 3.6 million $m^3$.

The total amount of sand required depends on the slope and width of the dams, which will be explored in the following sections.

## Slope

The slope depends on the internal friction angle of the sand, which is assumed to be 30 degrees. The permissible slope is half the angle of repose, i.e. an angle of 15 degrees or a slope of 1:3.5. This means the width of the inner slope facing the lower reservoir will be 250 meter and the one facing the upper reservoir will be about 60m. The width of the crest is about 5 meters, enough for a small maintenance road.

Separating dam slopes: lower reservoir side: 1:3, 71:220m

Upper reservoir side: 1:3, 71:220m

Total width: 445 meter

# 9. *Evaluation of the ideas*

## Introduction

In the previous sections, several options have been considered with their respective effect on the system in terms of design, energy capacity and power generation capacity. A combination of these ideas is possible and will positively influence the system function and reduce the effect of problems with the Slufter. With this evaluation of the ideas, the system Slufter will be optimized for the energy storage function.

## Evaluation of the optimization ideas

The construction of a dam inside the Slufter doubles the hydraulic head and power generation capacity and is preferable. The option of placing turbines in the new dam rather than a dual system has the benefit of creating a high power output, while lowering energy capacity. A higher head has the preference over a larger reservoir. It may even be possible to heighten the reservoir dams from the +23m NAP.

Lowering the depth of the reservoir has clear benefits. With a relative low investment, the height and therefore both the energy storing and generating capacity are increased.

Increasing the size of the reservoir is straightforward beneficial, especially because the Slufter utilizes low-head power generation. Therefore, it is worth to further investigate the possibility of increasing the reservoir size.

## Evaluation of the silt storage ideas

Moving all the contaminated silt to another location hardly seems feasible in the economic and practical sense. Not only does it depend very much on the availability of such a location, it requires large investments.

The silt that is stored in the depot isn’t highly contaminated. Therefore, it is expected that a lot can be reached with the recycling of the material. This seems to be the optimal solution, since it allows for the material to be re-used for other purposes, instead of simply occupying space that cannot be used for other functions. However, it is expected that recycling can only deal with a (small) portion of the silt and that this is a rather expensive operation.

Using the silt in the construction of the new dams is practically rather difficult and environmentally problematic. The silt is secluded because of its contamination and using it for the construction of the new dams could be risky.

With the construction of a new (upper) reservoir, the silt could be transferred there. As the upper reservoir, there will barely be any effect on power generation capacity. The transfer of function might lead to smaller energy storage capacity, which can be solved by raising the dams of the new reservoir.

# Appendix I Other calculations

## 1. ***Micro-stability of the slope***

The micro-stability of the slope deals with the internal forces inside the slope. For this the local balance must be maintained in order to full-fill the stability criteria. The focus is on the outer grains on the slope. Stability on the micro level deals with the stability of each individual grain with e.g. Shield, and the acting forces of the grains on the slope. This is achieved by a simple force balance on the local scale.

The stability of the grains depends on the force balance of the slope. In the case without porous flow through the dam, the equation simplifies to the angle of repose φ:
$\rho_s g cos(\alpha)\tan(\phi) \geq \rho_s g sin(\alpha) \qquad \rightarrow \qquad \phi \geq \alpha$
Since in this case there is no or very little porous flow in and out of the dam, the above equation holds for the micro-stability of the slope. For the sand dam this means that the angle should be equal or greater than the angle of repose. The angle of repose is assumed to be 35˚, requiring a slope of at least 1:2.5. The current slope of 1:3 is therefore sufficient and adds some additional safety.

## 2. ***Macro-stability of the slope***

The macro-stability deals with the stability of the slope as a whole rather than the micro-stability which deals with the stability of the particles. Macro-stability analysis focusses mainly on the analysis of slip circles, for the simplified method of Bishop is often used in practice. The general idea of this method is the balance between the loads causing the slope to slip resisted by the force that holds the slope intact.
The balance is given by the total strength divided by the load:

$$F = \frac{\sum[(c + \sigma_n' tan\varphi)/cos\alpha]}{\sum \rho_s g h sin\alpha}$$

## 3. ***Bearing strength of soil***

The underlying subsoil under the earth dam is sand that has an equal or even greater strength due to its long consolidation and settlement. It requires therefore no calculation that this has the adequate strength to cope with the stresses caused by the dam. However, at the site of the turbine casings, the soil bearing capacity should be checked. The design of the turbine casings should be done in order to calculate this. The design of the turbine casings is however outside the scope of this technical design.

## 4. ***Horizontal, parallel and perpendicular seepage***

Horizontal seepage of the water is a case that may be normative for this dam. This is because of the large amounts of sudden drops and rise of water level. When such a large water level change occurs, the water could seep through the dam horizontally. In such as case, the stability equation is given by:

$$tan\phi \geq \frac{\sin\alpha + \tan\alpha\cos\alpha}{\cos\alpha - \tan\alpha\sin\alpha} = \frac{2\sin\alpha}{\cos\alpha - \dfrac{\sin^2\alpha}{\cos\alpha}} = \frac{2\sin\alpha\cos\alpha}{\cos^2\alpha - \sin^2\alpha} = \tan 2\alpha \rightarrow \phi \geq 2\alpha$$

The used sand has an angle of repose of 35˚, which requires an $\alpha \approx 17.5°$ or 1:3.2. Adding some extra safety, the slope is made to be 1:3.5. Determined on a similar way as the horizontal seepage, the balance for parallel and perpendicular requires

$$\tan\phi \geq 2\tan\alpha \qquad \text{and} \qquad \tan\phi \geq \frac{\sin\alpha}{\cos\alpha - \sin\alpha}$$

Both the balances are less demanding than the requirement for horizontal seepage, ergo horizontal seepage is normative.

# Appendix J GeoStudio

## 1. ***Material specifications***

### Seep/W analysis

Three different materials are defined in the model as they have been defined in the program.

- Silty Clay Core
- Dam Fill Sand
- Subsoil Sand

The relevant characteristics are in this case the hydraulic conductivity and the volumetric water content of the soil. As this material data is unknown, some assumptions are made. As a reference, the following graphs have been used for the hydraulic conductivity and the volumetric water content (see Figure 34 till Figure 37).[22]

The dam fill material resembles characteristics of sand, while the core material resembles characteristics of silty clay. The subsoil characteristics have been cloned from the dam fill characteristics, meaning that in this analysis, no distinction has been made between the two (although the geometric model may suggest so).

The material models, added with these characteristics, have been assigned to each specific region of the geometric model (see Figure 33). By calling the soil inside the Slufter, what is actually meant is that this material has the same properties as the core material.

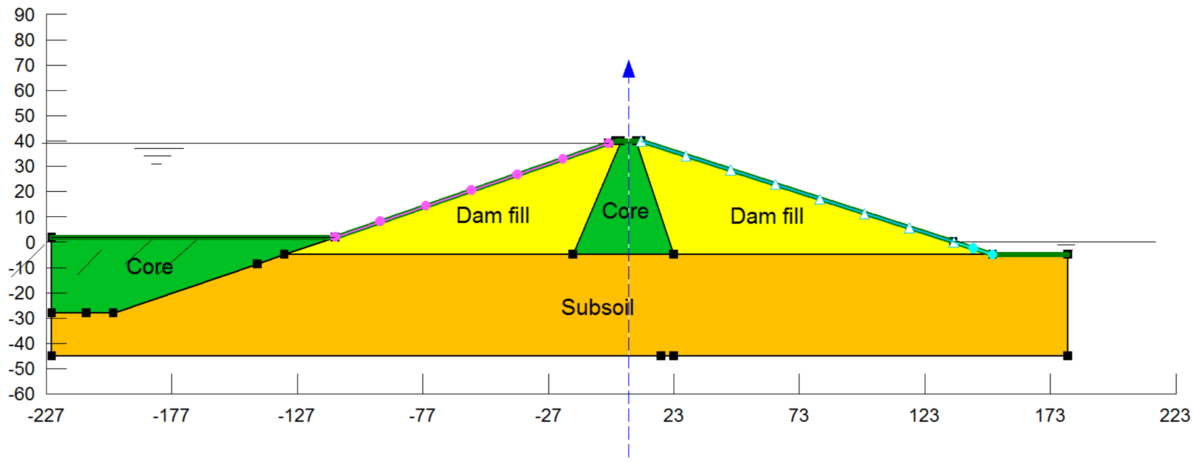


*Figure 33 ... Materials assigned to the geometric model*

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[22] *GEO-SLOPE International, SEEP/W Version 5 User Manual Appendix A: Hydraulic conductivity, 2001*

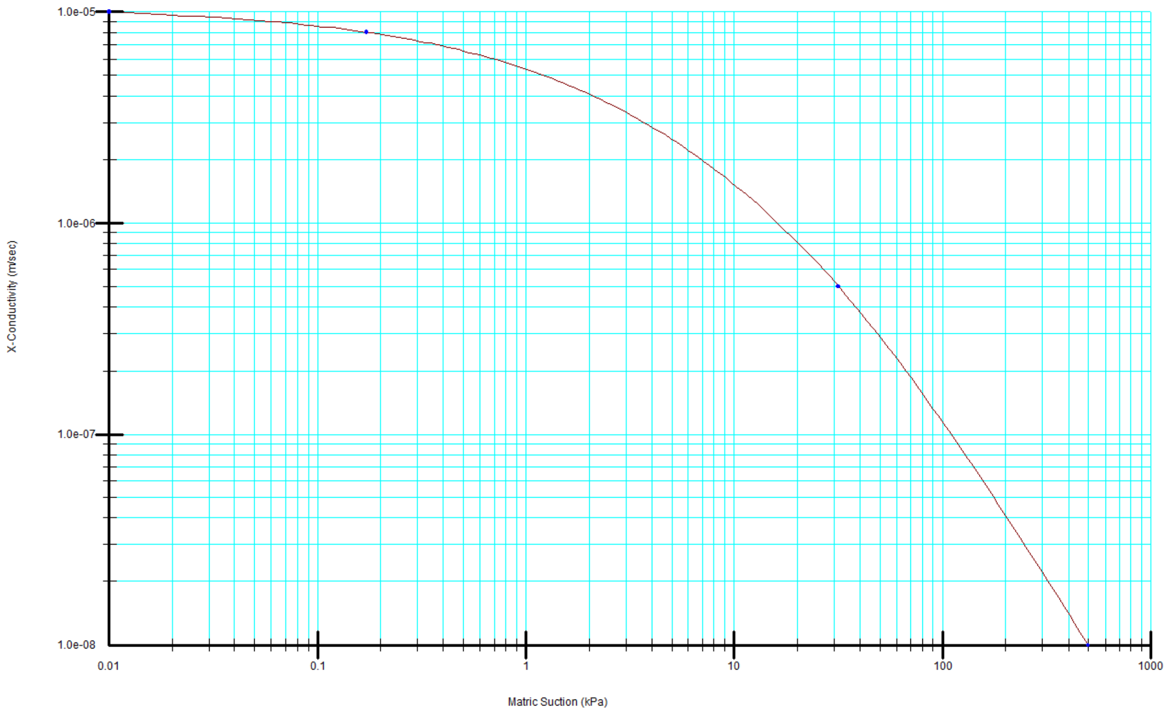



*Figure 34 ... Hydraulic conductivity curve for the dam fill material*

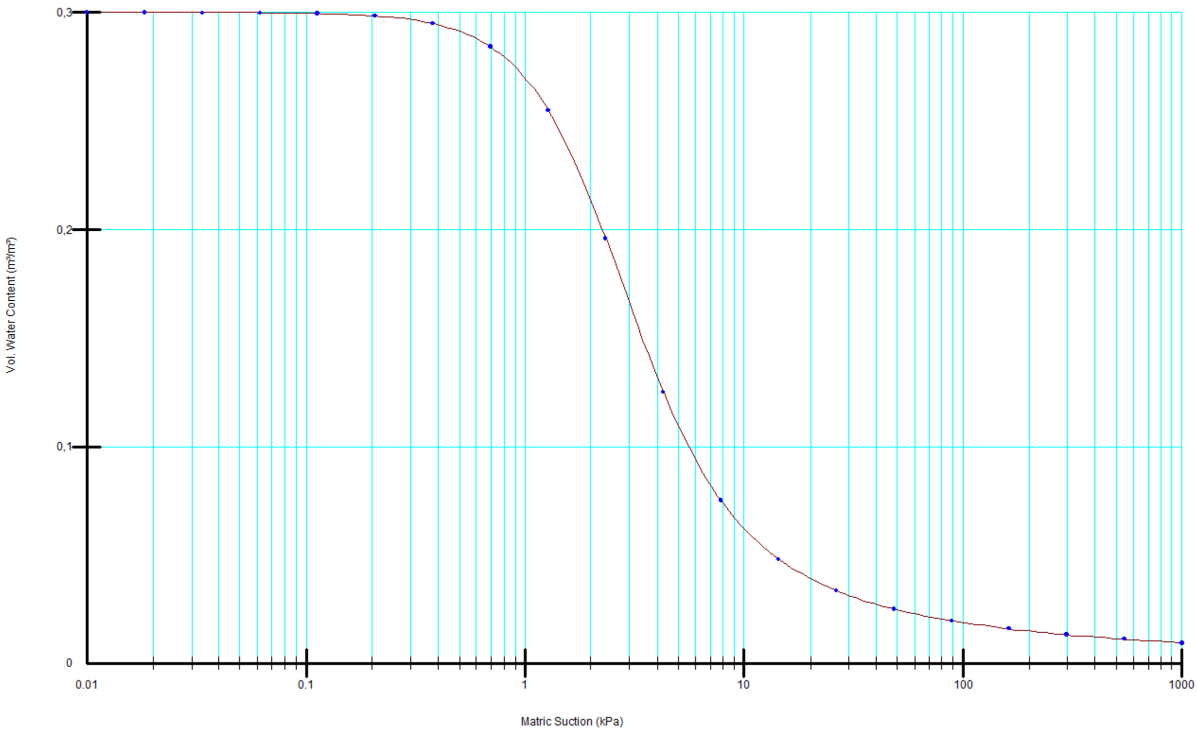



*Figure 35 ... Volumetric water content curve for the dam fill material*

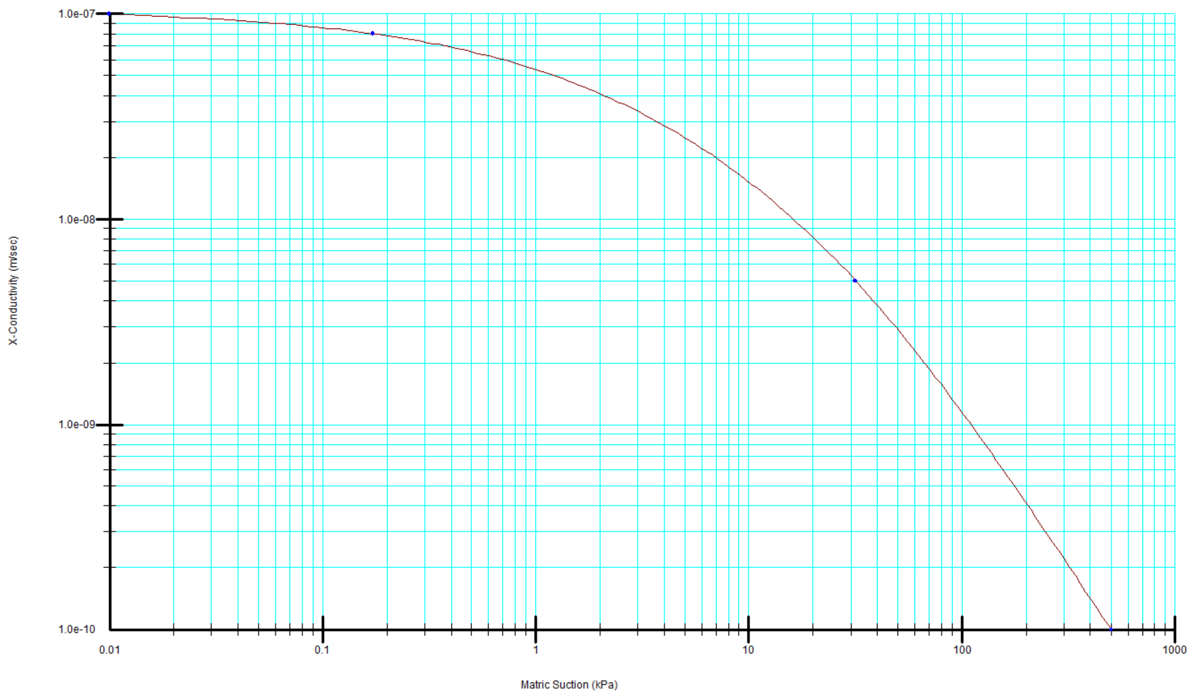



*Figure 36 ... Hydraulic conductivity for the core material*

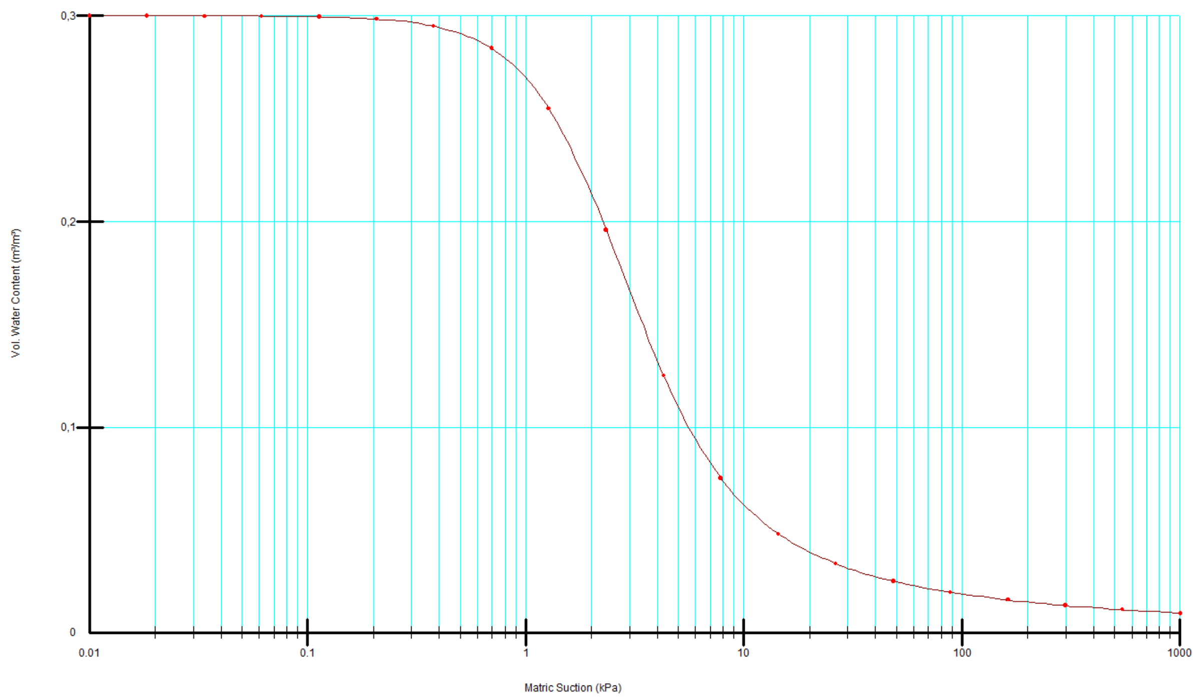



*Figure 37 ... Volumetric water content for the core material*

# 2. *Additional results SEEP/W*

The following sets of nodes are analyzed for their drop of pressure head along the x-axis.

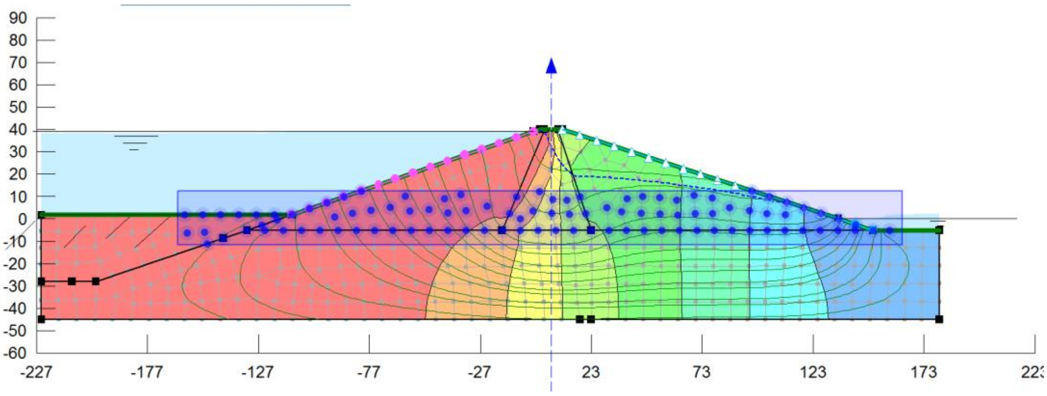



*Figure 38 ... Analyzed nodes for pressure head drop*

The pressure drops going along the x-axis towards the seepage point. The pressure head drop is visualized in Figure 40. The graph actually shows three different lines, a top one, a middle one and the lower one. Together the nodes show how the pressure drops along range. The drop increases at the core, which can be seen by the steepening of the slope. The amount of the groundwater flowing through the dam is highly affected by the core. The flux is measured along the x-axis. While the flux is increasing untill the dam, the presence of the dam causes the gradient in the x-direction to rise significantly. This can be accounted to the vectors going under the core which could be seen in the main report. The full set of nodes is analyzed for this. The x-gradient corresponds with the velocity of the water flow along the x-direction. A high gradient is an indication of a high velocity (see Figure 42).

The same can be said about the gradients and velocity in the y-direction (see Figure 43 and Figure 44). What is furthermore interesting is the fact the y-velocity of the flow is virtually zero at the core while the x-velocity reaches its maximum value (which is the flow under the core).

# 3. *Additional results for SEEP/W for dam without core*

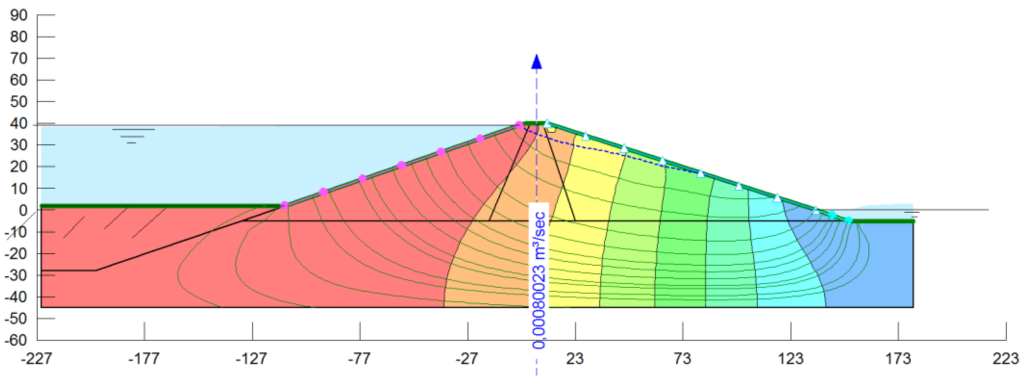



*Figure 39 ... Flow lines and flux through the dam without core*

The flux running through the cross-section of the dam without the core is $8.0*10^{-4}$ $m^3$/sec.

Compared to the situation with a core, this value is quite larger. Any water losses will lead to a lower efficiency of the system. A loss of 400.000 $m^3$ water each day is quite a significant number that should be limited by constructing a core.

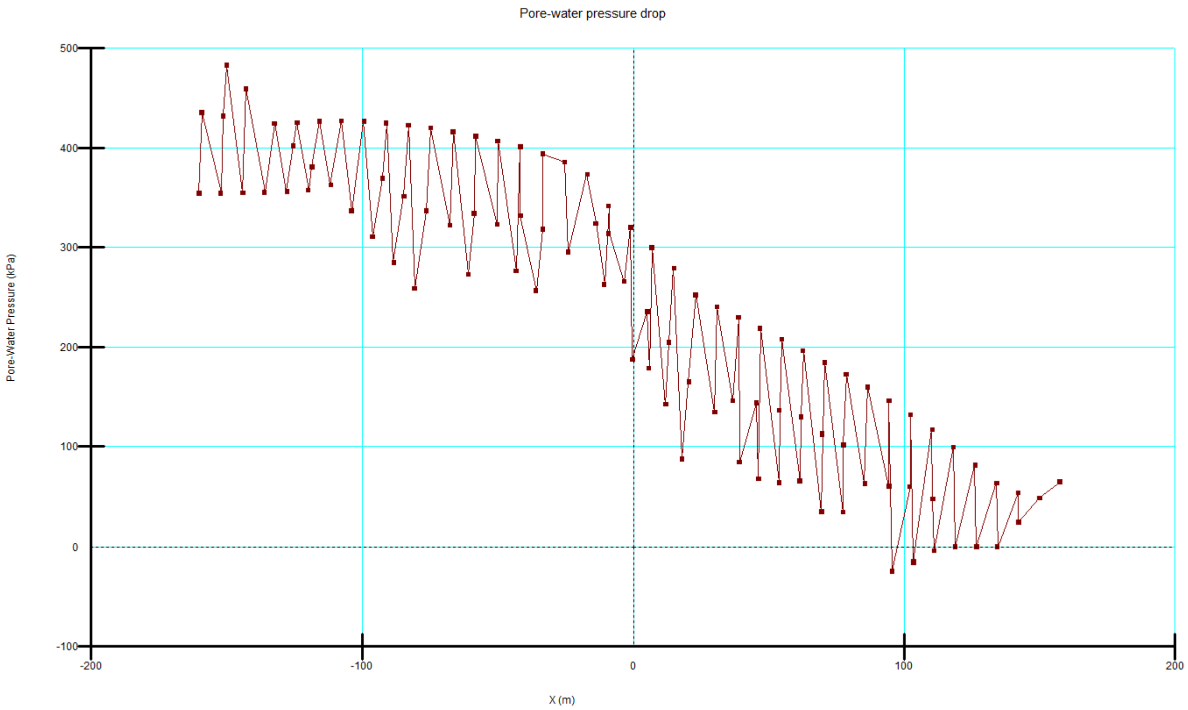



*Figure 40 ... Drop of pressure head level of the nodes indicated in Figure 38*

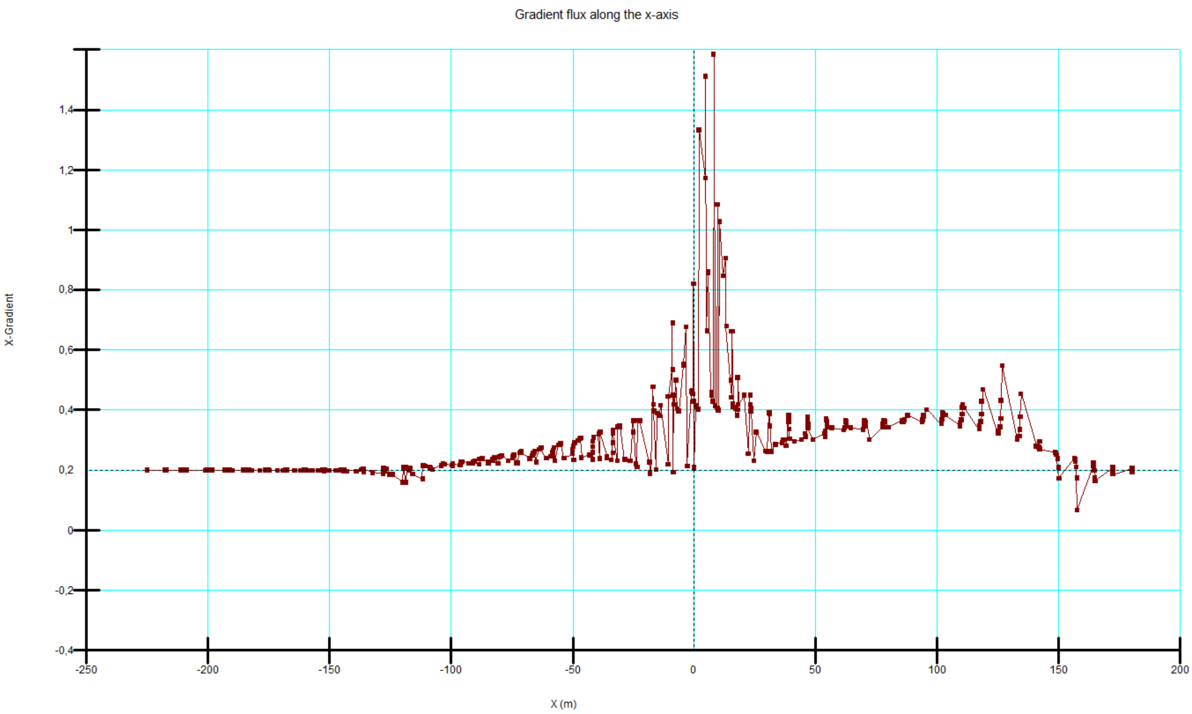



*Figure 41 ... Water flux gradient along the x-axis of the dam*

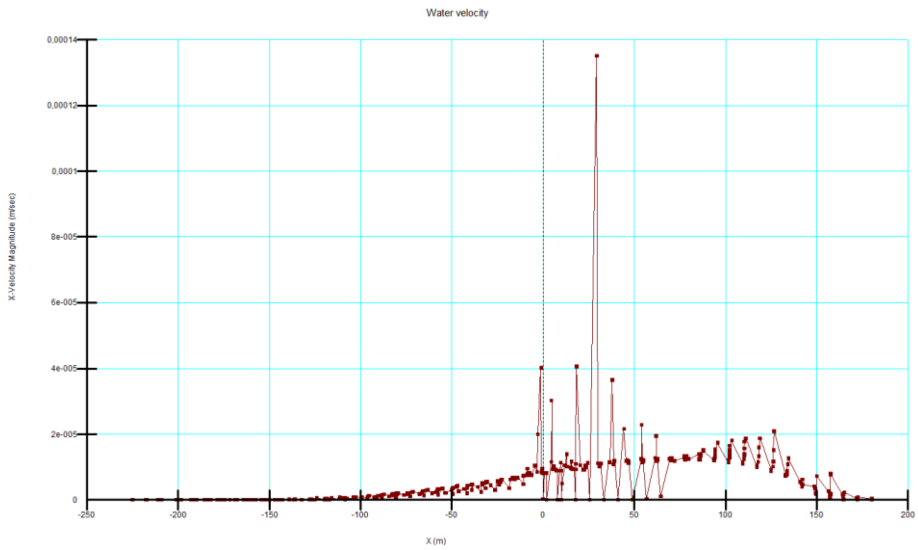



*Figure 42 ... Velocity of the water flow in X-direction*

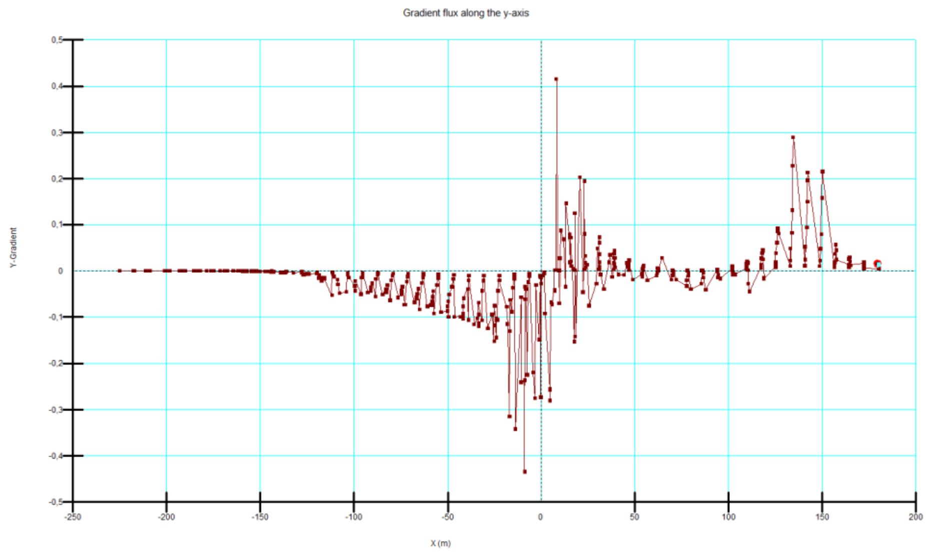



*Figure 43 ... Y-gradient along the x-axis*

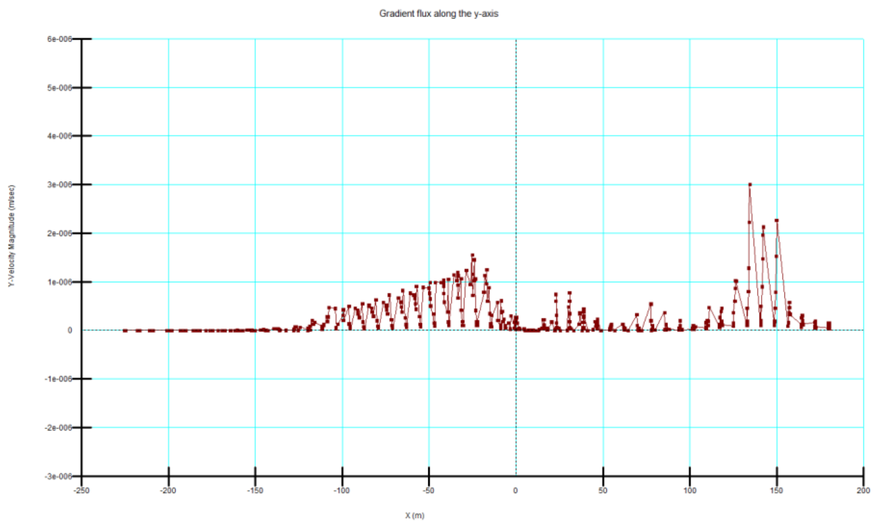



*Figure 44 ... Y-velocity along the x-axis*

# 4. *Slip circle stability*

## Limit equilibrium and difference between Bishop and Morgenstern-Price

The general idea of the limit equilibrium is load versus strength. While the load is represented by the weight of the soil acting on a specific slip circle, the strength is given by the shear resistance along the slip circle. The balance in between these two, gives the stability coefficient

$$F = \frac{strength}{load} = \frac{shear\ resistance}{weight\ of\ the\ soil}$$

When F > 1, the slip circle is stable. This check has to be performed on each possible slip circle along the defined ranges.

For computation, both Bishop and Morgenstern-Price Method act with this general idea. The way in which they differ from one another is how they define the slices and forces. Despite giving two alternative methods of calculation, both result in similar values.[23] This will be proven for one of the analysis.

## Materials

The materials are the same as they have been defined in the SEEP/W analysis. However, since a different form of analysis is performed, different soil characteristics are relevant. The characteristics that are relevant are the unit density, the cohesion and the internal angle. The material models are chosen to be More-Coulomb.[24] These have been chosen as they have been defined in Table 7.

| Material | Unit density (kN/m$^{3)}$ | Cohesion (kPa) | Phi (°) |
|---|---|---|---|
| **Dam fill** | 16 | 5 | 31 |
| **Core fill** | 16 | 0 | 25 |
| **Subsoil** | 17 | 1 | 35 |

*Table 7 ... Relevant material properties for slip circle analysis*

[23] *D.G. Fredlund and J.Krahn, Comparison of the slope stability methods of analysis, 1977*
[24] *Material Models Plaxis, 2011*

## Additional results core model

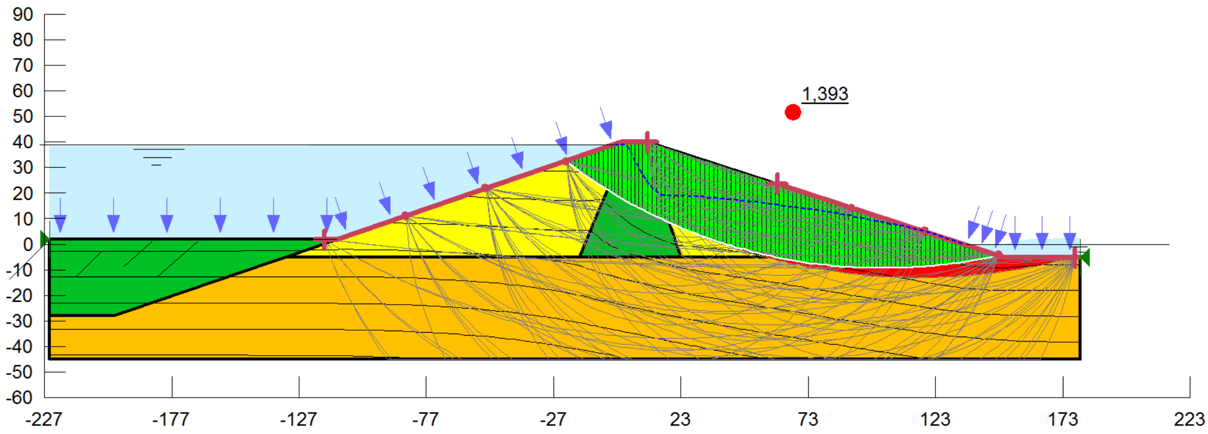



*Figure 45 ... Critical slip circle together with the top 100 critical slip circles and safety map*

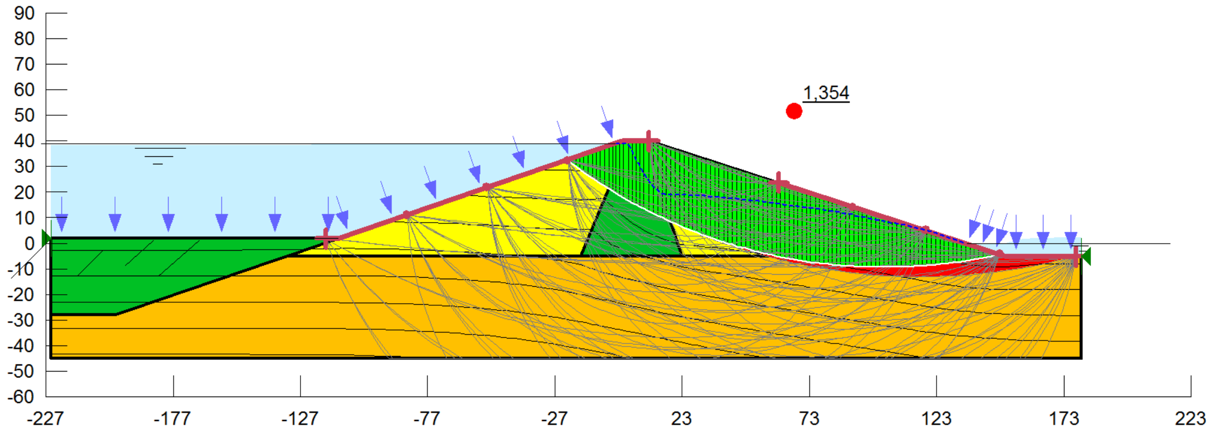
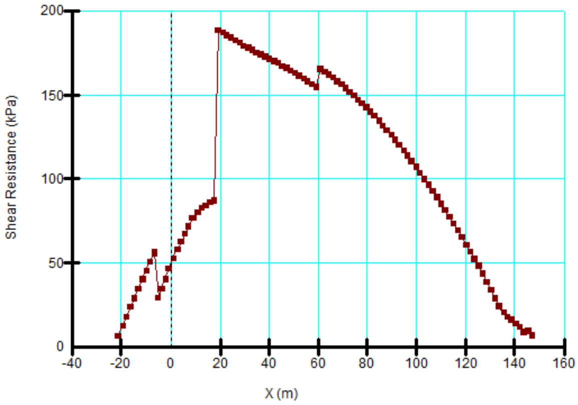



*Figure 46 ... Slip circle analysis using the method of Bishop*

The following figures represent the strength and pressures along the x-axis for the critical slip circle (see Figure 47 till Figure 49). The strength of the dam is declining rapidly upon reaching the groundwater flow level.



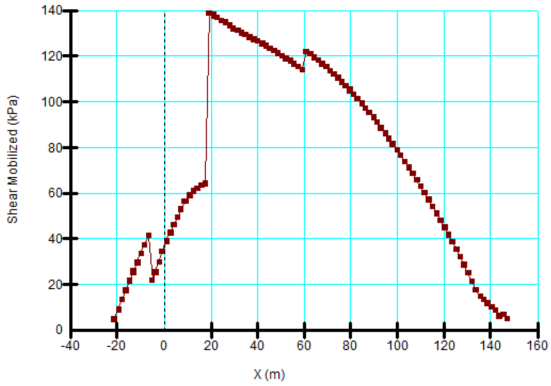
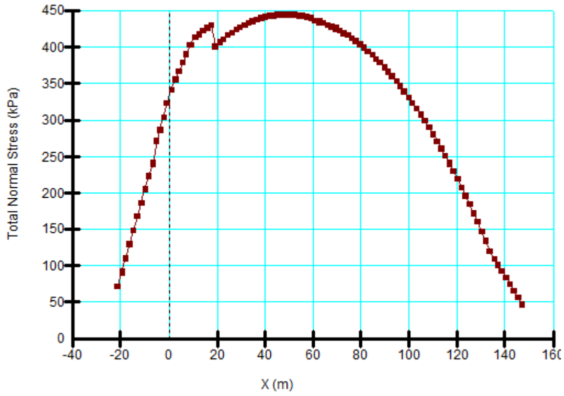



*Figure 47 ... (left) Shear resistance and (right) mobilized shear along the x-axis*



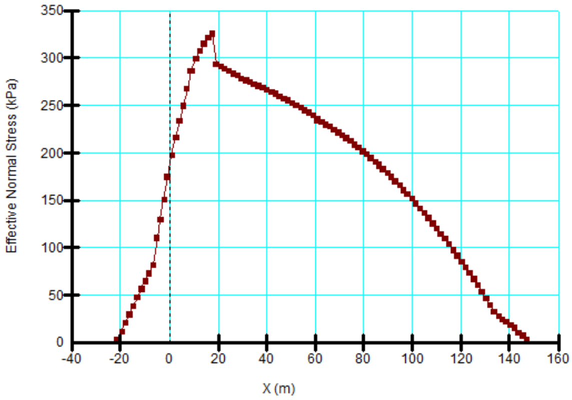



*Figure 48 ... (left) total normal stresses and (right) effective stresses*

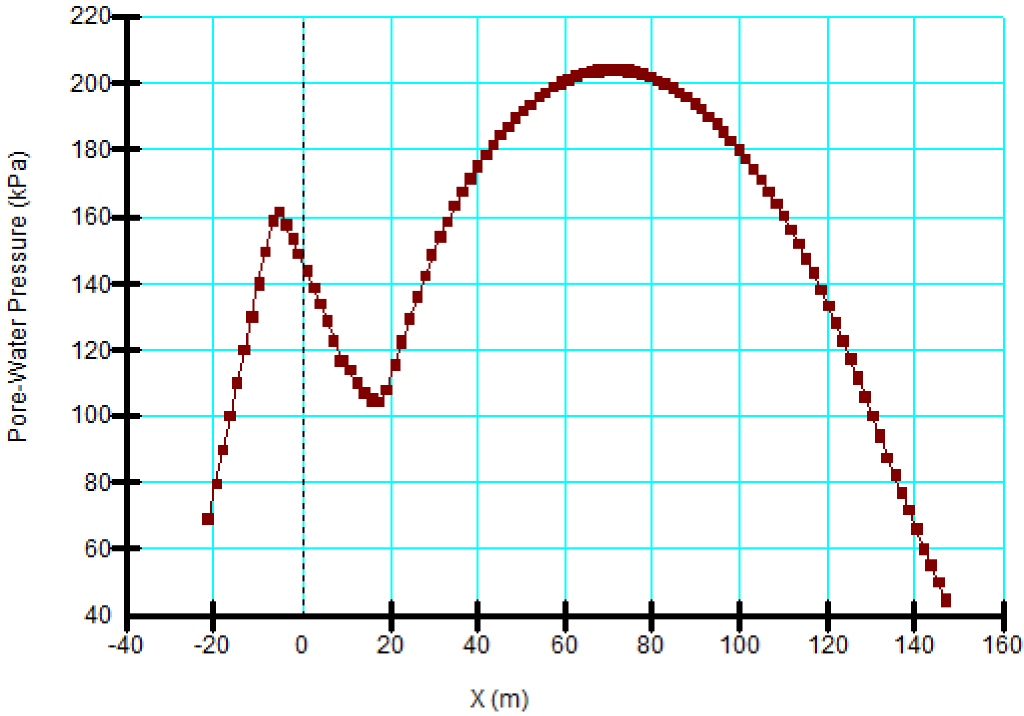



*Figure 49 ... Pore water pressures along the x-axis*

# 5. *Stability analysis for the dam without a core*

***Geometric model, boundary conditions and materials***

The geometric model is once again the same. The differences compared to the model presented in the flow analysis are the added material characteristics that have been shown in the stability analysis with the core. The change in between the model in the stability analysis above is the removal of core material in favor of sand (see Figure 50).

The calculation methods and analysis is exactly the same in any other way, so for more information about this; see the stability calculation above.

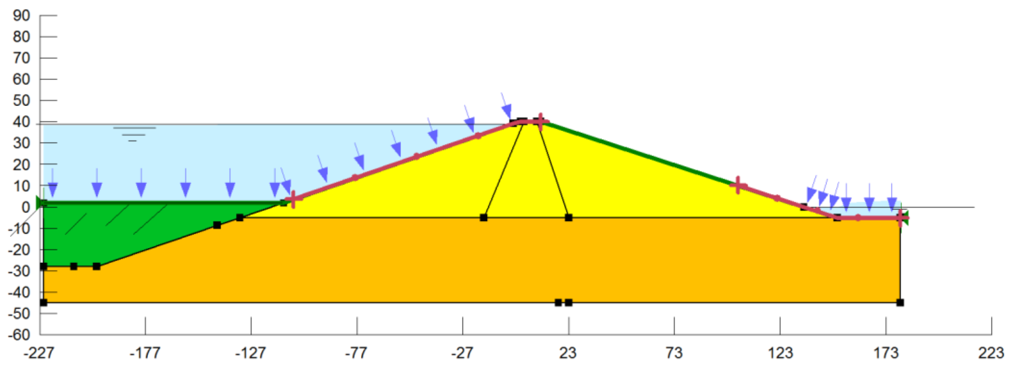



*Figure 50 ... Geometric model for the stability of the dam without core*

***Additional results***

The critical safety factor displays a value of 0.996. As explained before, any value below 1 means that the load is larger than the resistance. This means that the stability is not guaranteed for this case.

The 100 slip circles following the slip circle give more insight into the possible slip circles that might form (see Figure 51).

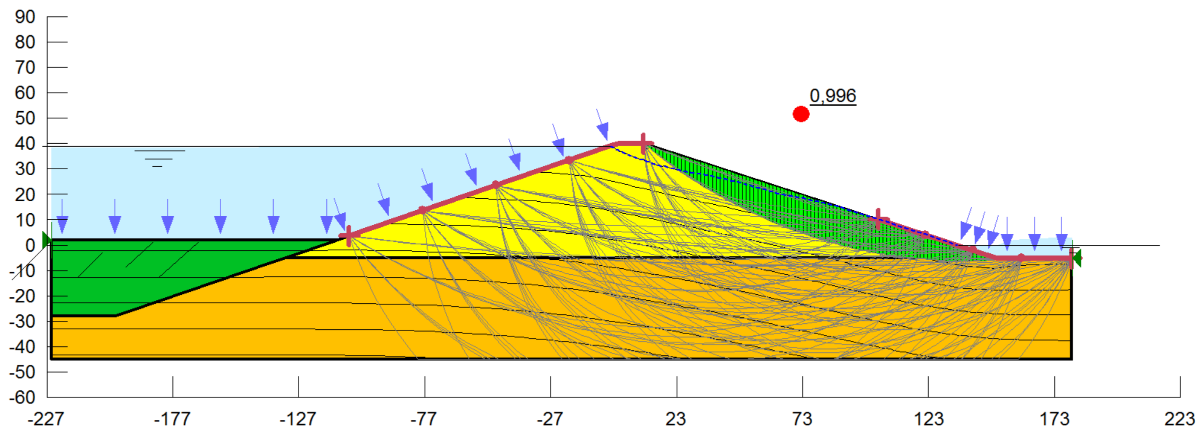



*Figure 51 ... Hundred possible slip circles after the critical slip circle*

# 6. *Grid and radius method*

## Determining the grid size

*The Grid and Radius Method* uses a grid of possible radius points to test multiple slip circles. To have an accurate calculation, the grid should be chosen as wide and large as possible. The grid size can be limited because the range of point location is known somewhat. The solver is then used to determine the exact location and the critical slip circle safety factor.

For this analysis, the grid has been purposefully chosen to be quite large (see Figure 52). This is because of the high reservoir level which can cause a variety of possible slip circles, far greater than for a normal slope.

With all other variables already determined, the solver can be run to compute the critical slip circle.

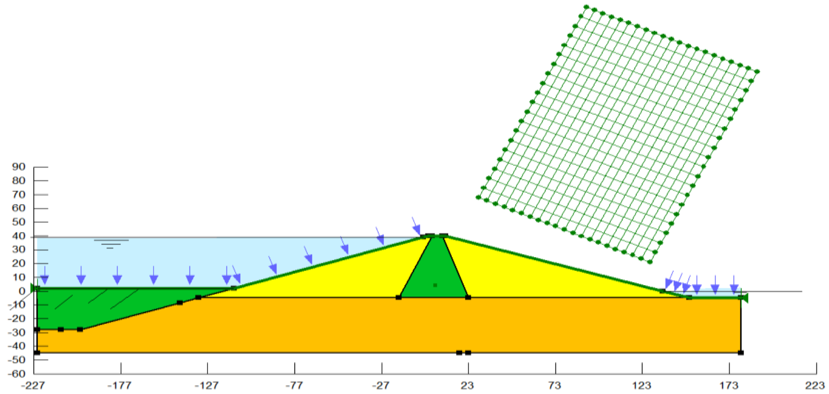



*Figure 52 ... Grid size for the Grid and Radius Method*

## Result

The critical slip circle safety factor is 1.382, which is very similar to the values obtained at the *Entry and Exit Method*. The slip circle that is formed is however a totally different one, which proves the essence of this method. Figure 53 shows the wide range of possible slip circles that are calculated.

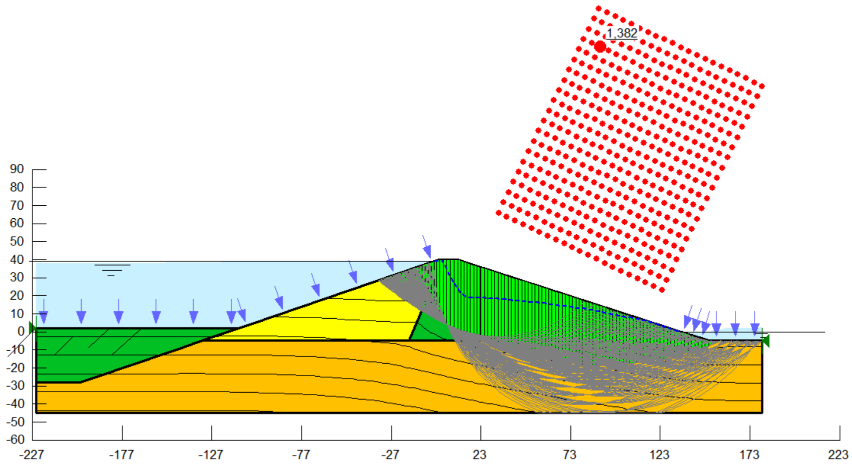



*Figure 53 ... Range of possible slip circles*

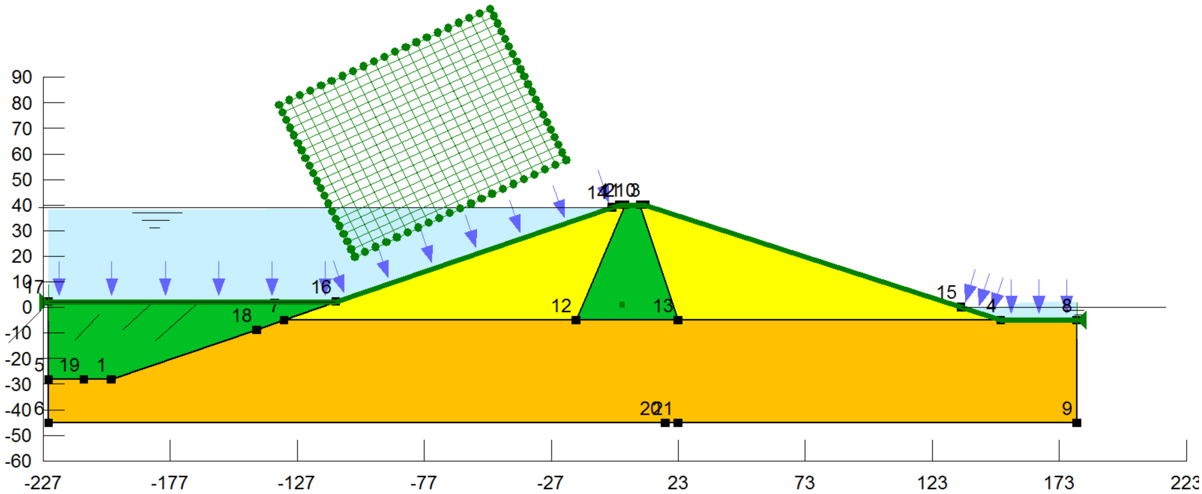
# 7. *Calculation of the upstream slope full reservoir*

## Introduction and modeling

The left side of the dam is expected to be strong enough, especially with the water level being as high as it is. This hypothesis will be tested in this section.

The model details are again the same, no adjustments are required there. The model is as it is at the *Grid and Radius Method* analysis.

The only change is in the calculation method. The characteristics of the method are changed from a *Left-to-Right* calculation to a *Right-to-Left* calculation.



## Additional results

The results support the previously mentioned hypothesis that the left-hand side is indeed deemed to be far more stable compared to the right side of the dam. The Grid and Radius Method provides a critical slip circle with a safety factor of *3.464*. This is a very high value and confirms that on this side of the slope, no instability issues are expected.

The possible slip circles are presented in Figure 54.

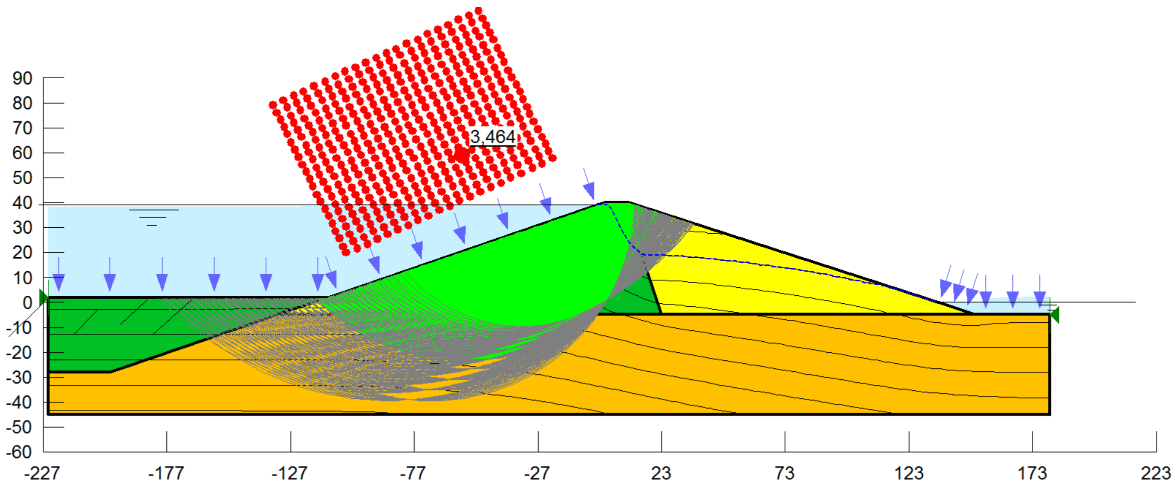



*Figure 54 ... possible slip circles*

# Appendix K PLAXIS

## 1. *Additional info about Phase 5 till 8: Safety calculations*

In Phase 5 till 8, safety calculations are performed for the corresponding Phases 1 till 4. For example, Phase 5 is a safety calculation of Phase 1, Phase 6 of Phase 2 and so on…

This safety calculation is a phi-c reduction method. This method is limit equilibrium state calculation method that calculates the safety factor by balancing the strength versus the load. In this way, it is similar to Bishop's method.

The Phi-C Reduction Method works by reducing the strength parameters tan(phi) and c of the soil until failure occurs. The result is the safety factor which is similar to the result of conventional slip surface analysis:

$$\sum Msf = \frac{available\ strength}{strength\ of\ at\ failure} = safety\ factor$$

Apart from the safety factor, PLAXIS also displays the development of Msf.

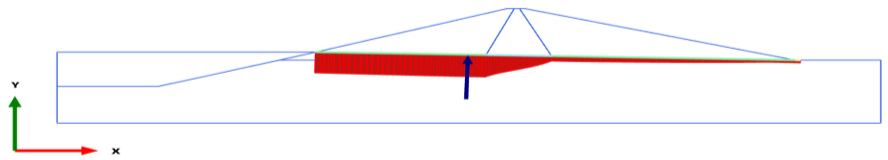
## 2. *Flow through CCM*

***Flow model and calculation***

The modeling will continue with an analysis of the flow through the dam. For this, the *Flow Mode* of Plaxis is used, in which the previously generated model of CCM is used. In this analysis, the cyclic up and down movement of the water level inside the reservoir is modeled using a harmonic fluctuation. The mesh and hydraulic conditions are the same as in the previous analysis. The calculation consists of three phases. In the initial phase, the groundwater flow is calculated for the stable reservoir level as a steady state groundwater flow. In Phase 1, the transient groundwater flow is calculated for the changing water level with time interval 0.25 days (6 hours). The same analysis is done for Phase 2 with an interval of 1 day. As the charging and generation will succeed right after each other, the fluctuations can be modeled as a harmonic fluctuation. The full analysis containing more curves is in *Appendix K*.

***Results***

What is interesting is the change of the active pore pressure as a result of the drawdown compared among the different phases. This change is visualized in a cross-section that is taken along the bottom of the dam (*see Figure 55*). The change in pressure is displayed in a more detailed way in *Figure 56* for all three phases.




Active pore pressures $p_{active}$ (scaled up 0.0500 times) (Pressure = negative)
Maximum value = -47.46 kN/m$^2$
Minimum value = -388.9 kN/m$^2$
Equivalent force is -56.77*10$^3$ kN/m at position (-27.538, -0.226) m

*Figure 55 ... Cross-section active pore pressure in the dam*

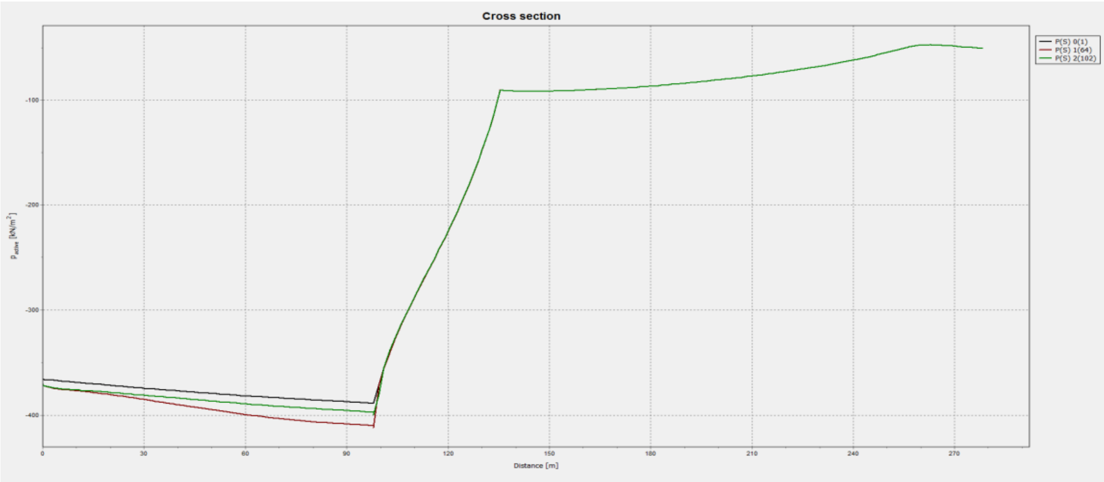



*Figure 56 ... Graph displaying the change in active pore pressure along the dam length (from bottom to top: Phase 1,2,0)*

The pressure curve develops as expected: in the sandy part, it builds up slowly until reaching the core. From there the line rises (note that the values are negative) in a steep manner because of the low permeability of the core material. The curve shows that the active pore pressure rises with the harmonic fluctuation of the water level. A clear difference between Phase 2 and Phase 1 is visible; while in Phase 1 the change is fast, the difference is sudden and therefore the pressure larger as opposed to Phase 2.

## Flow model

The modeling will continue with an analysis of the flow through the dam. For this, the *Flow Mode* of Plaxis is used, in which the previously generated model of CCM is used. In this analysis, the cyclic up and down movement of the water level inside the reservoir is modeled using a harmonic fluctuation.  Also the up and down fluctuations of the water level are analyzed.

The mesh and hydraulic conditions as used before are displayed in Figure 57 and Figure 58.

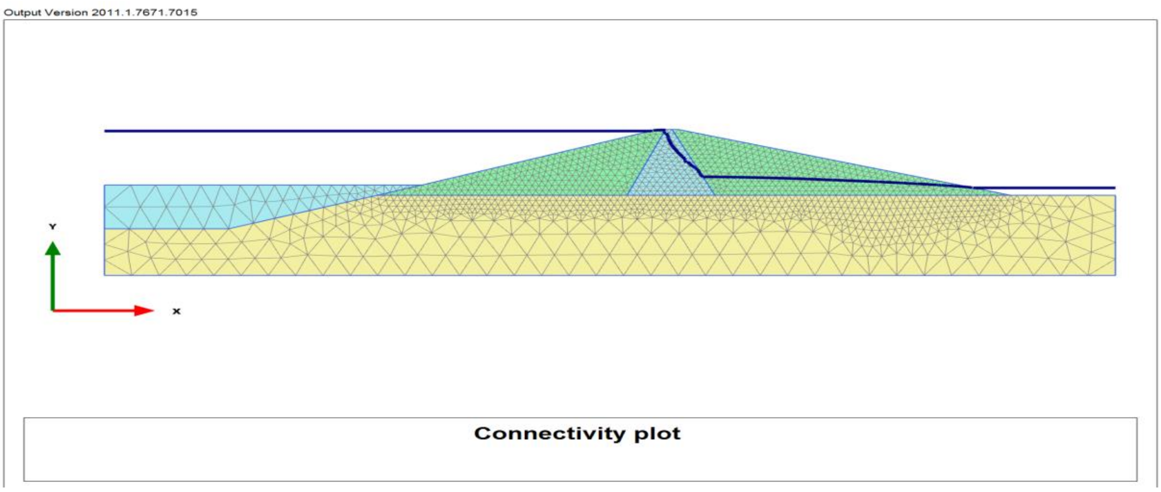



*Figure 57 ... Generated mesh for Center Core*

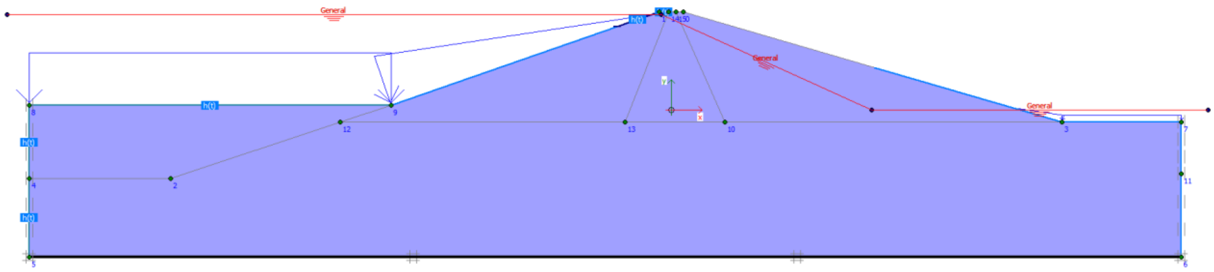


*Figure 58 ... Water conditions during the flow analysis*

## Calculation

As previously mentioned, the calculation method *Flow Mode* is selected. The calculation consists of three phases. In the initial phase, the groundwater flow is calculated for the stable reservoir level as a steady state groundwater flow.

In Phase 1, the transient groundwater flow is calculated for the changing water level. The same analysis is done for Phase 2, however this time the time period of the changing water level is longer. For Phase 1 the time interval is chosen to be 0.25 day, about 6 hours as for Phase 2, this interval is chosen to be 1 day to see what the difference between very fast lowering and slow lowering.

The changing water level is in this analysis analyzed as a harmonically varying water level. This approximation can be justified to simulate reality. Because just like tidal waves acting on a dike, the water level inside the reservoir will vary rapidly along a day. The pumping and generating will take place in respectively 10 hours and 6 hours. As the charging and generation will succeed right after each other, the fluctuations can be modeled as a harmonic fluctuation.

# 3. *No Core Model (NCM) additional results*

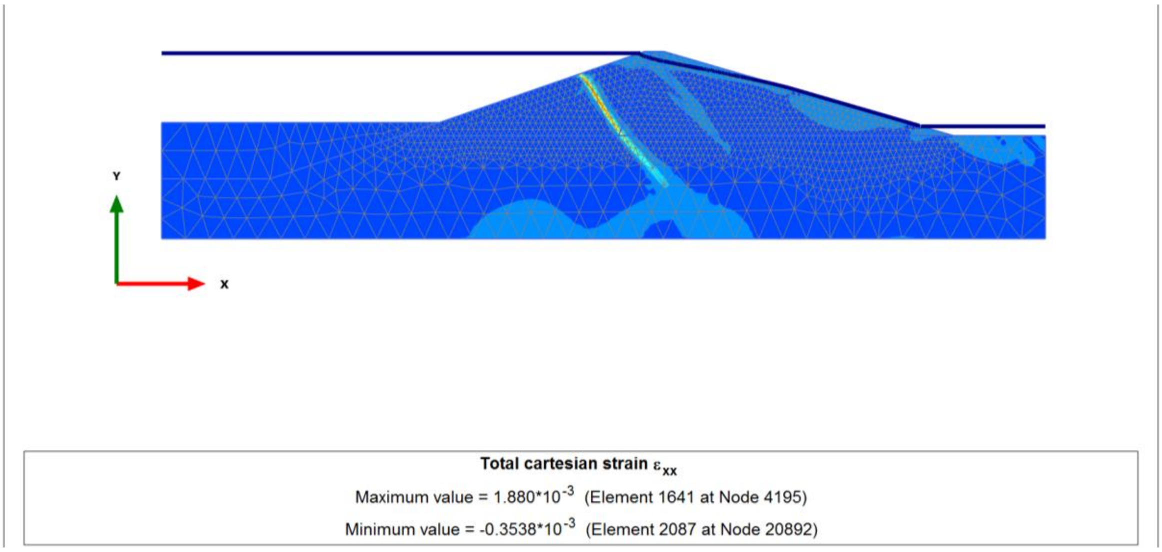



*Figure 59 ... Total strain for NCM*

# 4. *Alternative core models*

Two alternative cores are considered in this stage

- the Line Core Model (LCM)
- the Shifted Core Model (SCM)

## Line Core Model (LCM)

In essence the same geometric model is used. The only alteration is the change of core shape in order to optimize it for construction. The model as changed with the new core and mesh is presented in Figure 60. Apart from this, no changes have been made to any of the boundary conditions or the hydraulic conditions of each phase.

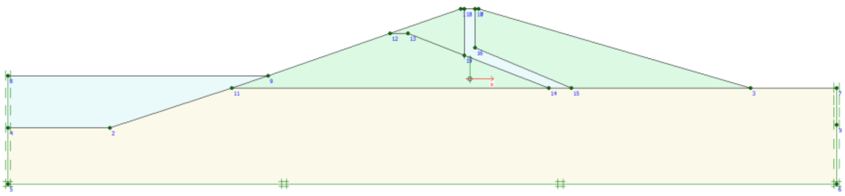


*Figure 60 ... Geometric model Line Core*

## Results

***Active pore pressure and settlements***

The settlements of the system are larger than they are for CCM, but not disproportionally larger (see Figure 62 and Figure 63). LCM shows very similar results as did CCM; however the stability of the core as it is dimensioned now is rather fragile as it is very sensitive.

## Shifted Core Model (SCM)

The other alternative core that is calculated is the Shifted Core Model (SCM). The goal with this model is to create a core that satisfies all criteria of stability and minimizes the removal of current soil. The model, its boundary conditions are displayed in Figure 61.

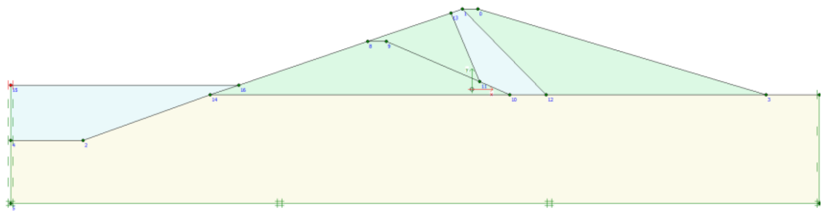


*Figure 61 ... Geometric model with the SCM*

## Results

The results of SCM show a similar profile as the other two alternatives, with all pressures in the same order of magnitude. However, the values are all a bit higher for SCM. Also this dam collapses due to low stability.

The deformation is significantly higher (up to double) and this is caused mainly by the direct contact of the water with the core (see Figure 64).

The pore pressure has an abrupt change when it reaches the core, unlike what was seen in the CCM (see Figure 65). This is because of the reversed angle the core has with respect to the one the CCM has with its core. As opposing to following the surrounding pressure lines, the pressure line changes shape. This is the cause of some other problems as the plastic points and strains.

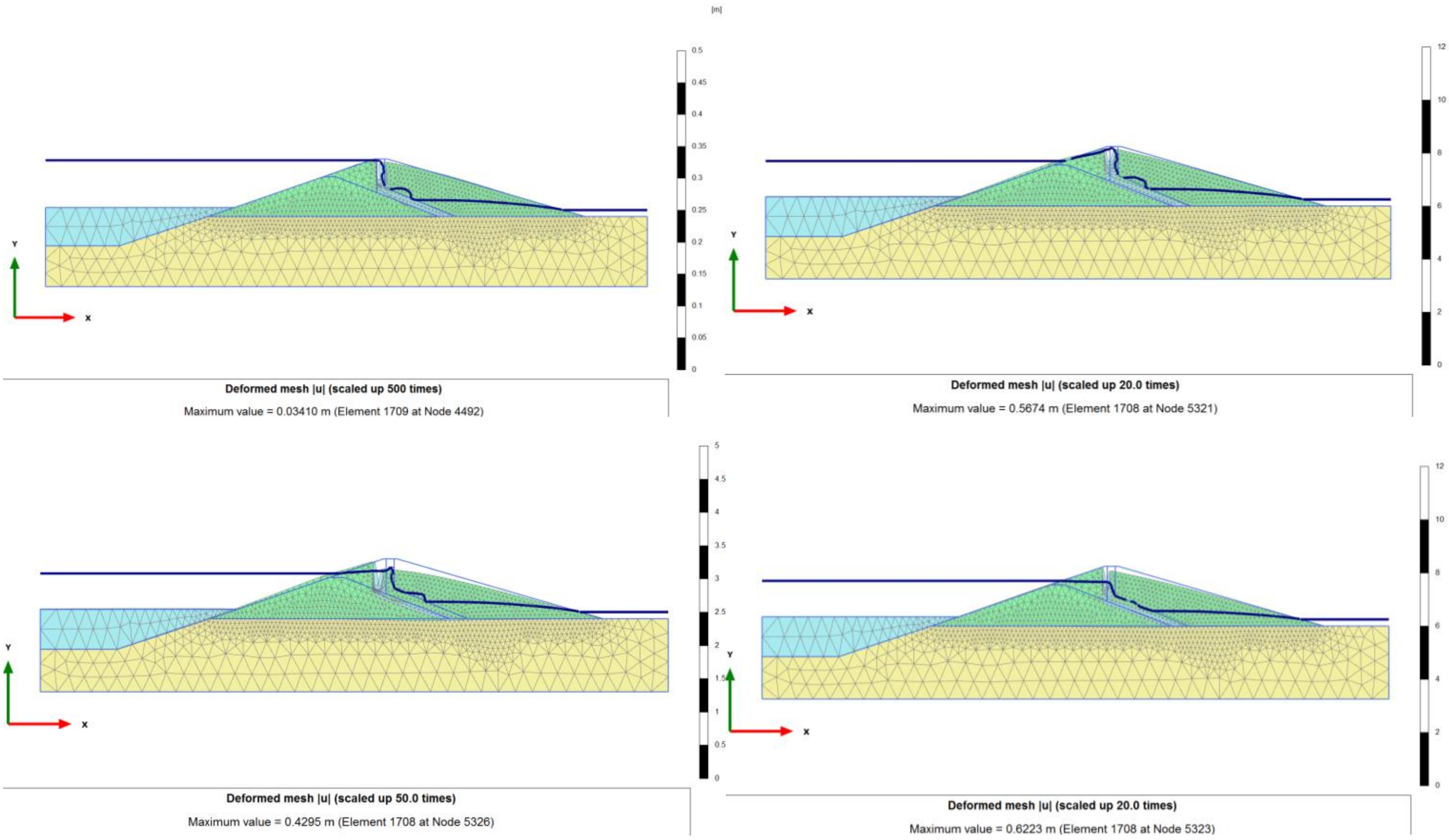



*Figure 62 ... Deformations for LCM for (from top till down) Phase 1, 2, 3 and 4*

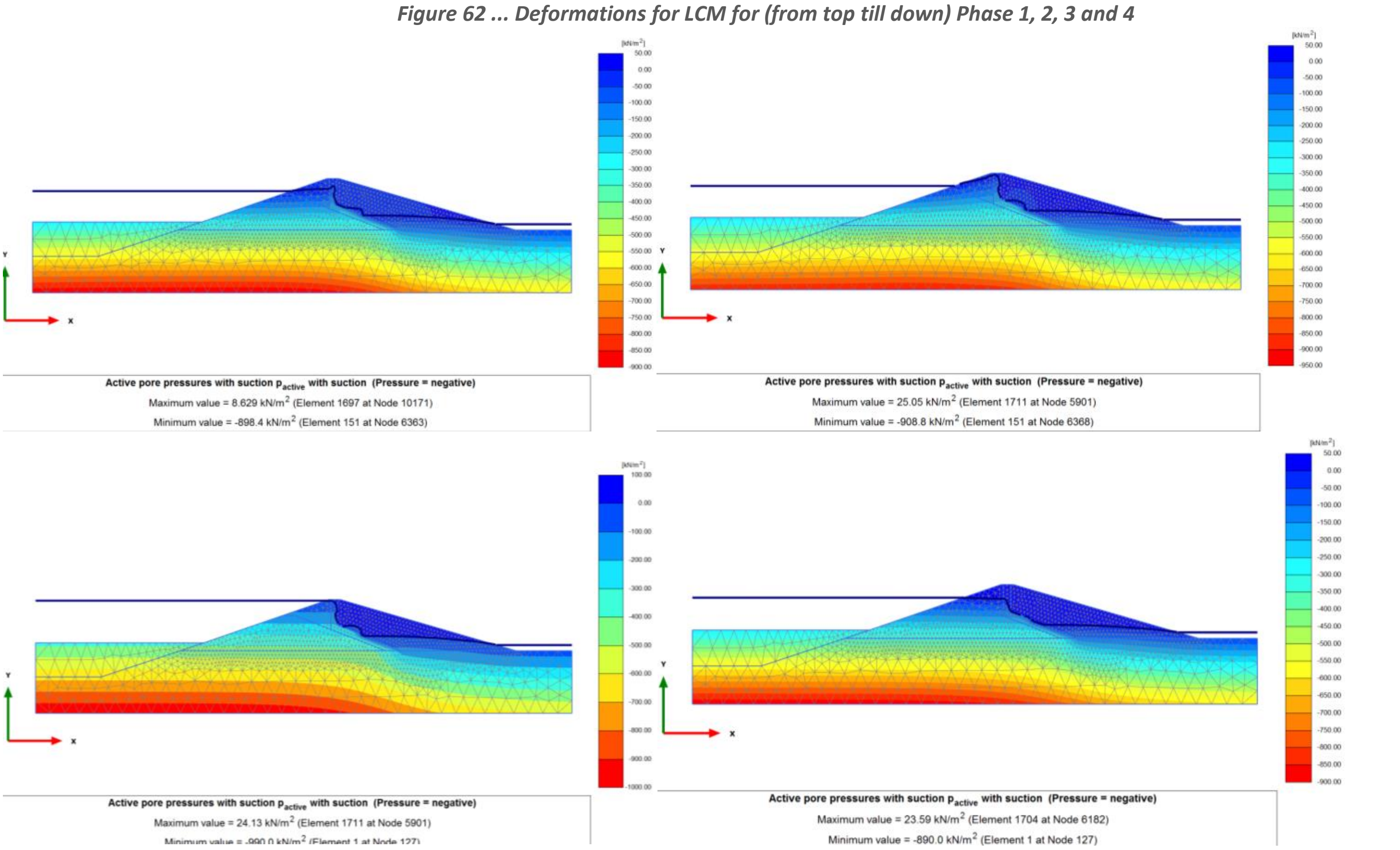



*Figure 63 ... Active pore pressures for LCM for (from top till down) Phase 1, 2, 3 and 4*

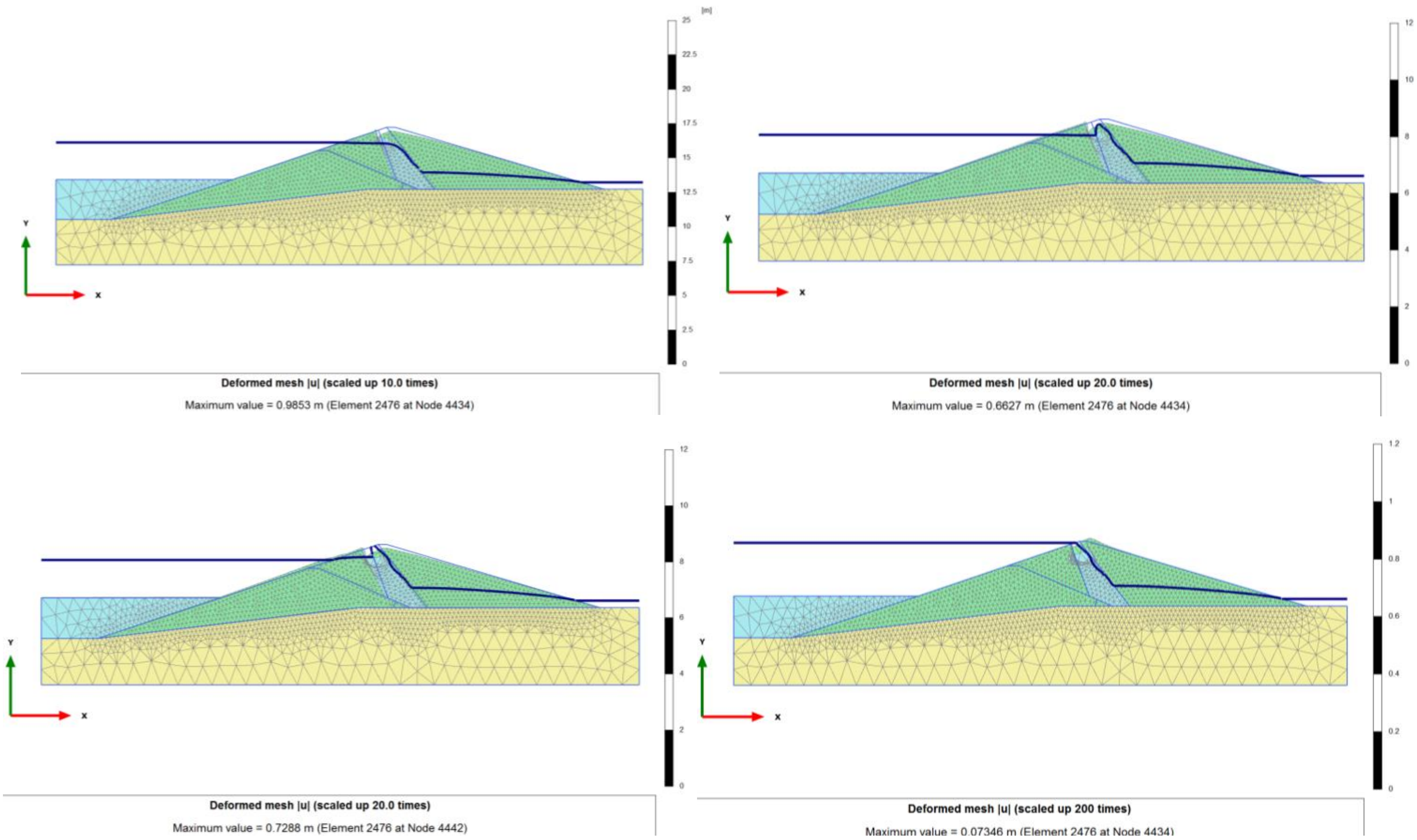



*Figure 64 ... Deformation for SCM for (from top till down) Phase 1, 2, 3 and 4*

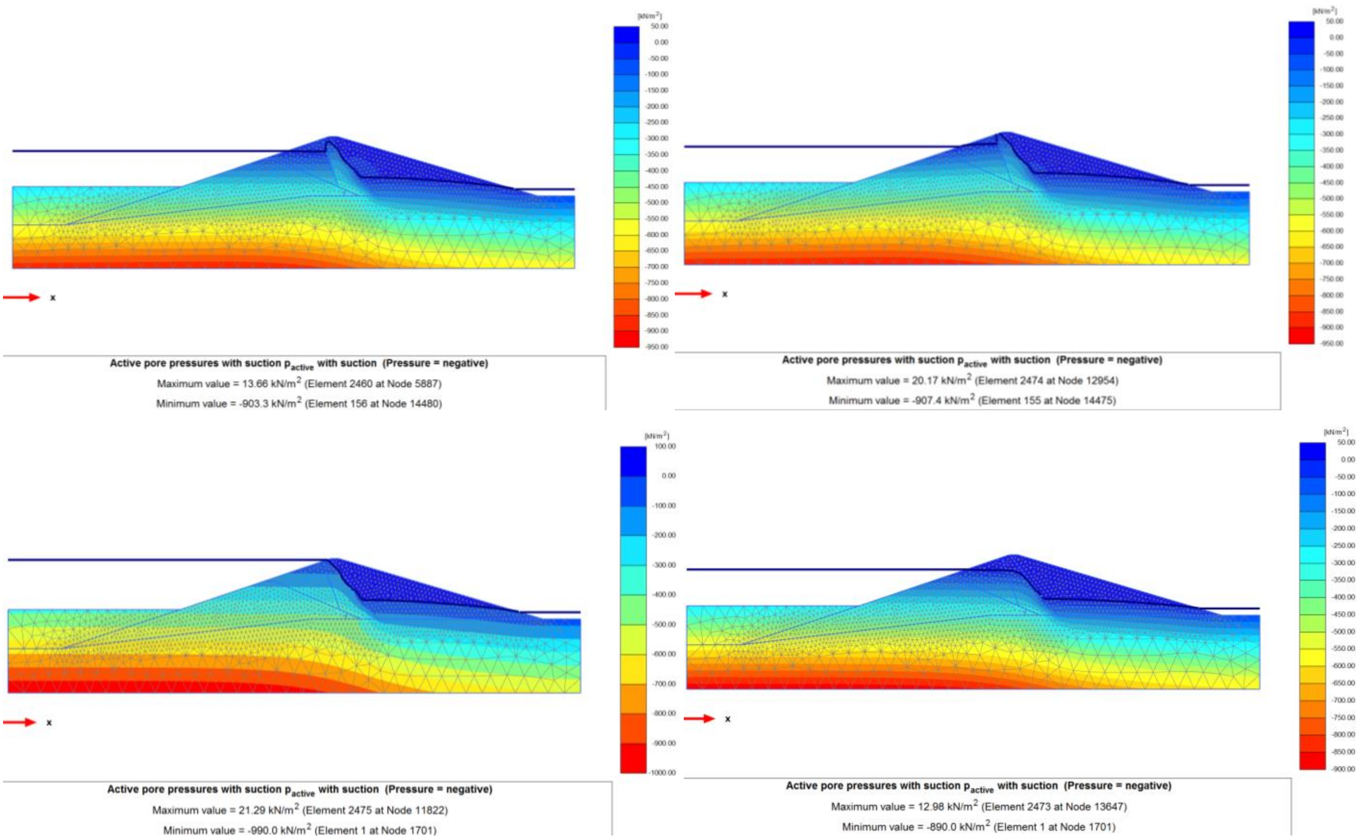



*Figure 65 ... Active pore pressure for SCM for (from top till down) Phase 1, 2, 3 and 4*

# 5. *Modeling of CCM with windmill on top*

## Results deformations

***Deformations***

Together with the drop stability the load is causing higher deformations at the top. As a consequence of the load, the two sections of Dam Fill Sand push down the core material further. This is causing large deformations for Phase 1 at which the high water level also pushes down. The other deformations seem to be controlled (*see Figure 66).*

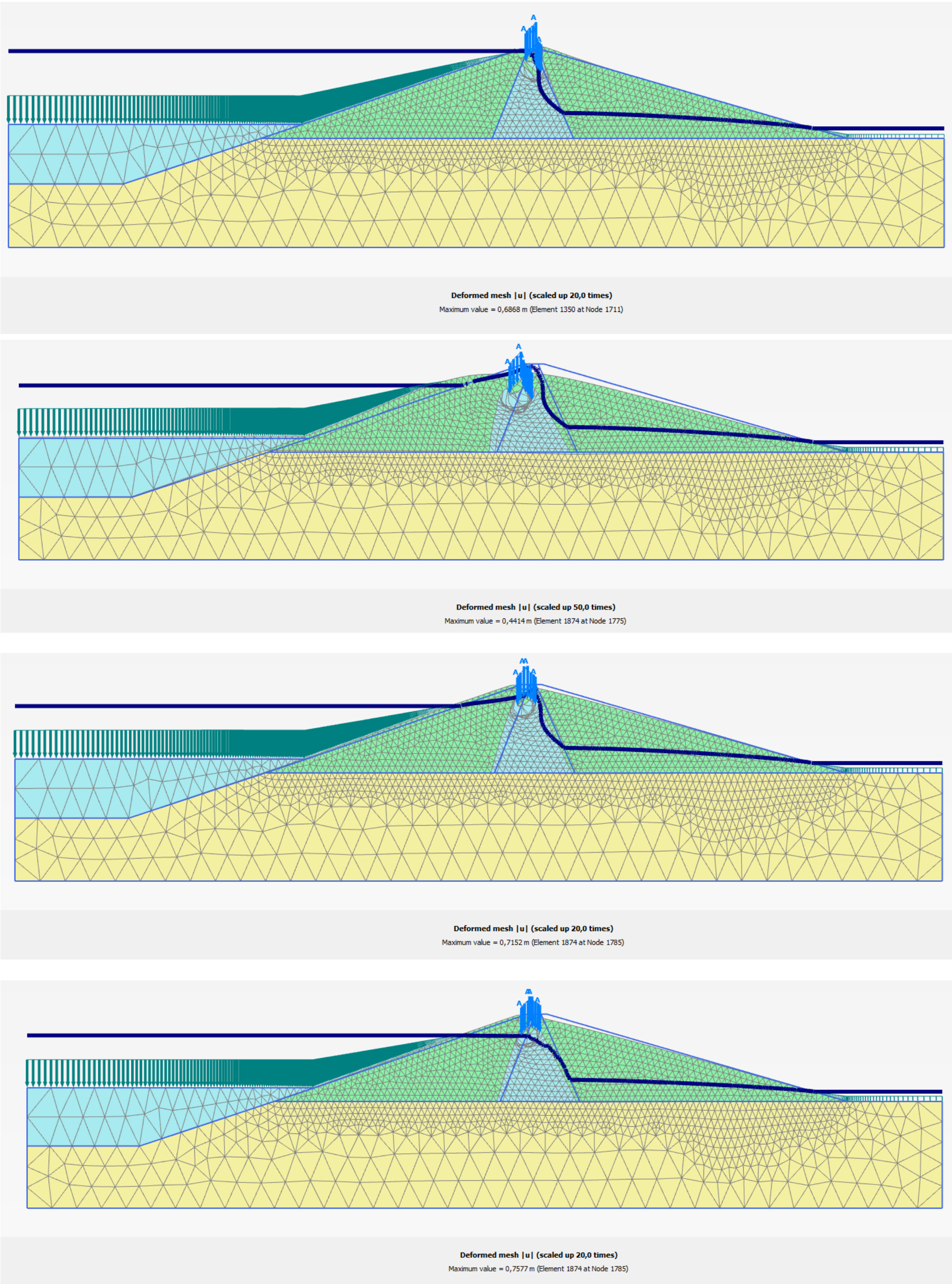



*Figure 66 ... Deformed mesh (from top to bottom) for Phase 1, 2, 3 and 4*

***Deformations***

The deformations are lower than they are for the previous model which is promising. A larger part of the Dam Fill Sand is resisting the deformation introduced by the distributed load which is causing much less deformations and a better stress distribution overall.

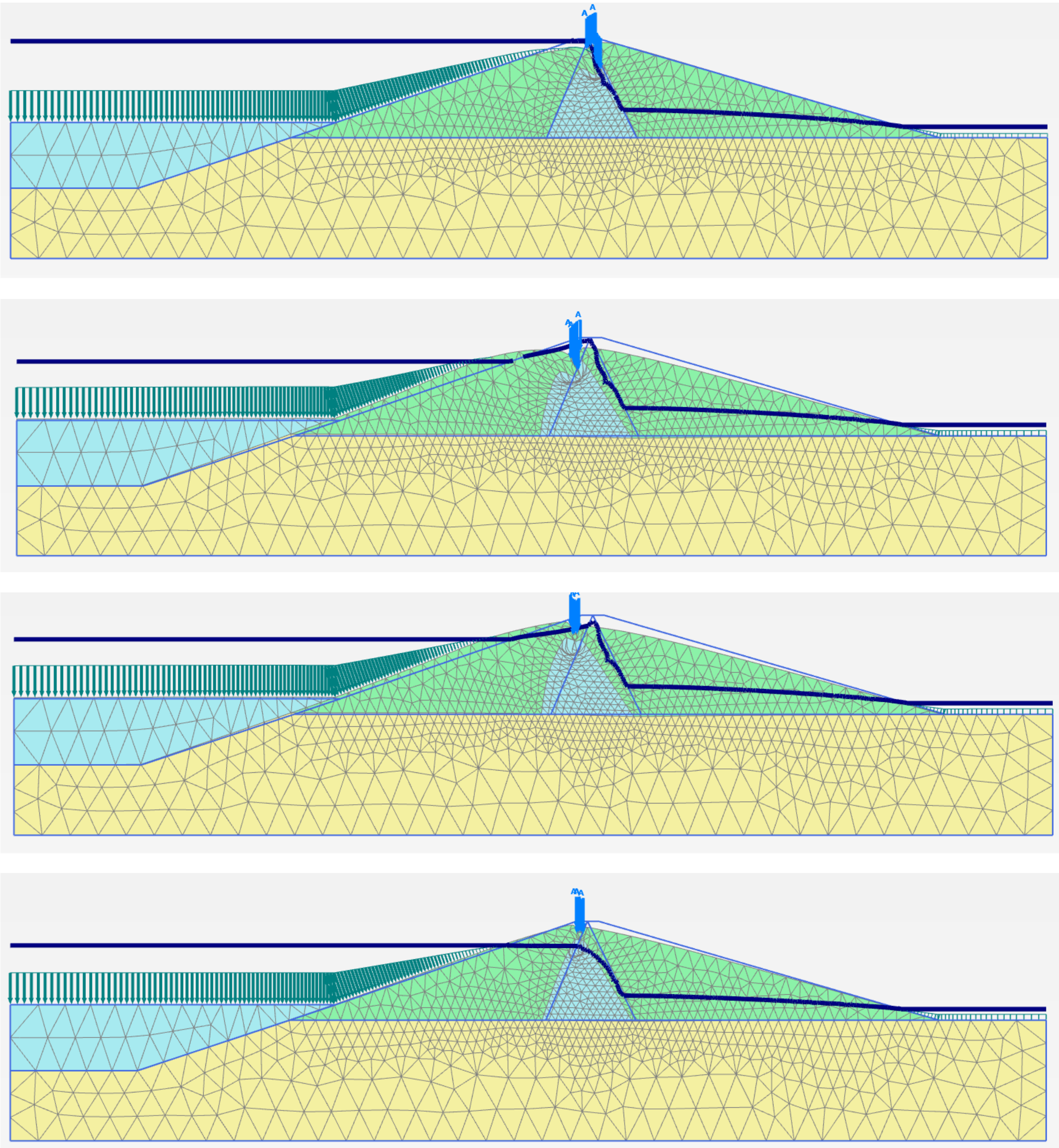


*Figure 67 ... Deformed mesh (from top till bottom) for Phase 1,2,3 and 4*

# 6. *Modeling the temporary sheet pile*

## Materials

Each of the above defined model and region have to be given certain properties in order for the FEM-analysis to work. Each of the four types is given certain properties. Where these properties are not present, they are estimated.[25] This estimation is not very far-fetched, as values for soil characteristics which are classified under a group name do not differ significantly from each other, i.e. sand in the Zuid-Holland province has a relative small range of varying properties.

The dam fill material is previously chosen to be of sand, a material that is widely available in the area. The properties of the dam material have already been estimated in the previous models. One change has been made for the sake of simplicity; no distinction is made between the subsoil sand and the dam fill sand. This can be justified by two reasons:

- The main objective of this analysis are not the soil movements of the subsoil
- The difference between the characteristics of the subsoil and the dam fill is small

The sheet profile characteristics are based upon a chosen profile. For this, the profiles of ArcelorMittal are investigated.[26] The AZ18 profile is chosen for the first assessment (see Figure 68).

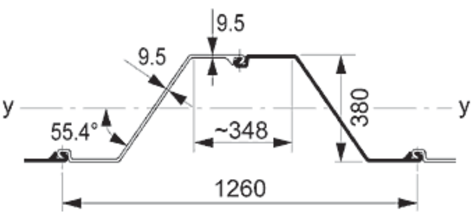



*Figure 68 ... profile of the AZ18 sheet pile*

Only the relevant material properties are displayed (see Table 8 till Table 11)

| Variable | Value | Unit |
|---|---|---|
| **Material model** | Mohr-Coulomb | - |
| **Unit weight above water** | 17 | $kN/m^3$ |
| **Unit weight under water** | 21 | $kN/m^3$ |
| **Young's modulus** | 30.000 | $kN/m^2$ |
| **Cohesion** | 1 | $kN/m^2$ |
| **Friction angle** | 35 | ° |
| **Dilatancy angle** | 1 | ° |

*Table 8 ... Material properties dam material*

| Variable | Value | Unit |
|---|---|---|
| **Material type** | Elastic; Isotropic | |
| **Bending stiffness EI** | $7.2*10^4$ | $kNm^2/m$ |

*Table 9 ... Properties of sheet pile*

| Variable | Value | Unit |
|---|---|---|
| **Material type** | Elastic; | |
| **Normal stiffness EA** | 200.000 | kN/m |

*Table 10 ... Properties of geo-grid*

---

[25] *Flowverse, Cameron Hydraulic Handbook, 2000*
[26] *ArcelorMittal product page, Arcelormittal.com, 2013*

| Variable | Value | Unit |
|---|---|---|
| **Material type** | Elastic; | |
| **Normal stiffness EA** | 500.000 | kN/m |
| **Spacing out of plane** | 2.5 | m |

*Table 11 ... Properties of node-to-node anchor*

## Calculation steps detailed explained

The calculations is performed in *Classical mode* (*utilizing Terzaghi's definition of stress*) using several phases.

**Initial phase:** This is the phase as it starts. The K0-procedure is used to calculate the model in initial mode. In this phase, all types except for the dam fill material are *'turned off'*, meaning they are inactive. The water level is set at 0m NAP using a phreatic level.

**Phase 1**: Within this phase, a plastic calculation is made for the model. The water conditions are as set for the initial phase. Since the sheet pile and the anchors are placed recently and the soil body has already been settling for many years now, the sheet pile and anchors are turned inactive for now and will be activated in the next phase.

**Phase 2**: The first phase in which the actual excavation is started. Part of the top of the triangle is excavated. In the model this is simulated by making this particular region inactive, allowing the program to think there is nothing present there (see Figure 69). Since the interest of this analysis is to see the deformation in the sheet pile, the settlements before the excavation are not regarded by turning on the option *reset displacements to zero*.

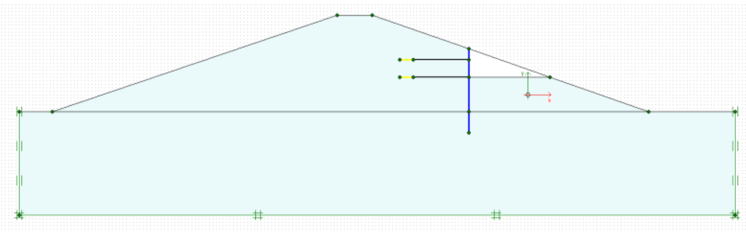


*Figure 69 ... Model with the first step of excavation*

**Phase 3:** The excavation continues and reaches its end at a level of -5m NAP (see Figure 70). This is done by making the final region of the exaction inactive. The displacements are a continuation of the displacements of phase 2 only.

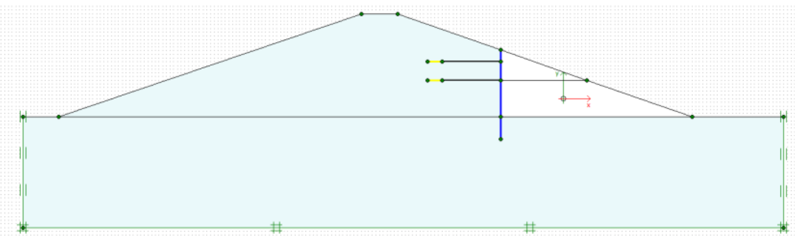


*Figure 70 ... Model with excavation complete*

**Phase 4:** This is a safety calculation for Phase 3. A safety calculation is performed to obtain information about the stability of the model. More information about safety calculations is given in the previous chapters. The variables are kept the same as in Phase 3; however the calculation type is changed from a *staged construction* to a *safety calculation.* The result of this phase should be the safety factors.

# Appendix L Closing off the Slufter

Here the possibility of closing off the Slufter is investigated. To prevent the in- and outflow of water, slurry walls are used. These walls will stretch all the way to the depth of the water enclosing clay layer at -50m NAP depth. The thickness of the slurry wall will be 0.5 m, which should be enough to create a water-sealing wall. Experience has proven the feasibility at even greater depths up to 120 meters.[27,28,29]

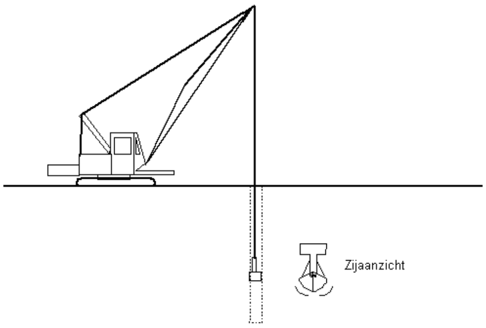



*Figure 71 ... (left) Construction of a slurry wall (EMIS, 2013) and (right) Digger of the slurry walls (Made in China, 2013)*

The material used for the slurry is important; an option is to use the silt inside the Slufter. This material is abundant, free and actually recycling it is preferable rather than storing it. The permeable character is obtained from the fact that currently, the bottom of the depot is covered with this material to make it somewhat water-tight. Already this contaminated silt is reaching deep inside the current dams of the Slufter.[30] Should the silt characteristics be unsuitable, bentonite can be used. [31] The water enclosing function of the slurry wall can be further enlarged with application of synthetic oil inside the mixture.[32]

The total length of the slurry walls will be 5.5 km, encircling the Slufter. This will be a costly and long operation, however unavoidable since closing off the area is essential to ensure efficiency.

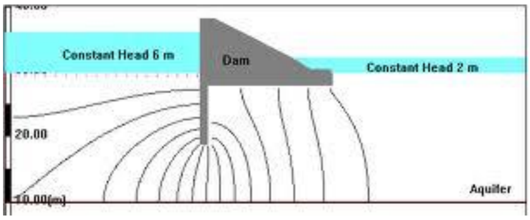



*Figure 72 ... Example of cross section sketch of sheet piles below surrounding dams*

The slurry walls will be placed inside the existing outer dams. The machine will be placed on top of the dam, from which the excavation will be done. During excavation, some mix of the silt and water will be inserted to prevent the excavation from collapsing. Once the clay layer is reached, the input of the contaminated silt can commence. The digging of the soil is done using a machine that is purpose built for this activity. The operation costs can be split into the rent of the machinery, the man-hours required for the operation and the filling of the excavated holes. In general, the following unit price for the slurry walls can be used.

---

[27] *Roy McLintock, Diaphragm walls, Esorfranki.co.za, 2009*
[28] *Arai M, and Naitoh T., High-accuracy position control system for underground diaphragm walls*
[29] *CUR, Damwandconstructies (6e Druk), 2012*
[30] *Rijkswaterstaat & Port of Rotterdam, Herziening acceptatiecriteria en scheiden van zand in het depot van de Slufter, 1998*
[31] *De Boer B., Met leem of bentoniet lukt uw vijver niet, 2010*
[32] *CUR, Damwandconstructies (6e Druk), 2012*

# Appendix M TSHP data

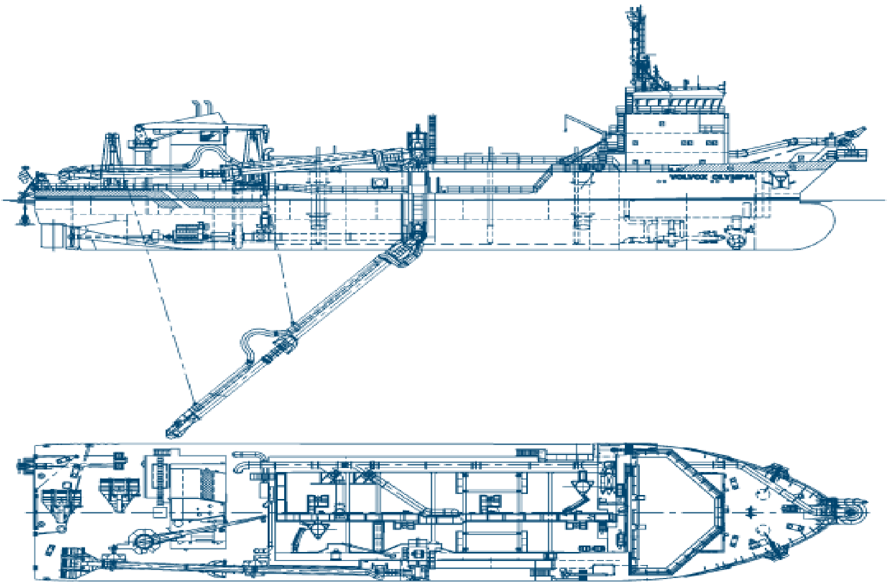




*Figure 73 ... Specifications of the Volvox Olympia (Van Oord B.V., 2013)*

**Table 9-1: The data of the TSHD's used.**

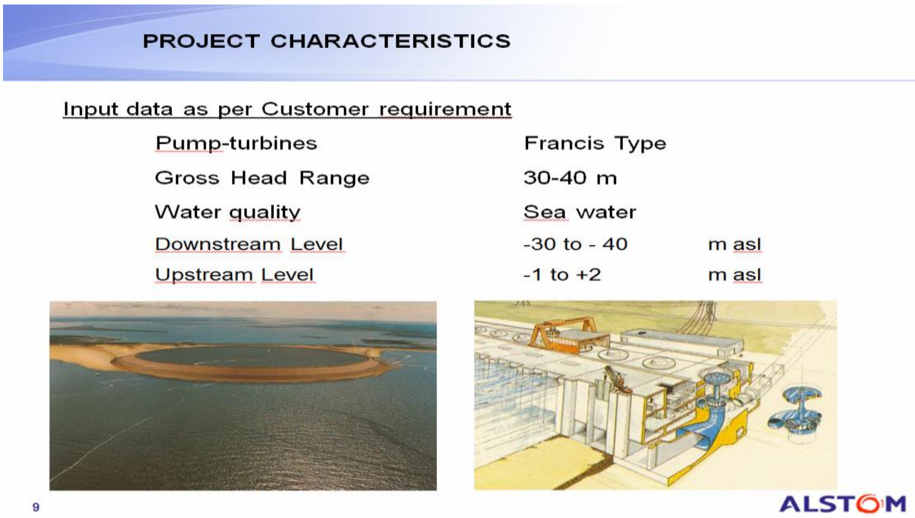
| Hopper | Load | Volume | Length | Width | Empty height | Flow | Hopper load $v_0$ | Mixture density |
|---|---|---|---|---|---|---|---|---|
| | ton | $m^3$ | m | m | m | $m^3$/sec | m/sec | ton/$m^3$ |
| Small | 4400 | 2316 | 44.0 | 11.5 | 4.577 | 4 | 0.0079 | 1.3 |
| Jumbo | 41000 | 21579 | 79.2 | 22.4 | 12.163 | 14 | 0.0079 | 1.3 |
| Mega | 70000 | 36842 | 125.0 | 30.0 | 9.825 | 19 | 0.0051 | 1.3 |

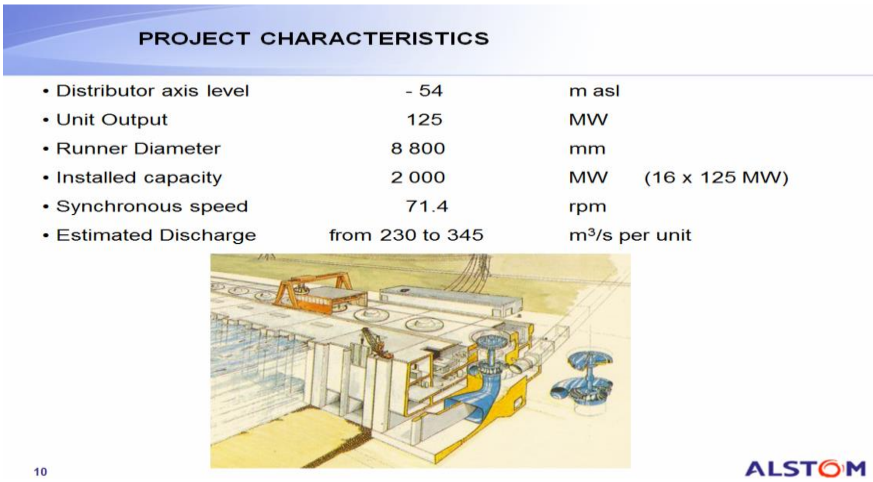
**Table 9-2: The hopper content after the filling phase.**

| Hopper | Load | Volume | Flow | Filling time | Total load | TDS | Overflow losses | Mixture density |
|---|---|---|---|---|---|---|---|---|
| | ton | $m^3$ | $m^3$/sec | min | ton | ton | % | ton/$m^3$ |
| Small | 4400 | 2316 | 4 | 9.65 | 3011 | 1039 | 20.0 | 1.3 |
| Jumbo | 41000 | 21579 | 14 | 25.69 | 28053 | 9678 | 20.0 | 1.3 |
| Mega | 70000 | 36842 | 19 | 32.32 | 47895 | 16523 | 16.6 | 1.3 |

*Table 12 ... Loading characteristics of a TSHD (Dr.ir.S.A. Miedema, Dredging processes the loading process of a Trailing Suction Hopper Dredge, 2012)*

# Appendix N Turbines characteristics



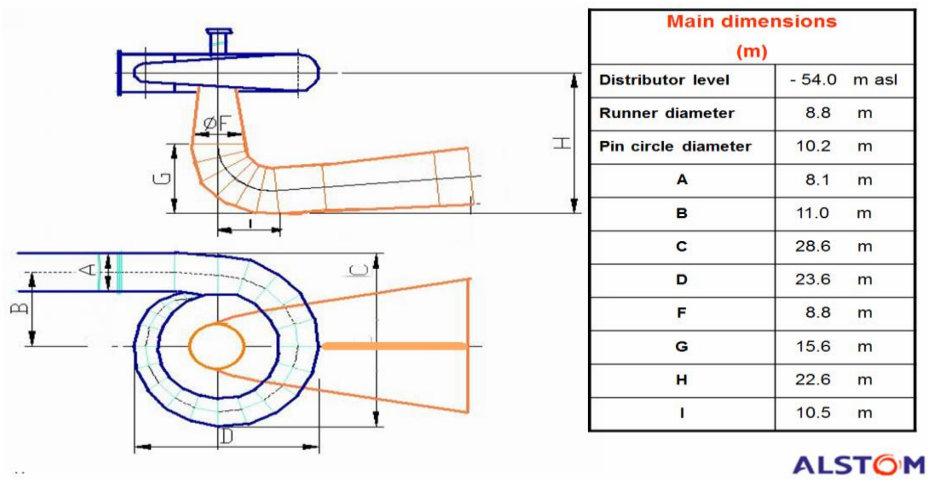




*Figure 74 ... PAC turbine characteristics (Alstom, PAC, 2006)*

# Appendix O Power Generation Model

## 1. *Introduction*

The Power Generation Model (PGM) is a tool to analyze and control the development of several important system parameters such as power, flow and reservoir level. In this section the development of the model and its characteristics will be explained where-as the content and results will be interpreted in the main report.

The model is created in Microsoft Excel 2010 and consists of two sheets: an input and results sheet and a calculations sheet. The interaction of the user happens in the first sheet whereas the second sheet runs in the background.

The model is made to be very flexible, working with a wide range of input parameters. Because of this flexibility, a deep understanding of the system is created by experimenting extensively.

## 2. *Assumptions and limitations*

The model is created under the following assumptions:

- The water is perfectly distributed over the amount of turbines
- The turbine characteristics are based upon the chosen turbine, however the Q,h-curve is scaled from the Alqueva turbines
- The pump capacity of the chosen turbines are derived from the Alqueva turbines
- The efficiency of the system is constant
- The characteristics of the turbine are only guaranteed in between 30 and 40m hydraulic head

## 3. *Input*

The input parameters into the model are presented in Table 13. The constants such as the water density and the gravitational acceleration are based on local values. The surface reservoir varies with the changing reservoir level (due to the effect of the dam slopes), which is implemented.

In this situation, the efficiency of the system is set at 0.9, which is determined as the efficiency during generation. The coefficients A till D are determined using MAPLE 17 by Maplesoft and are used to approximate the Q,h-curve of the chosen turbines. Finally, the chosen upper and lower limits of the reservoir are entered into the model.

| Input | | | |
|---|---|---|---|
| water density | rho | 1025 | kg/m3 |
| gravitational acceleration | g | 9,8 | m/s2 |
| surface high reservoir | A_high | 3,14E+06 | m2 |
| surface low reservoir | A_low | 3,00E+06 | m2 |
| efficiency | n | 0,9 | - |
| Fixed power output | P | 350 | MW |
| number of turbines | # | 4 | - |
| pump capacity | Q_pump | 170 | m3/s |
| coef | A | 0,08 | - |
| coef | B | -0,71 | - |
| coef | C | 0,16 | - |
| coef | D | 82,14 | - |
| | | | |
| upper limit reservoir | h_up | 39 | m |
| lower limit reservoir | h_low | 31 | m |

*Table 13 ... Input parameters and their values into PGM*

# 4. ***Calculations***

Three parallel scenarios can be calculated in the model:

1. The Pumping scenario: calculating the pumping characteristics
2. The Maximum scenario: calculating a full capacity output
3. The Fixed scenario: calculating a controlled output (output value defined as input (see Table 13)

To guarantee a high accuracy, the time step in between calculations is in seconds. The calculation of the flow, power and storage capacity happens based upon the principles of potential and basically all derivations of

$$E = mgh$$

- E = energy [joule]
- m = mass [kg]
- h = height [m]

This formula is re-written depending on the available and desired parameters.
The model is performing about 800.000 calculations for each set for parameters. The user is therefore forced to think twice before entering a rather disputable input parameter. There is still room for enough experimentation, since one cycle of calculations takes about a minute using an average laptop. Some screenshots are presented; see Table 16 and Table 17.

# 5. ***Results***

The model calculates a whole set of values for all parameters defined in the model along the time dependent on the chosen strategy. All the relevant performance indicators are presented back in the Input and Results sheet. This way the user can quickly see what the exact numbers are for the relevant values (see Table 14).

| Results | | | | | |
|---|---|---|---|---|---|
| Time till emptry | t | 21776 | s | 3 | min |
| | | 6,05 | hours | per turbine | |
| power at upper limit | P_up | 468 | MW | 117,0639 | MW |
| power at lower limit | P_low | 269 | MW | 67,27134 | MW |
| flow at upper limit | Q_up | 1328 | m3/s | 332,0214 | MW |
| flow at lower limit | Q_low | 960 | m3/s | 240,0296 | MW |
| storage capacity | E_cap | 7,78E+12 | J | | |
| | | 2,16 | GWh | | |
| power average | P_mean | 357 | MW | 89,34698 | MW |
| fluctuation water volume | V_water | 24,58 | million m3 | | |
| pumping reservoir | t_res | 36141 | s | | |
| | | 10,04 | hours | 2 | min |
| | | | | | |
| Time till full | t | 36138 | s | | |
| | | 10,04 | hours | 2,3 | min |
| power at lower limit | | 191 | MW | | |
| power at upper limit | | 240 | MW | | |

*Table 14 ... Summary of relevant model results*

Apart from this set of summarizing values, a whole set of data is available to create curves or analyze specific data and understand the relations and sensitivities. The interpretation of the results can be found in the main report

# 6. *Expansion of PGM: The Benefit Model*

The Power Generation Model (PGM) has been extended with the Benefit Model (BeM). This model adds the functionality to add day-ahead prices and calculates the daily turnover, expenses and profit.

These values are interesting in the analyzed of the economic benefits of the model.

## Input and calculations

Apart from the earlier defined set of parameters, the relevant price data is added. The data set that needs to be entered must be in a certain format; the price fluctuation in €/MWh along a day of 24 hours). This data can be found on a daily basis from the Dutch power market and/or the European Market.[33,34]

| Dataset for date: | | 21-10-2012 |
|---|---|---|
| hours | €/MWh | |
| 1 | 44,34 | |
| 2 | 44,01 | |
| 3 | 40,95 | |
| 4 | 35,65 | |
| 5 | 38,47 | |
| 6 | 45,49 | |
| 7 | 50,83 | |
| 8 | 63,67 | |
| 9 | 63,64 | |
| 10 | 64 | |
| 11 | 63,67 | |
| 12 | 64,36 | |
| 13 | 62,4 | |
| 14 | 61,27 | |
| 15 | 60,43 | |
| 16 | 58,6 | |
| 17 | 59,96 | |
| 18 | 65,93 | |
| 19 | 68,58 | |
| 20 | 66,29 | |
| 21 | 61,19 | |
| 22 | 51,57 | |
| 23 | 52,52 | |
| 24 | 48,57 | |

*Table 15 ... Example data set of prices per MWh*

The Calculations sheet is upgraded with columns handling the costs/benefits. Fitting to a certain generation strategy, prices from the data-set of market prices are provided to the model. The model than calculates the price for each second to heighten the accuracy of the model. Some screenshots are presented (Table 16 and Table 17)

Pumping

| IF | t [s] | t [hour] | Increased surface area | Flow | Head increase | Pumped head | Power | Energy Capacity | Price/MWh | Price/s |
|---|---|---|---|---|---|---|---|---|---|---|
| Column1 | Column1 | Column1 | Column1 | Column1 | Column1 | Column1 | Column1 | Column1 | Column1 | Column1 |
| 0 | 1 | 0,00 | 3004013,583 | 680 | 0 | 31 | 190,57374 | 190,57374 | 0,00990278 | 1,8872094 |
| 0 | 2 | 0,00 | 3004017,431 | 680 | 0,00022636 | 31,0002264 | 190,575132 | 381,148872 | 0,00990278 | 1,88722318 |
| 0 | 3 | 0,00 | 3004021,279 | 680 | 0,00022636 | 31,0004527 | 190,576523 | 571,725395 | 0,00990278 | 1,88723696 |
| 0 | 4 | 0,00 | 3004025,127 | 680 | 0,00022636 | 31,0006791 | 190,577915 | 762,303309 | 0,00990278 | 1,88725074 |
| 0 | 5 | 0,00 | 3004028,975 | 680 | 0,00022636 | 31,0009055 | 190,579306 | 952,882616 | 0,00990278 | 1,88726452 |
| 0 | 6 | 0,00 | 3004032,824 | 680 | 0,00022636 | 31,0011318 | 190,580698 | 1143,46331 | 0,00990278 | 1,8872783 |
| 0 | 7 | 0,00 | 3004036,672 | 680 | 0,00022636 | 31,0013582 | 190,582089 | 1334,0454 | 0,00990278 | 1,88729208 |
| 0 | 8 | 0,00 | 3004040,52 | 680 | 0,00022636 | 31,0015845 | 190,583481 | 1524,62888 | 0,00990278 | 1,88730586 |
| 0 | 9 | 0,00 | 3004044,368 | 680 | 0,00022636 | 31,0018109 | 190,584873 | 1715,21376 | 0,00990278 | 1,88731964 |
| 0 | 10 | 0,00 | 3004048,216 | 680 | 0,00022636 | 31,0020373 | 190,586264 | 1905,80002 | 0,00990278 | 1,88733342 |
| 0 | 11 | 0,00 | 3004052,064 | 680 | 0,00022636 | 31,0022636 | 190,587656 | 2096,38768 | 0,00990278 | 1,8873472 |
| 0 | 12 | 0,00 | 3004055,913 | 680 | 0,00022636 | 31,00249 | 190,589047 | 2286,97672 | 0,00990278 | 1,88736098 |
| 0 | 13 | 0,00 | 3004059,761 | 680 | 0,00022636 | 31,0027163 | 190,590439 | 2477,56716 | 0,00990278 | 1,88737476 |
| 0 | 14 | 0,00 | 3004063,609 | 680 | 0,00022636 | 31,0029427 | 190,59183 | 2668,15899 | 0,00990278 | 1,88738854 |
| 0 | 15 | 0,00 | 3004067,457 | 680 | 0,00022636 | 31,0031691 | 190,593222 | 2858,75222 | 0,00990278 | 1,88740232 |
| 0 | 16 | 0,00 | 3004071,305 | 680 | 0,00022636 | 31,0033954 | 190,594614 | 3049,34683 | 0,00990278 | 1,8874161 |
| 0 | 17 | 0,00 | 3004075,153 | 680 | 0,00022636 | 31,0036218 | 190,596005 | 3239,94283 | 0,00990278 | 1,88742988 |
| 0 | 18 | 0,01 | 3004079,001 | 680 | 0,00022636 | 31,0038481 | 190,597397 | 3430,54023 | 0,00990278 | 1,88744366 |
| 0 | 19 | 0,01 | 3004082,849 | 680 | 0,00022636 | 31,0040745 | 190,598788 | 3621,13902 | 0,00990278 | 1,88745744 |
| 0 | 20 | 0,01 | 3004086,697 | 680 | 0,00022636 | 31,0043009 | 190,60018 | 3811,7392 | 0,00990278 | 1,88747122 |
| 0 | 21 | 0,01 | 3004090,546 | 680 | 0,00022636 | 31,0045272 | 190,601571 | 4002,34077 | 0,00990278 | 1,887485 |
| 0 | 22 | 0,01 | 3004094,394 | 680 | 0,00022636 | 31,0047536 | 190,602963 | 4192,94373 | 0,00990278 | 1,88749878 |
| 0 | 23 | 0,01 | 3004098,242 | 680 | 0,00022636 | 31,0049799 | 190,604354 | 4383,54809 | 0,00990278 | 1,88751256 |
| 0 | 24 | 0,01 | 3004102,09 | 680 | 0,00022636 | 31,0052063 | 190,605746 | 4574,15383 | 0,00990278 | 1,88752634 |
| 0 | 25 | 0,01 | 3004105,938 | 680 | 0,00022636 | 31,0054327 | 190,607137 | 4764,76097 | 0,00990278 | 1,88754012 |
| 0 | 26 | 0,01 | 3004109,786 | 680 | 0,00022636 | 31,005659 | 190,608529 | 4955,3695 | 0,00990278 | 1,88755391 |
| 0 | 27 | 0,01 | 3004113,634 | 680 | 0,00022636 | 31,0058854 | 190,609921 | 5145,97942 | 0,00990278 | 1,88756769 |
| 0 | 28 | 0,01 | 3004117,482 | 680 | 0,00022636 | 31,0061117 | 190,611312 | 5336,59073 | 0,00990278 | 1,88758147 |
| 0 | 29 | 0,01 | 3004121,33 | 680 | 0,00022636 | 31,0063381 | 190,612704 | 5527,20344 | 0,00990278 | 1,88759525 |
| 0 | 30 | 0,01 | 3004125,178 | 680 | 0,00022636 | 31,0065644 | 190,614095 | 5717,81753 | 0,00990278 | 1,88760903 |
| 0 | 31 | 0,01 | 3004129,026 | 680 | 0,00022636 | 31,0067908 | 190,615487 | 5908,43302 | 0,00990278 | 1,88762281 |
| 0 | 32 | 0,01 | 3004132,874 | 680 | 0,00022636 | 31,0070171 | 190,616878 | 6099,0499 | 0,00990278 | 1,88763659 |
| 0 | 33 | 0,01 | 3004136,722 | 680 | 0,00022635 | 31,0072435 | 190,61827 | 6289,66816 | 0,00990278 | 1,88765037 |
| 0 | 34 | 0,01 | 3004140,57 | 680 | 0,00022635 | 31,0074699 | 190,619661 | 6480,28783 | 0,00990278 | 1,88766415 |

*Table 16 ... Calculations for the Pumping Scenario*

[33] *APX.nl*
[34] *EEX.com*

| Generating | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| IF | t [s] | t [hour] | Decreased surface area | Flow MAX | head decrease | New head | Power MAX | Energy Capacity | Price/MWh | Price/s | Total price | |
| Column1 | Column1 | Column1 | Column1 | Column1 | Column1 | Column1 | Column1 | Column1 | Column1 | Column1 | Column1 | Column1 |
| 0 | 1 | 0,00 | 3140000 | 1328,08571 | 0 | 39 | 468,255797 | 468,255797 | 0,01905 | 8,92027293 | 8,92027293 | |
| 0 | 2 | 0,00 | 3139992,81 | 1328,06403 | 0,00042296 | 38,999577 | 468,243075 | 936,498872 | 0,01905 | 8,92003058 | 17,8403035 | |
| 0 | 3 | 0,00 | 3139985,62 | 1328,04236 | 0,00042295 | 38,9991541 | 468,230354 | 1404,72923 | 0,01905 | 8,91978824 | 26,7600918 | |
| 0 | 4 | 0,00 | 3139978,429 | 1328,02068 | 0,00042295 | 38,9987311 | 468,217633 | 1872,94686 | 0,01905 | 8,9195459 | 35,6796377 | |
| 0 | 5 | 0,00 | 3139971,24 | 1327,999 | 0,00042294 | 38,9983082 | 468,204912 | 2341,15177 | 0,01905 | 8,91930357 | 44,5989412 | |
| 0 | 6 | 0,00 | 3139964,05 | 1327,97732 | 0,00042293 | 38,9978853 | 468,192192 | 2809,34396 | 0,01905 | 8,91906125 | 53,5180025 | |
| 0 | 7 | 0,00 | 3139956,86 | 1327,95565 | 0,00042293 | 38,9974623 | 468,179472 | 3277,52343 | 0,01905 | 8,91881894 | 62,4368214 | |
| 0 | 8 | 0,00 | 3139949,67 | 1327,93397 | 0,00042292 | 38,9970394 | 468,166753 | 3745,69019 | 0,01905 | 8,91857664 | 71,3553981 | |
| 0 | 9 | 0,00 | 3139942,481 | 1327,91229 | 0,00042292 | 38,9966165 | 468,154034 | 4213,84422 | 0,01905 | 8,91833434 | 80,2737324 | |
| 0 | 10 | 0,00 | 3139935,291 | 1327,89062 | 0,00042291 | 38,9961936 | 468,141315 | 4681,98554 | 0,01905 | 8,91809206 | 89,1918245 | |
| 0 | 11 | 0,00 | 3139928,102 | 1327,86894 | 0,0004229 | 38,9957707 | 468,128597 | 5150,11413 | 0,01905 | 8,91784978 | 98,1096742 | |
| 0 | 12 | 0,00 | 3139920,913 | 1327,84727 | 0,0004229 | 38,9953478 | 468,11588 | 5618,23001 | 0,01905 | 8,91760751 | 107,027282 | |
| 0 | 13 | 0,00 | 3139913,723 | 1327,8256 | 0,00042289 | 38,9949249 | 468,103162 | 6086,33318 | 0,01905 | 8,91736524 | 115,944647 | |
| 0 | 14 | 0,00 | 3139906,534 | 1327,80392 | 0,00042289 | 38,994502 | 468,090446 | 6554,42362 | 0,01905 | 8,91712299 | 124,86177 | |
| 0 | 15 | 0,00 | 3139899,345 | 1327,78225 | 0,00042288 | 38,9940791 | 468,077729 | 7022,50135 | 0,01905 | 8,91688074 | 133,778651 | |
| 0 | 16 | 0,00 | 3139892,156 | 1327,76058 | 0,00042287 | 38,9936563 | 468,065013 | 7490,56636 | 0,01905 | 8,9166385 | 142,695289 | |
| 0 | 17 | 0,00 | 3139884,968 | 1327,73891 | 0,00042287 | 38,9932334 | 468,052298 | 7958,61866 | 0,01905 | 8,91639627 | 151,611685 | |
| 0 | 18 | 0,01 | 3139877,779 | 1327,71724 | 0,00042286 | 38,9928105 | 468,039583 | 8426,65824 | 0,01905 | 8,91615405 | 160,52784 | |
| 0 | 19 | 0,01 | 3139870,591 | 1327,69557 | 0,00042286 | 38,9923877 | 468,026868 | 8894,68511 | 0,01905 | 8,91591184 | 169,443751 | |
| 0 | 20 | 0,01 | 3139863,402 | 1327,6739 | 0,00042285 | 38,9919648 | 468,014154 | 9362,69927 | 0,01905 | 8,91566963 | 178,359421 | |
| 0 | 21 | 0,01 | 3139856,214 | 1327,65223 | 0,00042284 | 38,991542 | 468,00144 | 9830,70071 | 0,01905 | 8,91542743 | 187,274848 | |
| 0 | 22 | 0,01 | 3139849,025 | 1327,63056 | 0,00042284 | 38,9911191 | 467,988727 | 10298,6894 | 0,01905 | 8,91518524 | 196,190034 | |
| 0 | 23 | 0,01 | 3139841,837 | 1327,60889 | 0,00042283 | 38,9906963 | 467,976014 | 10766,6654 | 0,01905 | 8,91494306 | 205,104977 | |
| 0 | 24 | 0,01 | 3139834,649 | 1327,58722 | 0,00042283 | 38,9902735 | 467,963301 | 11234,6287 | 0,01905 | 8,91470089 | 214,019678 | |
| 0 | 25 | 0,01 | 3139827,461 | 1327,56556 | 0,00042282 | 38,9898507 | 467,950589 | 11702,5793 | 0,01905 | 8,91445872 | 222,934136 | |
| 0 | 26 | 0,01 | 3139820,273 | 1327,54389 | 0,00042281 | 38,9894278 | 467,937877 | 12170,5172 | 0,01905 | 8,91421657 | 231,848353 | |
| 0 | 27 | 0,01 | 3139813,086 | 1327,52222 | 0,00042281 | 38,989005 | 467,925166 | 12638,4424 | 0,01905 | 8,91397442 | 240,762327 | |
| 0 | 28 | 0,01 | 3139805,898 | 1327,50056 | 0,0004228 | 38,9885822 | 467,912455 | 13106,3548 | 0,01905 | 8,91373228 | 249,67606 | |
| 0 | 29 | 0,01 | 3139798,71 | 1327,47889 | 0,0004228 | 38,9881594 | 467,899745 | 13574,2546 | 0,01905 | 8,91349014 | 258,58955 | |
| 0 | 30 | 0,01 | 3139791,523 | 1327,45723 | 0,00042279 | 38,9877366 | 467,887035 | 14042,1416 | 0,01905 | 8,91324802 | 267,502798 | |
| 0 | 31 | 0,01 | 3139784,336 | 1327,43556 | 0,00042279 | 38,9873139 | 467,874326 | 14510,0159 | 0,01905 | 8,9130059 | 276,415804 | |
| 0 | 32 | 0,01 | 3139777,148 | 1327,4139 | 0,00042278 | 38,9868911 | 467,861616 | 14977,8776 | 0,01905 | 8,91276379 | 285,328567 | |
| 0 | 33 | 0,01 | 3139769,961 | 1327,39224 | 0,00042277 | 38,9864683 | 467,848908 | 15445,7265 | 0,01905 | 8,91252169 | 294,241089 | |
| 0 | 34 | 0.01 | 3139762.774 | 1327.37058 | 0.00042277 | 38.9860455 | 467.836199 | 15913.5627 | 0.01905 | 8.9122796 | 303.153369 | |

*Table 17... Calculations for the Maximum Scenario*

## Results

The results of the expansion are displayed in terms of monetary units (see Table 18). For the set defined and the strategy designed, the program calculates the turnover and costs (expenses) for each second as well as the profit.

| | | | | |
|---|---|---|---|---|
| Expenses | | € | 94.994,13 | €/day |
| Turnover | | € | 142.065,22 | €/day |
| Profit | | € | 47.071,08 | €/day |
| | | | | |
| | | € | 329.497,58 | €/week |
| | | € | 1.412.132,46 | €/month |
| | | € | 17.180.944,99 | €/year |

*Table 18 ... Result displayed for an example set of data of the BeM*

To get some insight into the values, the daily price difference is added with the weekly, monthly and yearly time period. As also in this case, the model results are in terms of hundreds of thousands of calculations, these curves can be graphically displayed where relevant.

# 7. *Evaluation of BeM*

The expansion with the economic benefits offers a way to see the results of the generation directly coupled to the financial situation. Through experimenting with the model, the user can further optimize the generation strategy and the consequences it has on the economic benefits.

Whereas the original design definition and generation strategy would only be dependent on the technical capacity of the system, the BeM offers an additional dimension by calculating the real-time development of the expenses as well as the benefits. This way, one of the most important disadvantages of the system, its relative high investment costs can be countered by a high income rate during the exploitation.

# Appendix P Power demand and prices

## 1. *Tested sample data*

In this section, the relation between the power demand curves and the price curves is assessed as a justification of the Maximum Profit Strategy applied for the Slufter. The test data that is used is data ranging throughout the year taking one day in the middle of the month. Any monthly variations are therefore discarded and only the seasonal differences are analyzed.

The curves of the power demand are plotted against the power prices. The interest here is to compare the shapes rather than the values. Therefore, the curves are plotted using a scale factor for the power demand. This scale factor is chosen to be $4*10^{-3}$. The results are displayed in Figure 75

## 2. *Evaluation*

The price curve does not always follow the demand curve. There is a strong relation between power price and demand, backed by the general theory of market economy (supply-demand curve). As demand goes up, so should the prices. Looking at the data, this does not always seem to be true. The supply has a strong role in this as well. This is proven especially during the winter months; power price goes down significantly (down to the nightly levels) even though the demand stays rather steady. This can only be explained from the supply side. In the morning ramp, utility companies power up their power plants to supply the demand. As the plants which are just fired up operate under a low efficiency until reaching a certain temperature, it takes more fuel to supply the same power. The result is that prices go up. As their peak efficiency is reached after the ramp, the plants operate steadily with high efficiency, which lowers the power price. The same is happening when nearing the evening ramp.

Other small variations are caused by complex market mechanisms that have a strong incidental character. The reasons behind these are not the most interesting to define a daily strategy. Interesting are the similar parts of the price and demand curve, i.e. where the peak demand coincides with a buying strategy. The following results and findings are obtained:

- Power demand and price fluctuations show the same main shape and very strong relations.
- The prices go up before the demand, there is a slight shift of the curve, which can be explained by the fact the power plants are increasing their capacity before the rise of the demand and due to this rise, they cause the prices to rise
- During the afternoon when demand is steady, the prices shows a small dip, which can be explained by the high efficiency of the power plants once they are up and running after some while

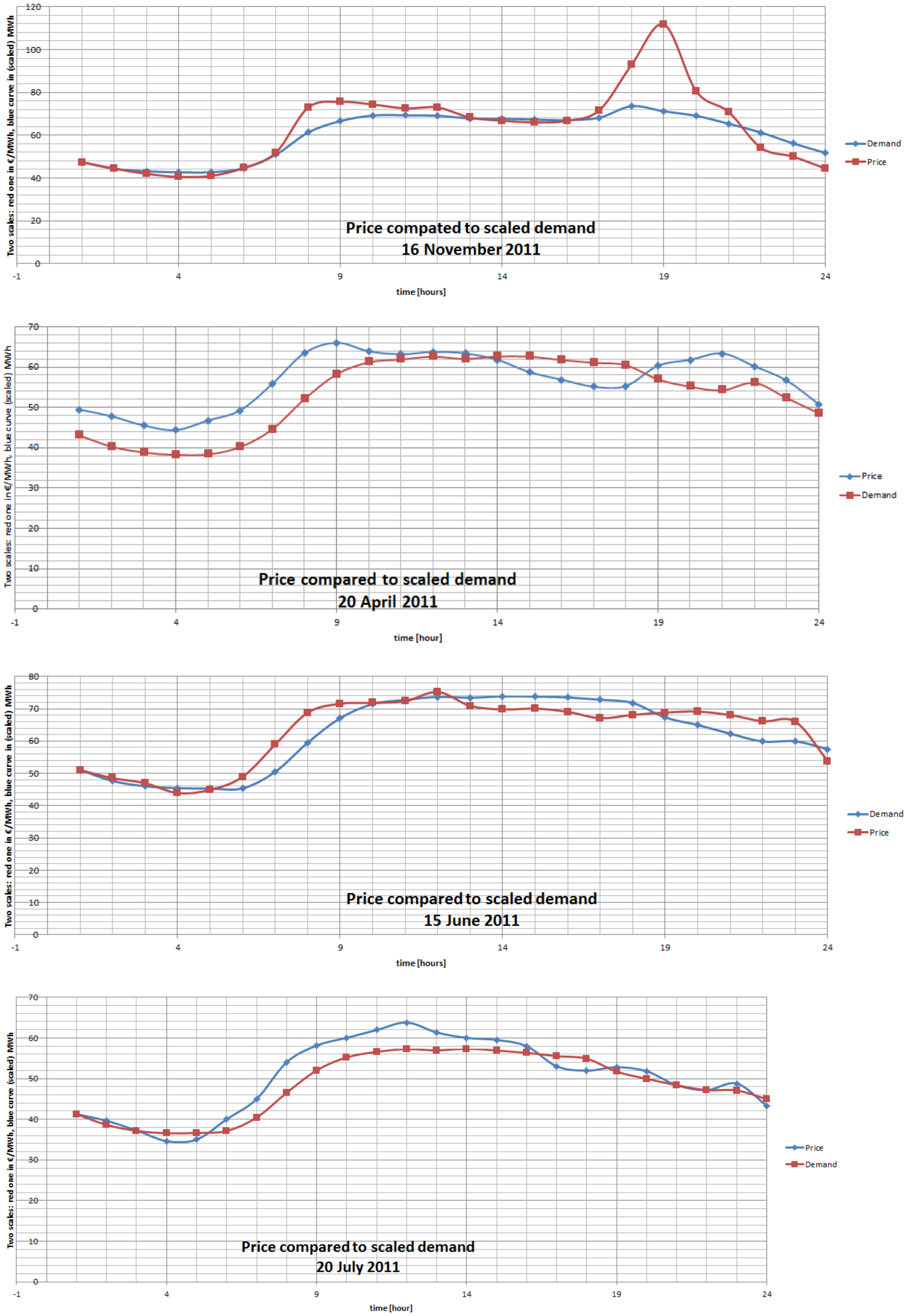



*Figure 75 ... Hourly price fluctuations compared to the demand, with demand scale factor of 4.0*10$^{-3}$, power price in €/MWh and power demand is in MW*

# Appendix Q Alternative costs calculation

*"While economists have spent three decades wrangling about how much a human life or a beautiful stretch of river is worth in dollars, ecologists, engineers and other specialists have gone about the business of saving lives and rivers, without waiting for formal, quantitative analysis proving that saving these things is worthwhile." – F. Ackerman & L. Heinzerling*

Costs can be split into major three parts: the primary investment, the operational costs and the maintenance costs. Primary investments are the capital goods that are required to build up the primary facilities and infrastructures to get the system working. Examples of these are the costs for building up the plants, the pipelines, the construction work, ground work etc.

The operational costs are costs in order for the system to continue its operations. Without these costs, the system could not function. Examples of these are fuel costs, processes like burning the fuel, transport, packing, labor etc. Lastly there are the maintenance costs. These are the costs to ensure the plants continuation of operation. Material deteriorates over time and machines have to get oiled or in some cases replaced. Without these costs the system would not perform or perform less.

It is thought that a cost-benefit analysis gives an overview of the costs and the benefits of a project. That through a cost-benefit analysis one might get a transparent and objective way of determining the costs and a good decision tool on how to proceed. However, there are some fundamentally wrong ways in a cost-benefit analysis.

In a traditional cost-benefit analysis the costs to pollute, to take resources from the planet, to warm up the earth are not taken in to consideration. When accounting these costs into the balance, the high cost price of renewable energy diminishes relatively. Ergo, it shouldn't be cheaper to invest in power generation from RES; it should be more expensive to invest in fossil fuels. This clear understanding should push governments to stop giving subsidies to renewable projects, but charge 'the actual real costs' to the fossil alternatives. This only ensures a more fair system for comparison between RES energy and fossil energy.

## Alternative methods of cost-valuation

Revealed preference method: infer what people are willing to pay from observation of their behavior in markets.

1. Environmental policies are mainly applied to save human lives,
2. What is the dollar risk to human life?
3. Economists usually calculate the extra wage – wage premium – that is paid to workers who accept more risky (and otherwise comparable) job
4. A common estimate (for the USA) is that workers are accepting an increase in the risk of dying by one in a million in exchange for a wage increase of $6.3. Or, some people are willing to forego $6.3 in wages to avoid one in a million risk of death.
5. Hence: avoiding a risk that would lead, on average, to one death is worth $ 6.3 million. Or, the value of a statistical life (VSL) is $6.3 million.
6. It is assumed that workers fully understand the risk involved and voluntarily accept the more dangerous job. They thus accept the increased risk of death in exchange for increased wages.

Contingent valuation: a cross section of the population is asked (via an opinion poll) how much they would be willing to pay to preserve or protect something that cannot be bought in a store.

# Appendix R Expenditure Model

## 1. *Assumptions*

***General***

- All costs in a particular year will be spend on 31 December of that year
- No demolition phase or demolition costs
- The time-preference rate is variable, but decisions in the project are based upon a value of 2%

***Planning***

- Project and design phase starts on 1 January 2014
- Designing and engineering takes two years
- Building phase starts on 1 march 2016
- Building phase duration can be determined from the construction plan
- Operational phase starts immediately after finishing building phase
- Operational phase lasts 50 years
- Project finishes when the operational phase has ended

***Costs***

- Costs for the total design phase are 10% of the construction costs
- Maintenance and exploitation costs per year are 0.5% of the construction costs
- Dispossession is not needed since the beaches are already property of the Brazilian government
- Risk is expressed in a percentage of the total building costs. A low risk percentage of 5% of the total building costs will be taken because the risks for this project are relatively low.

## 2. *Time-preference value*

The time-preference value (Dutch: *discontovoet*) is the factor that takes into account the drop in value of structures. This can be due to many aspects of economy, among the main factors: inflation, interest, economic growth etc. When determining the costs for this project, this time-preference value must be taken into account because this project is stretched along a relatively long time period. This time-preference value is also factoring in the growth of the energy prices.

The time-preference rate is used here to estimate the future costs of activities such as yearly income and expenses, i.e. what is the influence of the yearly income and expenses?

The Dutch economy faces difficult times at the moment. The stagnated growth of the economy in combination with the many risks and dangers of the recession offer difficulties when estimating the value of the time-preference rate. This value is therefore chosen to be variable, choosing the following values for different scenarios: 1%, 5% and 10%.

However, when making a comparison with for example a CCGT unit, one value has to be chosen to base the choice on. This choice of value is largely based upon the international capital market. This can be defended that domestic investment should have the same return as investments that are made abroad on the international market. This time-preference rate is set equal to the 2013 amount of the Dutch Ministry of Finance, which is 2.5%.[35]

The discounting rate is determined using the method described by the US Department of Commerce.

[35] *Werkgroep actualisatie discontovoet, Advies, Rijksoverheid.nl, 2007*

PART I:
TABLES FOR FEDERAL LIFE-CYCLE COST ANALYSIS

A. Single Present Value and Uniform Present Value Factors for Non-Fuel Costs

*Table A-1* presents the single present value (SPV) factors for finding the present value of future non-fuel, non-annually recurring costs, such as repair and replacement costs and salvage values. The formula for finding the present value (P) of a future cost occurring in year t ($C_t$) is the following:

$$P = C_t \times \frac{1}{(1+d)^t} = C_t \times SPV_t,$$

where d = discount rate, and
t = number of time periods (years) between the present time and the time the cost is incurred.

*Table A-2* presents uniform present value (UPV) factors for finding the present value of future non-fuel costs recurring annually, such as routine maintenance costs. The formula for finding the present value (P) of an annually recurring uniform cost (A) is the following:

$$P = A \times \frac{(1+d)^N - 1}{d(1+d)^N} = A \times UPV_N,$$

where d = discount rate, and
N = number of time periods (years) over which A recurs.

*Tables A-3 (a,b,c)* present modified uniform present value (UPV*) factors for finding the present value of annually recurring non-fuel costs, such as water costs, which are expected to change from year to year at a constant rate of change (or escalation rate) over the study period. The escalation rate can be positive or negative. The formula for finding the present value (P) of an annually recurring cost at base-date prices ($A_0$) changing at escalation rate e is the following:

$$P = A_0 \times \left(\frac{1+e}{d-e}\right)\left[1 - \left(\frac{1+e}{1+d}\right)^N\right] = A \times UPV^*_N \qquad (d \neq e)$$

or

$$P = A_0 \times N = A \times UPV^*_N \qquad (d = e),$$

where $A_0$ = annually recurring cost at base-date prices,
d = discount rate,
e = escalation rate, and
N = number of time periods (years) over which A recurs.

The tables that are referred to are presented in the full report of the US Department of Commerce.[36]

# 3. *Pricing date*

To compare the future value of the different activities of the different alternatives, a specific pricing date is determined. The values for the activities are adjusted (*Dutch: contanteerd*) to this specific date which is called the pricing date. This pricing date is chosen to be 1 January 2016, assuming the building phase will start in this year.

# 4. *Time horizon*

The time duration for the exploitation phase is chosen to be 50 years. This duration is reasonable given the lifetime of power plants. In 50 years the effect of the changes made to the area can also be seen and can be judged whether the proposed solution have the desired effect.

Also, this long time span allows for a more fair competition between the alternatives, since their initial and recurrent costs differ vastly.

# 5. *Results*

The results of the Expenditures model are presented in Table 19.

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[36] *National Institute of Standards and Technology, Energy price indices and discount factors for life-cycle cost analysis, 2013*

# Expenditure model Project Slufter

| | | | |
|---|---|---|---|
| Yearly trade benefit | € 19,30 million | yearly operation & maintance cost | € -0,50 million |
| Fuel cost savings | € 9,20 million | construction costs | € -580,00 million |

| | |
|---|---|
| payback year | 2043 |
| | 30 years |
| time pref. value | 1,1% |
| LEC | 709560 |

| costs in million €'s<br>Activity | Project year | year | Income<br>Power trade | Evaded fuel costs | Income total | Income cumulative | Expenses<br>General | Construction | Maintanance and operation | Expenses | Expenses cumulative | Balance<br>Balance | Balance cumulative without time-pref. | Balance incl. variable time-pref | Balance cumulative incl. 1.1% rel.time pref. | Discounted Expenses | Total life cycle costs | Energy produced |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Design | 1 | 2014 | | | € - | € - | € -29,00 | | | € -29,00 | € -29,00 | € -29,00 | € -29,00 | € -29,64 | € -29,64 | € -28,37 | € -28,37 | 709560 |
| | 2 | 2015 | | | € - | € - | € -29,00 | | | € -29,00 | € -58,00 | € -29,00 | € -58,00 | € -29,32 | € -58,96 | € -28,68 | € -57,06 | 1419120 |
| Start construction | 3 | 2016 | | | € - | € - | | € -580,00 | | € -580,00 | € -638,00 | € -580,00 | € -638,00 | € -580,00 | € -638,96 | € -580,00 | € -637,06 | 2128680 |
| Start exploitation | 4 | 2017 | € 19,30 | € 9,20 | € 28,50 | € 28,50 | | | € -0,50 | € -0,50 | € -638,50 | € 28,00 | € -610,00 | € 27,70 | € -611,27 | € -0,51 | € -637,56 | 2838240 |
| | 5 | 2018 | € 19,30 | € 9,20 | € 28,50 | € 57,00 | | | € -0,50 | € -0,50 | € -639,00 | € 28,00 | € -582,00 | € 27,39 | € -583,87 | € -0,51 | € -638,07 | 3547800 |
| | 6 | 2019 | € 19,30 | € 9,20 | € 28,50 | € 85,50 | | | € -0,50 | € -0,50 | € -639,50 | € 28,00 | € -554,00 | € 27,10 | € -556,78 | € -0,52 | € -638,59 | 4257360 |
| | 7 | 2020 | € 19,30 | € 9,20 | € 28,50 | € 114,00 | | | € -0,50 | € -0,50 | € -640,00 | € 28,00 | € -526,00 | € 26,80 | € -529,97 | € -0,52 | € -639,11 | 4966920 |
| | 8 | 2021 | € 19,30 | € 9,20 | € 28,50 | € 142,50 | | | € -0,50 | € -0,50 | € -640,50 | € 28,00 | € -498,00 | € 26,51 | € -503,46 | € -0,53 | € -639,64 | 5676480 |
| | 9 | 2022 | € 19,30 | € 9,20 | € 28,50 | € 171,00 | | | € -0,50 | € -0,50 | € -641,00 | € 28,00 | € -470,00 | € 26,22 | € -477,24 | € -0,53 | € -640,17 | 6386040 |
| | 10 | 2023 | € 19,30 | € 9,20 | € 28,50 | € 199,50 | | | € -0,50 | € -0,50 | € -641,50 | € 28,00 | € -442,00 | € 25,94 | € -451,31 | € -0,54 | € -640,71 | 7095600 |
| | 11 | 2024 | € 19,30 | € 9,20 | € 28,50 | € 228,00 | | | € -0,50 | € -0,50 | € -642,00 | € 28,00 | € -414,00 | € 25,65 | € -425,65 | € -0,55 | € -641,26 | 7805160 |
| | 12 | 2025 | € 19,30 | € 9,20 | € 28,50 | € 256,50 | | | € -0,50 | € -0,50 | € -642,50 | € 28,00 | € -386,00 | € 25,37 | € -400,28 | € -0,55 | € -641,81 | 8514720 |
| | 13 | 2026 | € 19,30 | € 9,20 | € 28,50 | € 285,00 | | | € -0,50 | € -0,50 | € -643,00 | € 28,00 | € -358,00 | € 25,10 | € -375,18 | € -0,56 | € -642,37 | 9224280 |
| | 14 | 2027 | € 19,30 | € 9,20 | € 28,50 | € 313,50 | | | € -0,50 | € -0,50 | € -643,50 | € 28,00 | € -330,00 | € 24,83 | € -350,36 | € -0,56 | € -642,93 | 9933840 |
| | 15 | 2028 | € 19,30 | € 9,20 | € 28,50 | € 342,00 | | | € -0,50 | € -0,50 | € -644,00 | € 28,00 | € -302,00 | € 24,56 | € -325,80 | € -0,57 | € -643,50 | 10643400 |
| | 16 | 2029 | € 19,30 | € 9,20 | € 28,50 | € 370,50 | | | € -0,50 | € -0,50 | € -644,50 | € 28,00 | € -274,00 | € 24,29 | € -301,51 | € -0,58 | € -644,08 | 11352960 |
| | 17 | 2030 | € 19,30 | € 9,20 | € 28,50 | € 399,00 | | | € -0,50 | € -0,50 | € -645,00 | € 28,00 | € -246,00 | € 24,02 | € -277,49 | € -0,58 | € -644,66 | 12062520 |
| | 18 | 2031 | € 19,30 | € 9,20 | € 28,50 | € 427,50 | | | € -0,50 | € -0,50 | € -645,50 | € 28,00 | € -218,00 | € 23,76 | € -253,73 | € -0,59 | € -645,25 | 12772080 |
| | 19 | 2032 | € 19,30 | € 9,20 | € 28,50 | € 456,00 | | | € -0,50 | € -0,50 | € -646,00 | € 28,00 | € -190,00 | € 23,50 | € -230,22 | € -0,60 | € -645,85 | 13481640 |
| | 20 | 2033 | € 19,30 | € 9,20 | € 28,50 | € 484,50 | | | € -0,50 | € -0,50 | € -646,50 | € 28,00 | € -162,00 | € 23,25 | € -206,97 | € -0,60 | € -646,45 | 14191200 |
| | 21 | 2034 | € 19,30 | € 9,20 | € 28,50 | € 513,00 | | | € -0,50 | € -0,50 | € -647,00 | € 28,00 | € -134,00 | € 23,00 | € -183,98 | € -0,61 | € -647,06 | 14900760 |
| | 22 | 2035 | € 19,30 | € 9,20 | € 28,50 | € 541,50 | | | € -0,50 | € -0,50 | € -647,50 | € 28,00 | € -106,00 | € 22,75 | € -161,23 | € -0,62 | € -647,67 | 15610320 |
| | 23 | 2036 | € 19,30 | € 9,20 | € 28,50 | € 570,00 | | | € -0,50 | € -0,50 | € -648,00 | € 28,00 | € -78,00 | € 22,50 | € -138,74 | € -0,62 | € -648,30 | 16319880 |
| | 24 | 2037 | € 19,30 | € 9,20 | € 28,50 | € 598,50 | | | € -0,50 | € -0,50 | € -648,50 | € 28,00 | € -50,00 | € 22,25 | € -116,48 | € -0,63 | € -648,93 | 17029440 |
| | 25 | 2038 | € 19,30 | € 9,20 | € 28,50 | € 627,00 | | | € -0,50 | € -0,50 | € -649,00 | € 28,00 | € -22,00 | € 22,01 | € -94,47 | € -0,64 | € -649,56 | 17739000 |
| | 26 | 2039 | € 19,30 | € 9,20 | € 28,50 | € 655,50 | | | € -0,50 | € -0,50 | € -649,50 | € 28,00 | € 6,00 | € 21,77 | € -72,70 | € -0,64 | € -650,20 | 18448560 |
| | 27 | 2040 | € 19,30 | € 9,20 | € 28,50 | € 684,00 | | | € -0,50 | € -0,50 | € -650,00 | € 28,00 | € 34,00 | € 21,53 | € -51,17 | € -0,65 | € -650,85 | 19158120 |
| | 28 | 2041 | € 19,30 | € 9,20 | € 28,50 | € 712,50 | | | € -0,50 | € -0,50 | € -650,50 | € 28,00 | € 62,00 | € 21,30 | € -29,87 | € -0,66 | € -651,51 | 19867680 |
| | 29 | 2042 | € 19,30 | € 9,20 | € 28,50 | € 741,00 | | | € -0,50 | € -0,50 | € -651,00 | € 28,00 | € 90,00 | € 21,07 | € -8,80 | € -0,66 | € -652,18 | 20577240 |
| | 30 | 2043 | € 19,30 | € 9,20 | € 28,50 | € 769,50 | | | € -0,50 | € -0,50 | € -651,50 | € 28,00 | € 118,00 | € 20,84 | € 12,04 | € -0,67 | € -652,85 | 21286800 |
| | 31 | 2044 | € 19,30 | € 9,20 | € 28,50 | € 798,00 | | | € -0,50 | € -0,50 | € -652,00 | € 28,00 | € 146,00 | € 20,61 | € 32,65 | € -0,68 | € -653,53 | 21996360 |
| | 32 | 2045 | € 19,30 | € 9,20 | € 28,50 | € 826,50 | | | € -0,50 | € -0,50 | € -652,50 | € 28,00 | € 174,00 | € 20,39 | € 53,04 | € -0,69 | € -654,21 | 22705920 |
| | 33 | 2046 | € 19,30 | € 9,20 | € 28,50 | € 855,00 | | | € -0,50 | € -0,50 | € -653,00 | € 28,00 | € 202,00 | € 20,17 | € 73,21 | € -0,69 | € -654,91 | 23415480 |
| | 34 | 2047 | € 19,30 | € 9,20 | € 28,50 | € 883,50 | | | € -0,50 | € -0,50 | € -653,50 | € 28,00 | € 230,00 | € 19,95 | € 93,15 | € -0,70 | € -655,61 | 24125040 |
| | 35 | 2048 | € 19,30 | € 9,20 | € 28,50 | € 912,00 | | | € -0,50 | € -0,50 | € -654,00 | € 28,00 | € 258,00 | € 19,73 | € 112,88 | € -0,71 | € -656,32 | 24834600 |
| | 36 | 2049 | € 19,30 | € 9,20 | € 28,50 | € 940,50 | | | € -0,50 | € -0,50 | € -654,50 | € 28,00 | € 286,00 | € 19,52 | € 132,40 | € -0,72 | € -657,04 | 25544160 |
| | 37 | 2050 | € 19,30 | € 9,20 | € 28,50 | € 969,00 | | | € -0,50 | € -0,50 | € -655,00 | € 28,00 | € 314,00 | € 19,30 | € 151,70 | € -0,73 | € -657,76 | 26253720 |
| | 38 | 2051 | € 19,30 | € 9,20 | € 28,50 | € 997,50 | | | € -0,50 | € -0,50 | € -655,50 | € 28,00 | € 342,00 | € 19,09 | € 170,79 | € -0,73 | € -658,50 | 26963280 |
| | 39 | 2052 | € 19,30 | € 9,20 | € 28,50 | € 1.026,00 | | | € -0,50 | € -0,50 | € -656,00 | € 28,00 | € 370,00 | € 18,88 | € 189,68 | € -0,74 | € -659,24 | 27672840 |
| | 40 | 2053 | € 19,30 | € 9,20 | € 28,50 | € 1.054,50 | | | € -0,50 | € -0,50 | € -656,50 | € 28,00 | € 398,00 | € 18,68 | € 208,36 | € -0,75 | € -659,99 | 28382400 |
| | 41 | 2054 | € 19,30 | € 9,20 | € 28,50 | € 1.083,00 | | | € -0,50 | € -0,50 | € -657,00 | € 28,00 | € 426,00 | € 18,48 | € 226,83 | € -0,76 | € -660,74 | 29091960 |
| | 42 | 2055 | € 19,30 | € 9,20 | € 28,50 | € 1.111,50 | | | € -0,50 | € -0,50 | € -657,50 | € 28,00 | € 454,00 | € 18,28 | € 245,11 | € -0,77 | € -661,51 | 29801520 |
| | 43 | 2056 | € 19,30 | € 9,20 | € 28,50 | € 1.140,00 | | | € -0,50 | € -0,50 | € -658,00 | € 28,00 | € 482,00 | € 18,08 | € 263,19 | € -0,77 | € -662,29 | 30511080 |
| | 44 | 2057 | € 19,30 | € 9,20 | € 28,50 | € 1.168,50 | | | € -0,50 | € -0,50 | € -658,50 | € 28,00 | € 510,00 | € 17,88 | € 281,07 | € -0,78 | € -663,07 | 31220640 |
| | 45 | 2058 | € 19,30 | € 9,20 | € 28,50 | € 1.197,00 | | | € -0,50 | € -0,50 | € -659,00 | € 28,00 | € 538,00 | € 17,69 | € 298,75 | € -0,79 | € -663,86 | 31930200 |
| | 46 | 2059 | € 19,30 | € 9,20 | € 28,50 | € 1.225,50 | | | € -0,50 | € -0,50 | € -659,50 | € 28,00 | € 566,00 | € 17,49 | € 316,24 | € -0,80 | € -664,66 | 32639760 |
| | 47 | 2060 | € 19,30 | € 9,20 | € 28,50 | € 1.254,00 | | | € -0,50 | € -0,50 | € -660,00 | € 28,00 | € 594,00 | € 17,30 | € 333,55 | € -0,81 | € -665,47 | 33349320 |
| | 48 | 2061 | € 19,30 | € 9,20 | € 28,50 | € 1.282,50 | | | € -0,50 | € -0,50 | € -660,50 | € 28,00 | € 622,00 | € 17,11 | € 350,66 | € -0,82 | € -666,29 | 34058880 |
| | 49 | 2062 | € 19,30 | € 9,20 | € 28,50 | € 1.311,00 | | | € -0,50 | € -0,50 | € -661,00 | € 28,00 | € 650,00 | € 16,93 | € 367,59 | € -0,83 | € -667,11 | 34768440 |
| | 50 | 2063 | € 19,30 | € 9,20 | € 28,50 | € 1.339,50 | | | € -0,50 | € -0,50 | € -661,50 | € 28,00 | € 678,00 | € 16,74 | € 384,33 | € -0,84 | € -667,95 | 35478000 |
| | 51 | 2064 | € 19,30 | € 9,20 | € 28,50 | € 1.368,00 | | | € -0,50 | € -0,50 | € -662,00 | € 28,00 | € 706,00 | € 16,56 | € 400,89 | € -0,85 | € -668,80 | 36187560 |
| | 52 | 2065 | € 19,30 | € 9,20 | € 28,50 | € 1.396,50 | | | € -0,50 | € -0,50 | € -662,50 | € 28,00 | € 734,00 | € 16,38 | € 417,27 | € -0,85 | € -669,65 | 36897120 |
| | 53 | 2066 | € 19,30 | € 9,20 | € 28,50 | € 1.425,00 | | | € -0,50 | € -0,50 | € -663,00 | € 28,00 | € 762,00 | € 16,20 | € 433,48 | € -0,86 | € -670,51 | 37606680 |

*Table 19 ... Expenditure Model Slufter*

# Appendix S Planning description

## 1. *General*

The construction of the project is planned to start at the 2nd of March 2015. The Slufter is appointed as a silt depot and the managing company has a contract until 2015 (see Part B in main report). To prevent unnecessary premature contract ending fees, the construction is planned to start after. The site preparations however can already by started in the meanwhile.

The sum of the critical activities is indicated as the red line in the project scheme.

## 2. *Preparation*

### Permits and licenses

Getting the required permits and licenses for the construction is a time-consumes however not so intensive task. This process can start already in the winter months leading up to the start of the construction on March 2nd 2015. Since a project cannot be executed and the Dutch bureaucracy is breath-taking, a long period with a long margin is planned.

### Public Awareness

Before the construction is commenced, people in the surrounding areas are made aware of what's going to happen and the possible consequences of these activities on them.

### Site preparation

The contents of this activity are described in the construction method description. Since the area is quite large, it is expected that these processes will about 3 weeks to complete

### Re-routing Maasvlakteweg

The re-routing of the road will take an estimated 2 weeks.

Since all other elements can continue without waiting for this, this activity is not critical in terms project deadline. The accessibility is ensured by the construction of the new road before demolishing the old one.

### Reserving working space

Workspace has to be reserved for labor and machines. The pipes will be stored on the beach as will other machinery. The location where the windmills will be stored is reserved for the construction phase. Huge area will be used for temporary storage of the dam fill material. This space is widely available in the area.

### Sheet piles

The sheet piles are driven into the ground using a pile driver. A pile driver accompanied by two workers can drive about 50 meters dam per working day.[37]

Considering the dredging is done for a 24 hour cycle, also these teams should be operational for 24 hours, utilizing several shifts. The production rate is expected to double to 100 m/day per team.

[37] *Rijkswaterstaat, Damwand aan buitenzijde verbreding, Geonet.com, 2010*

In total, 3320 meters of sheet piles have to be driven for each phase. Utilizing 4 teams working in parallel, the driving of the sheet piles takes 1 week.

## Foundation of turbine housing

The foundation of the turbine housing is placed right after the sheet piles are placed the water is pumped out. This is to ensure that the turbine housing can be constructed as soon as possible.

# 3. *Execution Phase 1*

## Partial excavation of the old dam

Once the building site is fit for construction, the part of the old dam is removed in order to put the core in place. The amount of soil excavation that is required per phase is

$$10 * 30 * 0.5 * 1500 = 225.000\ m^3$$

This soil can be recycled and used during the construction of the dam as dam fill material. This excavation will take about 3 weeks

## Dreding works

The construction can only start when sufficient amount of sand is available at the site. This is dependent on the dredging of the TSHD's. Their operation scheme has been presented in the construction method.

Each cycle of operation consists of 5 steps of each taking 30 minutes, so in total 2.5 hours. Before construction can commence, at least one cycle is finished so that sufficient material is available and any delay in the dredging (e.g. due to weather conditions) does not immediately halt all construction.

After the first cycle, the dredging will go on continuously dropping 5844 $m^3$/hour of soil onto changing locations.

Getting the required 17.2 million $m^3$ with the given scheme will take 149 day or 21.3 weeks

## Construction turbine housing

The construction of the turbine housing can commence once the building site is ready for construction. Because the dam facing wall will be constructed first, it will be separated from the construction of the dam. Then, this is a parallel construction that will be dependent on the construction of the dam only at near the ending of the construction when the dam has reached a height nearing the top of the turbine housing.

The construction of the turbine housing will take 20 weeks.

## Partial construction of the dam

The dam construction will commence once the sand of the first dredging cycle has reached the projects site. The dam will be raised incrementally together with the construction of the core. The total construction of the dam in phase 1 will depend on the construction speed of the bulldozer, scrapers and dump trucks. The amount of equipment is chosen in a way that it can handle the inflow of 5844 $m^3$ of soil per hour. Using shifts, the construction will continue 24 hours a day.

## Placement of the pipes

The pipes will be brought in segments to the project site where they will be joined and placed on top of the partly constructed dam. The penstocks will be placed within a 3 days

# Appendix T Dam failure

## Slope stability

The slope stability has been the essence of the stability calculations performed in GeoStudio 2012. The failure of the slope happens when the resisting force is smaller than the weight pushing down. This balance is incorporated into the Factor of Safety. The safety is analyzed according to the following conditions:

- Steady state (analyzed using GeoStudio 2012)
- Fast lowering of water level (analyzed using PLAXIS 2011)
- Seismic activity (not analyzed)

The steady state situation often causes a failure at the downstream slope caused by high pore pressures in the dam as result of the seepage. The fast lowering can cause a failure on the upstream side of the dam. Due to the fast lowering of the reservoir level this may cause instability. Seismicity is not a major issue in the Netherlands. This aspect does not require further analysis or consideration.

## Piping failures

The goal in the technical design has not been to remove the seepage totally, but rather to control it more. This has been the main reason for the construction of the impervious core. The soil surrounding the dam has been found to be sufficiently permeable to help drain the water that does seep through. Piping is a process which is caused by cavities and cracks inside the dam where water can flow through, causing erosion inside the dam. Underground piping under the core may be an issue for the Slufter dam. More locally, underground piping can occur under the turbine housing. This is due to the location at the toe of the dam and the heavy load of the dam leaning on the turbine housing.

## Overtopping failures

When overtopping occurs, soil on the inside of the dam is eroded which can cause instability. Many hydropower dams are constructed with spillways; emergency gates that can be opened fully in case the reservoir level is close the dam height. Since the reservoir level inside the Slufter is not subject to external effects and small effects that could form a threat can be controlled using the turbine openings of the dam.

## Foundation failures

Because there is a significant load on the subsoil, it must be considered whether this soil is strong enough to resist this load. The Slufter subsoil consists of strong sandy material. The same material is used for build up the Maasvlakte are and Maasvlakte 2, areas in which the subsoil is also under heavy load. Specific foundation analysis has to be performed for the foundation of the turbine housing. Not only do these have to cope with large forces of the dam leaning on the housing, also the location is at the toe of the dam, where the seeping water contacts the sea water. Underground water movements have to be analyzed to ensure safety.

# Appendix U Cost references

- Costs of Alqueva dams [38]
- Dredging costs [39]
- Ludington PHS turbines[40]
- Cost numbers for sheet piles[41]
- Ground works, sheet pile wall, anchoring, road construction[42]
- Sheet pile costs, pile driver rent, driving sheet piles costs[43]
- Pricelist ground moving works[44]
- Dredging rental costs[45]
- Costs for slurry walls[46, 47]

[38] *M. Harris, Portugal Inaugurates Alqueva Pumped-Storage Hydroelectric Project.., Hydroworld.com, 2013*
[39] *Master project Brazil, 2010*
[40] *Wikipedia, Ludington Pumped Plant, Wikipedia.com, 2013*
[41] *SoilSoft, 2013*
[42] *Startnotitie verbetering Diefdijk kostenraming 2008*
[43] *Rijkswaterstaat, Damwand aan buitenzijde verbreding, Geonet.com, 2010*
[44] *Prijslijst grondverzetmatariaal, Pon-Cat.com, 2013*
[45] *Van Oord Dredging and Marine Contractors*
[46] *BAM Contractors, Diaphragm walls, BAM, 2010*
[47] *We@Sea, Energie Eiland, 2006 (these walls cost €150 million for 60 m depth and 32 km length)*

# Appendix V Colebrook-White equations

## Solutions Of Colebrook & White Equation

**Input**

| | | | |
|---|---|---|---|
| e | **Pipe roughness** | | m |
| D | **Pipe internal diameter** = nominal pipe size - 2*pipe schedule. | | m |
| L | **Pipe length** | | m |
| V | **Average fluid velocity** – the mean velocity of the flow at the cross section. | | m/s |
| v | **Kinematic viscosity** – the kinematic viscosity of the working liquid. | | $m^2/s$ |
| ρ | **Density** - the density of the working liquid at the reference temperature. | | $Kg/m^3$ |

**Output**

Re **Reynolds number** – it determines the type of flow in the pipe.

**Laminar**: $Re_{pipe} < 2300$

**Transient**: $2300 \le Re_{pipe} \le 4000$

**Turbulent**: $Re_{pipe} > 4000$

$$Re_{pipe} = \frac{D \times V}{v}$$ - -

Type of flow in the pipe: - -

### 1. Solution by iteration process

- **Colebrook and White equation:**

$$\sqrt{f} \times \left[-2 \times \log_{10}\left(\frac{e/D}{3.7} + \frac{2.51}{Re_{pipe} \times \sqrt{f}}\right)\right] = 1$$ - -

f **Friction factor** - -

### 2. Swamee - Jain's solution

f **Friction factor**

$$f = \frac{0.25}{\left[\log_{10}\left(\frac{e}{3.7 \times D} + \frac{5.74}{Re^{0.9}}\right)\right]^2}$$ - -

## Solutions Of Colebrook & White Equation

### 3. Haaland's solution

f Friction factor

$$f = \left\{\frac{1}{\left[-1.8 \times \log_{10}\left(\left(\frac{e/D}{3.7}\right)^{1.11} + \frac{6.9}{Re_{pipe}}\right)\right]}\right\}^2$$ - -

### 4. Serghides' solution

$$A = -2 \times \log_{10}\left(\frac{e/D}{3.7} + \frac{12}{Re_{pipe}}\right)$$ - -

$$B = -2 \times \log_{10}\left(\frac{e/D}{3.7} + \frac{2.51 \times A}{Re_{pipe}}\right)$$ - -

$$C = -2 \times \log_{10}\left(\frac{e/D}{3.7} + \frac{2.51 \times B}{Re_{pipe}}\right)$$ - -

f Friction factor

$$f = \left[A - \frac{(B-A)^2}{C - 2B + A}\right]^{-2}$$ - -

### 5. Goudar - Sonnad's solution

$$a = \frac{2}{ln(10)}$$ - -

## Solutions Of Colebrook & White Equation

$$b = \frac{e/D}{3.7}$$ - -

$ln(10) \times Re_{...}$

$$d = \frac{ln(10) \times Re_{pipe}}{5.02}$$ -

$$s = b \times d + ln(d)$$ -

$$q = s^{\left(s/_{s+1}\right)}$$ -

$$g = b \times d + ln\frac{d}{q}$$ -

$$z = ln\frac{q}{g}$$ -

$$D_{LA} = z \times \frac{g}{g+1}$$ -

$$D_{CFA} = D_{LA} \times \left[1 + \frac{z/2}{(g+1)^2 + (z/3) \times (2g-1)}\right]$$ -

f Friction factor

$$f = \left\{\frac{1}{a \times \left[ln\left(\frac{d}{q}\right) + D_{CFA}\right]}\right\}^2$$ -

# Solutions Of Colebrook & White Equation

## Results comparison

### Friction factor

| | Solution | f | | % |
|---|---|---|---|---|
| 1. | Iteration process | - | | - |
| 2. | Swamee - Jain | - | - | - |
| 3. | Haaland | - | - | - |
| 4. | Serghides | - | - | - |
| 5. | Goudar - Sonnad | - | - | - |

$$\% = 100\% \frac{f_{solution} - f_{iteration}}{f_{iteration}}$$

### Head loss

| | Solution | $h_f$ | | % |
|---|---|---|---|---|
| 1. | Iteration process | - | m | - |
| 2. | Swamee - Jain | - | m | - |
| 3. | Haaland | - | m | - |
| 4. | Serghides | - | m | - |
| 5. | Goudar - Sonnad | - | m | - |

$$h_f = f \times \left(\frac{L}{D}\right) \times \frac{V^2}{2g}$$

### Pressure loss

| | Solution | ΔP | | % |
|---|---|---|---|---|
| 1. | Iteration process | - | KPa | - |
| 2. | Swamee - Jain | - | KPa | - |
| 3. | Haaland | - | KPa | - |
| 4. | Serghides | - | KPa | - |
| 5. | Goudar - Sonnad | - | KPa | - |

$$\Delta P = \rho \times g \times h_f$$

The method that gives results closer to iteration process is -

# Appendix W APX price numbers

## Comparison of EEX with APX

The numbers shows high similarities for the values from EEX.com which are tested in the report (see Table 20). The values are specifically compared with the values for November from EEX.com. There are however some anomalies in the data. The analysis on this scale shows another trend in the data which could not have been seen in with the analysis for EEX, which is the fluctuations along a week. The data shows that especially weekends (19 and 20 October) present different profiles, while the weekdays are confirming the trends that are also found for the EEX data.

| hour | 9-okt | 12-okt | 15-okt | 17-okt | 18-okt | 19-okt | 20-okt | 21-okt | 1-nov |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 47,41 | 55,84 | 51,06 | 40,25 | 44,96 | 31,48 | 34,8 | 33,05 | 47,44 |
| 2 | 36,78 | 48,51 | 46,75 | 35,54 | 43,53 | 35,15 | 37 | 33,83 | 35,21 |
| 3 | 33,41 | 40,21 | 39,96 | 36,8 | 40,56 | 36,27 | 36,27 | 33,05 | 33,72 |
| 4 | 33,34 | 34,1 | 35,68 | 36,61 | 37,43 | 34,17 | 34,8 | 33,11 | 42,27 |
| 5 | 33,36 | 36,3 | 37,44 | 36,56 | 37,49 | 33 | 35,45 | 33,33 | 40 |
| 6 | 35,41 | 36,88 | 38,3 | 34 | 42,81 | 32,75 | 35,52 | 30,92 | 39,29 |
| 7 | 53,72 | 37,11 | 50,77 | 40,88 | 50,88 | 36,27 | 35,52 | 44,61 | 52,44 |
| 8 | 67,45 | 48,96 | 61,93 | 56,9 | 59,4 | 38,11 | 37,5 | 58,1 | 72,34 |
| 9 | 69,53 | 51,54 | 64,7 | 60,82 | 65,4 | 39,96 | 36,27 | 59,47 | 61,13 |
| 10 | 72,85 | 54,94 | 62,75 | 57,38 | 57,16 | 45 | 38,96 | 59,22 | 63,11 |
| 11 | 70,8 | 59,51 | 63,19 | 55 | 67,58 | 50 | 39,92 | 59,52 | 82,61 |
| 12 | 69,96 | 59,8 | 62,37 | 57,44 | 62,34 | 52,42 | 40,56 | 57,36 | 84,96 |
| 13 | 65,37 | 60,78 | 51,77 | 58,79 | 59,14 | 52,44 | 42,44 | 57,78 | 74,25 |
| 14 | 63,38 | 58,53 | 50,57 | 57,38 | 55,74 | 50 | 42,42 | 56,12 | 60,81 |
| 15 | 60,57 | 52,69 | 49,94 | 51 | 52,36 | 49,94 | 39,96 | 52,77 | 49,96 |
| 16 | 58,91 | 47,64 | 52,26 | 48 | 49,8 | 45 | 40,56 | 50,48 | 49,34 |
| 17 | 50,67 | 47,41 | 52,43 | 48 | 45,71 | 47,08 | 43,68 | 49,99 | 47,44 |
| 18 | 52,97 | 49,71 | 57,16 | 48,74 | 50,66 | 51,09 | 52,44 | 52,71 | 68,18 |
| 19 | 58,34 | 53,34 | 65,38 | 58,99 | 57,81 | 61,04 | 61,87 | 61,87 | 60 |
| 20 | 63,9 | 64,2 | 82,22 | 75,05 | 60,53 | 69,98 | 79,96 | 70,49 | 45,34 |
| 21 | 60,73 | 62,77 | 60,89 | 60,93 | 54,44 | 59,94 | 64,87 | 56,09 | 44,93 |
| 22 | 55,86 | 50,48 | 52,67 | 50,48 | 45,91 | 47,44 | 54,94 | 45,6 | 43,63 |
| 23 | 57,44 | 59,78 | 52,48 | 53,47 | 44,92 | 39,96 | 44,94 | 44,85 | 46,72 |
| 24 | 44,82 | 60,7 | 52,57 | 54,93 | 46,53 | 37,89 | 37,44 | 37,95 | 34,96 |

*Table 20 ... APX day-ahead price fluctuations*

# Appendix X Modeling the temporary ground retaining pile

***Geometric model and materials***

The geometric model that is inserted into PLAXIS is derived from the technical design. The sheet pile is placed 5 meters into the soil and sticks out 10 meters, resisting also 10 meters of dam soil. The placement of the anchor is chosen initially based upon the expected force distribution. They are placed at +5m and +10m NAP, while the ground level is at -5m NAP *(see Figure 76)*.

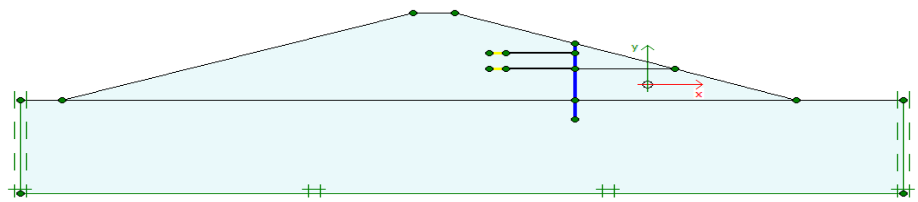

***Figure 76 ... Geometric model of sheet pile analysis***

The anchors are modeled as so-called *node-to-node-anchors* inside *PLAXIS 2D 2011*. These anchors are springs that are used to model the tie between two points. The spring has a certain (normal) stiffness. This is a suitable model type because a real anchor behaves the same way. The anchors have a length of 10 meters in the geometric model and are fixed with a grouting in the soil. This grouting is simulated with the *Geo-grid* option. These are slender structures with only a normal stiffness and can only be used for tensile forces. The grouting has a length of 1 meter in the model. The sheet pile is modeled using the *Plate* option. This type is used whenever a pile with a specific normal and bending stiffness is being modeled. The rest of the geometric model and boundary conditions is equal to the cross-section of the West-Voorne dam.

Each of the four types is given certain properties. Where these properties are not present, they are estimated.[48] This estimation is not very far-fetched, as values for soil characteristics which are classified under a group name do not differ significantly from each other, i.e. sand in the Zuid-Holland province has a relative small range of varying properties. The dam fill material is previously chosen to be sand, which is widely available in the area. One change has been made for the sake of simplicity; no distinction is made between the subsoil sand and the dam fill sand. This can be justified by two reasons:

- The main objective of this analysis are not the soil movements of the subsoil
- The difference between the characteristics of the subsoil and the dam fill is small

The sheet profile characteristics are based upon a chosen profile. For this, the profiles of ArcelorMittal are investigated.[49] The AZ18 profile is chosen for the first assessment (*see Figure 68)*. All the relevant material properties are attached in *Appendix K*.

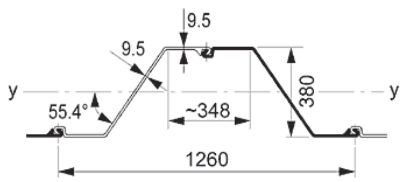


***Figure 77 ... profile of the AZ18 sheet pile***

[48] *Flowverse, Cameron Hydraulic Handbook, 2000*
[49] *ArcelorMittal, Information Calculation Sheet Piles, ArcelorMittal.com, extracted on 2013*

***Mesh and calculation***

The mesh is generated using a *general coarseness* set to *fine*. Since the area around the sheet pile is rather interesting, the mesh is further refined around this particular line. Point A, B and C (*see Figure 78*) are set as points of interest for detailed analysis. The calculation is performed in *Classical mode* (*utilizing Terzaghi's definition of stress*) using four phases.

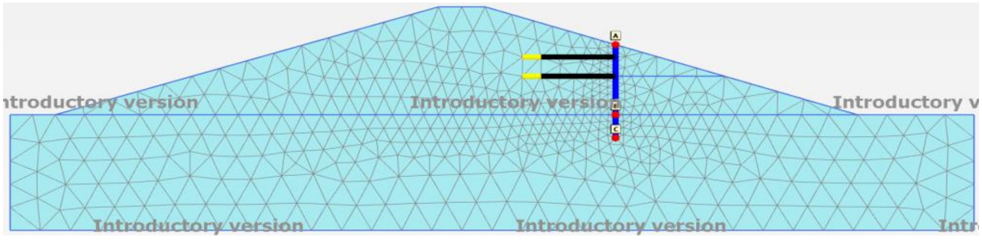


***Figure 78 ... Generated mesh for geometric model***

The initial phase is the phase as it starts. The K0-procedure is used to calculate the model in initial mode. In this phase, all types except for the dam fill material are *'turned off'*, meaning they are inactive. The water level is set at 0m NAP using a phreatic level. Within Phase 1, a plastic calculation is made for the model. The water conditions are as set for the initial phase. Since the sheet pile and the anchors are placed recently and the soil body has already been settling for many years now, the sheet pile and anchors are turned inactive for now. Phase 2 is the first phase in which the actual excavation starts; part of the top of the triangle is excavated. In the model this is simulated by making this particular region inactive, allowing the program to think there is nothing present there (*see Figure 69*). Since the interest of this analysis is to see the deformation in the sheet pile, the settlements before the excavation are not regarded by turning on the option *reset displacements to zero*.

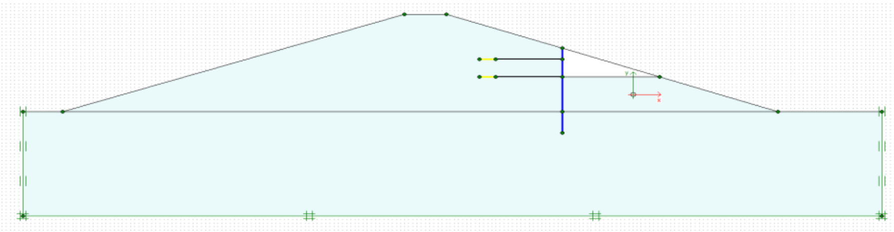

***Figure 79 ... Model with the first step of excavation***

In Phase 3 the excavation continues and reaches its end at a level of -5m NAP (*see Figure 70*). This is done by making the final region of the exaction inactive. The displacements continue from phase 2.

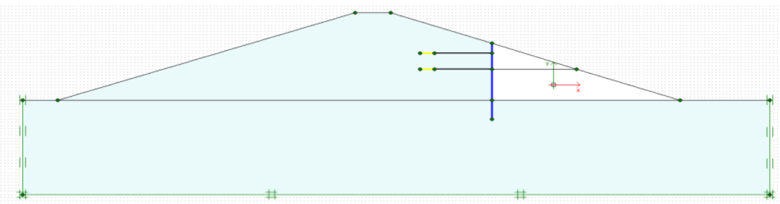

***Figure 80 ... Model with excavation complete***

Phase 4 is a safety calculation for Phase 3. A safety calculation is performed to obtain information about the stability of the model (*more information about safety calculations in Appendix K*). The variables are kept the same as in Phase 3; however the calculation type is changed from a *staged construction* to a *safety calculation.* The result of this phase should be the safety factors.

***Results Phase 1***

In Phase 1 the plastic behavior of the soil is analyzed without any influence of the sheet pile. The mesh looks pretty deformed *(note that image is scaled, see Figure 81)*, with a maximum deformation of 0.15m.

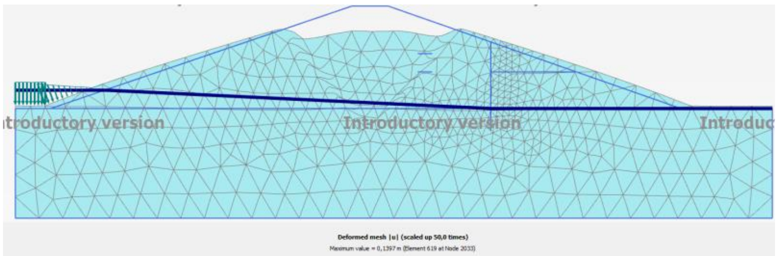

*Figure 81 ... Deformed mesh in phase 1*

### Results Phase 2

The displacements are reset and the sheet pile and anchor are turned active while the soil is partially removed (*see Figure 82*). Due to the excavation of the soil, the maximum deformation is 0.032m. The sheet pile is bending slightly because of this deformation; however the main deformation is of the soil with a maximum deformation of 0.057m. The bending moments are still relatively small (*see Figure 83*).

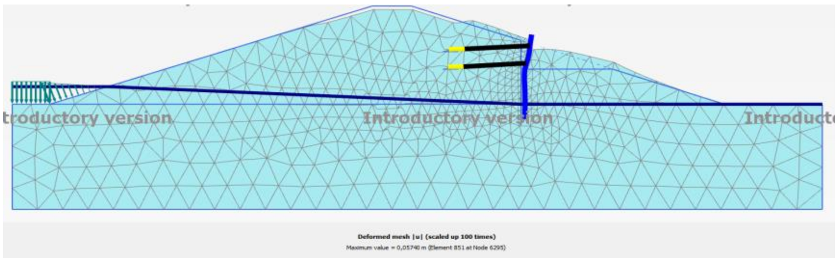

*Figure 82 ... Deformed mesh in phase 2*

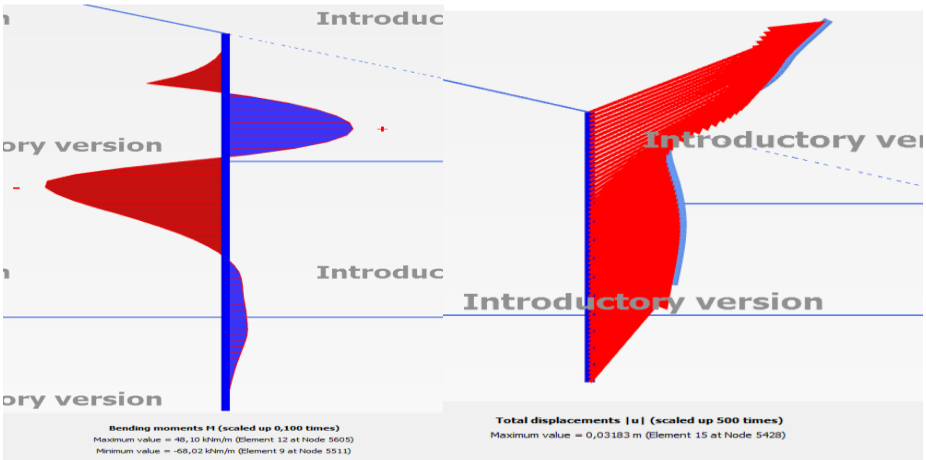


*Figure 83 ... Bending moments in phase 2 of the sheet*

### Results Phase 3

During the final excavation phase, the model deforms substantially (*see Figure 84*). The deformations in the sheet pile increase way beyond a critical level. While in phase 2, the deformation were mainly caused by the primary settlement of the soil in phase 2 and the effect of the excavation was rather small, phase 3 presents are different view. What is furthermore interesting is the moment distribution in the sheet pile (*see Figure 85)* which is very uneven and allows the load to cause a high moment near the bottom of the excavation at -5m NAP. This high moment is probably the cause of the high local deformation. The chosen profile AZ18 is not strong enough to withstand these moments. The solution is a better distribution of the anchors over the sheet pile length and for the high deformation at the end of the sheet pile is to increase the depth of the sheet pile further.

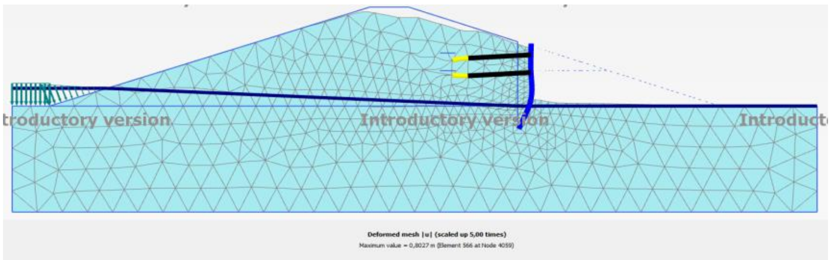

*Figure 84 ... Deformed mesh in phase 3*

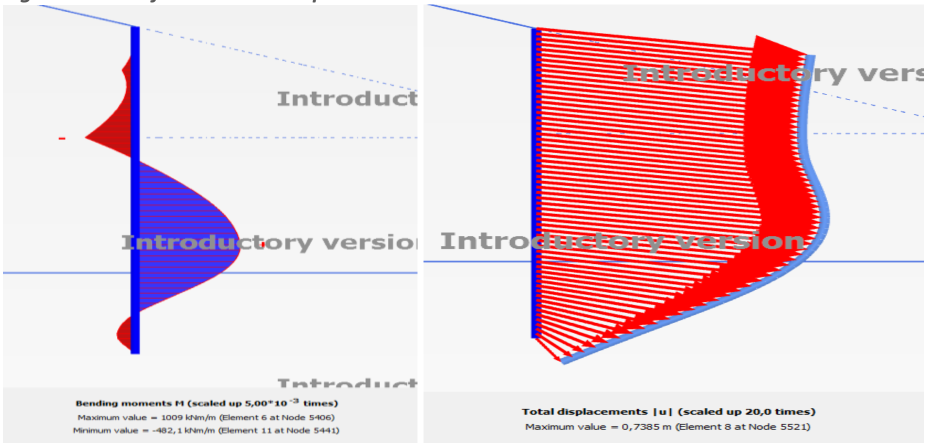


*Figure 85 ... (left) Bending moment distribution and (right) deformation in sheet pile in phase 3*

The analysis has shown some possibilities for improvement. Because of this, some changes are made to increase the resistance. The above mentioned actions will be performed to see if they have a positive effect on the strength and stability:

- Increase the depth of the sheet pile
- Better distribute the anchors along the sheet pile
- Stronger sheet pile with better characteristics

***Improved model***

The adjustments are made to the geometric model to see whether their influence is like hypothesized. Both the upper and lower anchor is lowered along the depth of the sheet pile. The upper one is placed at a level of +5m NAP whereas the lower one sets at a level of -2m NAP (the excavation goes on till -5m NAP). The depth of the sheet pile is improved to a level of -15m NAP, making the pile 20 meter long. The profile is upgraded from the AZ18 to the AZ25, which has a higher bending moment resistance of 109725 kNm$^2$/m. The improved model is entered and re-meshed with the chosen points of interest (A, B and C) *(see Figure 86)*. The model is calculated using the same calculation phases defined for the previous model. The changes will not affect the initial and phase 1, so only the results of phase 2,3,4 are presented.

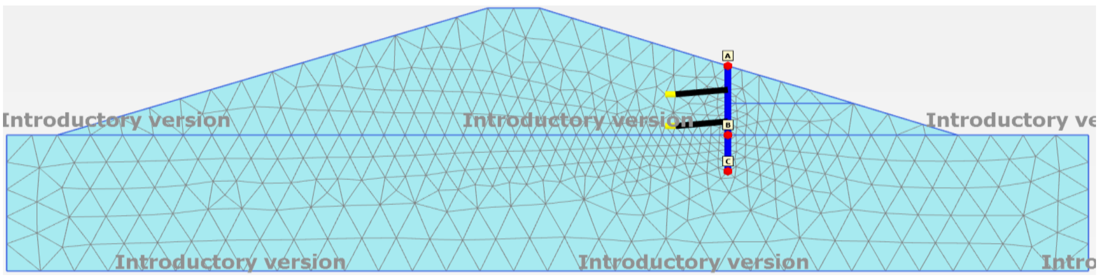


*Figure 86 ... Improved model and re-meshed*

### *Results Phase 2*

The overall displacements seems to be equal compared to the previous model even though the sheet pile distinctively deforms in a different way because of the anchor placement change *(see Figure 87).* However, when looking closer to the sheet pile and its deformations, it seems that the displacements are even larger than they were observed for the previous model (*see Figure 88*). The sheet pile is also subject to much greater bending moments. It seems that the changes that were implemented result in an unfavorable effect during phase 2. This is however not the dominating phase as the results of phase 3 are normative.

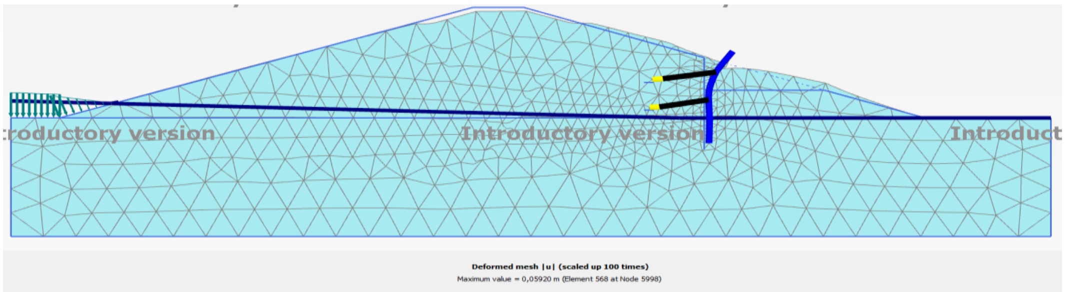


*Figure 87 ...deformed mesh in phase 2*

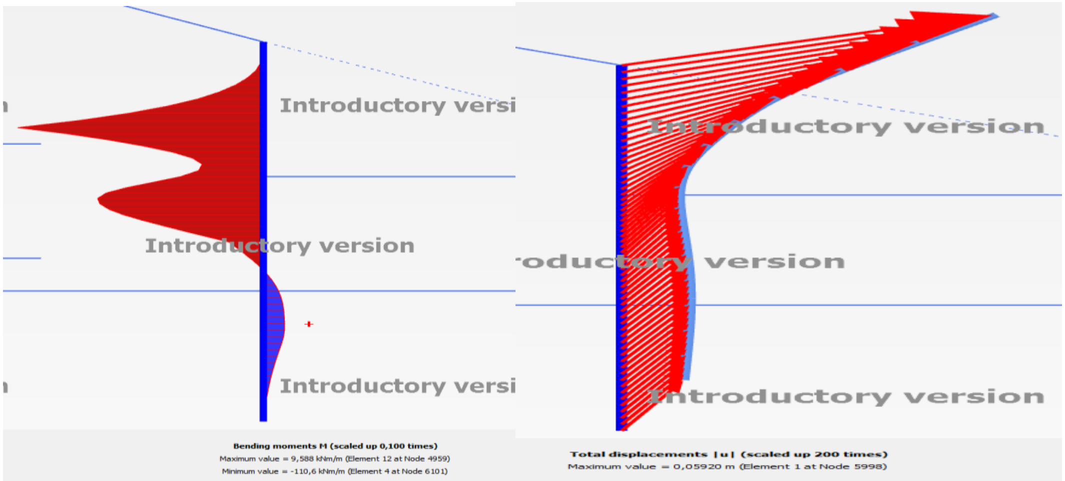


*Figure 88 ... (left) bending moments and (right) deformations of the sheet pile in phase 2*

### *Phase 3*

The displacement is only a fraction of the displacements seen in the previous model (*see Figure 89*). In contrast to the negative effect that is seen in Phase 2, the results in Phase 3 are very favorable. Bending moments that are exerted have been reduced drastically as well as the deformations of the sheet pile. As the entire plate moves slightly, the deformation of the place is smaller. Point A (top of the sheet pile)) moves only 0.08m relative to Point C (the bottom of the plate).

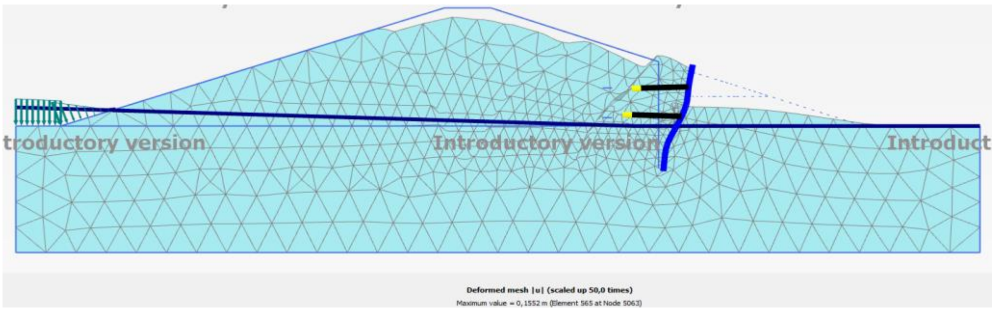


*Figure 89 ... deformed mesh in phase 3*

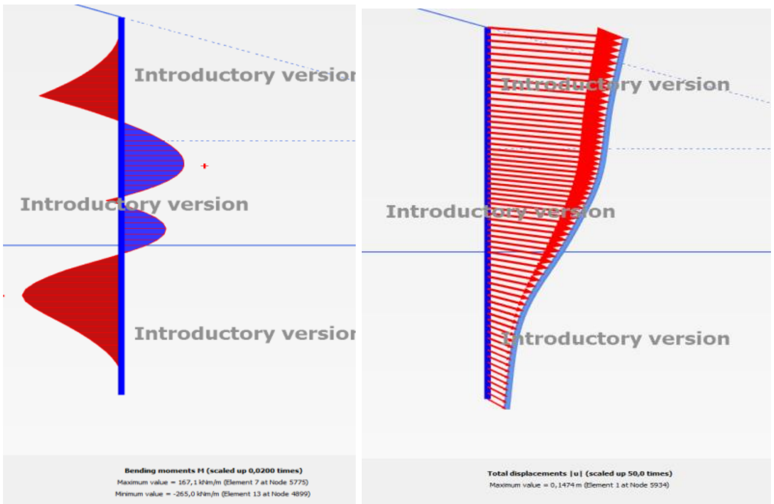


*Figure 90 ... (left) bending moments and (right) deformations of the sheet pile in phase 3*

***Phase 4***

In this phase the stability during Phase 3 is checked. The results are compared with the results that have been obtained in the previous model to see whether there are improvements in stability due to the longer depth of the sheet pile (*see Figure 91*). What is visible is that the previous model was barely stable, having a very low safety factor. Any changes that decrease the strength only slightly will possibly result in a soil body collapse which has been confirmed. In contrast, the improved model is displaying safety factors that reach up to 1.2, which is sufficiently safe.

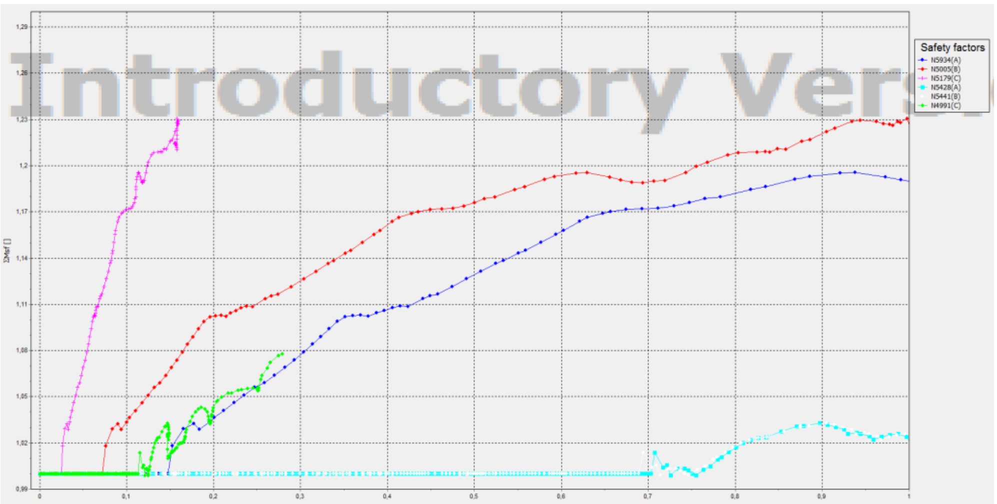


*Figure 91 ... Safety factors chancing with displacement (stability curves of points A, B, C (in decreasing order) for the improved model (top three curves) and the initial model (lower 3 curves)*

## Concluding remarks on the sheet pile analysis

The improved model performs substantially better than the previous model, reducing the moments in the sheet pile and thus allowing for a cheaper sheet pile for construction. The maximum bending moment in the sheet pile is 267 kNm/m. The sheet pile that is chosen was the AZ-18, which was improved to the AZ25 in the improved model. Even with the smallest steel grade, which is S240, the maximum bending moment resistance is 589 kNm/m, which is way above what is 265 kNm/m which is calculated above. Considering this wide safety margin, it should be considered whether there is still room for further optimization by choosing a smaller profile.

# Appendix Y Contaminated silt

The requirements regarding contaminated sediment are defined in the NEN5720. Depending on the level of contamination, the soil is divided into five classes (0 to class 4, higher class indicating greater contamination). Sediment research is required when work is being done that revolves with or around soil and this research is mainly commissioned by water authorities, the Ministry of Infrastructure and Waterworks, the municipality, the province or the respective owners. As a result of this sediment research, the sediment is classified according:

- **Class 0** (clean sediment) can be disposed and applied at any location without much consideration
- **Class 1 and 2** (lightly contaminated sediment) can be distributed in close to the extraction area
- **Class 3** (medium contaminated sediment) must be processed or taken to a depot or facility
- **Class 4** (highly contaminated sediment) requires a detailed remediation plan or plan of action.

In recent years, the total amount of contaminated soil arriving from the rivers has been reduced greatly due to pollution restrictions upward in the rivers. Therefore, the amount of highly contaminated silt which is being dredged and stored nationally is reduced.[50] An overview of the all the silt storage locations and their capacity is displayed in *Figure 92*. It should be analyzed whether the Slufter has the same reduction of annual silt inflow and how large this is. This is done in the following sections.

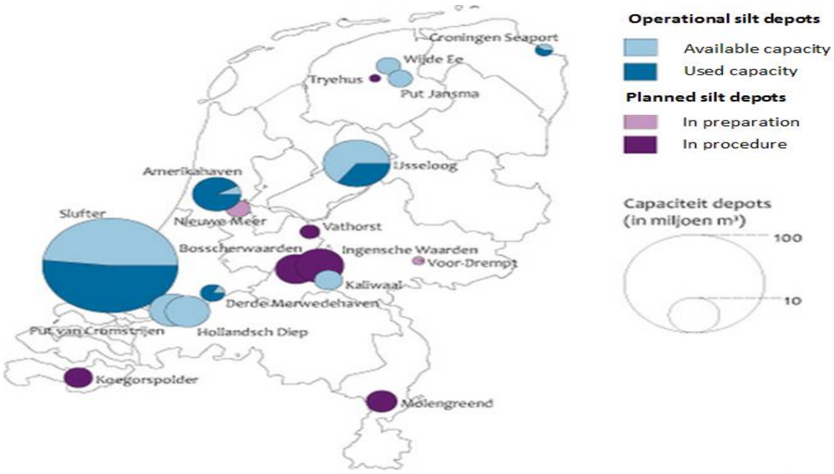


***Figure 92 ... Silt depots in the Netherlands (RWS/AKWA-DWW (2003, 2008)***

There are many techniques for the re-use of contaminated soil and doesn't require a rather expensive seclusion. Among the techniques are cleaning techniques which filter out contaminations and re-use in construction without the application of extensive cleaning techniques.[51,52,53] A promising technique is the use of contaminated soil in the buildup of dikes and dams. In a pilot-project by Rijkswaterstaat, the isolation of the soil proved to be sufficient. In another project, elevations using silt in the lower lying areas of the Netherlands is explored. This idea solves two problems, namely by heightening the lower areas and getting rid of the silt. Both projects are realistic options when dealing with the re-application of (contaminated) silt. [54,55]

[50] *Bodemrichtlijn, Behandelen en bestemmen van baggerspecie, introductie Nederlandse waterbodemproblematiek, Bodemrichtlijn.nl*
[51] *Y. Shen et al., A combined application of different engineering and biological techniques…, Ecological Engineering, 2013*
[52] *C.N. Mulligan, An evaluation of technologies for the heavy metal remediation…, Journal of Hazardous Materials, 2001*
[53] *TOA Corporation, Recycling of dredged material, Toa-const.co.jp, 2012*
[54] *Rademakers, 2005*
[55] *Rijkswaterstaat, Terpen van baggerspecie, 2004*

# Appendix Z Evaluation MSc-Thesis

Looking back at the months of work done, it feels satisfactory to present results which have a high degree of practical feasibility.

I wanted to really expand my current knowledge over the boundaries of Hydraulic Engineering, while staying true to the core. This expansion has been achieved by the detailed analysis of energy, power generation and energy storage techniques, which has been a very unexposed field during my studies.

Along the course of the graduation, I have

- Substantially expanded my knowledge in the world of energy and power production, while specializing in renewable energy sources
- Learned to work with two different finite-element-method packages; Plaxis 2011 by Plaxis and GeoStudio 2012 by GEO-Slope International
- Modeled a dam under conditions of a very fast lowering water level, interpreted the results and performed a cyclic feedback on the design
- Created a solution that is competitive with the current power systems

This has become a topic which is very dear to me that I would like pursue somewhere along my future career. Secretly, I am hoping to receive a call one day from the Port of Rotterdam, any engineering company or contractor whether I would like to be involved in the restructuring of the Slufter.