A follow-up feasibility study to an amphibious spray pontoon

MSc thesis

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Delft University of Technology

Section of Dredging Engineering

TU Delft

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Preface

This master thesis forms the final part of my master program Hydraulic Engineering at the Delft University of Technology. It's the result of a discovery expedition through the field of dredging technology. The journey started at a university of applied sciences, and after issuing the propaedeutic diploma a step forward was made towards a university's level. The journey consisted of many ups and downs.
I express my gratitude to my parents for providing me with unfailing support and encouragement throughout my years of study. This accomplishment would not have been possible without them.

I'm grateful towards Royal IHC for providing the opportunity to do my thesis at the company. During the period of graduating many valuable lessons were learnt regarding insight in the dredging industry and a professional working environment.
At the start of the graduation it became clear that a (second) reorganization was necessary to withstand tough times ahead. As a result I experienced a full cycle of a reorganization without having to deal with the uncertainties related with a reorganization. There was a consequence related to my graduation project as my daily supervisor from Royal IHC, R.H.A. (Ron) Kuypers, was declared redundant. Luckily Erik van der Blom stepped up to take over the daily supervision. Whenever needed, he showed me the bigger picture of the project and helped me keep the relation with the practical aspects of the project. Thanks for that!

I'm also grateful towards Hilko Timmer. By representing Witteveen+Bos he gave practical aspects to consider which he experiences in the day-to-day dredging practice.

Special thanks to Sape Miedema for the useful comments and support during the individual meetings. He consistently allowed this study to be my own work, but steered me in the right the direction whenever he thought I needed it.

I would also like to thank my professor, Cees van Rhee, for the valuable and constructive progress meetings.
Lastly I would like to thanks Mark Duinkerken for joining the graduation committee.

Thank you all,

Jeroen Dicker
August 2017

Abstract

Beach nourishments or sand replenishments are applied by the use of pipelines or the rainbow method. Replenished sand is then moved and levelled by bulldozers. This is a passive approach to process the outflow of material. The land based equipment is dependent from tides and water levels, and significant effort is required to install and maintain the onshore discharge pipeline. In remote (off-shore) areas mobilization of site equipment to move the sand may be quite a challenge.

The ideal method considers an active approach regarding processing the outflow of material. Instead of distributing the settled material by site equipment, the pipeline out flow point has to be relocated such that the design could be constructed.
To increase workability the pipeline must have the ability to be relocated in water as on land.
Enabling this approach the pipeline system has to be displaced by some sort of means. The main problem is the rigid behavior of the pipeline. Displacement of the pipeline will result that the entire pipeline length has to be displaced. Assuming that in water relocation of a floating pipeline is not that difficult as floating equipment is able to reach the floating pipeline. When the pipeline is situated on land huge pull or push requirements follows when the pipeline needs displacing.

A distinction has been made between depositing material at the designated spot so called point B, and delivering material from the dredger's discharge location to the deposit spot, called section A-B. Reference is made to section 2.2 for an overview of the schematization of the ideal method. The ideal method must cope with the following aspects:

Aspect	On land	In water	Action
Displacement point B	Difficult	Easy	Decrease total friction force when on land
Displacement section A-B	Difficult	Easy	Decrease total friction force when on land
Hold position point B	Easy	Difficult	Produce holding force when in water
Hold position section A-B	Easy	Difficult	Produce holding force when in water
Different water depth	Not applicable	Applicable	Generate floating capacity versus generating holding force
Multiple segments section A-B	Difficult	Easy	1. Decrease total friction force 2. Or create flexibility in section A-B

Concepts both for point B as for section A-B have been generated by setting up a morphological overview. A morphological overview holds all the possible solutions for each sub-function. By combining all the individual solutions for each sub function a concept is generated. To determine the most promising concept the generated concepts have been analyzed by a multi criteria analysis.

The most promising method for depositing material is to apply a spray pontoon. By adding amphibious propulsion technique to the spray pontoon the pontoon is able to work on the interface between water and land.
The most promising method regarding delivering material to the spray pontoon is by applying a steel pipeline.
During depositing the spray pontoon have to be displaced frequently. Also the spray pontoon has to be able to displace the pipeline system. Properties of the pipeline system dictate the required amount of tractive effort that have to be generated by the spray pontoon. Focus is on maximizing the tractive effort to be generated by the spray pontoon.

The hypothesis is that dragging the pipeline along requires so much effort such that the spray pontoon is not able to generate such a pull force. To decrease the amount of resistance the pipeline will be mounted on platforms. Focus is on minimizing the required amount effort to displace the pipeline system.

Next a theoretical review was performed to determine how much effort it takes to displace a pipeline situated on land. Also the resistance force encountered to displace the platform concepts has been investigated together with a calculation method to determine the pull force each amphibious propulsion concept is able to generate.
Goal is to create numeric values that will serve as input for the multi criteria analysis.
By performing a workability assessment numeric input values will be provided for the theoretical review, and numeric output values are created. In this way the concepts can be compared with each other. Scores per criterion can be obtained and serve as input for the multi criteria analysis.

From the theoretical review follows that lateral displacement of the pipeline system requires the most amount of effort. Due the properties of the pipeline system rolling is not possible. Sliding is the way forward to displace the pipeline system. Due to the formation of a berm in front of the pipeline the resistance forces increase to large numbers.

Along the pipeline section flexibility is created by applying ball joints to enable a degree of freedom in the x-y plane. These are commonly available in the dredging industry. Maximum angle in the x-y plane is around 40 degrees. Also a ball joint have to be placed at the first platform that allows for a 360 degree of freedom in the x-y plane. In this way the spray pontoon and the platforms can swing around this ball joint. On each platform 24 meter of pipeline will be mounted.
The outer end of the pipeline system towards the spray pontoon will be mounted on platforms. Not the entire pipeline system has to be mounted on platforms when a review period of one week of production is applied. By generating flexibility along the pipeline system the pipeline could swing independent of each other. Production figures will determine the amount of flexibility along the pipeline needed.

Main function of the spray pontoon is, besides depositing material, generating tractive effort to displace the platforms whereby the spray pontoons are mounted on. The amphibious technique that is able to generate the biggest amount of tractive effort is a track propulsion system. A track system is less mobile in lateral movement compared to the other amphibious propulsion techniques but the spray pontoon is situated at the outer end of the pipeline system so mobility is less of an issue.
The most promising amphibious propulsion technique to be mounted on the spray pontoon is to apply a track system. The track system of the ASP is ideal as the spray pontoon will mostly apply axial movement seen from the orientation of the spray pontoon. The spray pontoon is working from left to right, and vice versa. As a consequence the pipeline and therewith the platforms have to be able to follow the spray pontoon.

Main function of the platforms is to decrease the resistance force to displace the pipeline system. In order to do so the platforms must be able to follow the spray pontoon and generate a small as possible resistance force. From the multi criteria analysis follows that regarding the aspect of mobility and resistance force the hoverbarge is the most promising platform to mount the pipelines on. Second place goes to a three wheeled platform with a caster set-up. This caster set-up allows movement of the platform(s) of 360 degrees in the x-y plane.
In addition the pipeline cannot be used to distribute the pull force generated by the spray pontoon to displace the platforms. Other means have to be found.

Dredging operation takes place in a marine environment; this is an aggressive environment due to salt water and the scour effect of the dredged material. Ideally the platform concept must have the simplest possible set-up. In this way a low risk of failure to minimize downtime and to create small capex and opex values is ensured. Regarding this aspect the wheeled platform is preferred.

Main objection against the wheeled platform is that the platform is dependent of the water levels and accordingly with the water depth as the wheels need to stay in contact with the soil surface. At the other hand, the water depth won't be that large because otherwise the ordinary floating equipment will be deployed.
When obstacles are encountered wheels could enhance the need of very high pull forces to overcome these obstacles. A hoverbarge has a superior behavior regarding obstacles.

Downside is the expected fuel consumption of the hover barges when on hover. It could be stated that the wheeled platforms requires much less fuel. This has consequences for the OPEX values, and also for the environmental impact.
In addition it is expected that the CAPEX values for a hoverbarge (due to its complex technique) are larger than a wheeled platform.
But a hoverbarge has superior capabilities to operate on the interface of water and land.

It depends on the type of project, and the regarding conditions which platform have to be put into action. On project locations were small variations of water levels is expected, and the soil surface has high bearing capacities values the wheeled platform can be applied.
However, on soft soils with low bearing capacity values the wheels will experience significant sinkage; the resistance force to displace the wheeled platforms may possibly not be generated by the spray pontoon. In addition on soft soil the spray pontoon can generate a smaller pull force compared to when on sandy soil surface.
On (very) soft soils hoverbarges are advantageous compared to wheeled platforms.

Summarizing: it depends on the type of project, and site conditions which type of platform have to be applied. On project locations were small variations of the water levels is expected and the soil surface has high bearing capacities values the wheeled platform can be applied.
However, on soft soils with low bearing capacity values the wheels will experience significant sinkage; the resistance force to displace the wheeled platforms can possible not be generated by the spray pontoon. In addition on soft soil the spray pontoon is able to generate a smaller pull force compared to when on sandy soil surface.
On (very) soft soils hoverbarges are advantageous compared to wheeled platforms.

Concluding: a uniform concept doesn't exist because there is a large amount of parameters and aspects involved, resulting in complexity in the determination of the most promising total concept. More investigation is needed to state the most promising solution with more evidence.

'Is it technical feasible to apply an amphibious spray pontoon?'
From the test case follows that the following aspects have major influence on the spray pontoon:

- Water levels and corresponding the water depth
- Pipeline length that needs displacing
- Soil conditions
- Creating flexibility in the pipeline system.

All of those mentioned aspects could be dealt with by the suggested most promising concepts, so the application of an amphibious spray pontoon seems feasible. However, still a lot needs investigating, especially regarding the soil interaction with the spray pontoon, and the behavior of the pipeline during displacement when situated on land. Also methods have to be found to distribute the pull force from the spray pontoon to the platforms.

Table of Content

Chapter 1

Introduction

1.1 Context

Beach nourishments or sand replenishments are done by the use of pipelines or the rainbow method. Replenished sand is then moved and levelled by bulldozers (possibly with assistance of excavators and dump trucks). The land based equipment is dependent from tides and significant effort is required to install and maintain the onshore discharge pipeline. In remote (off-shore) areas mobilization of site equipment to move the sand may be quite a challenge.

Spray pontoons are able to deposit sand in particular layers at once, without the installation of an onshore pipeline system. Spray pontoons even allow reclaiming soft soil by spraying thin layers of sand. Though spray pontoons requires sufficient water depth and are, like land based equipment, more or less dependent from tides.
In the day-to-day practice a significantly amount of downtime is noticed when working in tidal areas due to a limited water depth.

Taking into consideration the mentioned aspects this raises the question whether there is a more efficient method to place the sand.
Consulting engineering firm Witteveen+Bos (*H. Timmer, 2015*) came up with a concept of an amphibious spray pontoon creating an efficient piece of equipment that could work independently from water levels and tide.
Royal IHC (engineering and manufacturing of specialized equipment for the dredging, offshore, and wet mining industries) was asked to elaborate the concept of the amphibious spray pontoon.

In 2015 a feasibility study was performed to an amphibious spray pontoon by generating various concepts (*Koen, 2015*). The feasibility study suggested that an amphibious spray pontoon is feasible but still a lot needs to be checked.
A follow-up feasibility study is required in order to determine the technical feasibility of an amphibious spray pontoon. In this study the possibilities of applying amphibious techniques on a spray pontoon are studied together with an analysis of the regarded problems when an amphibious spray pontoon is applied in dredging works executed in limited water depths.

1.2 Main research question

The main research question of this study is formulated as follows:

What are the possibilities for replenishing sand continuously, independent from water levels and tides in order to increase workability?

The following requirements are chosen as boundary conditions for the research project. The method should be able to:

1. Deposit sand both in water and on land
2. Operate in an intertidal area
3. Move both in water and on land

4. Hold position both in water and on land
5. Operate continuously
6. Sand is supplied by a pipeline.

Goal of this study is to find and to develop a method for replenishing sand continuously, independent from water levels and tide in order to increase workability.

Economical aspects and technical aspects are not related to each other in this study. It's about finding a technical solution/determining a method for replenishing sand continuously.

1.3 Methodical design process

To give an overview of the systematics and the methodology used in this study Figure 1-1 shows the subsequent design phases. As stated in the context the development of the new method is still in the feasibility phase. This means that the problem definition phase needs elaboration. After this phase the determination method phase comes into play.

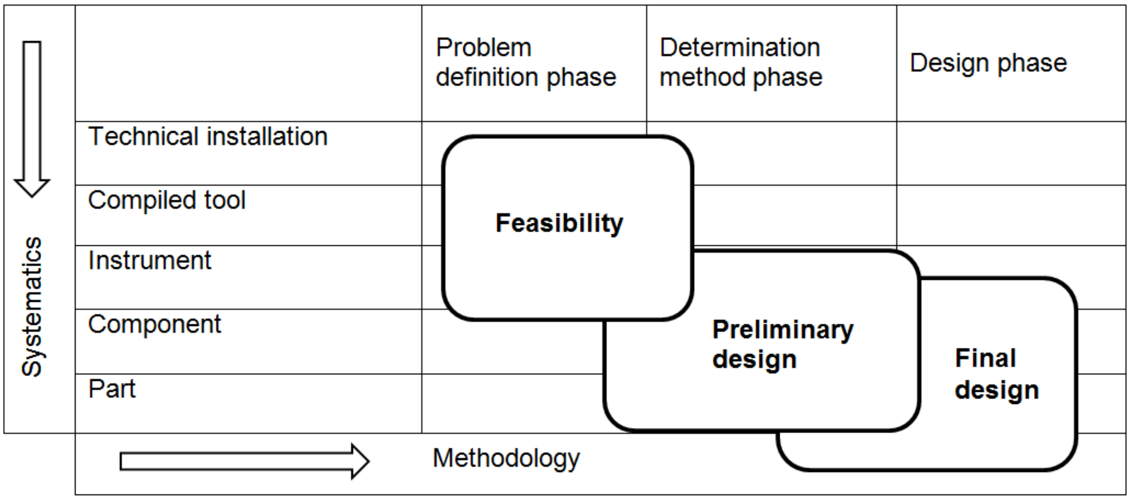


Figure 1-1: Subsequent design phases. (Source: *van den Kroonenberg et al, 1998*)

1.4 Approach

To find and develop a new method the methodical design process developed by Prof. van den Kroonenberg (*van den Kroonenberg et al, 1998*) will be applied.
In Figure 1-2 this process is represented as a process that starts with an abstract problem definition and ends with a specific solution.

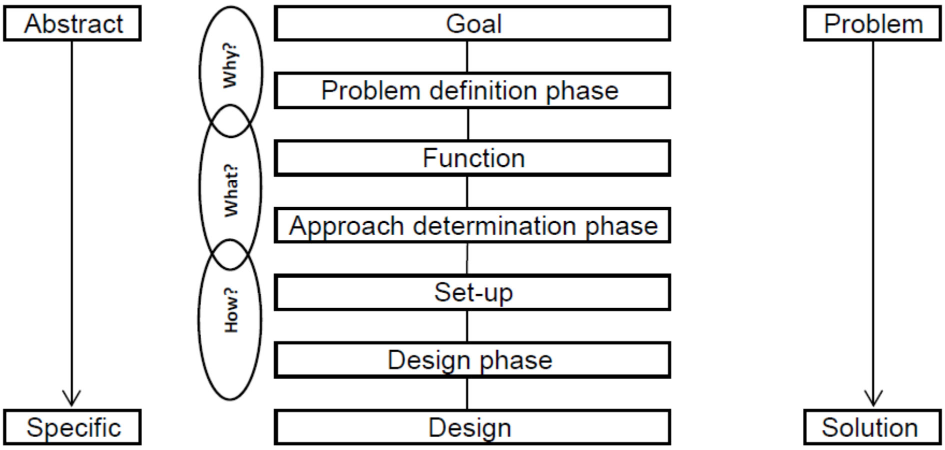


Figure 1-2: Methodical design process. (Source: *van den Kroonenberg et al, 1998*)

1.4.1 Approach generation of concepts

For generating concepts for replenishing sand in intertidal areas a morphological approach will be applied (*Pahl et al, 2007*). The approach helps to find all theoretically possible concepts for a problem. First all the elements that are essential for all concepts, called 'parameters', are found. Next an inventory is made of possible realizations of each element, the 'components' or 'ideas'

The morphological approach strictly makes a separation between creating and evaluating ideas.

The approach is as follows:

- Step 1: Formulate the problem to be solved as accurately as possible
- Step 2: Identify and characterize all parameters that might occur in the method
- Step 3: Construct a morphological chart or multidimensional matrix, which contains all methods to the problem
- Step 4: Analyze all methods carefully and evaluate against the objectives
- Step 5: Select and implement the best methods, in so far as the means are available.

<u>Morphological Chart</u>

A morphological chart consists of parameters and components (or ideas). The parameters describe the characteristics or functions which a product or process should have or fulfill.

The components are the means by which the parameters may be realized. Parameters are abstract and general. Each parameter indicates a category of similar objects or process.

The components are concrete and specific.

1.4.2 Approach for selecting the most promising concept

To find the most promising concept for replenishing sand in intertidal areas the following approach will be followed:

1. Generation of concepts
   There are many concepts available. Goal is to take some distance from the problem. In this way a better overview is created.
2. Most promising concept
   The boundary conditions from section 2.3 are held against the generated concepts and its variants. For some concepts or variants it's obvious that at first glance some doesn't comply with the boundary conditions. Those won't be used in the multi criteria analysis.
3. Use of weight factors
   The criteria used in the MCA don't have equal weight to each other. By applying weight factors differences between the criteria is shown.
4. Multi-criteria-analysis (MCA)
   The most promising concept is selected by applying a multi-criteria-analysis. Weight factors will be used as described under item three.

After following this approach, the most promising concept will be known. This concept will be elaborated in the next chapter. Deliverables of this study is an elaborated method that is in the preliminary design phase.

1.5 Structure of the report

Chapter two 'Problem description' starts with a problem identification for replenishments executed in shallow waters. Next an analysis of the ideal method is described. From this analysis follows the problem identification of the ideal method. The problem description ends with an approach to develop concepts for depositing material and for delivering material.

This study makes a distinction between depositing material and delivering material from the discharge location to the deposit location. For the distinction 'depositing material' concepts will be generated in Chapter three. Also the most promising concept to deposit material is determined.
For the distinction 'delivering material' the most promising method will be determined in Chapter four. Concepts of this method will be generated. By means of the list of criteria a selection will be made which criteria will be selected to perform a theoretical review.

The theoretical review presented in Chapter five holds content related to displacement of the pipeline system. This theoretical review is still quite abstract but by applying a test case in Chapter six by performing a workability assessment quantification of the selected criteria is enabled. This makes comparing the concepts more convenient.

The numeric output generated by the test case will serve as input for the determination of the most promising concept regarding delivering material. Reference is made to Chapter seven.
Together with the most promising concept for depositing material a total concept for material replenishments in shallow waters is provided.

Finally, Chapter eight holds the conclusive remarks, recommendations, and a discussion part.

Chapter 2

Problem description

Chapter two will start with an analysis and problem identification of sand nourishments and land reclamation projects executed in intertidal areas.
First a general overview of the dredging processes is presented together with execution aspects and conditions. Difficulties and problems are described.
Next the ideal method is described for replenishment in intertidal areas. By analyzing the ideal method the associated problems of the ideal method will be identified.
The ideal method will be split into two aspects; depositing the material and delivering the material. For both aspects the problem identification will be given.
Chapter two will end with an overview of the related problems of the ideal method.

2.1 Problem identification for replenishments in shallow waters

This paragraph starts with a general overview of the dredging process. By applying scenarios of available water depths difficulties during depositing and processing the deposited material will be known.
Next the type of projects will be described related to replenishments and land reclamation projects. Then the opportunities will be stated that have to keep in mind in the development of the ideal method.
The paragraph will end with a description of other methods for accretion of material.

2.1.1 General overview of the dredging process

Figure 2-1 gives a general overview of the dredging process (simplified).

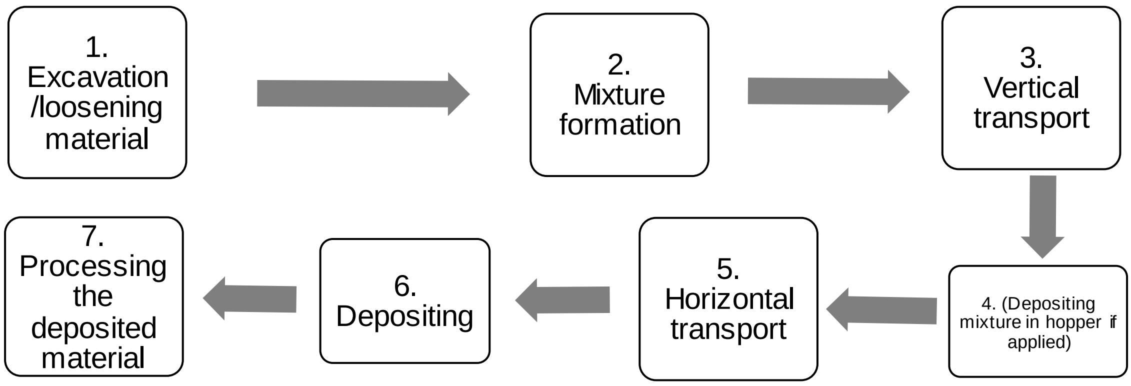


Figure 2-1: General overview of the dredging process.

This study will focus on the aspects five till seven of the dredging process; horizontal transport, depositing, and processing the deposited material.

<u>Horizontal transport (item number 5) of the material by means of:</u>

- Pipeline
- Barge or trailer suction hopper dredger (TSHD)
- Road transport
- Conveyor belt

- Combination of the mentioned transport modes

Depositing the dredged material (item number 6) by:
- Direct dumping
- Pipeline placing it on the dry beach or by means of a spray pontoon
- Rain bowing

In the figures below the mentioned depositing techniques are represented.

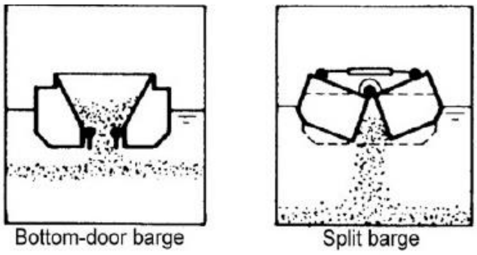


Figure 2-2: Direct dumping

Figure 2-3: Rainbowing

Figure 2-4: Depositing by pipeline.

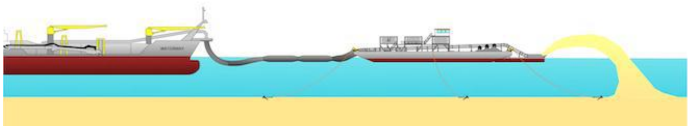


Figure 2-5: Depositing by means of a spreader pontoon.

Processing the deposited material (item number 7)
Land based equipment, like bulldozers and excavators, are applied in order to construct the required profile / design. This equipment processes the deposited material from the pipeline or material deposited after rain bowing by moving and leveling the material into the specified design.

2.1.2 Scenarios of available water depths

When replenishing sand in coastal areas, pipelines and (hopper) barges are almost always applied in order to transport the material from the borrowing area towards the dumping spot. The available water depth is the most critical parameter in the depositing process when floating equipment is applied. The water depth determines which dumping technique is applied.
Below four dumping scenarios are presented with several water depths and several horizontal distances between the dredger and the dumping spot.

1. Sufficient water depth present
Trailer suction hopper dredger's and barges are able to dump their load directly on the seafloor by opening their bottom doors or by hull splitting. At least 3.5 meter of water depth must be present. Dumping at high tides only, might be acceptable. In that case efficiency might be improved by simultaneously dumping and loading of several units. To increase the available dumping window, sailing with lower loads might also prove to be an option. At calmer conditions a lower keel clearance might be acceptable. Special attentions must be given to dumping via bottom doors because there is a risk of running aground.

Also direct dumping on the foreshore might be part of a larger beach nourishment project. If planned well, nature might help to profile the deposit site, either by waves or by the current.
Dredging methods A, B, E, and J in Figure 2-6 could be applied when a sufficient water depth is available at the depositing site.

2. No sufficient water depth but within rainbow distance

On a vessel (either a dredge or a spray pontoon connected to the dredge by pipeline) a rainbow nozzle is fitted at the end of the pipeline. The mixture is jetted onto the beach. This method can successfully be applied if the spraying vessel can approach the beach within jetting distance, being 25 meter up to 150 meter. An important aspect is the wind direction: the wind shall have to be favorable: blowing from vessel to the beach in order to reduce sand losses and to improve workability onboard of the spray vessel.
Figure 2-6 shows with dredging method C, G, and H the rainbow technique.
The use of the rainbow technique is widely spread nowadays. This technique is very useful on reclamations projects in open sea of close to the shore. The technique comes into play when the minimum depth for normal dumping through the bottom doors is no longer possible because of limited depth. The aim of this technique is to bring the sand level as high as possible above sea level while not having to install a costly onshore pipeline and floating pipeline together with a costly tugboat assistance. Also not in every load cycle time is lost through the coupling time necessary to couple the ship's bow pipeline to the end of the pipeline.

3. No sufficient water depth and out of reach of rainbow distance

When there is no sufficient water depth available and when the horizontal distance when rainbowing is not sufficient, a pipeline is applied directly on the beach. A combination of floating, submerged and pipes transfers material from the dredge and placing it into the required section, see dredging method F and I in Figure 2-6.
This system has a large flexibility and could be accommodated for all water depths, sea conditions and specific project requirements. The material is placed on the dry beach.
A set of dry earth moving equipment will have to reshape the deposit to the required profile: when filling by pipeline the initial deposited profile will be more accurate, so less dozing might be required.

4. Rehandling

This discharge method is a combination of dumping and pumping. The material is dumped by a TSHD or barge in a stockpile or dump pit close to the project location. From there a CSD reclaims the material and pumps it direct to the beach. Dredging method D and K in Figure 2-6 represent the rehandling scenario.
Justification for this method (mobilizing a second dredge and a double handling of all material) is an extremely high output or in case of extreme pumping distances. Sand losses from the rehandling pit might occur; fines might be washed out from the stock pile. If the transport unit (trailer or barge) is able to approach the shore at high tide very closely, rehandling by dry earth moving equipment during low tide might become feasible.

<u>Shift in dumping scenarios</u>

When constructing artificial islands in a tidal area, there might be a shift in the dumping scenario. At the start of the project, dumping scenario 1 is applied. During construction the available water depth decreases as the deposit area merge/increases in height. As a result a shift is required from scenario 1 to scenario 2.
Also at low tide it may occur that the horizontal distance becomes too large in order to apply the rainbow technique. To continue depositing process, the contractor might shift to scenario three.

This study will focus on scenarios two and three; limited water depths can put a strain on the workability and accessibility of (floating) dredging equipment.

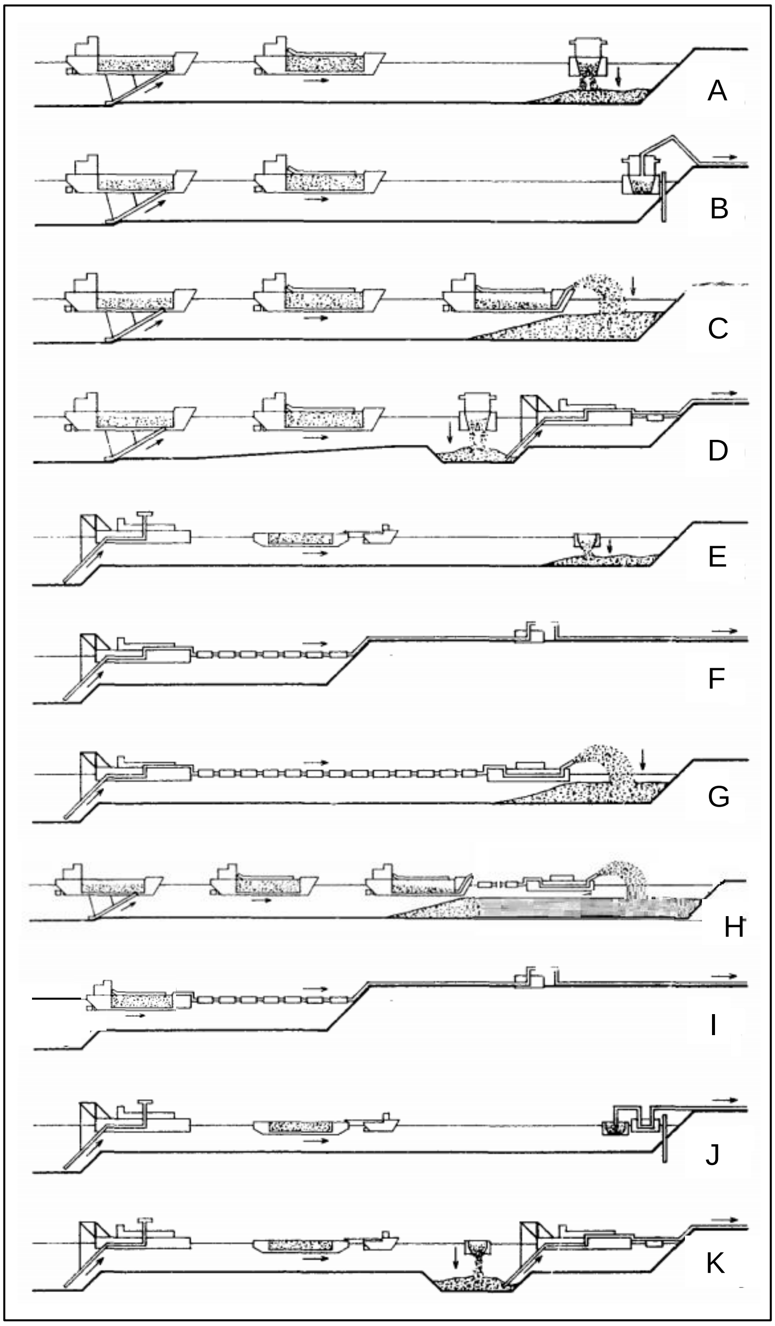


Figure 2-6: Dredging methods. (Source: *J.H. van Oorschot, 1990*)

2.1.3 Difficulties during depositing and processing the deposited material

When executing beach (re)nourishments and land projects an onshore discharge pipeline is installed and significant effort is required to keep the pipeline in operation. The land based equipment used for moving and leveling the replenished sand, is dependent of the water depth. In remote (off-shore) areas mobilization of site equipment to move the sand may be quite a challenge.

Limited water depths put a strain on the workability and accessibility of (floating) dredging equipment. Areas that are too shallow for floating equipment or inaccessible with land based equipment cause inefficiencies in the dredging cycle.

Figure 2-7 gives a nice representation of the limits of the applied equipment in dredging projects. Boats/floating equipment need a sufficient water depth to operate, and land based equipment need sufficient firm soil in order not to sink or get stuck.
The area between sufficient water depth and soil with sufficient bearing capacity values poses challenges as the equipment applied in this area is subjected to a small water depth and low bearing capacities. I.e. the interface between land and water poses challenges.

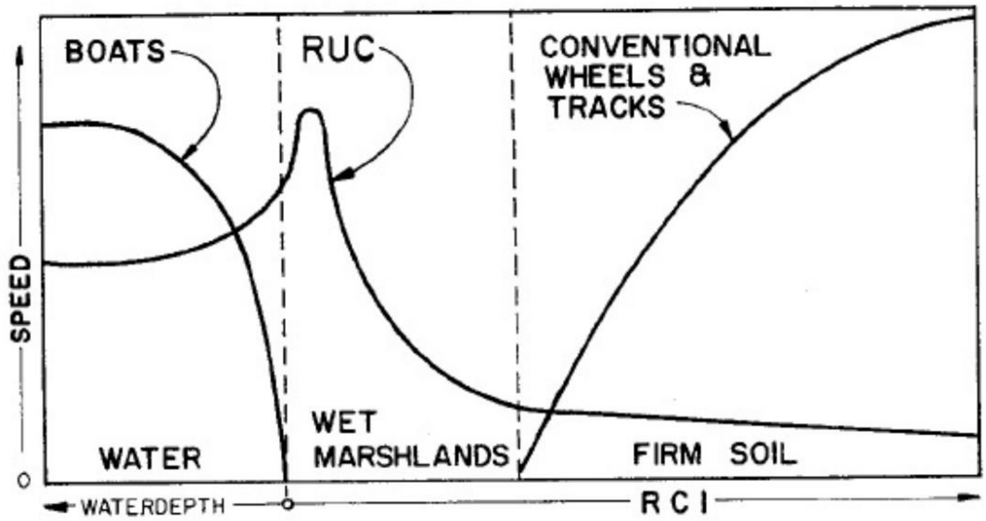


Figure 2-7: Speed of different equipment versus terrain firmness. RUC = Riverine Utility Craft (Source: *Freeberg, 2010*)

Often in coastal areas a (semi) diurnal tide is present. This will cause the location of areas of limited water depth to shift during the tidal cycle. In addition during high water the land based equipment may have to be demobilized to prevent flooding of the equipment and to guarantee safety of the operators. Production can only be resumed if the water levels have been dropped.
In order to increase workability in tidal areas the working method 'working with the tide' could be adapted. This method means that the floating equipment goes along with the tidal sequence. During high tide the floating equipment deposit the material on locations that are accessible during high tide and move along when the water level drops.
However, from a planning point of view this working method is quite complicated.
In addition surge levels due to wind cannot be predicted during the planning stage of a project, increasing the difficulty to plan the project.
It can be stated that the improvement in workability is marginal.

Another aspect when reclaiming land is the presence of soil that has low bearing capacity properties. Applying land based equipment requires sufficient bearing capacity of the subsoil in order to prevent sinkage of the equipment. Amphibious excavators with a low footprint are to existence but such excavators' processes the replenished sand much slower compared to traditional bulldozers.

The transition from water to land also challenges the installation of the pipeline. Especially when the water level is not constant due to tide and wind surges, there is a risk of the pipeline to getting afloat in an uncontrolled way at the transition from water to land. As a consequence there is risk that the pipeline will burst.

Final aspect is when applying an onshore pipeline system the distance between the deposited sand from the pipeline and the location where the sand is required according to the design might become quite large because adaptation of the onshore pipeline system requires a shutdown in the supply of sand. As a result the land based equipment have to push the sand over large a horizontal distance which is very energy consuming.

Summarizing
During depositing and processing the deposited material the interface between water and land poses the following problems:

- A limited water depth causes the floating equipment to run aground
- Land based equipment is only able to work in very small water depths
- Mobilization of the land based equipment is time consuming
- Also the land based equipment requires sufficient bearing capacities of the soil surface
- There is a risk of pipeline bursting on the interface from water to land
- Large horizontal pushing distance of the material by land based equipment because adaptation of the pipeline system is expensive.
- The water levels are hard to predict in the planning stage of a project.

Taking into consideration the mentioned aspects this raises the question whether there is a more efficient method to place the soil.

2.1.4 Type of projects

To give an idea of the type of projects whereby the related problems can be present as described in section 2.1.3 a couple of projects are briefly described below.

Beach nourishments
Beach nourishments or beach fill is the mechanical placement of sand on the beach to advance the shoreline or maintaining the volume of sand in the littoral system as represented by Figure 2-8. It is a soft protective and remedial measure that leaves the beach in a natural state and preserves its recreational value. This method is relatively cheap if the borrow area is not too far away (<10 km). Nourished beaches needs regular maintenance (replenishment) of sand, otherwise the nourished material will gradually disappear due to erosion.

Water level changes due to tidal influence on the water body and wind surges challenges operation activities.

Land reclamations
Land reclamation is the process of creating new land from ocean, riverbeds, or lakes beds, Objectives for land reclamation are for instance the construction of airports, expansion of ports and harbors, tourism and the creation of residential areas. Figure 2-9 holds an example of land reclamation project.

Reclaiming on soft subsoil is possible by spraying thin layers of sand.
This working method is very reliant on the water depth, especially when spraying the final layer. Together with an unfavorable direction of the wind this depth can further be reduced.
All auxiliary equipment had to be able to work at these same restricted water depths. Despite this shallow draft equipment, delays could be encountered because of grounded equipment or pipelines stuck on a sand shoal (*de Leeuw et al, 2002*).

Figure 2-8: Example of a beach nourishment.

Figure 2-9: Example of a land reclamation project.

<u>Salt marsh / intertidal flats restoration through direct placement of dredged material</u>

Partly because of human activities, barrier islands and marshlands are eroding in many places. These areas are seen as areas with high ecological values. A decrease in size is seen as unacceptable. Eroding marshlands lose their dissipating properties and eroding barrier islands can only withstand lower-classed storms.
Taking into consideration the relative sea level rise erosion rates may even increase.

For the time being counter acting measures, such as suppletion and/or protecting the flats, for tackling the decrease of the intertidal-flats are being investigated.
Marshland creation or re-creation offers a possible way to reduce the threat of storm surges. When restoring formerly interrupted marches by sediment nourishment to these areas, re-creation will be gradually and naturally, hardly influencing existing use and values (*Doody, 2008*).

Main challenge of salt marsh / intertidal flats is the limited water depth. The areas have limited access, and have high ecological values (*Doody, 2008*).
Figure 2-10 and Figure 2-11 are both showing areas with limited water depths during depositing of dredged material.
The layer thickness that has to be deposited is relative small. As a result the pipeline needs a lot repositioning, causing inefficiencies in the dredging cycle.

Figure 2-10: Example of intertidal flat restoration.

Figure 2-11: Example of depositing in shallow waters.

Erosion of mangrove-mud coasts

Muddy coastal areas all over the world are increasingly threatened by rapid shoreline degradation and erosion (*Winterwerp et al, 2014*). In just a few decades, some coastal areas have retreated by more than two kilometers. Housing, roads and valuable land is literally swept into the sea. This loss of land continues unabated, sometimes by tens of meters per year.

Erosion along with soil subsidence has also led to massive flooding during storm surge, high tides or periods of excessive rainfall. Meanwhile projected climate change aggravates vulnerability: sea-level rise and increased frequency of extreme events have introduced new challenges to which no adequate coping capacity exists. This increasingly threatens the well-being and self-reliance of millions of poor coastal communities. They are gradually losing the land and natural resource-base on which they depend.

There are several measures available to cope with the coastal erosion of mud coasts but it takes a considerable time-span before these measures to have a net effect.

If immediately action is required, large scale mud nourishment might prove to be an effective solution on the short run.

Muddy coasts have the following general characteristics (*Winterwerp et al, 2014*):

- Muddy coasts are relatively flat; the bottom gradient is 1:200 or flatter
- The energy levels/gradients are low to very low in the water column
- The subsoil has a low bearing capacity
- A (semi) diurnal tide is present.

In order to apply mud nourishments, a pipeline is applied. Because of the characteristics of muddy coasts, applying a pipeline yields difficulties due to the large horizontal distances, periods of low water, and the low bearing capacity of the subsoil causing the site equipment to have difficulties to process the outflow.

2.1.5 Opportunities

This section states the opportunities that could be considered in the development of the ideal method for replenishing sand in limited water depths.

If the hopper size continues to grow, as displaced by in the trend in Figure 2-12 , there are two aspects that may cause problems:

- *Processing the output flow from the trailer suction hopper dredger*
  Jan de Nul mentioned in (*ARCADIS U.S., Inc, 2011*) that because of the recent tendency of increased TSHD sizes, very large volumes of sediment can be dredged at very high rates but that the handling of the sediment at the disposal area has become the restrictive factor.
  This is especially the case when the dredged material consists of sand, which has to be profiled by site equipment. This equipment (e.g. bull dozers) is normally not able to handle quantities of 10,000 m^3/hr unless arrangements are made such as multiple pipe bifurcations. This creates more than one disposal site, and enables deployment of more profiling land-equipment.

- *Draught of the trailer suction hopper dredger*
  A bigger hopper size corresponds to a greater payload. In return the draught of the TSHD also is increased. This aspect is nicely represented in Figure 2-13 by the payload – draught relationship.
  When the draught increases, the usability of the ship decreases. The ship is less capable of reaching the deposition spot in limited water depths. As a result an

increased amount of pipeline length is needed in order to compensate for the larger horizontal distance.

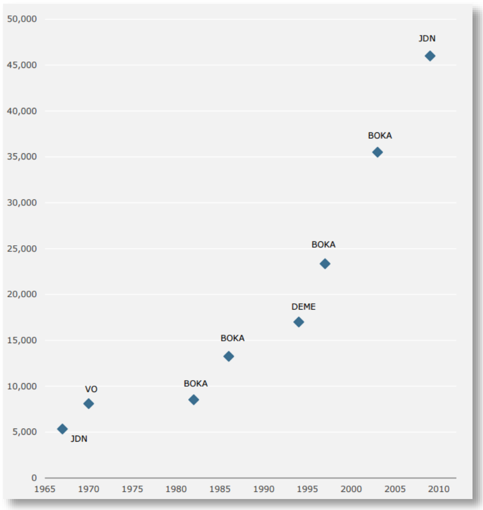


Figure 2-12: Development of largest hopper m^3 per dredging compagny. (Source: *R. Brakenhoff, 2013*)

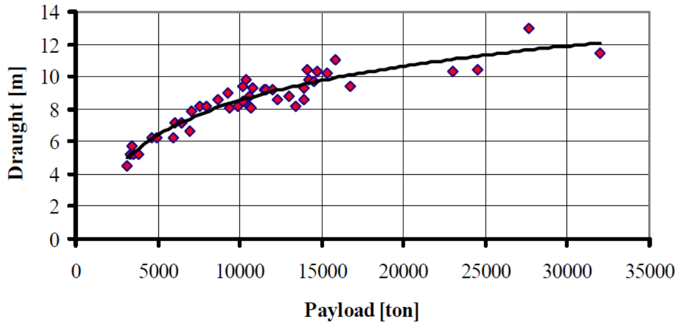


Figure 2-13: Payload - draught relation. (*Source: Vlasblom, 2013*)

Together both aspects compromise the workability during replenishments. This asks for a different approach in order to process the outflow of large TSHD's if the hopper size continues to grow.

When the new method is able to handle outflow quantities more than 10,000 m^3/hr the outflow of the biggest TSHD's can still be processed.

2.1.6 Other methods for accretion of material

There are other methods available in order to counteract coastal erosion rather than sand nourishments (called soft measures).
One approach is to prevent (coastal) erosion in the first place. By applying so called hard measures like breakwaters, groins or revetments. Those structures lower the shear stresses on the individual sand grains, preventing erosion.

A different approach is to let nature do the (majority of the) work. I.e. so called Building with Nature approach. The Sand Engine[1] is a fine example of this approach. A giant suppletion was placed in one spot and the thought is that nature will distribute the sand in such a way that the sand is placed by nature where required, decreasing erosion rates.
This approach can be applied to limit the amount of sand replenishments on the beach.

This study assumes that it is already decided on that sand (re)nourishments are the most promising measure to counteract coastal erosion. Thorough studies were already performed taking all the aspects into consideration regarding to solve or counteract the problem.
Also for land reclamation projects this study assumes that reclaiming land is the best option to solve the underlying problem.

[1] The Sand Engine is a full scale experiment adopted at the Dutch Coastline. A giant sand suppletion was placed in the nearshore and it is expected that this sand is then moved over the years by the action of waves, wind and currents along the coast. Regularly performed sand replenishments are no longer needed for the years to come.

2.2 Analysis ideal method

In this paragraph an analysis of replenishing sand will be performed. Goal is to identify which functions the ideal method has to fulfill in order to deposit sand both in water as on land.

Before analyzing the new method, the definition of 'method' is given as used in this study:

> *A method for replenishing sand in intertidal areas is more than equipment only. It is an approach/system that works according to a method that includes equipment.*

2.2.1 Desired ideal method for replenishments in intertidal areas

In the previous sections it was elaborated that a significantly amount of downtime can be noticed due to a limited amount of water depth.
To decrease the amount of downtime the ideal method for executing material replenishment projects should be independent of water levels and tide.

The following advantages could be obtained by the ideal method:

- 24-hour cycle production (continuous process)
- Improvement of workability
- Decrease of mobilization costs/movements
- Application of thin layers of sand
- Benefits to be obtained from an ecological point of view
- Less dozing / less movement required of the deposited material from the pipeline in order to construct the design.

2.2.2 Schematization ideal method

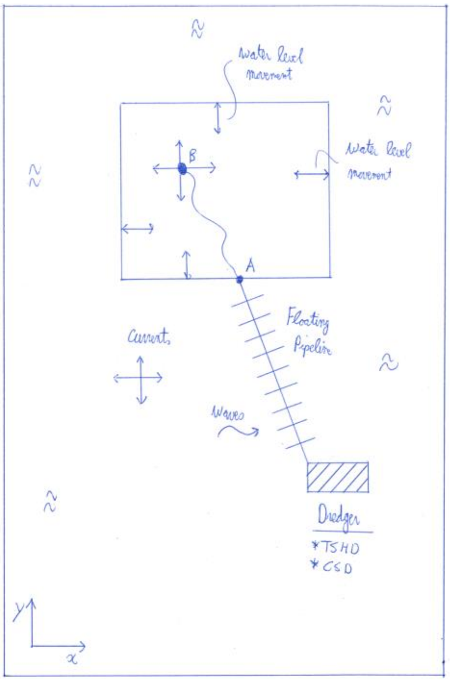


Figure 2-14: Replenishing sand in an intertidal area.

In Figure 2-14 the replenishment of sand in an intertidal area is represented. An intertidal area is an area that is above water at low tide and under water at high tide. I.e. the area between the tide marks. The area can have a narrow tidal range resulting in a narrow strip or can include many meters of shoreline in case of a wide tidal range.

The tidal range varies from one location to the other, and together with the bottom gradient this determines how wide the intertidal area is.

Sand is dredged by TSHD's, CSD's, or by other means like The Punaise[2] and pumped ashore by a (floating) pipeline. In this study it is assumed that sand is available in point A as a sand-water mixture. The method of delivering sand to point A is outside the scope of this study.
Point A in the figure is fixed in this study. Also point A is such that no forces are present in or at A. I.e. point A will not deliver or absorb forces to/from the system; the forces at point A are zero.

Point B is the end of the pipeline and must be able to replenish sand. This point is not fixed however, like point A, but has to be able to move.
To increase workability, point B should be displaceable both in x and y direction. In this way sand could be deposited on every spot of the deposition area. This means that the distance between point A and point B is not constant.
As a result the land based equipment used for distributing the deposited material and profiling into the desired profile could be omitted.

The deposition area is subjected to water level changes due to tide or wind surges. I.e. the location at point B might be flooded for some period, and no water may be present when the water level drops.
Beside hydrodynamic aspects can present at the deposit area.

2.2.3 Function overview ideal method

Summarizing, the ideal method has to fulfill the following functions:

- Depositing sand
- Hold position for point B
- Ability to operate continuously
- Ability to move point B in x and y direction
- Deliver sand from point A to point B

Those functions have to be fulfilled both in water and on land. Figure 2-15 gives an overview of the functions that the method has to fulfill.

[2] The Punaise is a rather unique machine since it is designed to stay underwater on a single location, from where it pumps the sand towards the beach. The Punaise is placed on the sea bottom and fluidizes sand with water jets. This results in a breaching process during which sand is pumped up with the central suction mouth. The device moves downward in the created pit and is positioned using ballast water and anchor lines. It's possible to move the device when the pit is considered deep enough, but it is also possible to dump new sand in the pit and hence on top of the Punaise.
The device is controlled from an operation station on land.

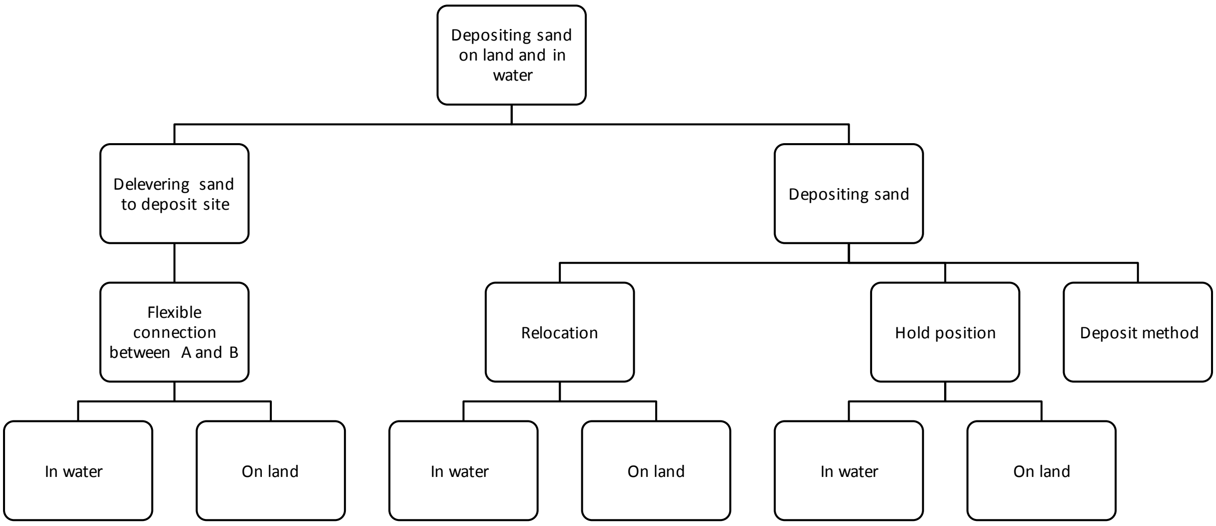
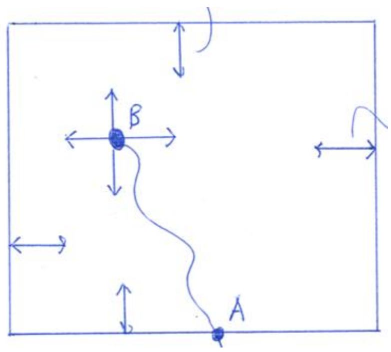


Figure 2-15: Function overview for depositing sand in intertidal areas.

2.3 Problem identification ideal method

There are two main challenges regarding the ideal method for replenishing sand in shallow waters:

1. How can point B made such that it can deposit sand both in water as on land while being independent of water levels and tide and having the ability to move in x and y direction?
2. How to deliver sand to point B?
   Sand is available at point A and has to be transported to point B.



It's important to recognize that the method for depositing sand in point B and the method for delivering the sand from A to point have a strong relationship with each other. Choices made related in how to deliver sand to point B have consequences for point B itself, and vice versa.

To accent the interaction between point B and the method of delivering sand from A to point B four scenarios will be presented. In these scenarios point B will be relocated, and point B have to hold position, both in water and on land. In this way the consequences for delivering sand to B will become clear. Point is chosen for review B instead of section A to B because the purpose of replenishments is to deposit material. Point B utilizes this goal, and therefore has a central role in this study.

2.3.1 Scenario 1 – Relocation point B in water

When a certain water depth is present at the location of point B, and point B needs repositioning than it's assumed that there is also water present along section A-B. I.e. from point A to and including point B water with a certain depth is present.

<u>Point B</u>
To cope with any water depth point B should have floating capacities. It's assumed that point B itself is not allowed to flood. When point B is high enough and the water depth is not able of reaching large numbers, flooding won't occur. But the water depth is hard to predict and differs per deposit location.

Relocation of point B could be done relatively easily if point B has floating capacities.

Section A-B
When section A-B shows a rigid behavior this has consequences when point B has to relocate. When point B is moved in any x or y direction the whole section from A to B also has to be moved due to the rigid behavior.

In water section A-B is subjected to the Archimedes' Principle; there is net upward force acting on section A-B. For the time being it's assumed that section A-B also have floating capacity. Because of this floating capacity it is assumed that relocation of section A-B is quite easy.
Floating equipment is able to reach section A-B, and by pulling or pushing section A-B could be moved. As a result section A-B could be, despite the rigid set-up, relocated relative quite easily.

2.3.2 Scenario 2 – Relocation point B in absence of water

When there is no water present at the location of point B, it's not automatically assumed that the whole section A-B also is situated on land. A part of section A-B could also be located in water. This could happen if point B has deposited material, and as result the deposit will emerge from the water.

In absence of water the Archimedes' Principle will also be absent. When displacing point B and section A-B the friction aspect becomes more and more important. Friction depends amongst others on the soil conditions.
Together with the rigid behavior of section A-B it can be stated that a huge effort is required to displace point B and section A-B.
Especially the rigid behavior of section A-B significantly contributes to the total effort during displacement.

Floating equipment is not able to reach the deposit spot, so the main question is how to displace point B and section A-B.

2.3.3 Scenario 3 – Hold position point B in absence of water

When point B is located on land and section A-B is also located on land it can be stated that the required force to initiate movement of the total system is such that the whole system can hold position without additional measures. The amplitude of the friction force generated by interaction between the system and the subsurface is sufficient.

2.3.4 Scenario 4 – Hold position point B in water

In water hydrodynamic aspects could be present. These aspects could initiate movement of point B, or section A-B, or the whole system all together.
Movement could be initiated when:

- Floating capacity is present and there isn't a holding force of any kind
- The holding force is not sufficient in relation to the hydrodynamic forces.

2.3.5 Summary

After running through the scenarios it can be concluded that the main challenge is to displace section A-B when there is no water at the deposit site. Problem is that when section A-B has a rigid behavior the whole section has to be displaced when displacement is needed. Concepts have to be generated to allow for a more flexible set-up of section A-B.

Subsequent is the question on how to enable displacement of point B and section A-B. Concepts have to be generated enabling movement of both items.

To come up with the most promising ideal method for replenishing sand in shallow waters, distinction will be made between depositing the material at point B, and delivering the material from point A to point B.

In the two following sections problem identifications will be given both for point B 'depositing material' as for section A-B 'delivering material'. Goal is to identify which functions have to be fulfilled by the sub functions.

2.4 Approach for depositing material

2.4.1 Functions

Main function of point B is to deposit material, and in order to do so, point B has to be able to:

- Relocate in x and y direction in water as on land
- Hold position in water as on land
- Depositing the material and constructing the desired profile both in water as on land
- Section A-B has to be displaced by point B as well.

2.4.2 Approach

In this study two approaches will be followed in order to come up with methods for replenishing material at point B:

- Point B will be made mobile creating a piece of equipment that is able to displace itself. In this way the desired profile could be constructed by point B itself. I.e. point B will be made 'active'.
- Or the site equipment used for processing the outflow will be adjusted to work in intertidal areas. The adjusted site equipment will distribute and level the deposited material.

  When required the adjusted site equipment will reposition point B. As a result point B needs less repositioning compared to the 'active' set-up.

Questions that need answering are:

- What is the most promising method to deposit material?

  By making point B 'active' of by adjusting the site equipment as described above.
- How to make point B 'active'?
- How to adjust the site equipment so the equipment is able to work in areas with ranging water depths?

To displace section A-B a pull or push force have to be generated by some sort of means. It depends on the approach but point B must enable this pull or push force. Additional displacing power could also be generated by section A-B itself.
However, section A-B has to be displaced as well in both approaches. In the next section the problem identification will be performed to get insight in what is involved when section A-B is displaced.

For both approaches concepts have to be developed. This will be done in Chapter 3.

2.5 Approach for delivering material

2.5.1 Functions

Main function of section A-B is to deliver material from point A to and including point B. A lot of functions of point B are also applicable for section A-B. Section A-B has to fulfill the following functions:

- Deliver material from point A to an including point B
- Relocate in x and y direction in water as on land
- Hold position in water as on land

2.5.2 Approach

During repositioning of point B, section A-B has to be able to follow point B. It's assumed that section A-B will consist of multiple segments.
This has consequences for the available flexibility of section A-B. When multiple segments are coupled to each other in a rigid set-up the result will be that when point B moves, the entire section A-B also have to be displaced. A rigid set-up is very likely due to properties of available material at point A.
The hypothesis is that displacement of the entire section A-B when on land (when the total system is on land the friction aspect will be significant) will take too much effort.

As stated in section 2.1.3 'Difficulties during depositing and processing the deposited material' adaptation of the pipeline system is very time consuming and takes a lot of effort.
Goal of this study is to develop a method that enhances the workability of replenishment projects. One requirement of the new method is the ability to operate continuously, as stated in Chapter 1 'Introduction'. Workability is increased when the amount of adaptation to section A-B is reduced to a minimum. By assuming a fixed length for section A-B, and adaptation of this length just before displacement is not allowed, will result that no time will be lost by adapting section A-B.

To decrease the required amount of effort to displace section A-B when on land two perspectives will be applied in this study:

1. *Decrease of the friction coefficient*
   To decrease the friction coefficient, concepts will be generated enabling a decrease in the total friction force during displacement of section A-B.
2. *Incorporating flexibility in the pipeline system*
   By creating a more flexible set-up between the segments of section A-B, will result in a smaller length of section A-B that has to be displaced. In this way the required effort is decreased.

Questions that need answering are:

- What is the most promising method for delivering material from point A to and including point B?
  The method must fulfill the functions as stated in section 2.5.1.
- How much effort is required for displacement of section A-B?
- How to decrease the friction coefficient?
- How to create flexibility in section A-B?
- How much flexibility is required in section A-B?

In Chapter 5 the most promising method for delivering material from point A to point B will be determined. Concepts will be generated that will decrease the friction force. Also the question 'How to create flexibility in section A-B' will be answered.

2.6 Summary problem description

This chapter started with the problem identification for replenishments in shallow waters. Next the analysis of the ideal method was described. Subsequent the problem identification of the ideal method was presented.

Table 2-1 gives an overview of the aspects the ideal method has to be able to cope with.

Table 2-1: Overview aspects pipeline system

Aspect	On land	In water	Action
Displacement point B	Difficult	Easy	Decrease total friction force when on land
Displacement section A-B	Difficult	Easy	Decrease total friction force when on land
Hold position point B	Easy	Difficult	Produce holding force when in water
Hold position section A-B	Easy	Difficult	Produce holding force when in water
Different water depth	Not applicable	Applicable	Generate floating capacity versus generating holding force
Multiple segments section A-B	Difficult	Easy	1. Decrease total friction force 2. Or create flexibility in section A-B

Point B is all about depositing material so point B has to be able to displace itself. The relationship between point B and section A-B is such that point B is able to generate a displacement force for section A-B.
Point B has to be able to cope with a certain water depth so floating capacity or properties have to be fitted. It should be noted that the maximum water depth is such that once the traditional floating equipment is able to reach the deposit area; this equipment will be put into action.

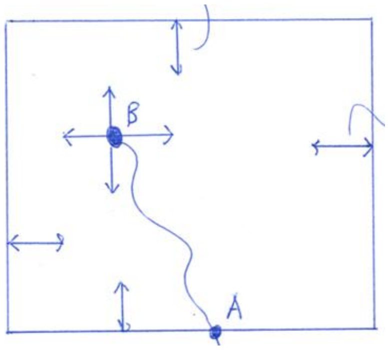
Approach to develop the ideal method will be as follows:

1. Generate methods for depositing material at point B
2. Determine the most promising method for depositing material at point B
3. Generate methods for delivering material from point A to and including point B
4. Determine the most promising method for delivering material from point A to point B
5. Generate concepts for decreasing the friction coefficient
6. Investigate how much effort is required to displace the concepts
7. Investigate how to create flexibility in section A-B
8. Determine the most promising concept for delivering material
9. The most promising method for depositing material and the most promising concept for delivering material will be integrated.

In the following chapters this approach will be elaborated. In the chapter lay-out distinction will be made between depositing material (point B) and delivering material from point A to and including point B (section A-B). A separate chapter will elaborate on how to integrate the two separate most promising solutions into a most promising solution as a total concept.

Chapter 3

Depositing material



Aim of this chapter is to generate and to find a suitable concept that increases workability of material replenishments projects executed in intertidal areas.

Definition of 'amphibious' as used in this study is:

Amphibious is the ability to move both in water as on land and is capable to overcome the interface between water and land. The bearing capacity of the subsoil might be such that it is not sufficient resulting in sinkage of the equipment. A technique is called amphibious if it enables the method to cope with the mentioned aspects. The vertical distance between the surface area and the device is limited.

3.1 Categorization

This paragraph is all about categorizing how to make point B active by enabling depositing material, and how to adjust the site equipment such that it's able to process the material in intertidal areas.

3.1.1 Point B actively depositing material

Point B has to be able to construct the desired profile of the deposit area by itself.
To make 'point B' active and therefore independent of water levels and tide two options are given:

- Amphibious spray pontoon
- Helicopter

<u>Amphibious spray pontoon</u>
A spray pontoon could be applied if the draft of a TSHD is too large and the rainbow installation on the TSHD is not capable of reaching the disposal site. A spray pontoon has a much smaller draft than a TSHD, able to replenish sand in shallow waters. In general, the draft of a spray pontoon is about one meter (*de Leeuw et al, 2002*). Figure 3-1 represents a spray pontoon in shallow waters.
Also spray pontoons are able to deposit sand in particular layers at once, without the installation of an onshore pipeline system. Spray pontoons even allow reclaiming on soft subsoil by spraying thin layers of sand. Though spray pontoons require sufficient water depth and is, like land based equipment, more or less dependent from tides.

Figure 3-1: Application of a spray pontoon. (Source: *de Leeuw et al, 2002*)

The spray pontoon as represented in Figure 3-1 is repositioned by an anchor winch system. The spud poles enable a holding force to hold position.

By adapting the spray pontoon such that it can move on land in absence of water an amphibious spray pontoon is created. This amphibious spray pontoon is able to deposit material both on land as on water.

Main question is how to displace the amphibious spray pontoon when on land.

Helicopter
A helicopter is a type of rotorcraft in which lift and thrust are supplied by rotors. This allows the helicopter to take off and land vertically, to hover, and to fly forward, backward, and laterally. As a result the helicopter has no relation with the available water depth.
If a helicopter is applied to position point B by lifting the outflow of material of section A-B, material can be deposited independent of water levels because the helicopter is flying above the water surface. In addition the helicopter has to be able to lift /drag (a part) of section A-B along.

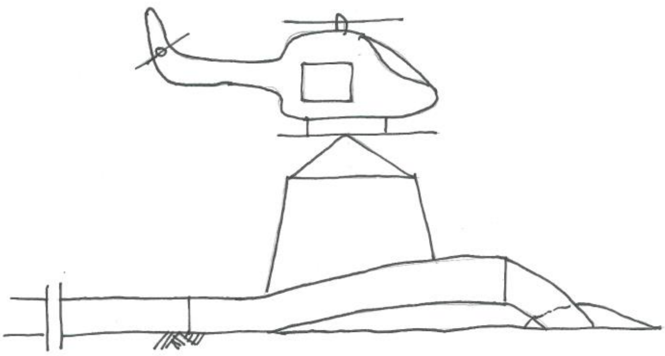


Figure 3-2: Applying a helicopter to control the outflow of material.

3.1.2 Adaptation of the site equipment

If the land based equipment, used for processing the outflow of sand, could be adapted in such a way that it could cope with certain water depths, demobilization of the site equipment during (periods of) high water could be reduced and therefore increasing the workability of the dredging project. Production could continue during periods of significant water depths.
Idea is that the adapted land based equipment distributes the deposited sand over a specified area Point B is repositioned only if the distance over which the land based

equipment distributes the sand becomes too large. The adapted site equipment has to be able to reposition point B.

This study will approach adaptation of the site equipment as follows:

- Ability to fully afloat
- Situated in water
- Elevated above water level but still in contact with soil surface

Below variants of the method adaptation of the site equipment are represented.

Fully afloat
An amphibious excavator is a type of excavator that can perform dredging while afloat in shallow water.
The amphibious excavator can work in water, because the chassis crawler floats on sealed pontoons. It moves using a dual-body boat form buoyancy tank. A reducer drives the crawler chain, allowing free and smooth movement. Its upper structure is a modified excavator that allows 360° full rotation and hydraulic operation.

The pontoons are manufactured from high tension steel and they are atmospheric corrosion- and saltwater-resistant. Each pontoon has five independent water tight compartments with maintenance panel. The bottoms of the pontoons are reinforced for rough terrain operation. The power for the pontoon tracks is provided by an excavator engine and main hydraulic pumps with traveling motors.

The amphibious excavator can perform in water depths up to 1.5 meter. Additional pontoons with spud poles can be fitted to the pontoons. The additional pontoons provide extra buoyancy and stability. This enables the excavator to work in water depths up to four meter. The excavator is then fully afloat.

Figure 3-3: Amphibious excavator.
(Source: *bardaigroup.com*)

Situated in water
Komatsu was the first in the world to commercialize an amphibious bulldozer, the D155W, capable of underwater operations at a maximum depth of seven meter and onshore operations via remote control. The bulldozer's engine is encased in a watertight compartment while the machine is equipped with a high stack for air intake and exhaust. Originally developed and manufactured in 1971, the bulldozer was sold worldwide, including in Japan, the Soviet Union (currently Russia), Czechoslovakia (currently the Czech Republic and Slovakia) and Italy. A total of 36 machines were produced, of which 14 machines were sold overseas.

Figure 3-4: Amphibious bulldozer.
(Source: *komatsu.com*)

<u>Elevated above water level but still in contact with soil surface</u>
Hitachi has developed an excavator that is capable of working under water. The excavator is capable of working in water depths up to five meter and can cope with tidal action.
The upper carriage has been disconnected from the under carriage and connected to each other with a scissor shaped structure.
From a stability point of view all the heavy components were placed on the under carriage. Two hydraulic cylinders were fitted in order to lift the upper carriage containing the engine and the cabin.
Special GPS-software enables that the boom and the fitted adapter are visible. In case of engine failure the back-up engine makes sure that the operator can drive the excavator towards shallow water.

Figure 3-5: Excavator with elevated platform.
(Source: *bouwmachines.nl*)

3.2 Generation of concepts for depositing material

3.2.1 Fulfilment sub functions

To make point B actively depositing or by adapting the site equipment, both approaches have general functions to fulfill. These general functions are:

- Relocate in x and y direction in water as on land
- Hold position in water as on land
- Depositing the material and constructing the desired profile both in water as on land
- Section A-B has to be displaced by point B as well.

Below per function solutions are given to fulfill the function. All these separate solutions will be placed in a morphological overview in order to produce concepts.

Relocation – on land

- Tracks
- Wheels
- Screws
- Anchor/winch system together with hover craft technology
- Spud pole system à la CSD

Relocation – in water

- Screws
- Propellor
- Spud pole
- Anchor winch system + lifting (by hovercraft technology)

Depositing

The location of outflow of material doesn't matter because the material will flow anyway. That's why this aspect is not that important. It relates to the in-situ production → the amount of repositioning has to be known.

- Rainbowing
- Diffusor
- Straight pipeline

Hold position in water

- Contact soil body
    - Friction as is
    - Anchor
    - Spud pole
- Floating by
    - DP system

Displacement section A-B

- Pull force
- Lifting section A-B

Hold position – on land

- Friction based → no action required

3.2.2 Morphological overview

A morphological overview states all the possible methods for each sub function.
The combination of all the sub functions and the corresponding method to execute the sub functions together, will result in concepts to perform the main function; enabling point B to deposit material in intertidal areas.

In Figure 3-6 an overview is presented of the solutions/techniques per function. Not all combinations produce realistic methods. The realistic methods will be extracted from the morphologic overview.
Per concept a short description on how it will work will be provided after the morphological overview.

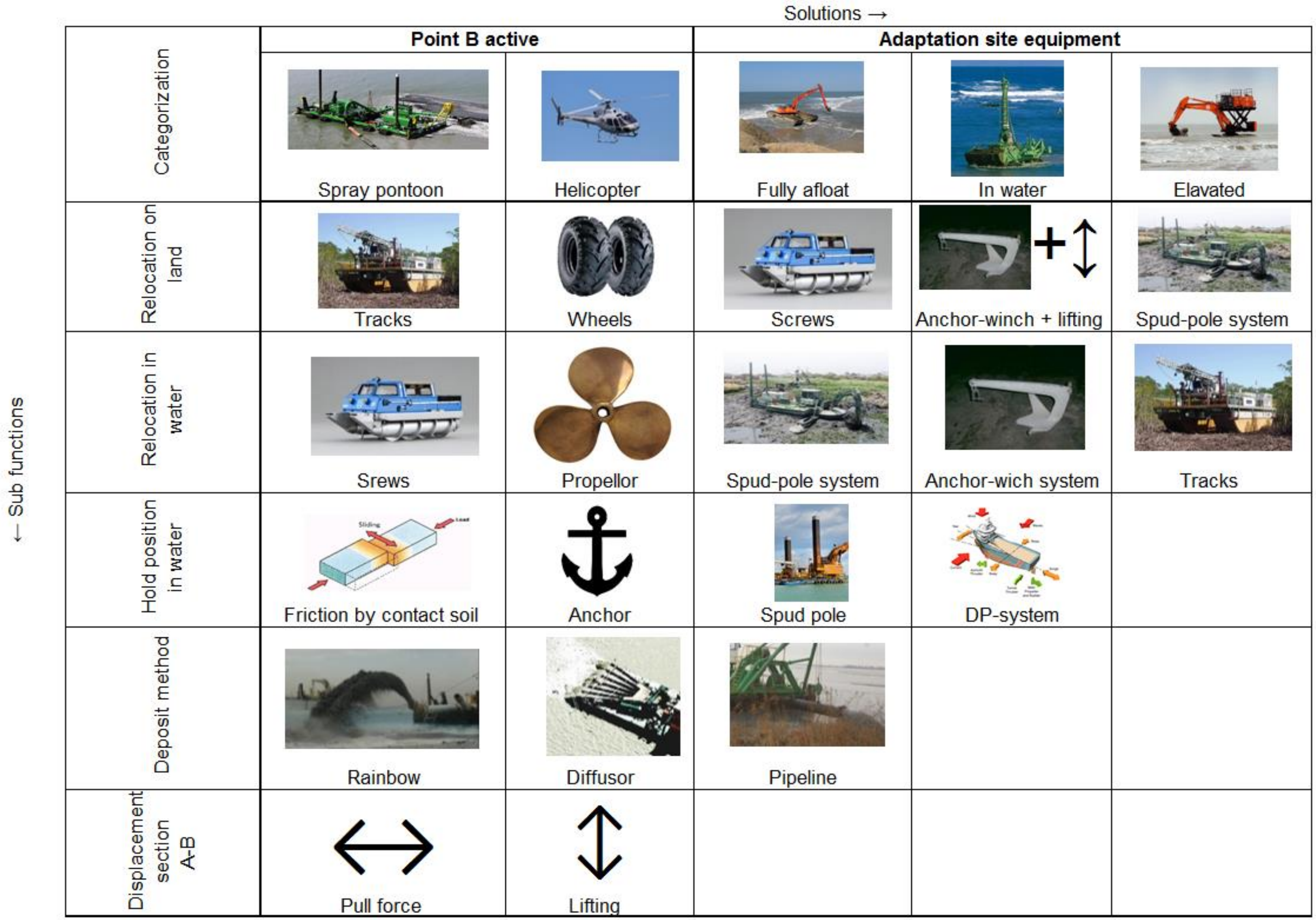


Figure 3-6: Morphological overview.

3.2.3 Elaboration per concept

Table 3-1: Overview of concepts regarding depositing material.

#	Categorization	Relocation on land	Relocation in water	Hold position in water	Deposit method	Displacement section A-B
1	Spray pontoon	Anchor winch + lifting	Anchor - winch	Anchor	Diffusor	Pull force
2	Spray pontoon	Tracks	Anchor + winch	Anchor	Diffusor	Pull force
3	Spray pontoon	Screws	Screws	DP-system	Diffusor	Pull force
4	Spray pontoon	Spud pole system	Spud pole system	Spud pole	Diffusor	Pull force
5	Spray pontoon	n.a.	Anchor - winch system	Anchor	Rainbow	n.a.
6	Helicopter	Lifting + propeller	Lifting + propeller	DP-system	Pipeline	Pull force
7	Fully afloat	Tracks	Spud pole system	Spud pole	Pipeline	Pull force
8	In water	Tracks	Tracks	Friction by contact soil	Pipeline	Pull force
9	Elevated	Tracks	Tracks	Friction by contact soil	Pipeline	Pull force

1. Spray pontoon with hovercraft technology

By applying hovercraft technology on the spray pontoon the amount of friction is reduced significantly when the spray pontoon is displaced on land.
During hovering only a small pull force could be generated as the support force required to generate a pull force is limited because the pontoon is, as to speak, floating.
By applying an anchor-winch system the pontoon can be displaced when in water and on land. This anchor also provides a force to displace section A-B. Also the anchor can be used to hold position in water as the pontoon is afloat.

Figure 3-7: A hoverbarge spray pontoon. (Source*: Koen, 2015)*

<u>2. Spray pontoon with tracks</u>

The spray pontoon is equipped with a track propulsion system. This enables the pontoon to move when on land. This track system will also be used to displace section A-B. When in water the spray pontoon will be afloat. The tracks won't be in contact with the soil surface; no traction can be generated. The anchor-winch system will be used when afloat to provide a holding force and for displacement of the spray pontoon and section A-B.

Figure 3-8: A spray pontoon equipped with tracks. (Source: *Koen, 2015)*

<u>3. Spray pontoon with screws</u>

The Archimedes screws will provide floating capacity and tractive effort on land and in water for the spray pontoon. In water the tractive effort is less than on land. By applying a dynamic position system (by turning the screws) the pontoon can hold position.

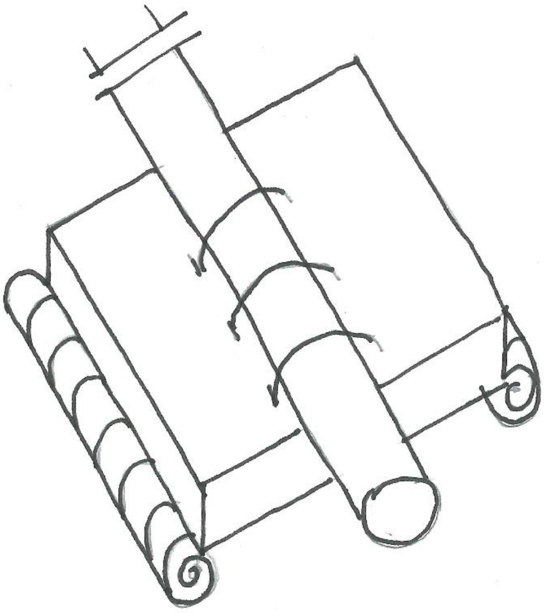


Figure 3-9: A spray pontoon equipped with Archimedes screws.

4. Spray pontoon watermaster concept
A cutter suction dredger is pushed forward by a spud-pole system. This system could also be fitted on a spray pontoon. When on land the required push force could be too large. By lifting the pontoon a little by hydraulic arms and applying action from the spud pole system the pontoon is moved forward with a smaller resistance force. This system creates also a holding force when in water. Section A-B could also be displaced using this system.

Figure 3-10: Spray pontoon equipped with spuds as propulsion.
(Source: *dredgingtoday.com*)

5. Spray pontoon with adjustable rainbow / more powerful installation
The previous concepts all assume that depositing the material close the spray pontoon or pipeline exit. If the material could be placed a significant distance from the pipeline exit the material could be placed over a large area. Idea is to control the outflow of material such that the exit angle and horizontal spraying distance.

By applying a spray pontoon with a booster system and a rainbow installation the material could be deposited.
The spray pontoon is allowed to run aground (if a tide is present) and an anchor winch system will provide the holding force in water and to move the pontoon when in water.
The rainbow installation will acts like lawn sprinkler. The exit angle of (let's say) 120 degrees in the x-y plane and the ability to control the horizontal spray distance a large area could be deposited.

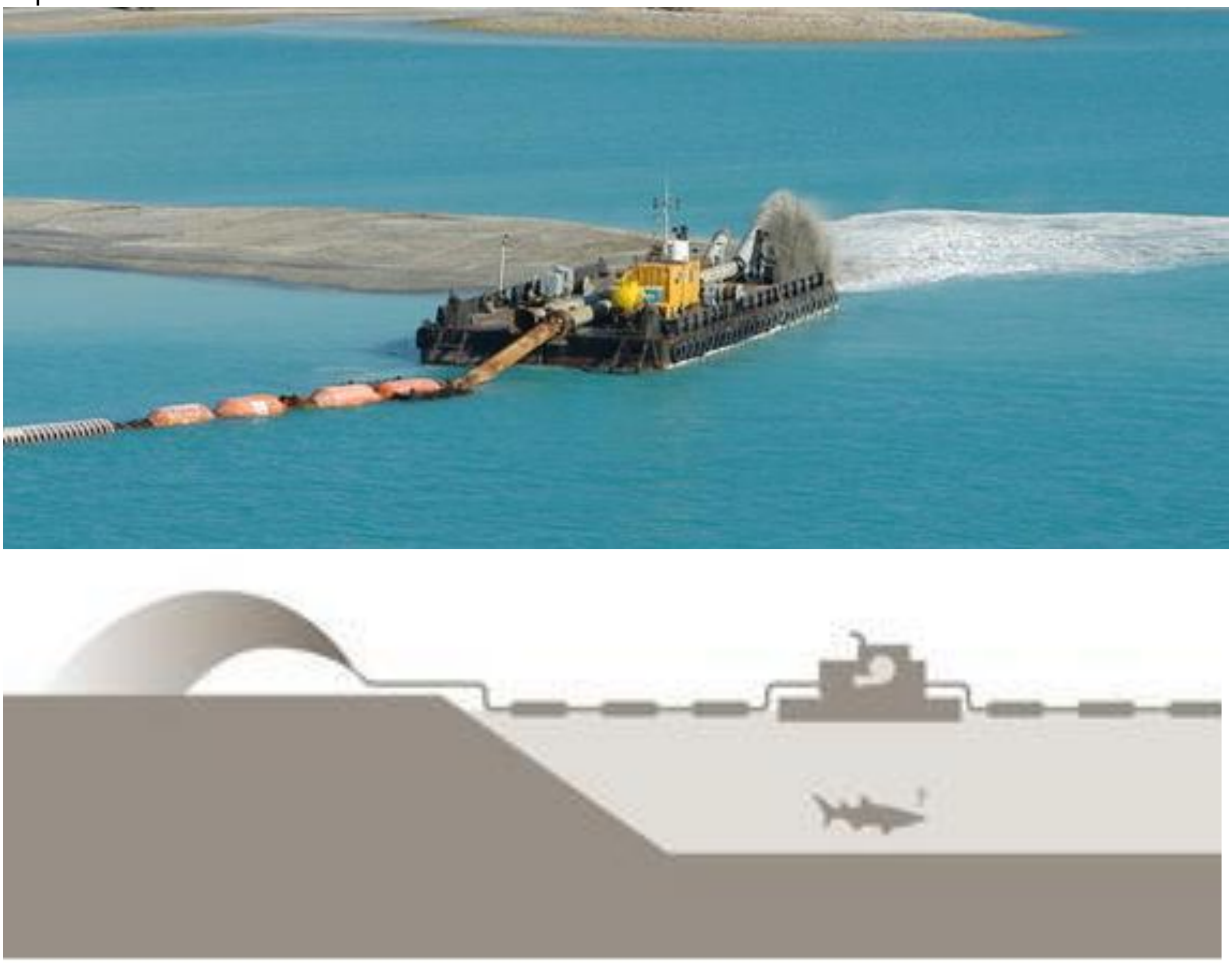


Figure 3-11: The adjustable rainbow concept. (Source: *Jan de Nul & Royal IHC*)

<u>6. Helicopter</u>
The helicopter will be used to lift the pipeline outflow. By position the helicopter, and therefore the pipeline exit, above the desired deposit spot the desired profile could be constructed. The helicopter is not dependent on water levels and tide.
The helicopter must have a large lifting capacity to lift (a part of) section A-B.
Reference is made to Figure 3.2.

<u>Adapted site equipment</u>

- Amphibious bulldozer
- Amphibious excavator
- Equipment elevated platform

These three concepts are already described in section 3.1.2. All three concepts utilizes a track system to propel themselves on land.
The equipment will process the outflow by distributing and leveling the material. When needed the adapted site equipment will displace section A-B.

3.3 Selection most promising concept

3.3.1 Boundary conditions for the ideal method

From the problem description and the schematization presented in Chapter two the following set of criteria emerges:

1. Continuous sand replenishment
   Key element of the method is its ability to replenish sand continuously independent of water levels and tide.
2. Reliability
   The method has to be reliable to minimize the risks on delays.
3. Safety
   Since equipment and people are present at / in the dredging project, safety needs to be taken into account.
4. CAPEX and OPEX
   To be economically feasible, the method may not be too expensive.
5. May work in remote areas
   Mobilization of equipment must be reduced to a minimum.
6. Flexibility
   The method should be able to deposit sand both in water as well as on land.
7. Dosage
   The method must be able to dose the sand in a controlled way. Different deposit methods might be required depending on the design.
8. Different sub surfaces
   When replenishing sand, different sub surfaces might be present and as a result the bearing capacity of the sub surface may vary. The method must be able to cope with this aspect. Different surfaces are, for example sand, mud, peat, silt and such.
9. Forces
   The method must be able to guide and offset the forces. As an example: if a pipeline is applied, the method must be able to cope with the forces resulting from the pipeline.
10. Environment
    Environmental aspects may not be neglected. The method will be operational in an ecosystem. The impact on the environment must be reduced to minimum. E.g. pollution of air, noise levels, a decrease of ecological values, and spillage of lubricants.
11. Availability of power supply
    Availability of a power supply must be guaranteed in order to realize a continuous operation. Especially in remote areas supply of power may form a challenge. Also consumption of energy must be reduced to a minimum. This from an environmental point of view and in remote areas the amount of energy consumption must be reduced to minimum from a mobilization point of view.
12. Crew
    If the method has to be operated by personnel, this has to be possible. The method must allow for safe operations and accommodation space for the crew.
13. Flowrate
    A minimum flow of sand is required in order to guarantee a minimum production rate. Since in dredging projects the aim is to maximize production a minimum flowrate is required.

3.3.2 Weight factors for the Multi Criteria Analysis

The boundary conditions listed in section 3.4.2 will be used as input arguments for the MCA. Some arguments are more important than other arguments. To distinguish the importance between the input arguments, weight factors will be used. Each criterion will be assigned with a weight factor.
There are different ways to assign weight factors. One way is to list the outcome of the calculation to a value of importance. The criterion with the lowest outcome will be assigned with weight factor 1 and the criterion following the lowest outcome will get a weight factor of the outcome +1. The most important criterion will have a weight factor of 13 in this study. This method is called weight factor 'batch 1'.

Another approach is to cluster the outcome of the calculation into groups. In this study the outcome will be divided into three groups.

Table 3-2: Range per clustered weight factor.

Range outcome calculation	0-3	4-8	9-12
Weight factor	1	2	3

It must be kept in mind that the weight factor 2 will have relatively more influence on the outcome of the MCA due to the uneven distribution range of the calculation outcome. This method is called weight factors 'batch 2'.

Both weight factors methods will be used in the MCA to determine the influence of both methods on the MCA outcome.
In Table 3-3 the weight factors for both methods are represented.

Reference is made to Appendix A where the determination of the weight factors is elaborated in more detail.

Table 3-3: Weight factors per criteria.

Criteria	Outcome calculation	Weight factor batch 1	Weight factor batch 2
[-]	[-]	[-]	[-]
1. Continuous production	10	11	3
2. Reliability	11	12	3
3. Safety	12	13	3
4. CAPEX and OPEX	3	4	1
5. Remote areas	1	2	1
6. Flexibility	4	5	2
7. Dosage	5	6	2
8. Different sub surfaces	9	10	3
9. Forces	6	7	2
10. Environment	0	1	1
11. Availability of power supply	7	8	2
12. Crew	2	3	1
13. Flowrate	8	9	2

3.3.3 Most promising concepts

From the morphological overview several configurations could be generated which, at first glance, seems feasible and the methods to execute the sub functions doesn't contradict each other.

As mentioned in the previous paragraphs the conveyor belt, the helicopter, and the wheels for point B won't be taken into account in the determination of the most promising method.

Focus is on the general picture; details and unknown factors (for now) will pop-up when elaborating the most promising method. There is a possibility that there will be a loop back in the design process if it becomes clear that some aspects cannot be solved with the available resources/means.
Also for the time being the deposit method won't be taken into account as the main challenge is to deliver the sand to point B. When the material is available at point B, the material will deposit anyway, independent of the deposit method.

Below eight methods or variants are listed that will be analyzed in the MCA. All the methods use a pipeline for delivering sand from point A to depositing site B.

- Amphibious technique
  - Hovercraft
  - Tracks
  - Screws
  - Water master
- Land based equipment
  - Amphibious bulldozer
  - Amphibious excavator
  - Equipment elevated platform
- Adjustable rainbow

3.3.4 Least promising concepts

In a first selection in order to determine the most promising method, the boundary conditions stated in section 3.3.1 are held next to the generated methods and its variants. For some methods or variants it is obvious that at first glance some doesn't comply with the properties of the methods to execute the several sub functions. Below those methods or variants are stated with arguments.

1. Point B – Helicopter
A helicopter has very high capex and opex values. The weather conditions have a big influence on the helicopters' ability to operate. The net payload of a helicopter is limited. The net payload depends amongst others on the size of the helicopter and ranges between 5,000 and 10,000 kg.
If readjusting of the pipeline is needed, the pipeline has to be lifted. A pipeline with a diameter of 800 mm and the following properties:

- Density slurry : 1,300 kg/m^3
- Wall thickness pipeline : 20 mm
- Internal diameter pipeline : 800 mm
- Density steel : 7,800 kg/m^3

will result in a total weight of around 1,000 kg per meter. In total between five and ten meter of pipeline can be lifted by one helicopter. It can be stated that the helicopter method will fail on production/flowrate.
All in all this method does not translate into a (large) improvement of the workability compared to the current method, especially taking into consideration the high capex and opex values.

2. Amphibious technique – Wheels
It is assumed that point B will have a significant weight because of the weight of the pipeline and auxiliaries. Also point B has to be able to create sufficient tractive effort in order to displace the pipeline.
The weight of point B has consequences for the pressure underneath the wheels. A maximum ground pressure is allowed, and in order not to exceed this value, the dimensions

of the wheel have to become very large or a large amount of wheels have to be applied for point B.

3.3.5 Results Multi Criteria Analysis

In order to determine the most promising method for replenishing sand in intertidal areas, a Multi Criteria Analysis (MCA) will be performed. A MCA is a scientific evaluation method in order to make a rational decision between several discreet alternatives based on more than one criterion. The criteria have been assigned with weight factors; these have been determined in the previous paragraph.

In paragraph 3.3.3 the most promising methods/variants of those methods have been determined.
The methods/variants will be assigned with a value ranging between 0 (bad score) and 4 (good score).
If a method scores a zero on one or more arguments and obtain high scores for the rest of the arguments while not being excluded, it may result in that this method is the most promising method according to the MCA while this method is not realistic at all. When this method is excluded, the most promising method is (much) more plausible. This will speed up the design process and as a result the most promising method is (much) more realistic.
If a method/variant scores a zero on one or more criteria, the power of veto will be applied. This method will be excluded in the analysis as a consequence.

In Table 3-4 the results of the MCA are presented. Reference is made to Appendix A for details of the MCA.

Table 3-4: Results multi criteria analysis.

Method	Weight factor batch 1		Weight factor batch 2	
	Total score	**%**	Total score	**%**
Amphibious spray pontoon - *Hovercraft*	269	**73.9**	76	**73.1**
Amphibious spray pontoon - *Tracks*	281	**77.2**	79	**76**
Amphibious spray pontoon - *Screws*	251	**69.0**	71	**68.3**
Amphibious spray pontoon - *Watermaster*	266	**73.1**	76	**73.1**
Adjustable rainbow	0	**0**	0	**0**
Amphibious bulldozer	216	**59.3**	62	**59.6**
Amphibious excavator	204	**56.0**	60	**57.7**
Equipment with elevated platform	213	**58.5**	61	**58.7**
Ideal	364	**100**	104	**100**

Below the scores per criteria are stated. Only the scores 0 and 1 are elaborated per criterion.

1. Continuous production

The method ‘adjustable rainbow’ scores a zero on this criterion due to the limited production capacities in case of limited water depths. The horizontal spraying distance is limited to a maximum of 150 meter. A sufficient production cannot be guaranteed because of this limited spraying distance. Also the method is dependent of water levels and tide. As a result the power of veto is applied on this method.

2. Reliability

The amphibious bulldozer has obtained a 1 for reliability because in case of a failure the bulldozer is stuck under water whereby the bulldozer is hard to reach. This also holds when the bulldozer is stuck due to other reasons.
Beside the technique is not applied as much. There is a big uncertainty present regarding the reliability of the bulldozer in the long run.

3. Safety

The Amphibious excavator scores a 1 for safety because the safety of the operator might be compromised. If the excavator is at work many kilometers offshore in an intertidal area and an emergency situation happens, evacuation of the operator might prove to be difficult.
Another aspect is the stability of the excavator when lifting. The stability of the excavator may be compromised when lifting. This aspect may contribute to the probability of occurrence of an emergency situation.

4. CAPEX and OPEX

The amphibious spray pontoon equipped with hovercraft technology has scored a 1 on this criterion because especially the OPEX values are high due to the fuel consumption when hovering.

5. Remote areas

All the methods have obtained scores greater than one.

6. Flexibility

The method ‘adjustable rainbow’ has scored a 1 for flexibility but this method is rejected because it scored a zero on the criterion continuous production.

7. Dosable

The amphibious excavator and the equipment with elevated platform both scored a 1 because both methods have difficulties with distributing the material released from the pipeline over the disposal site. The set-up is not suited for distributing large quantities of soil.

8. Different sub surfaces

The amphibious bulldozer scores a 1 because the bulldozer requires a sub-surface with sufficient bearing capacity in order to prevent getting stuck in the soft subsoil. The bulldozer will have a big weight in order to create sufficient traction for pushing the material around.

The method adjustable rainbow scores also a 1 but is rejected anyway due to the power of veto.

9. Forces

The ASP equipped with hovercraft technology scored a 1 because when hovering the pontoon is not able to guide the forces. Action = minus reaction so, one little push is enough to move the pontoon when it is hovering so to speak. I.e. when the pontoon is hovering it is not able to push itself of in any horizontal direction.

10. Environment
The ASP equipped with hovercraft technology scored a 1 because this method consumes a lot of energy and as a result the air pollution will be significant. Also the noise levels generated by the fans will be quite significant to the surroundings.

11. Availability of power supply
As the ASP with hovercraft technology consumes a lot of energy this will translate into a score of 1 for this criterion. A significantly amount of energy has to be available for this method, so this is not favorable, especially not in remote areas.

12. Crew
All the methods scored a value greater than 1.

13. Flowrate
The amphibious bulldozer, amphibious excavator, and equipment with elevated platform all scored a 1 for flowrate. The three methods process the outflow of material quite slowly because of the low horizontal speed of the equipment.
Besides the bulldozer works underwater so, the speed of the bulldozer will be even lower and it's hard to keep track what happens under water.

3.3.6 Most promising concept

In Table 3-4 the scores of the MCA are presented using weight factors batch 1 and batch 2.
The two methods to determine the weight factors does have some (small) influence on the values of the MCA but the determination of the most promising method isn't affected as it can be concluded from the results of the MCA.

It can be concluded from the MCA that the amphibious spray pontoon equipped with tracks is the most promising method.
However, the four variants of the amphibious spray pontoon have obtained scores that doesn't have significantly big differences between each other. As a result it cannot be concluded that one variant of the method amphibious spray pontoon is the most promising method due to the uncertainties present in the MCA.
The MCA does state that adaptation of site equipment is not the way forward in order to increase the workability for sand replenishment projects. Therefore the methods amphibious bulldozer, amphibious excavator and equipment with elevated platform won't be taken into consideration anymore.

An amphibious spray pontoon is the most promising concept to deposit material. Next question is which amphibious technique is the most promising technique to construct an amphibious spray pontoon.

The most promising method for delivering material to the spray pontoon is not determined yet. The outcome will have a major influence on the required characteristics of the spray pontoon. I.e. the method for delivering material to the spray pontoon will dictate which amphibious technique should be mounted on the spray pontoon.

In the following chapter the most promising method for delivering material to the spray pontoon will be determined.
The most promising amphibious technique will be determined after the workability assessment has been performed.

Chapter 4

Delivering material from A to B

Goal of this chapter is to determine the most promising method for delivering material from the discharge area at point A to the spray pontoon.
Next concepts will be developed that will enhance the most promising method.

4.1 Methods for delivering material from A to B

4.1.1 Generation of methods

Below two methods for delivering material from point A up to and including point B are described.

Pipeline
Pipelines are commonly applied in the dredging industry for delivering material from the dredger to the deposit spot in areas with limited water depths. Figure 4-1 holds an example of a pipeline used for depositing material. In this figure the outflow of material from the pipeline is distributed by a bulldozer.

Figure 4-1: Outflow at a pipeline. (Source: *dredgingtoday.com*)

Pipeline transport takes place in a closed circuit system and has the following advantages:

- Can be regarded as a safe and clean method
- There is a small chance of leakage of dredged material if the pipeline system is not maintained properly
- Noise and air pollution are almost non-existent.

Disadvantages are:

- The requirement to mix the excavated material with transport water. This increases the volume for storage and/or further treatment, which in case of contaminated fine-grained sediments can be a serious issue
- If pipelines are applied in the surf zone, the transition between land and water and under influence of waves and/or currents, the forces on the floating pipelines can become really large. This may result in a burst of the pipeline

- Another aspect is the accessibility of the pipeline that might become an issue in case of maintaining the pipeline and of course installing and removing of the pipelines. Waves, currents and insufficient water depths are aspects which are responsible for difficulties if a pipeline system is applied in the surf zone.

Conveyor belt
The application of this transport method in the dredging industry is limited to few specific cases. However, there are potential advantages, especially when there are environmental concerns.
Hydraulically lifted soil is transported on a belt after passing through a drainage system (e.g. a screen installation or a drainage wheel).

Figure 4-2: Conveyor belt. (Source: *suprememfg.net*)

Advantages of a conveyer belt transport system are:

- Mechanical loading of dredged material without the need to add transport water
- A continuous transport system capable of conveying large volumes of material
- Environmental effects are relatively low, but special precautions have to be taken to reduce noise and to avoid dust.

Disadvantages are however:

- Alignment is fixed. Changes to this alignment during the transport process are difficult and costly.
- Special precautions have to be taken to avoid losses of dredged material with normal water content.
- Spread the transported material at the destination site can be complicated.

4.1.2 Selection most promising method for delivering material for A to B

In this study it is assumed that sand is dredged hydraulically by mixing sand with water. At point A the material is available as a sand-water mixture.
A conveyor belt is not suited for transporting mixtures so; the hydraulically lifted soil has to be dewatered first. A drainage system like a screen installation or a drainage wheel has to be integrated in the system before sand can be transported to the depositing site.
Another aspect of a conveyor belt is its limited flexibility. The alignment of the conveyor belt installation can be assumed as fixed. Modification of the installation will take a lot of time and requires auxiliary equipment in order to construct and adapt the conveyor belt system.

It's convenient to keep the state of the available material at point A the same over section A-B. This will result in excluding the conveyor belt as a method for transporting sand from point A to point B.

Most promising method is to apply a pipeline system because of the characteristics of the available material at point A.

Next step is to investigate what's involved in displacing the pipeline. This will be done next.

4.2 Generation of concepts for functions pipeline system section A-B

In this paragraph concepts are generated that will result in a decrease of the total required effort to displace the pipeline system, as described in paragraph 4.1

4.2.1 Sub functions

In section 4.1 the most promising method for delivering sand from point A up to and including point B is to apply a pipeline.
The amphibious spray pontoon has to be supplied with a sand-water mixture. The pontoon will distribute the sand-water mixture over the deposit site.
From the boundary conditions it follows that it's desired that the spray pontoon is able to move in a two-dimensional horizontal direction.

Due to the properties of the sand-water mixture, the pipeline is connected to the spray pontoon. As a result the pipeline has to be able to follow the spray pontoon when the spray pontoon moves towards another deposition spot.

The pipeline system on section A-B has to able to:

- Relocate in x and y direction in water as on land
- Hold position in water as on land

<u>Relocation of section A-B</u>
Hypothesis is that dragging the pipeline along when situated on land requires too much effort. The hypothesis will be checked by calculating the required force to displace the pipeline. The outcome will be compared with the required force to displace the generated concepts that enables a smaller effort to displace the pipeline.

Main idea is that the pipeline can be displaced such that the pipeline itself exerts a small as possible force to the spray pontoon. In this way the spray pontoon is able to displace the pipeline system.
To decrease the required effort for displacing the pipeline when it's situated on land the idea is to mount the pipeline on platforms. Reason being is the prediction that the pipeline will dig itself into the subsoil, increasing the required force to displace the pipeline to very high numbers. By avoiding digging in of the pipeline the resistance value will be decreased.

It's assumed that displacement of the pipeline when in water is not challenging for two reasons:

1. If the pipeline could be displaced on land, displacement in water should pose no problems.
2. Displacement of a floating pipeline is already common practice in the dredging industry.

<u>Hold position</u>
When the pipeline system is situated in water, hydrodynamic forces may be present. These forces could enable movement of the pipeline system. Movement of the pipeline system is not such a big of deal but the pipeline is connected to the spray pontoon. Uncontrolled movement of the pontoon is not desired as this poses problems during constructing of the design.

So, the pipeline system must be able to hold position when in water to prevent uncontrolled movement of the spray pontoon.

When the pipeline is situated on land the hypothesis is the friction force creating a holding force is (much) bigger than the driving force. An example of a driving force is the impulse force caused by the mixture inside the pipeline.

Different water depths
The water depth will vary during the execution of the project. Also the water depth will differ for one project to the other.
The pipeline system must be able to cope with different water depths. Several solutions are available with different working principles.

4.2.2 Concepts for fulfilling sub functions

Below solutions will be presented in order to fulfill the sub functions.

Decreasing friction

- *Efficient shape for sliding*
  Idea is to improve the friction coefficient. The walnut shape has an efficient shape when pushing or pulling the pipeline forward. Focus is on pushing or pulling the platform. The shape allows for displacement in x and y direction. Also the shape of the shell will decrease the wedging effect.

- *Hover craft technology*
  By hovering the friction part and the footprint (ideal for soft grounds) will be reduced to a minimum.

- *Platform*
  The pipeline will be mounted on platforms. On the platform the auxiliaries will be installed in order to allow for displacement and hold position.

Relocation on land

- Tracks
- Archimedes screws
- Anchor-winch system
- Wheels
- Spud-pole system

Relocation in water

- Tracks
- Archimedes screws
- Anchor-winch system
- Wheels
- Spud-pole system

Hold position in water

- Friction
- Spud pole
- Anchor

Different water depths

- Jack-up

Idea is that the platforms will position itself above the water level. The jacks will rest on the bottom.

- Adding weight

The platform(s) with floating properties by adding weight a weight increase will cause sinkage of the platforms. For example by adding water inside tanks (when filled with air the tank will generate floating capacity) the total weight will increase. As a result the platform will

have a bigger draft. If the draft is such that the platform will make contact with the soil surface, a friction force can be generated.
A simple ballast tank system containing pumps and tanks the weight of the platform could be adjusted.

- Suffcient height

When the total platform height is larger than the water depth (and floating of the platform is prevented) the platform will stay in contact with the soil surface. This solution could be applied when flooding of the platform is not allowed.

- Floating capacity

By applying floating capacity to the pipeline system the pipeline system is able to float. In this way every the pipeline system is independent of the water depths.

Summarizing: a choice regarding a solution for each sub solution has consequences. It should be mentioned that all sub functions must be full filled. Not every combination is feasible. In the next paragraph concepts will be generated via the morphological overview.

4.2.3 Morphological overview

In Figure 4-3 the morphological overview is presented. The overview will be used to generate concepts for displacing the pipepline system.
The generated concepts will be eleboated after the morphological overview.

← Sub functions

Solutions →

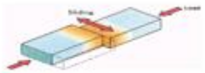
Delevering material	 Pipeline				
Decreasing friction	 Efficient shape for sliding	 Hover craft technology	Platform		
Relocation on land	 Tracks	 Archimedes screws	 Anchor-wich system	 Wheels	 Spud-pole system
Relocation in water	 Tracks	 Screws	 Anchor + winch	 Wheels	 Spud-pole system
Hold position in water	 Friction	 Spud pole	 Anchor		
Different water depths	 Jack-up system	 Adding weight	 Sufficient height	 Floating capacity	

Figure 4-3: Morphological overview for delivering material from point A up to and including point B.

4.2.4 Elaboration per concept

Below the generated platform concepts will be elaborated. Hypothesis is that to displace the pipeline system multiple platforms have to be applied. The pipeline segments will be mounted on platforms. Below a sketch is presented of a suggested set-up.

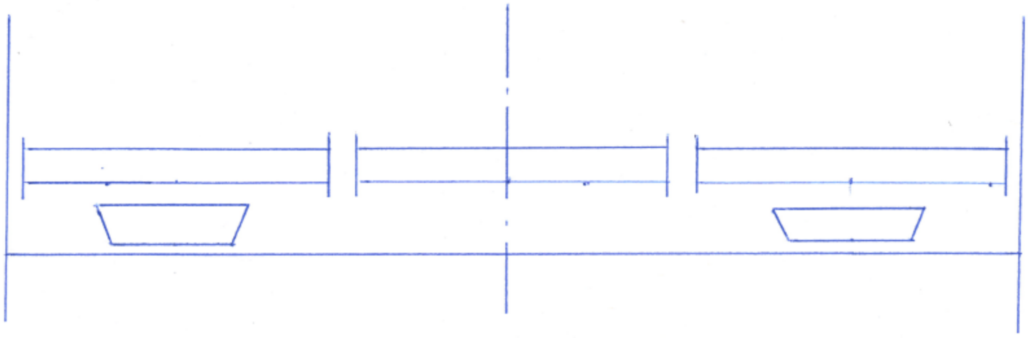


Figure 4-4: Sketch of multiple platforms

Platform with tracks
Displacement of the platform will be enabled by a track system, both in water as on land. The platform must have sufficient height to maintain a frictional contact with the soil surface when in water.
By applying two tracks, adjustments in the x-y plane are made possible.
A hinged turret mounted on the platform also allows for rotation of the pipeline system.

Figure 4-5: Platform on tracks. (Source: *Koen, 2015*)

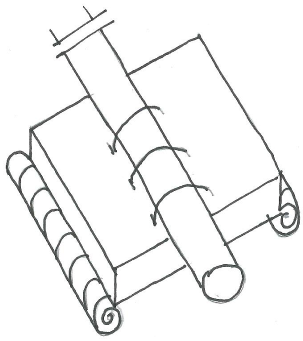


Figure 4-6: Archimedes platform

Archimedes platform
The Archimedes' screws installed on the platform will have three functions: to enable displacement of the platform on land as in water. Also the screws will provide floating capacity when in water due to large volume.
When afloat the screws won't have any contact with the soil surface when afloat, so the platform will be fitted with a spud pole. One spud is sufficient as multiple platforms will be applied. Regarding the total system there are multiple spuds present, preventing rotation of the pipeline system.

The screws enable movement in the x-y plane, both in water as on land. The tractive effort in water is less than on land. This aspect must be kept[t in mind.
Two screws must be applied to allow forward movement. Also lateral movement can be generated by rotating the two screws in the same direction.

Hoverbarge
If hovercraft technology is installed on a platform a so called hover barge will be created. The hover barge is able to lift itself during hovering. During hovering very little effort is required to displace the hover barge in any direction. The hoverbarge will have floating capacity, so when afloat displacement also doesn't require a lot of effort.
As the hover barge is floating or during hovering a hoverbarge is not able to generate a tractive effort. By applying an anchor-winch system the hover barge is able to displace in water and on land. Also a holding force is created when in water.

During displacement and hovering there will be friction present only between the rubber skirt and the soil surface.

Figure 4-7: Hover platform (Source: *Koen, 2015*)

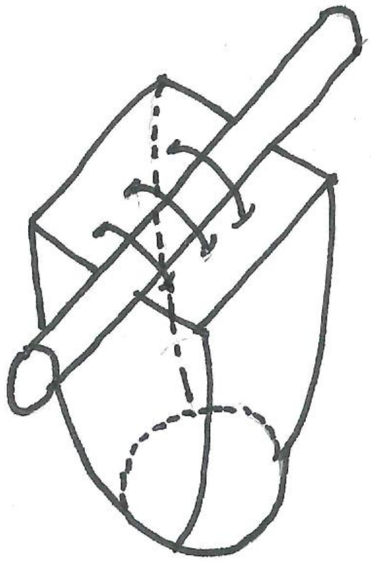


Figure 4-8: Walnut platform

Walnut concept
This concept is called such because the idea behind this concept is the shape of a walnut. The walnut shape will minimize the formation of wedges during sliding of the platform. The shape is present on the whole circumference of the platform. As a result the resistance force is reduced to a minimum, independent of the direction of displacement.

Due to the shape the concept will have floating capacity. To generate a holding force when afloat, a spud will be installed.

Wheeled platform
By installing wheels on a platform, the platform could be displaced. Wheels with a fixed caster are not well suited for the application of mounting the pipeline on platforms whereby the platforms are being pulled by the spray pontoon.
The platform must be able to move in any direction of the x-y plane. A rigid caster only has the ability to move in one direction (back and forth) and perpendicular movement of the platform cannot be realized.
A swivel caster set-up allows for movement in any direction of 360 degrees in the x-y plane. In this way the platform is able to follow the spray pontoon.

There will be three wheels installed on each platform. Three wheels allows installed on a platform will create a statistically stable platform. Four wheels installed on a platform will create, from a mechanical point of view, an unstable platform. Also there extra costs involved regarding the extra wheel.

To create a holding force the wheels have to stay in contact with the soil surface when in water. In this way a friction force could be generated.
The platform must have sufficient height to keep the platform above the water level. The pipeline will therefore also be above the water level. In this way no hydrodynamic forces will be acting on the pipeline. Only on the platform the hydrodynamic forces will be acting. As a result the holding force to be generated by the wheels is smaller in comparison with the pipeline in water.

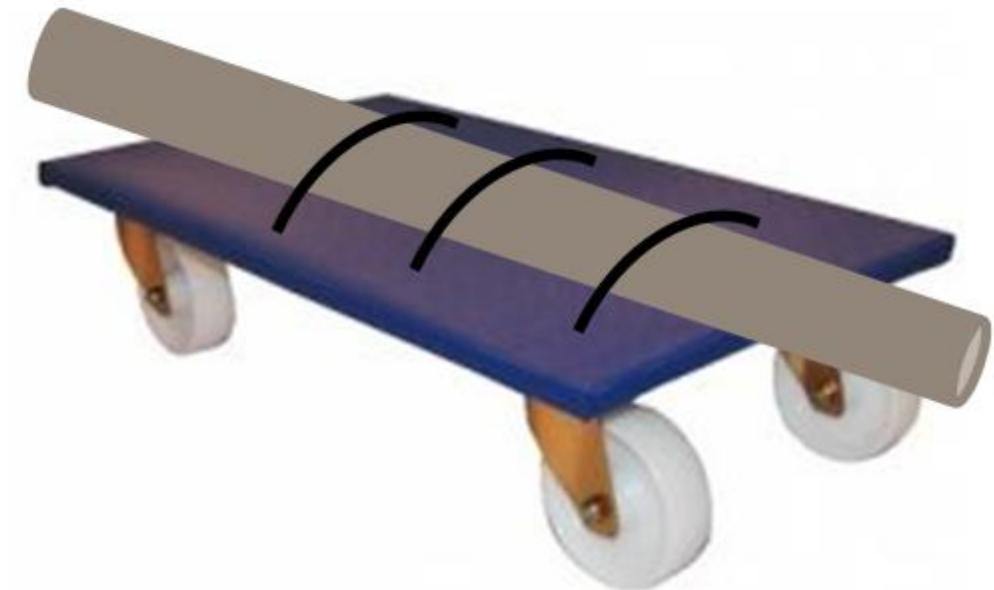


Figure 4-9: Platform equipped with a caster wheel set-up.

4.3 Criteria for the pipeline displacement concepts

4.3.1 Criteria regarding the pipeline displacement concepts

Five concepts have been developed to enable displacement of the pipeline on section A-B. To determine the most promising concept a multi-criteria analysis will be applied. This analysis applies criteria; these criteria are presented below.

1. *Forces*
   The required force to displace the pipeline system is of importance because when the pipeline is situated on land, the force to displace the pipeline is significant. The method that will result in the lowest required force will be assigned with the highest score.
2. *Reposition*
   The spray pontoon has to be able to move to a different spot when the required thickness is applied. The concepts have to enable repositioning in x and y direction.
3. *Flexibility*
   The pipeline system and the ASP have to be able to work both on land as in water. The deposition area could be flooded for any period of time. Also during construction the deposition area will increase in height. The concepts have to be able to cope with this aspect.
4. *Operation*
   This criterion covers the aspects on how well each concept will work in the dredging practice. Aspects are like: resistance against wear and tear, fuel consumption, maintainability, general dimensions, and so on.
5. *Reliability*
   Reliability covers the amount of disruption of the production process because the pipeline cannot be displaced due to whatever reason. Aspects are application of technology availability as known presently today, amount of components used, and serviceability.
6. *CAPEX and OPEX*
   The capital expenditures and the operational expenditures must not be too high.
7. *Wear*
   Wear covers the amount of maintenance required, OPEX values, usability and amount of disruption of the dredging process.
8. *Supply of energy*
   This criterion deals with fuel consumption, engine choice, supply of energy, location engine, etc.
9. *Environmental impact*
   Environmental impacts are among others emissions, pollution, disturbance subsurface, and amount of construction materials used.
10. *Obstacles*
    This covers: gradient subsurface, local elevations/protrusions, emergence of the sand deposits. The concepts have to be able to cope with this criterion because in dredging projects, obstacles will be encountered.
11. *Remoteness*
    Dredging projects may occur in remote locations. As a consequence mobilization of equipment should be reduced to a minimum. This also translates into a minimum of fuel consumption because the fuel also has to be mobilized. Further reliability and accessibility of the concept (components) plays a role in this criterion.

4.3.2 Selection criteria and weight factors

Next the order of importance is determined. The order will determine the weight factor per criterion. Reason being is because not every criterion has the same rate of importance.

Reference is being made to Appendix A for details of the calculation. In Table 4-1 results of the calculation are represented.

Table 4-1: Weight factors per criterion.

Criteria	Outcome calculation
[-]	[-]
1. Forces	9
2. Reposition	8
3. Flexibility	10
4. Operation	7
5. Reliability	2
6. CAPEX & OPEX	6
7. Wear	4
8. Supply of energy	3
9. Environmental impact	1
10. Obstacles	5
11. Remoteness	0

To assign score and the corresponding prove for each score per criterion in the MCA for all five concepts will take a lot of effort. Also it will be quite hard to assign scores to some criteria because a fully elaborated detailed design is not yet available. In this way scores cannot be assigned to the criteria. For example the criterion ‘reliability’ is difficult to assign values to as no components of the concept itself are known yet.

Balancing time, goal of this study (technical feasibility), order of importance of the criteria, and an estimation of the amount of effort in order to produce content for each criterion, the following four criteria have been selected:

- Forces
- Repositioning
- Flexibility
- Operation

Main reason for selecting these four criteria is the ease for generating numeric output.
Numeric output values can easily be compared with one another. The numeric output will be used as input for the Multi Criteria Analysis (MCA) to assign scores for each criterion. These scores will be applied in the MCA to determine the most promising concept for displacing the pipeline system on section A-B.

For each selected criterion the weight factor is determined again.
There are several methods available to determine the weight factor per criterion.
One way is to simply apply a hierarchy form; i.e. the weight factors ranges between 1 and 4. However, there is a risk present that the MCA becomes skewed towards the most important criterion as this criterion has the largest weight factor. In order to decrease the amount of skewness the weight factors could be constructed in such a way that the gap between the criterions is decreased. Another way is to categorize the criteria in groups. There are 4 criteria so, 2 groups seem appropriate at first glance.
As a result the two most important criteria will be assigned with a weight factor value of two and the other two criteria will be assigned with a value of 1.

In Table 4-2 the results are represented.

Table 4-2: Weight factors selected criteria

Criteria	Forces	Reposition	Flexibility	Operation	Total	Weight factor
1. Forces	x	1	0	1	2	2
2. Reposition	0	x	0	1	1	1
3. Flexibility	1	1	x	1	3	2
4. Operation	0	0	0	x	0	1

4.3.3 Conclusion

To generate numeric output values for the four selected criteria a theoretical review will be performed. Aspects which are of importance for that specific criterion have to be determined. Once these aspects are known, through a theoretical review a method to generate numeric output values will be available. Together with the workability assessment quantification of the selected criteria are available. These values will be used in the MCA to determine the most promising platform concept.

First the theoretical review will be performed in the next chapter.

Chapter 5

Theoretical review displacement pipeline system

Chapter five is all about performing a theoretical review of all the aspects that are involved to displace the pipeline system. The pipeline system consists of the pipeline running from point A to the spray pontoon (point B), and the spray pontoon itself.
The theoretical review will be used together with a test case, presented in Chapter six, to produce numeric output. This numeric output will serve as input for the Multi Criteria Analysis that will be performed in Chapter seven.

Chapter five kicks off with a review to determine the amount of effort required to displace a pipeline that is situated on land. This is related to the criterion forces.
Next a review will be presented to determine the amount of platforms needed along section A-B; the pipeline will be mounted on platforms. This relates to the criterion flexibility.
Once the method for determining the amount of platforms is known, a theoretical review will be presented to determine the resistance force encountered per pipeline displacement concept. These concepts have been developed in Chapter four. This aspect is related to the criterion forces.

Next the required amount of effort to hold the pipeline in position while in water is given. Also this aspect is related to the criterion forces.
Subsequent a method to determine the amount of repositioning of the pipeline system will be presented (criterion related to be 'repositioning').
From the amount of repositioning a review will be presented how to create flexibility in the pipeline system. Of course this is related to the criterion flexibility. Also a method for determining the most efficient pipeline set-up will be presented. This is related to the criterion operation.

In the final part of this chapter methods will be presented to determine the tractive effort per amphibious spray pontoon concept as presented in Chapter three. This tractive effort is intended for displacing the platforms installed along section A-B. The amount of tractive effort will relate to the criterion operation.

5.1 Displacement of a pipeline situated on land

First a static pipeline segment on land will be analyzed. The static sinkage of the pipeline into the soil will be known.
Next the displacement of a single pipeline segment will be investigated. Both rolling as sliding the pipeline in lateral and axial direction will be presented. For sliding the static sinkage will serve as an input argument.

5.1.1 Static pipeline

Starting with a straight pipeline segment, without flanges or other protrusions from the pipeline, with a length of L_{pipe} resting on the soil surface in absence of water, one needs to know how much the pipeline will sink into the subsoil. This is of importance later on when the pipeline is being displaced. Figure 5-1 represents the principle of static sinkage of the pipeline.

The force that the wind is generating perpendicular on the pipeline is ignored in this analysis because the wind profile shows a logarithmic profile. The pipeline will have a limited maximum height, so the wind force will not be significant compared to its own weight.

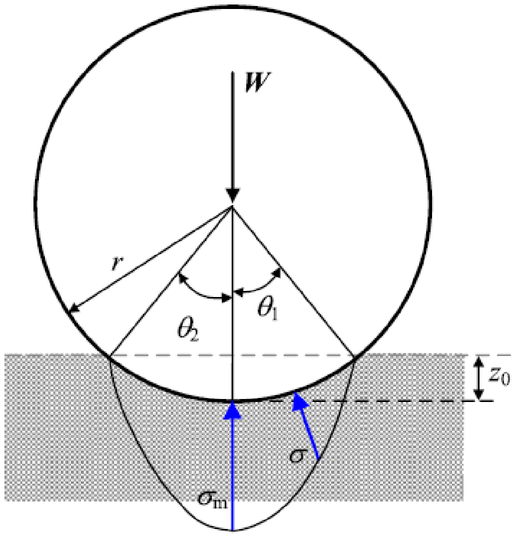


Figure 5-1: Static pipeline. (Source: *Ding et al, 2015*)

The static pipeline sinkage z_0 [m] is determined by Bekker's explicit equation (*Ding et al, 2015*):

$$z_0 \approx \left[\frac{W}{\sqrt{(2\cdot r)}\cdot b\cdot K_s\cdot(1-\frac{n}{3})}\right]^{\frac{1}{n+\frac{1}{2}}} \quad (1)$$

W	Vertical load	[N]
r	Outside pipeline radius	[m]
b	Width support	[m]
K_s	Equivalent sinkage modulus of terrain	[Pa/m^n]
n	Sinkage exponent of terrain	[-]

The vertical load W [N] is determined by:

$$W = W_{pipe} + W_{mixture} \quad (2)$$

W_{pipe}	Weight pipeline	[N]
$W_{mixture}$	Weight mixture	[N]

Each pipe has flanges at both outer ends. To account for the weight of these flanges, a value of 600 N (*VOUB, 1998*) will be used in this study, and represented as W_{flange}.

Weight of the pipeline W_{pipe} [N] is calculated with:

$$W_{pipe} = Area_{steel} [= (\pi \cdot r^2 - \pi \cdot (r - t_{wall})^2)] \cdot \rho_{steel} \cdot g \cdot L_{pipe} + W_{flange} \qquad (3)$$

L_{pipe}	Length pipeline segment	[m]
t_{wall}	Thickness wall pipeline	[m]
W_{flange}	Weight flanges per pipeline segment	[N]

And the mixture weight $W_{mixture}$ [N]:

$$W_{mixture} = Area_{throughput} [= \pi \cdot (r - t_{wall})^2] \cdot \rho_{mixture} \cdot g \cdot L_{pipe} \qquad (4)$$

Equivalent sinkage modulus of terrain K_s [Pa/m^n]

$$K_s = \frac{k_c}{b} + k_\varphi \qquad (5)$$

k_c	Cohesive modulus of terrain in Bekker's model	[Pa/m^{n-1}]
k_φ	Frictional modulus of terrain in Bekker's model	[Pa/m^n]

With the represented literature the amount of static sinkage could be determined, assuming a smooth (no local elevations along the track of the pipeline) subsurface.
The simplest case is a pipeline without flanges. In that case the width of the support b is equal to the length of the pipeline. The static sinkage will be small.

If flanges are present, these flanges will protrude outside the body of the pipeline, as can be seen in Figure 5-2. The pipeline segments will rest on these flanges, resulting that the weight force of the pipeline will be distributed over the flanges at both ends of the pipeline. The width of the support b will be very small compared to a pipeline without flanges whereby b is the whole pipeline length. As a result the flanges will sink significantly deeper into the soil than without flanges due to higher contact stresses.
It depends on the height of the flanges and the bearing capacity of the soil how much the flanges will sink into the soil. If the bearing capacity of the soil is sufficient, the flanges will not sink with their entire flange height into the soil.
On soft soil soil, the flanges may sink over the entire flange height into the soil. If this is the case, the body of the pipeline will also come into contact with the soil. This is of importance in case of pipeline displacement because it determines the amount of friction.

Figure 5-2: Pipeline flanges

5.1.2 Displacement single pipeline segment

A pipeline can be displaced in several manners, depending on the orientation of the pipeline. The following methods are possible:

- Rolling; because of the cylindrical shape of the pipeline
- Sliding; both in axial direction and lateral direction

Below each method will be elaborated. Just like the case of determining the static sinkage one pipeline segment with a length of L_{pipe} will be analyzed.

<u>Rolling</u>

If a force is applied perpendicular to the pipeline, the pipeline has the tendency to roll due to cylindrical shape.

In the method developed by Bekker (*Ding et al, 2015*) for predicting the performance of a rigid wheel, it is assumed that the terrain reaction on the contact patch is purely radial (= no shearing will occur), and that the radial pressure is equal to the normal pressure beneath a horizontal sinkage plate.

Considering the equilibrium of the horizontal and vertical forces acting on a towed rigid wheel as shown in Figure 5-3 where F'_{RC} is the motion resistance, also called the compaction resistance. F'_{RC} [N] is the force that has to be applied in order to move the wheel (in this study a pipeline) and is determined by:

$$F'_{RC} = \left(\frac{3 \cdot W}{\sqrt{2 \cdot r}}\right)^{\frac{2 \cdot n+2}{2 \cdot n+1}} \cdot \left[(n+1) \cdot (3-n)^{\frac{2 \cdot n+2}{2 \cdot n+1}} \cdot (b \cdot K_s)^{\frac{1}{2 \cdot n+1}}\right]^{-1} \qquad (6)$$

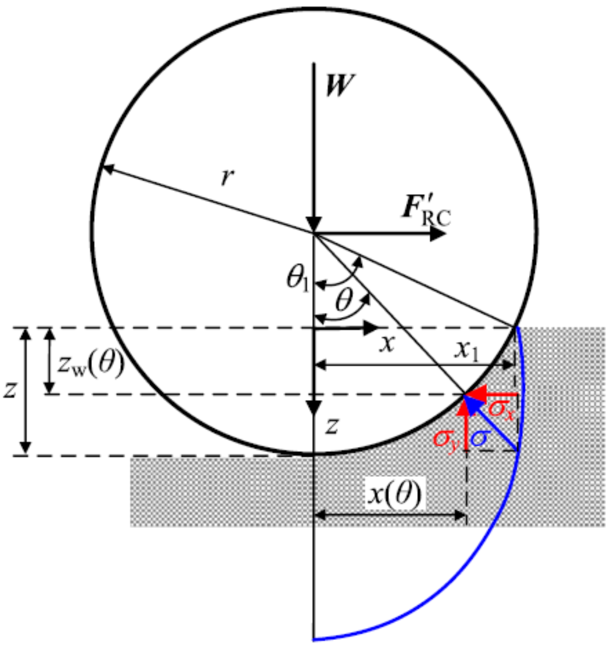


Figure 5-3: Bekker's wheel soil interaction model (Source: *Ding et al, 2015*).

<u>Sliding</u>

Sliding of the pipeline can take place both in axial direction and lateral direction. Figure 5-4 shows the orientation of pipeline movement. For both directions friction between the soil and the pipeline will be generated.

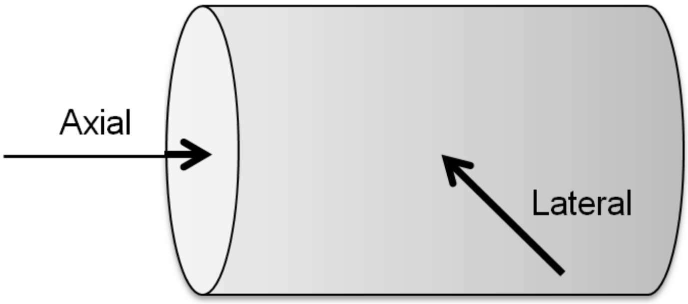


Figure 5-4: Definition of movement of the pipeline.

During displacement of the pipeline the friction force is calculated as a normal force multiplied by the tangent of the external (soil-steel) friction angle. The horizontal friction force [N] that is encountered is determined by the vertical load and a friction factor (*Beindorff et al, 2012*):

$$F_{friction} = \tan(\delta) \cdot W \tag{7}$$

W	Vertical load (weight pipeline + weight mixture)	[N]
δ	External friction angle	[°]

According to literature the external and internal friction angles have a certain relation to each other depending on size, particle shape and relative density. In this study, a simple indicative relationship, often used in dredging engineering, will be applied (*Beindorff et al, 2012*):

$$\delta = \frac{2}{3} \cdot \varphi \tag{8}$$

φ	Internal friction angle	[°]

Axial sliding

At startup of the pipeline displacement in axial direction, the pipeline has to push strong enough to overcome the minimum possible occurring force in order to displace the soil. This is called passive soil failure and Figure 5-5 gives a representation of passive soil failure.

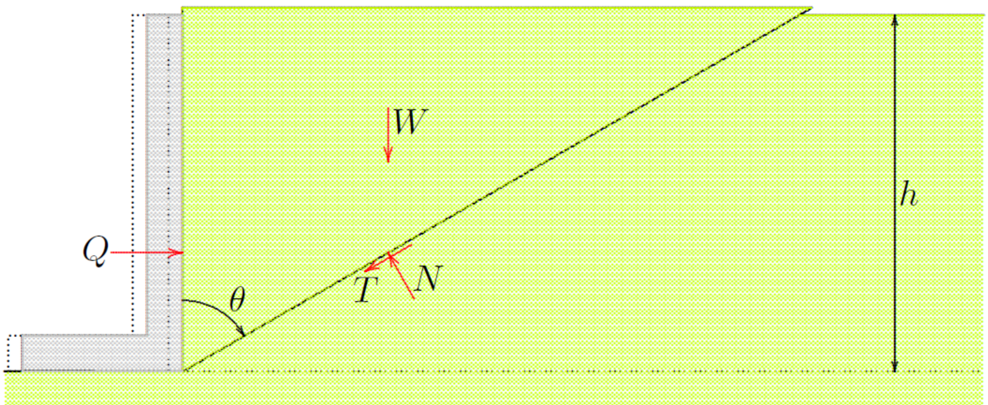


Figure 5-5: Passive soil failure. (Source: *Verruijt, 2012*)

The L-shape positioned left in the figure represents the pipeline. h is the static pipeline sinkage z_0. Q is the minimum possible horizontal occurring force.

Q [N] is calculated according to (*Verruijt, 2012)* as follows:

$$Q = \frac{1}{2} \cdot \rho_{soil} \cdot g \cdot {z_0}^2 \cdot K_p \cdot w \qquad (9)$$

K_p	Coefficient of passive failure	[-]
w	Width pipeline at surface level	[m]

$$K_p = \frac{1+\sin(\varphi)}{1-\sin(\varphi)} \qquad (10)$$

Another aspect is that the total pipeline height is equal to the pipeline diameter. The pipeline diameter is larger than the static pipeline sinkage z_0. As a result during movement of the pipeline in axial direction the formation of a wedge will occur. I.e. so called dozing effect. Figure 5-6 gives an impression of the formation of a wedge.

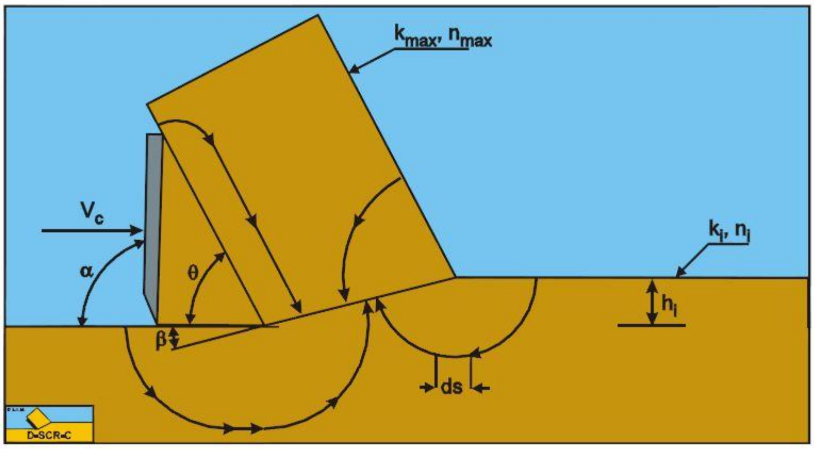


Figure 5-6: Wedge formation. (Source: *Miedema, 2014*)

During displacement the size of the wedge in front of the pipeline tends to increase in size.
Q has to increase significantly to keep the pipeline moving as h represented in Figure 5-5 increases quadratic in Equation 9. The pipeline will dig itself into the soil so to speak.

The flanges (if present) may also have an effect on the amount of digging into the soil. The flanges can cause a greater displacement of the soil compared to a pipeline without flanges. As a result the horizontal force Q will become even larger.

Lateral sliding

During lateral movement of the pipeline, soil accumulates in front of the pipe, leading to the growth of soil berms. These berms create significant additional resistance while displacing the pipeline.
According to (*Wang et al, 2016*) vertical displacement of the pipe segment changes as the lateral displacement increases. As shown in Figure 5-7, the pipeline segment tends to uplift with increasing lateral displacement in stage (a) and (b), in which the embedment of the pipeline segment z is greater than zero, and the berm volume increases gradually. As the lateral movement of the pipe segment increases, the pipe segment reaches stage (c), in

which z = 0, and the berm volume reaches its maximum value $A_{berm(max)}$. The vertical displacement of the pipe segment still increases after stage (c).
Then, the pipe segment reaches stage (d), in which the vertical location of the bottom of the pipe segment gradually exceeds the initial soil surface, and the berm volume decreases gradually as the lateral displacement of the pipe segment increases.

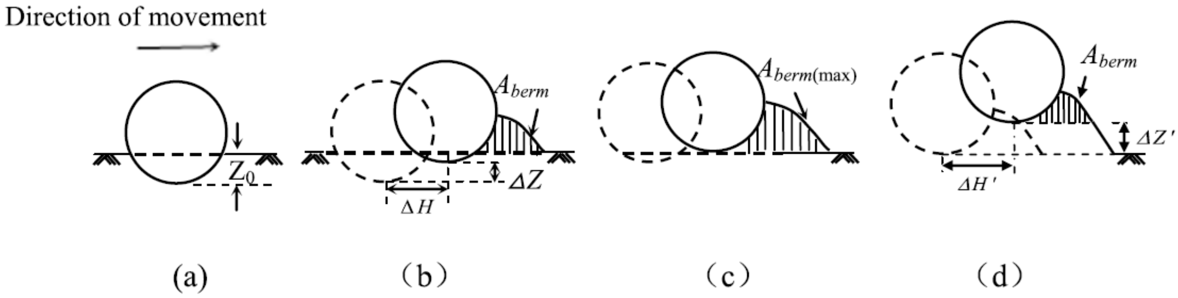


Figure 5-7: Stages of berm formation. (Source: *Wang et al, 2016*)

When the pipe segments reaches stage (c), the pipe segment moves with the berm. The maximum resistance to displace the pipeline is reached in this stage because the berm is at its maximum.
During displacement the pipeline experiences shear along the plane in the bottom of the pipeline. The total resistance $F_{lateral}$ consists only of the Coulomb friction F_{cf} and the resistance offered by the berm F_{berm}:

$$F_{lateral} = F_{berm} + F_{cf} \qquad (11)$$

The formula of F_{cf} can be expressed as:

$$F_{cf} = \mu \cdot W \qquad (12)$$

(*Wang et al, 2016*) performed horizontal pushing tests on pipe segments resting on sand. A pipe segment was chosen with a weight such that penetration into the soil was insignificant. As a result the pipe segment moves along the lateral direction without vertical displacement. Test data shows that μ = 0.8.

Computational methods to calculate the berm resistance F_{berm} have been proposed in the report DNV-RP-F109 (*DNV, 2007*). The formula to calculate F_{berm} can be expressed as:

$$\frac{F_{berm}}{W} = \begin{cases} (5.0 \cdot \kappa - 0.15 \cdot \kappa^2) \cdot \left(\frac{z}{D}\right)^{1.25} & if\ \kappa < 26.7 \\ \kappa \cdot \left(\frac{z}{D}\right)^{1.25} & if\ \kappa > 26.7 \end{cases} \qquad (13)$$

$$\kappa = \frac{\gamma \cdot D^2}{W} \qquad (14)$$

D	Pipe outer diameter	[m]

Summary
Hypothesis regarding displacement of the pipeline when on land is that it will require too much effort to displace the pipeline because it's expected that the pipeline will dig itself into the soil.
In this paragraph the equilibrium conditions of a static, rolling, and sliding pipeline segment with a length of L_{pipe} are represented. It concerned just one pipeline segment. In practice

multiple pipelines have to be coupled to each other because the distance between point A and point B is (much) larger than L_{pipe}.
It can be seen that lateral sliding requires the most effort due to berm formation along the length of the pipeline. In case of axial sliding a berm will only form in front of the pipeline, so a lower resistance force is encountered.
The ideal set-up to displace the pipeline is by rolling. Methods have to be found to enable this. However, by only rolling the pipeline, no axial movement of the pipeline is created. Sliding in one way or the other is required to enable axial movement.
To decrease the amount of effort the pipeline will be installed on platforms. Question is how much pipeline length each platform has to be able to carry. Once the length of section A-B is known, the amount of platforms could be determined.

5.2 Amount of platforms

To determine the amount of platforms the deflection of the pipeline will be analyzed. Also the acting stresses and the maximum allowable stresses will be reviewed. These aspects will determine the length of the pipeline to be carried per platform.

5.2.1 Deflection pipeline system

According to the VOUB (*VOUB, 1998*) the pipeline discharge system must fulfill the following criteria:

- Strong enough to carry own weight and mixture weight without continuous support.
- Must provide least amount of resistance to the mixture.

The criterion strength, stated as the pipeline must be strong enough to carry the own weight and mixture without continuous support, is applicable in this study. It is expected that platforms will be applied whereby the pipeline is placed on top. This raises the question what distance is applicable between the platforms. By determining the maximum deflection of the pipeline between the platforms the distance between the platforms is determined.

Another aspect is the desire to make the pipeline displacement system scalable. In this way the user, i.e. the contractor, is able to vary the total length of the pipeline system. Figure 5-8 gives an impression of the scalability.

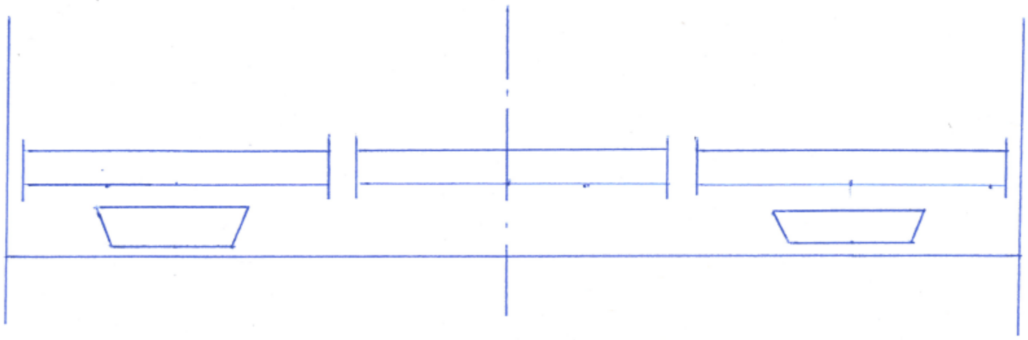


Figure 5-8: Impression scalability pipeline system.

To determine the distance between the platforms, the following items have to be known:

- Deflection pipeline
- Strength pipeline
- How the pipeline will be supported on the platforms.

The pipeline is modelled as follows:

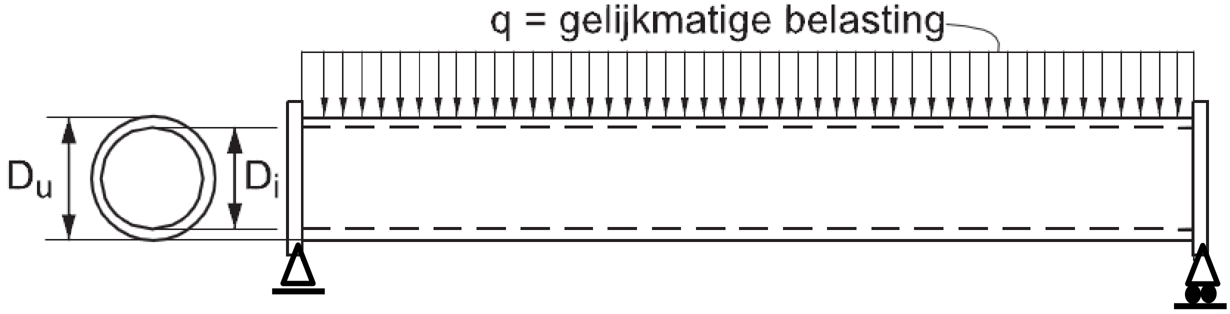


Figure 5-9: Concept for determination deflection pipeline. q is a uniform distributed load. (Source: *VOUB, 1998*)

The deflection of the pipeline depends on the total weight of the pipeline during operation, and the distance between the platforms.

The total weight of the pipeline is:

- Weight pipeline itself
- Weight of the flanges
    - *Weight flanges per pipeline segment is estimated on 600 N.*
- Weight mixture in case of almost silted up pipeline.
    - *VOUB uses 1,800 kg/m^3. (VOUB, 1998)*

Dividing the total weight of the pipeline by the length of the pipeline segment, q will be known.

Next the pipeline support on the platforms has to be determined because this dictates the amount of deflection of the pipeline. In Figure 5-10 three standard load situations for a uniform distributed load are represented.

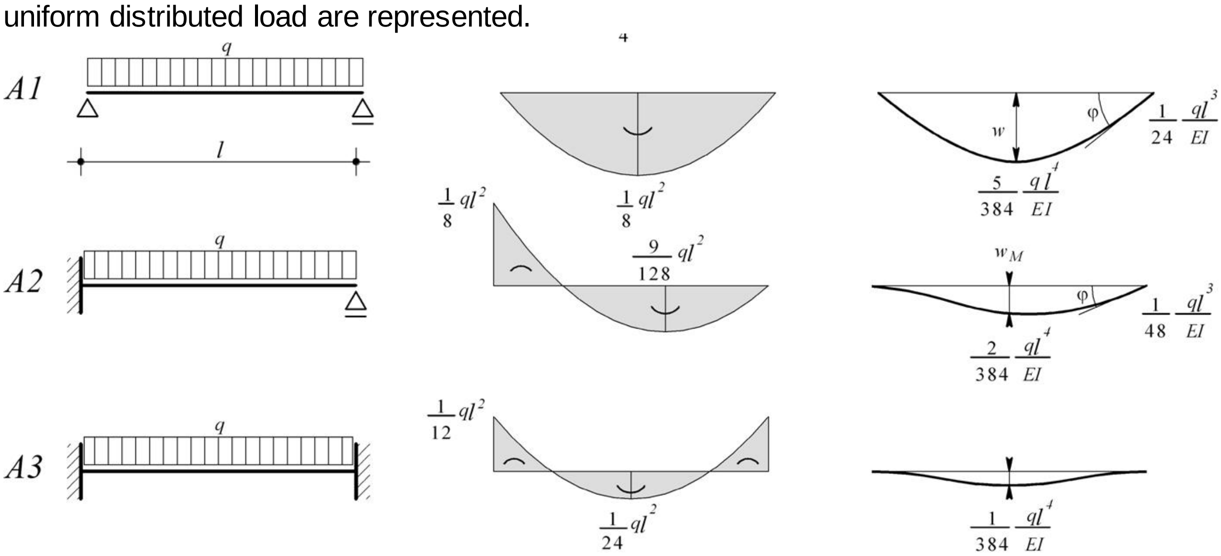


Figure 5-10: Moment and deflection formulas for standard load situations. (Source: *Hartsuijker, 2007*)

It's plausible that on the platforms pivot points will be present in order to create flexibility in the pipeline system. Pivot points are not able to cope with torque values, so case A1 in Figure 5-10 is applicable. The maximum deflection w_{max} is determined by:

$$w_{max} = \frac{5}{384} \cdot \frac{q \cdot l^4}{E \cdot I} \quad (15)$$

With:

w_{max}	=	Maximum deflection	[m]
q	=	Distributed load	[N/m]
l	=	Length	[m]
E	=	Young modulus (material pipeline is steel → $210 \cdot 10^9$)	[N/m^2]
I	=	Second moment of area	[m^4]

Second moment area I for a tube is calculated as follows:

$$I_{yy} = I_{zz} = \frac{\pi}{64} \cdot (D^4 - d^4) \quad (16)$$

With:

D	=	Outside pipeline diameter	[m]
d	=	Inside pipeline diameter	[m]

By iteration of the length between the platforms the maximum deflection could be determined.
The maximum allowable deflection is restricted by an operation point of view.
The pipeline is not allowed to touch the soil surface (resistance during displacement) or the pipeline gradient becomes too large, affecting the mixture velocity whereby the risk of clogging becomes greater.

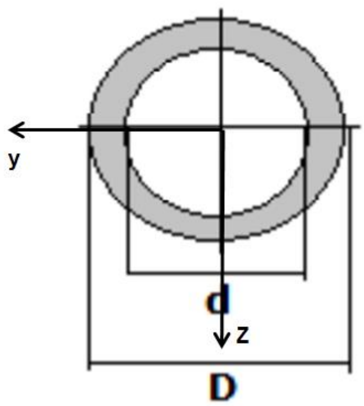


Figure 5-11: Reference frame tube.

5.2.2 Material stresses

When the pipeline will be used to transfer the normal force in order to pull the platforms (or the pipeline segments itself) stresses are acting in the material of the pipeline.
If platforms are applied a moment is acting on the pipeline due to its own weight. This causes stresses due to deflection.

The material of the pipeline is only able to handle a certain amount of stresses. According to (*VOUB, 1998*) most pipelines are constructed with S235 steel with the following properties (*Leijendeckers et al, 1997*):

σ_{yield}	=	Yield stress	=	235	[N/mm^2]
σ_{max}	=	Maximum stress	=	360	[N/mm^2]

However, the yield stress is normative in stress calculations.

<u>Stresses due to deflection</u>
Formula for calculating stresses due to deflection (*Hartsuijker, 2007*):

$$\sigma_{deflection} = \frac{M}{W} \quad (17)$$

With:

$$\text{Moment, M} = \frac{1}{8} \cdot q \cdot l^2 \qquad \text{Section modulus, W} = \frac{\frac{\pi}{32} \cdot (D^4 - d^4)}{D}$$

Stresses due to pull action

Formula for calculating stresses due to pulling (*Hartsuijker, 2007*):

$$\sigma_{pull} = \frac{N}{A} \quad (18)$$

With:

N	=	Normal force	[N]
A	=	Cross sectional area	[m^2]

5.2.3 Amount of platforms

The sum of the stresses due to deflection and pulling must not exceed the yield stress. In this way the maximum pipeline length between the platforms can be determined. Also the maximum pull action can be determined. When the maximum allowed normal force is not sufficient, other means rather than the pipeline have to be used in order to cope with the normal force.

When the desired total pipeline length is known, by dividing this length by the maximum pipeline length between the platforms, the amount of platforms could be determined.

In this study only the stresses inside the steel pipeline are reviewed. Stresses and maximum allowable stresses in ball joints, flanges, welds, and so on are not checked/considered.

5.3 Resistance force per pipeline displacement concept

Below for each concept that enables movement of the pipeline from point A to the spray pontoon a literature review is presented to determine the amount of resistance during displacement of the pipeline. It should be noted that for each concept the resistance applies for one platform. In section 5.2.3 it's stated that probably multiple platforms have to be applied to carry the pipeline system. When the resistance force per platform is known, the total resistance force can be calculated easily by according by multiplying the amount of platforms.

5.3.1 Tracks

One of the better known methods for parametric analysis of tracked vehicle performance is that originally developed by Bekker (1956). In this method, the track in contact with the terrain is assumed to be similar to a rigid footing. If the center of gravity of the vehicle is located at the midpoint of the track contact area, the normal pressure distribution may be assumed as uniform, as shown in Figure 5-12. On the other hand, if the center of gravity of the vehicle is located ahead of or behind the midpoint of the contact area, a sinkage distribution of trapezoidal form will be assumed. Based on the assumed contact pressure, and making use of the pressure-sinkage relationship, the sinkage of the track can be predicted.

Using the Bekker pressure-sinkage equation, for a track with uniform contact pressure, the sinkage z_0 is given by:

$$z_0 = \left(\frac{\frac{W}{b \cdot l}}{\frac{k_c}{b}+k_\varphi}\right)^{\frac{1}{n}} \tag{19}$$

b	=	Width of track	[m]
l	=	Contact length	[m]
W	=	Normal load on the track	[N]
n	=	Exponent of sinkage	[-]

If the track is pulled a distance l in the horizontal direction, the work done by the towing force, which is equal in magnitude to the motion resistance due to compaction R_c, can be equated to the work done in making a rut of width b and a length l to a depth of z_0 as expressed by:

$$R_c = \frac{1}{(n+1) \cdot b^{\frac{1}{n}} \cdot \left(\frac{k_c}{b}+k_\varphi\right)^{\frac{1}{n}}} \cdot \left(\frac{W}{l}\right)^{\frac{(n+1)}{n}} \tag{20}$$

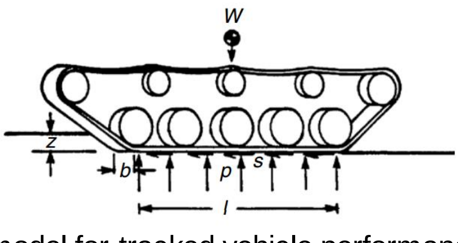


Figure 5-12: A simplified model for tracked vehicle performance. (Source: *Wong, 2010*)

In very soft ground where significant sinkage occurs, Bekker suggested that a bulldozing resistance should be taken into account and that it may be estimated using the retaining wall theory of soil mechanics (*Verruijt, 2012*).

As a first estimation for R_c it is assumed that no significant sinkage of the tracks will occur. Because the expected (sub) soil will consists of sandy material. Sand has in general a high bearing capacity, so the tracks will not sink significantly into the subsoil.
Soft soils, like clay and peat, have a low bearing capacity, so the track system will encounter (large) sinkage into the soil. This will result in high compaction resistance forces.

The compaction resistance R_c for one track system can be calculated by (*Equation 20*). The total resistance force for the complete pipeline system has to be known or, at least for a uniform pipeline length.
In order to answer this question, the amount of tracked platforms that has to be put into action has to be known. In this way the total resistance R_c could be determined.

During displacement of a track system not only a resistance force due to compaction of the soil is encountered but also a friction force inside the track system.
As the track is operating in an area where soil material could enter the track propulsion system the resistance force inside the track system could increase.
To take this aspect into account, a friction coefficient of 0.25 will be applied. This friction coefficient will be multiplied with the net weight force of the track system.

Summarizing: the total resistance during displacement of platform equipped with tracks is the summation of the soil compaction force R_c and the friction inside the track system.

5.3.2 Archimedes platform

The Archimedes screw propulsion system consists of one or more helices twisted around a cylinder shaped core. When the screw is rotated, the helix will create forces in the longitudinal direction and it will start moving in the longitudinal direction.
An important property of the Archimedes screw is the ability it can displace a large volume generating buoyancy. This effect can be exploited in water, but even examples are known of displacing (very) soft soils.

An important force is the magnitude of the required forward thrust, which mainly consist of resistance to be overcome (*Lotman et al, 2011*)

- Motion resistance caused by forward speed
- Riser introduced force by current, speed and dynamics
- Skin friction in the soil by track or screw
- Bulldozer force due to motion in the soil in front of Archimedes screw

In this study an Archimedes platform experiences a motion resistance force consisting of a bulldozer force and a skin friction along the screw, as represented in Figure 5-13.

Below a method is presented to calculate the bulldozer force, and the skin friction force.

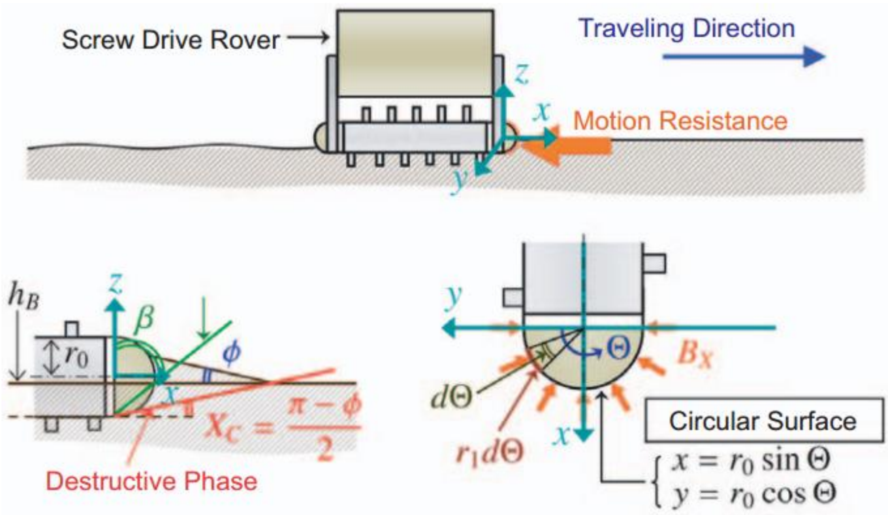


Figure 5-13: Motion resistance force experienced by an Archimedes platform.
(Source: *Nagaoka, 2011*)

<u>Bulldozer force</u>
(*Nagaoka, 2011*) is assuming the ideal bulldozing line is acting on the hemispherical surface. The bulldozing force is introduced as follows (*Nagaoka, 2011*):

$$F_{dozing} = \frac{1}{2}\gamma_E h_B^2 \frac{\cot X_C - \tan\beta}{\cot(X_C+\phi) - \tan\beta} + c h_B \left[\frac{\tan(X_C+\phi) + \cot X_C}{1 - \tan\beta \tan(X_C+\phi)}\right] \quad (21)$$

where,

$$h_B = h - (R_0 - r_0) \quad \text{: Bulldozing Depth}$$

$$\beta = \sec\left(\sqrt{\frac{h_B}{2r_0}}\right) \quad \text{: Ideal Bulldozing Angle}$$

$$X_C = \frac{\pi - \phi}{2} \quad \text{: Critical Rapture Angle}$$

<u>Skin friction</u>
The skin friction is determined in the same way as at the ‘Wallnut concept’ (*Equation 23*). The only difference is the weight force.

The presented methods are applicable for one screw. The Archimedes platform will be applied with two screws, so the calculated resistance force has to be multiplied by two.

5.3.3 Hoverbarge

Idea behind the hoverbarge is that the barge(s) will carry the pipeline system, almost eliminating the friction between the pipeline and the soil.
Assuming the lift capacity of the barges to be sufficient, friction will only be present between the rubber skirt and the soil when the hoverbarge is displaced (ignoring friction in pivot points for the time being).
A skirt is present at the circumference of the hoverbarge in order to hold as much air as possible in the chamber(s) of the hoverbarge. Air will escape from the chamber, decreasing the efficiency of the hoverbarge. The skirt will make contact with the soil in order to hold as much air in, so there is friction present between the material of the skirt and the soil.

Ignoring friction in the pivot points, the encountered friction by the hoverbarge during displacement is expressed by:

$$R_{hb} = W_s \cdot L_s \cdot \mu_r \quad (22)$$

R_{hb}	=	Resistance soil-skirt per barge	[N]
W_s	=	Weight skirt per meter	[N/m]
L_s	=	Length skirt	[m]
μ_r	=	Coefficient of friction	[-]

The weight of the pipeline system, the weight of the hoverbarge, and the lifting capacity of a single hoverbarge dictates the amount of hoverbarges that have to be applied.

5.3.4 Walnut concept

During displacement of the walnut shell the friction force is calculated as a normal force multiplied by the tangent of the external friction angle. The horizontal friction force on the shell is determined by the vertical load and a friction factor. Due to the shape of the shell, a circular circumference, in this study no distinction is being made in the direction of movement. I.e. displacement in any direction in the horizontal plane will require the same amount of force for a single platform.

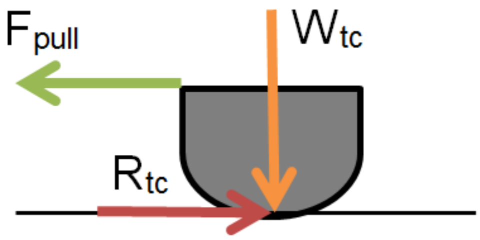


Figure 5-14: Schematic view forces acting on walnut concept.

The friction force is determined with:

$$R_{tc} = W_{tc} \cdot \tan(\delta) \quad (23)$$

R_{tc}	=	Resistance per walnut concept	[N]
W_{tc}	=	Weight force per platform	[N]
δ	=	External friction angle	[-]

5.3.5 Wheeled platform

The wheels of the platform will be equipped with a caster set-up. A caster wheel is wheeled device that enables relatively easy rolling movement of the object.
Main idea is that the total floating capacity of the wheels is not sufficient to enable floating of the platform when in water. The wheels will stay in contact with the soil surface, even when in water. The wheels provide a holding force to withstand the hydrodynamic forces.

Swiveling, or turning resistance
Manufactures design caster with an offset to reduce the force required to turn and swivel. The offset design, meaning the wheel is laterally offset from the point where the caster housing connects to the equipment, provides a horizontal lever arm between the equipment and the point where the wheel contacts the ground. Without this offset, a swivel caster would not swivel unless the equipment was moved in an arc. With the offset lever arm, a horizontal force applied to the equipment acts through the lever arm to the wheel with much greater ease and with a much smaller arc or travel. When fine positioning a piece of equipment, the small travel arcs are very desirable.

A well designed and maintained caster will have low frictional resistance to turning at the bearings in the caster housing, so the real friction force concern is related to any pivoting at the wheel/ground interface.

For the application for this study the caster has to be able to rotate as well as rolling (movement in x and y direction). A swivel caster with a pivot point will be applied.

Rolling resistance: forces that resist movement:

- Inertial forces
- Physical interference
- Friction forces
    - The axle-wheel interface
    - Swivel housing (for swivel casters)
    - Ground-wheel interface when a wheel is slid or pivoted on a surface

Figure 5-15 shows an overview of the forces that resist movement.

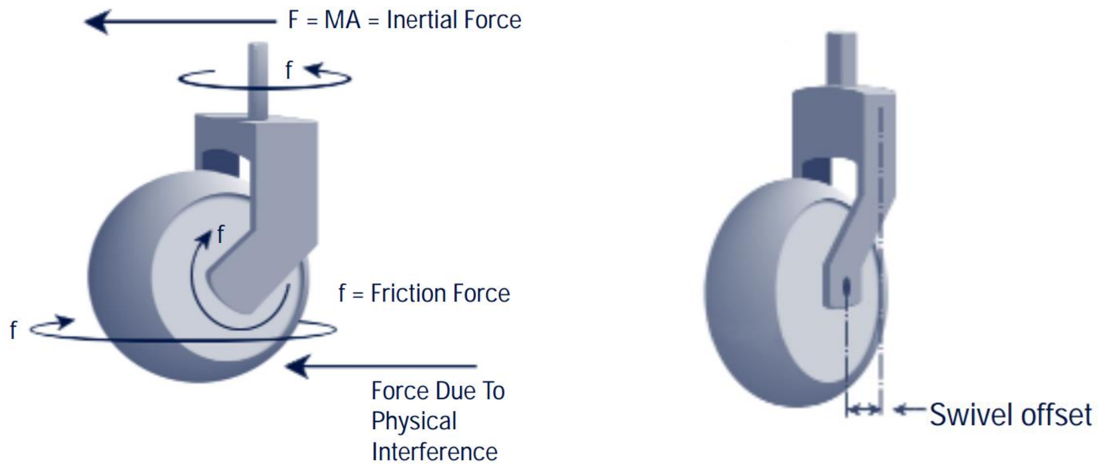


Figure 5-15: Caster wheel set up, and overview acting forces. (Source: *Darcor et al, 2001*)

To determine the rolling resistance this study will focus on the ground-wheel interaction when the platform is being displaced. Reason being is that it is expected that friction at the axle-wheel interface and the friction in the swivel housing will be much smaller than the resistance force caused by the compaction of the soil surface.

<u>Calculation resistance force</u>
The theory of Bekker (*Ding et al, 2015*), presented in section 5.1.2, will be used to determine the soil compaction force caused by movement of the wheel.

The input parameters are:

- Width wheel
- Radius wheel
- Amount of wheels

Goal is to minimize the resistance force. By adjusting the input parameters the resistance force can be minimized.

The force required to overcome the rolling friction is according to (*Wein, 2014*):

$$F_{rf} = \frac{f \cdot W}{R} \tag{24}$$

F_{rf}	=	Rolling force	[N]
f	=	Coefficient of rolling friction	[-]
W	=	Wheel load	[N]
R	=	Wheel radius	[m]

The amount of wheels has consequences for the individual load per wheel assuming a constant load per platform.

What can be seen from (*Equation 24*) is that a large wheel radius is favorable in order to decrease the rolling force. A larger wheel radius requires a smaller force to encounter obstacles compared to a smaller wheel radius.
However, push and pull forces are greater with larger wheels when swivel wheels are not aligned in the direction of travel (*Wein, 2014*). When the wheel swivels in a soil a bulldozer action can be noticed at the soil-wheel interface. This dozing effect increases the required force to displace the wheel.
I.e. there is an optimum regarding the wheel radius and the required force to displace the platform.

5.3.6 Conclusion

To determine the amount of resistance force encountered for each platform concept the numeric input values from the workability assessment by applying a test case (will be performed in Chapter six) will be used to generate numeric output. Reason being is the ease of comparing the numeric values to determine the concept with the least amount of resistance.
What can be seen of the theoretical review is the hover barge will have a very low resistance force compared to the other concepts.

5.4 Hold position in water

When water is present the pipeline system is subject to forces exerted by the water. These forces have an effect when the pipeline system needs to hold position.
The water exerts the following forces on the pipeline system:

- Currents
- Waves

Wind also plays a role and when the pipeline is afloat, and the pipeline system is not a straight line the impulse from the mixture flow will cause impulse forces at bends in the pipeline system. This effect can also be seen in the uncontrolled movement of a garden hose.
Below the mentioned forces are treated.

5.4.1 Current forces

When a current attacks a pipeline, it will be subject to a force. The force can be split into two elements, a drag force F_D, and a lift force F_L. Reference is made to Figure 5-16.

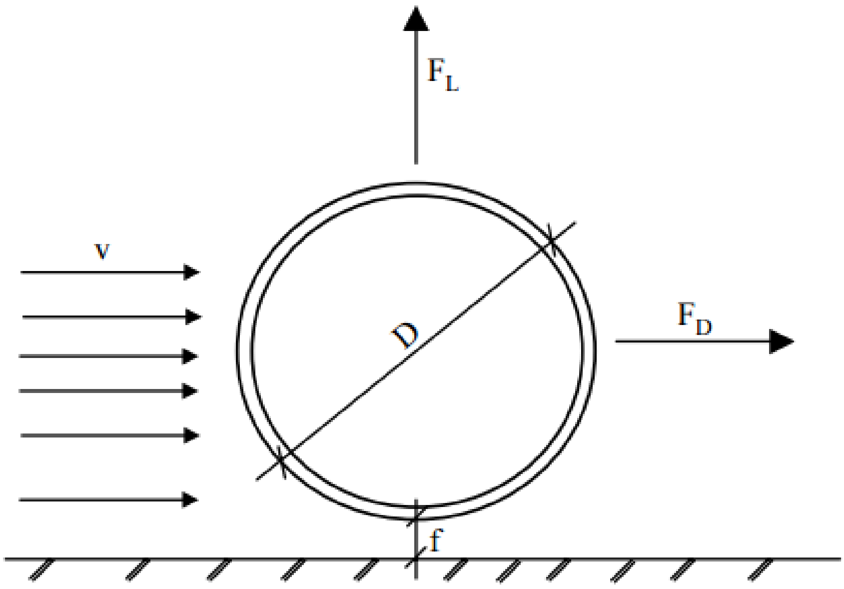


Figure 5-16: Current forces acting on a pipeline. (Source: *Pipelife Norge AS, 2012*)

The amplitude of the forces is mainly dependent on:

- Current velocity v
- Pipeline diameter D
- Density streaming water ρ_w
- Distance pipeline above bed f

The forces can mathematically be expressed as follows:

$$F_D = 0.5 \cdot C_D \cdot \rho \cdot |u| \cdot u \cdot D \qquad (25)$$

$$F_L = 0.5 \cdot C_L \cdot \rho \cdot |u| \cdot u \cdot D \qquad (26)$$

With

F_D	=	Drag force	[N/m]
F_L	=	Lift force	[N/m]
C_D	=	Drag coefficient	[-]
C_L	=	Lift coefficient	[-]
ρ	=	Density water	[kg/m^3]
u	=	Current velocity	[m/s]
D	=	Outer diameter pipeline	[m]

The coefficients F_D and F_L are in principle dependent of the Reynolds number and roughness of the bottom.
The Reynolds number can be expressed as

$$R_e = \frac{v \cdot D}{\upsilon} \qquad (27)$$

With

ν	=	Kinematic viscosity of water	[m^2/s]

The drag and lift coefficients for a pipeline laying on the seabed can be taken from graphs as represented in Appendix C.

The lifting force will be reduced as the distance f between pipe and seabed increases. If f = 0.5·D the lifting force will be approximately 10% of the lifting force for a pipeline lying directly on the seabed.

<u>Floating pipeline</u>
The drag coefficients presented in Figure 5-17 are valid for objects which are situated not close to the bottom or water surface. The VOUB-course (*VOUB, 1998*) suggests increasing the drag coefficients by 50% for objects situated close to the bottom or water surface in order to account for the extra drag effects.
Since a floating pipeline is situated at the water surface, the increased drag coefficient will be applied.

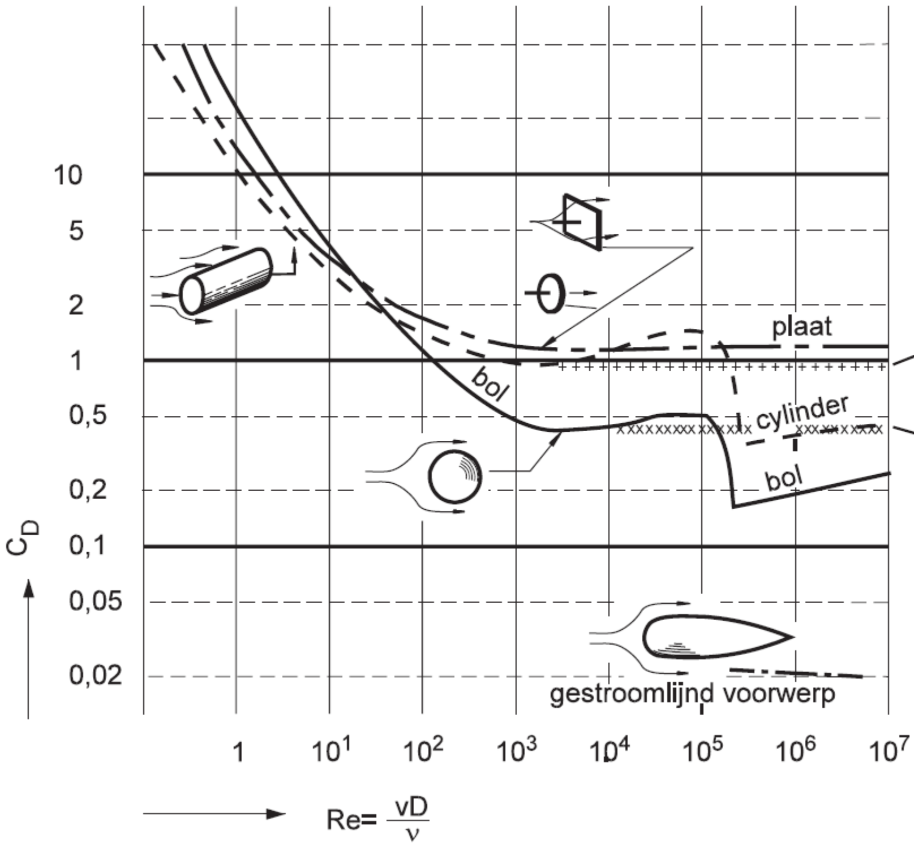


Figure 5-17: Drag coefficient C_D = f(Re). (Source: *VOUB, 1998*)

5.4.2 Wave force

The pipeline is floating on the water by added buoyancy. Therefore the floating hose is vulnerable to ocean current and waves.
Morison's equation (*Zhang et al, 2015*) is used for estimating the hydrodynamic forces on the relativity slender members of offshore structures. The equation is a semi-empirical formula based on flow theory, and assumes that the small-scale marine structure has no significant effect on the wave motion. The effect of waves on the structure is mainly composed of viscous effect and the added mass effect.
Morison holds that the wave-induced force consists of an inertia term (depending in wave acceleration) and the drag term (depending on square velocity).

Waves will apply big forces on a pipeline installed directly on the seabed. The main parameters involved are:

- Wave height
- Wave period
- Pipe diameter
- Distance between pipe and sea bottom
- Angle between pipeline and the wave's moving direction
- Depth of water
- Condition of seabed

There are several theories, but a common feature is the dividing force of the force components into three elements (*Pipeline Norge AS, 2012*):

- Drag force
- Lift force
- Inertial force

The movement of the water particles dictates the impact of waves on the pipeline.

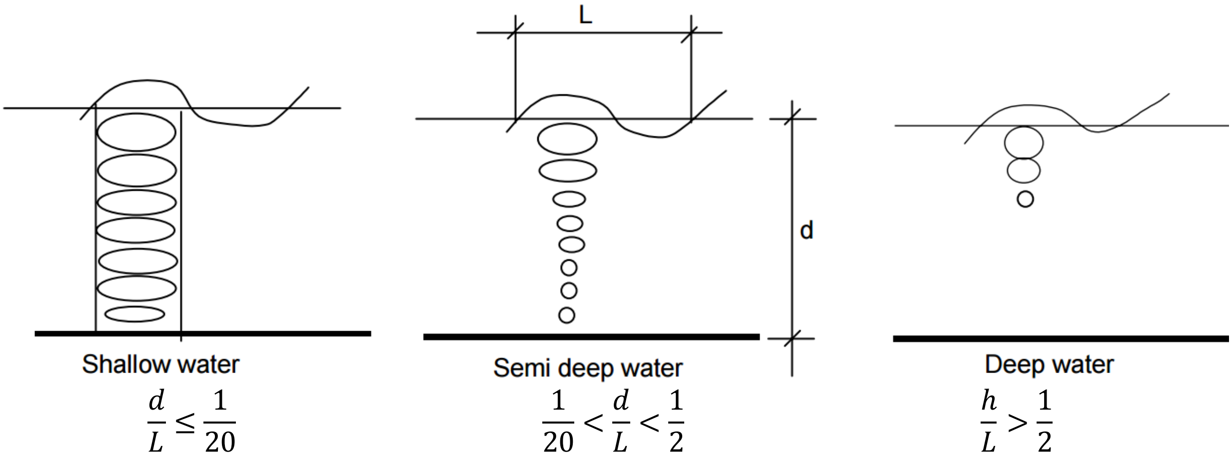


Figure 5-18: Movement of water particles in a wave. (Source: *Pipelife Norge AS, 2012*)

To check the stability of the pipe it is sufficient to know the extreme values of the force components. It is expected that the ASP will be working in small water depths, so a shallow water approach will be used in this study. This have to be checked based on the expected wave length.

The force components could be determined as follows (*Pipelife Norge AS, 2012*):

$$F_i = \pi \cdot C_i \cdot f \cdot \gamma \cdot \frac{\pi \cdot D^2}{4} \cdot \frac{H_0}{L_0} \qquad (28)$$

$$F_D = C_D \cdot f^2 \cdot \gamma \cdot \frac{\pi \cdot D^2}{4} \cdot \frac{H_0}{L_0} \cdot \frac{H_0}{D} \qquad (29)$$

$$F_L = C_L \cdot f^2 \cdot \gamma \cdot \frac{\pi \cdot D^2}{4} \cdot \frac{H_0}{L_0} \cdot \frac{H_0}{D} \qquad (30)$$

F_i	=	Inertial force	[N/m]
F_D	=	Drag force	[N/m]
F_L	=	Lift force	[N/m]
f	=	Refraction factor	[-]
C_i	=	Inertial coefficient	[-]
C_D	=	Drag coefficient	[-]
C_L	=	Lift coefficient	[-]
γ	=	Specific gravity of water	[N/m^3]
D	=	External pipe diameter	[m]
H_0	=	Wave height on deep water	[m]
L_0	=	Wave length on deep water	[m]

It is assumed that the waves will approach the pipeline perpendicular.

Force coefficients

The coefficients C_i, C_D and C_L are dependent of the distance between the pipeline and the seabed. If there is a passage for the water under the pipeline, the coefficients will be reduced.

Some practical values are presented in

Table 5-1.

Table 5-1: Force coefficients for waves. (Source: *Pipeline Norge AS, 2012*)

Coefficient	Distance to bottom = 0	Distance to bottom ≥ D/4
C_i	3.3	2
C_D	1	0.7
C_L	2	0

Refraction factor
This factor tries to describe how waves are influenced by the bottom conditions when the waves are approaching the shore. The factor can be expressed as:

$$f = \frac{2 \cdot a}{H_0} \cdot sin\alpha \qquad (31)$$

a = Wave particles amplitude in orbit at the bottom
α = Angle between wave's speed direction and pipeline

5.4.3 Wind

The wind profile shows a logarithmic profile as presented in Figure 5-19. In case of a floating pipeline the pipeline will not protrude much above the water surface. It is expected that the wind will not exert much force to the pipeline system because the wind speeds close the water surface are limited, as can be seen in the figure aside.
Also the wind is included in the current and wave forces (as the wind speed increases, also the current and the wave force will increase) the wind force is not included in the analysis of a floating pipeline.

The platforms, however, will have a larger height above the water surface, and therefore the wind force will experience a bigger wind force. In that case the wind force cannot be neglected.

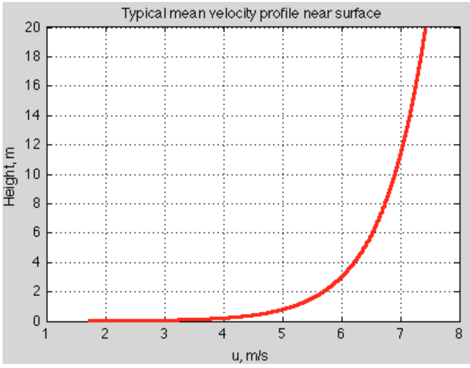


Figure 5-19: Wind speed distribution profile. (Source: *scienceofdoom.com*)

5.4.4 Impulse forces

When a fluid undergoes a change in direction, a change in momentum will be generated. As a result a force is exerted on the pipe wall where the pipeline changes in direction. The product of this force and the time over which it is exerted is called an impulse.
When the pipeline is resting on the soil surface the friction between the soil and the pipeline is probably sufficient to balance the impulse force.
The impulse force is especially of importance when the pipeline system is afloat. An uncontrolled movement of the pipeline might be possible, and needs to be checked.

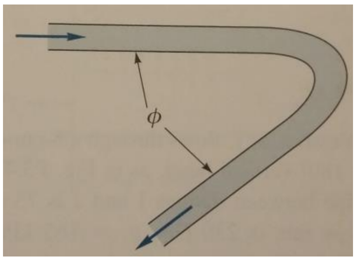


Figure 5-20: Pipe bend

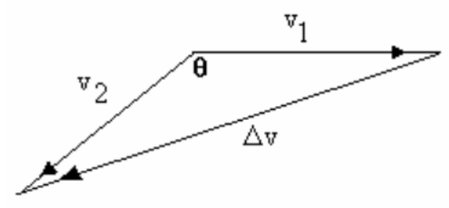


Figure 5-21: Force diagram

Assuming the pipeline diameter doesn't change along the trajectory of the pipeline, and ignoring friction, the ingoing velocity v_1 will be same as the exit velocity v_2. The velocity difference Δv is represented in Figure 5-21, whereby the fluid changes direction over an angle of Φ.
The impulsive force F_{impuls} is determined by multiplying the mass flow rate ṁ with the velocity difference Δv. In equation form (*Bezuyen et al, 2009*):

$$F_{impuls} = \dot{m} \cdot \Delta v \qquad (32)$$

With

F_{impuls}	=	Impulsive force	[N]
ṁ	=	Mass flow rate	[kg/s]
Δv	=	Velocity difference	[m/s]

Mass flow rate ṁ is calculated with:

$$\dot{m} = \rho_{fluid} \cdot A_{pipeline} \cdot v \qquad (33)$$

With

ρ_{fluid}	=	Density mixture	[kg/m^3]
$A_{pipeline}$	=	Cross sectional area pipeline	[m^2]
$v_{mixture}$	=	Mixture velocity	[m/s]

The mixture velocity is assumed to be the same over the entire regarded section as represented in Figure 5-20. This velocity will be determined in section 5.5.1.

The velocity difference Δv is determined with the following formula:

$$\Delta v = \sqrt{(v_1 + v_{2\,horizontal})^2 + (v_{2\,vertical})^2} \qquad (34)$$

Special attention must be paid at the orientations of the velocities.
v_2 is decomposed in a horizontal and a vertical part by making use of angle ø in Figure 5-20.

5.4.5 Conclusion

Since this study is all about depositing material in shallow waters on the interface of water and land it is expected that the hydrodynamic force in this very shallow areas won't be very significant. However, the water depth is hard to predict due to the (wind) surges.
The workability assessment (reference is made to the following chapter) will apply data how well the pipeline system can hold position. For instance the water depth at point A can be significant so a part of the pipeline have to be positioned on the bottom of the soil surface. In this way a holding force can be created, decreasing the amount holding force on the rest of the pipeline system. This will be elaborated in Chapter six.

5.5 Required amount of displacement

During depositing of material the amphibious spray pontoon have to be repositioned, both on land as in water. Especially on land this is of importance because displacement of the pipeline system on land requires much more effort compared to displacement in water. The amount of repositioning on land should therefore be reduced to a minimum.
Question that follows from this is how often the spray pontoon has to be displaced. And if so, what are the horizontal distances? The amount of movement of the ASP dictates the amount of movement of the pipeline system because the two are coupled to each other.

In order to answer the questions how often and how much movement of the ASP is required, an analysis of the production is presented.
The production by dispositioning depends amongst others on the following aspects:

- Solids production, both in pipeline and in-situ
- Required layer thickness to be sprayed
- Critical mixture velocity in pipeline
- Mixture density
- Behavior sand-water mixture when depositing sand, both in water and on land
- Slope gradient.

By first determining the solids production (and related to that the minimum mixture velocity) next the in-situ production is determined. From the in-situ production the occurring slope gradients could be calculated. This is of importance because it dictates the distance the material travels (range of influence). Also the bottom gradient has influence on the movement of pipeline system (uphill) and could be a requirement for the degree of freedom in the pipeline system.

5.5.1 Mixture velocity and solids production

The concepts have to be able to cope with the commonly applied pipeline diameters in the dredging industry. The mixture flow velocity in the pipeline must be at a certain minimum in order to prevent sedimentation in the pipeline. Clogging of the pipeline must be avoided at all times.
For a first estimation of the limit deposit velocity in a pipeline the following formula is used (*Miedema, 2016*):

$$v_m = 7.5D^{0.4} \quad (35)$$

With

v_m	=	Limit deposit velocity	[m/s]
D	=	Internal diameter pipeline	[m]

To be on the safe side (because clogging must be avoided at all times) the limit deposit velocity will be increased by 10%. This also allows for fluctuations in the production process.

The transport factor can be determined with:

$$f_t = \frac{v_s}{v_m} \quad (36)$$

With

f_t	=	*Transport factor*	*[-]*
v_m	=	*Mixture velocity*	*[m/s]*
v_s	=	*Velocity solids*	*[m/s]*

(*Miedema, 2016*) assumes that there is almost bed present in the pipeline. I.e. all the sediment particles are in suspension. This translates to a transport factor f_t = 1. The velocity of the solids is the same as the mixture velocity.

The volumetric flow rate of mixture is calculated as follows:

$$Q_m = A v_m \tag{37}$$

With

Q_m	=	Volumetric flow rate of mixture	[m³/s]
A	=	Cross sectional area pipeline	[m²]
v_m	=	Mixture velocity	[m/s]

The volume concentration that the sediment particles occupy in the mixture that is transported through the pipeline is as follows:

$$C_v = \frac{\rho_m - \rho_f}{\rho_s - \rho_f} \tag{38}$$

With

C_v	=	Volume concentration	[-]
ρ_m	=	Mixture density	[kg/m³]
ρ_f	=	Water density	[kg/m³]
ρ_s	=	Solids density	[kg/m³]

Finally the volumetric flow rate of solids at the outflow of the pipeline could be calculated:

$$Q_s = A C_v v_s \tag{39}$$

With

Q_s	=	*Volumetric flow rate of solids*	*[m³/s]*
A	=	*Cross sectional area pipeline*	*[m²]*
C_v	=	*Volume concentration*	*[-]*
v_s	=	*Velocity solids*	*[m/s]*

5.5.2 In-situ production

In order to determine how often the amphibious spray pontoon has to be repositioned during production, the in-situ production has to be known. To determine the in-situ production the following aspects have to be known:

- the solids production Q_s at the outflow of the pipeline
- the wet density of the deposited solids ρ_{si}
- The porosity of the deposited solids n
- The effective sedimentation of the solid particles. I.e. amount of losses into the surrounding water body have to be calculated. Q_{s_eff}.

A method to determine Q_s has already been suggested in section 5.5.1.
The wet sand density of deposited solids will be about 2,000 kg/m³ (*Matousek, 2004*). This corresponds to a porosity n of:

$$n = \frac{\rho_s - \rho_{si}}{\rho_s - \rho_f} \tag{40}$$

With

n	=	*Porosity of soil*	*[-]*
ρ_s	=	*Density of solid grains*	*[kg/m³]*
ρ_{si}	=	*Density of soil in-situ*	*[kg/m³]*
ρ_f	=	*Density of water*	*[kg/m³]*

In (*Mastbergen et al, 1988*) distinction is being made between periods of rising water and periods of falling water.
During rising water, the mixture often spreads out over a series of terraces and cascades. The terraces and cascades are moving slowly upstream.
Apparently sedimentation occurs before the flow meets the water. The sediment concentration C_v decreases considerably to about 10% by volume during the flow from pipeline to the waterline.

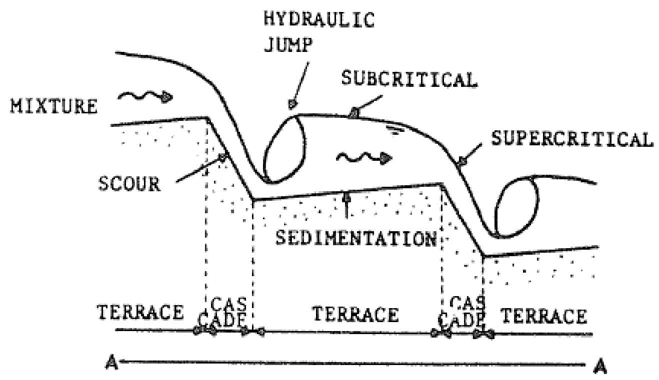


Figure 5-22: Longitudinal section during rising water. (Source: *Mastbergen et al, 1988*)

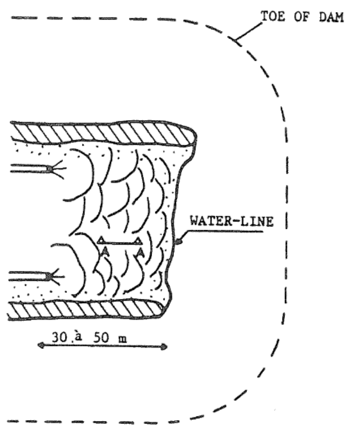


Figure 5-23: Plan view of depositing sand during rising water. (Source: *Mastbergen et al, 1988*)

During periods of falling water the flow often concentrates in meandering channels, a few meter wide and up to one meter deep. The solid concentration in the channel is and stays about the same as in the delivering pipeline. Most of the solids are transported to the water through the channels. The solids will deposit after flowing in the stagnant water body. As a result the underwater slope is building out quickly.

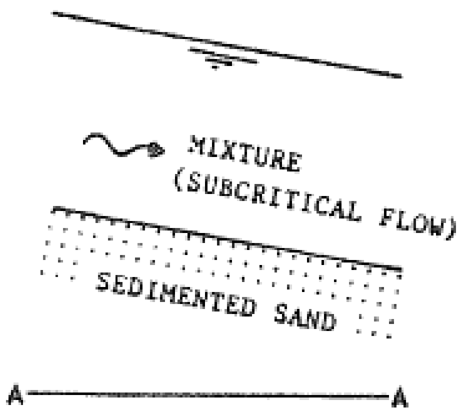


Figure 5-24: Longitudinal section during falling water.
(Source: *Mastbergen et al, 1988*)

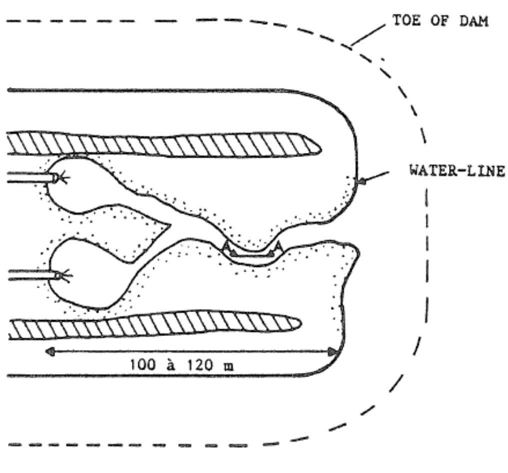


Figure 5-25: Plan view of depositing sand during falling water.
(Source: *Mastbergen et al, 1988*)

$C_{v\,end}$ decreases to a certain value; the volume concentration $C_{v\,pipeline}$ in the pipeline is related to the mixture density in the pipeline, so a C_{v_eff} of $C_{v\,pipeline}$ - $C_{v\,end}$ will deposit from the pipeline exit along the way towards the waterline.

Q_{s_eff} can be calculated with:

$$Q_{s\_eff} = Q_s \frac{C_{v\_eff}}{C_v} \quad (41)$$

With

Q_{s_eff}	=	*Effective volumetric flow rate of solids*	*[m³/s]*
Q_s	=	*Volumetric flow rate of solids*	*[m³/s]*
C_{v_eff}	=	*Effective volume concentration*	*[-]*
C_v	=	*Volume concentration*	*[-]*

During deposition of the solids a body of solids will be formed. Figure 5-26 represents this phenome. The body of solids has a certain porosity n because during depositing the solids leave a certain space between each other. This body of space will be filled with air or water in case of submerged deposition.
A typical value for n is 0.40 or 40% according to (*Matousek, 2004*). I.e. 60% of the total body volume is occupied with solids.

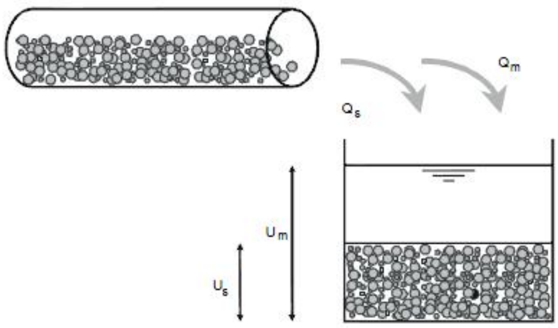


Figure 5-26: Definition of volumetric delivered concentration. U_s = volume fraction of solids in mixture. U_m = total volume of mixture. Spatial concentration > delivered concentration. (Source: *Matousek, 2004*)

Spatial concentration = transport concentration and refers to the instantaneous local conditions inside the pipeline.
Delivered concentration refers to the slurry state at exit from the pipeline.

The effective volumetric flow rate of solids Q_{s_eff} is already known. This is the total volume rate of solids without pores. 60% of U_s is known and U_s is the desired parameter that one want to know in order to determine production values.
The delivering production Q_d is:

$$Q_d = Q_{s\_eff} \frac{1}{1-n} \quad (42)$$

With

Q_d	=	*delivering volumetric flow rate of a solids body*	*[m³/s]*
Q_{s_eff}	=	*effective volumetric flow rate of solids*	*[m³/s]*
n	=	*porosity*	*[-]*

When the minimum spray thickness has to be sprayed the theoretical production area per hour could be determined. The outcome is an indication how much the amphibious spray pontoon has to move within a specified time frame.

5.5.3 Slope gradient

When sand is sprayed / deposited a resulting slope will develop. This slope has to be known in order to calculate how much sandy material is needed in order to construct the desired design. Also this slope has an indicative value in the determination of the horizontal velocity of the spray pontoon.
If a slope develops that has a small gradient, the spray pontoon has a wide reach and therefore the pontoon doesn't have to be displaced that often compared to a slope with large incline.

According to (*Mastbergen et al, 1988*) the underwater slope is generally being steeper than above water. The gentlest slopes are being observed in the tidal zone.

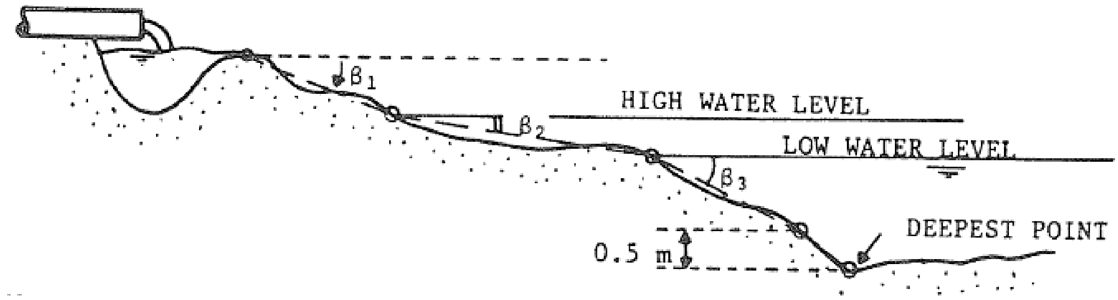


Figure 5-27: Gradient definitions. (Source: *Mastbergen et al, 1988*)

In Figure 5-27 the slope definitions are represented. β_1 is the slope above water. β_2 the slope in the tidal zone and β_3 is the slope under water.

β_1 depends on the diameter of the grains and the volume discharge of the sand water mixture per unit width. Coarse sand will adopt a gradient of about 1:20 and the gradient will decrease to 1:100 for very fine sands (*VOUB, 1998*).
In (*Mastbergen et al, 1988*) β_1 is 1:28,5 for sand with D_{50} of 210 µm.

β_2 is in (*Mastbergen et al, 1988*) 1:40 for sand with D_{50} of 210 µm.

In the same study β_3 is 1:25 for the same sand properties as for β_1 and β_2.
Nearly all the sand settled within a relatively distance (10 to 50 m) from the waterline, so at the upper part of the underwater slope.
Steeper slopes are being formed with smaller sand transport rates and coarser grain sizes. Influence of grain size is strong and the influence of the sand transport is less clear: a wide scatter can be observed. This can be explained by the occurrence of flow slides in the case of fine sand.

5.5.4 Speed of repositioning

The in-situ production and the gradient which the deposited material assumes are determined.
This study assumes that by depositing the material a cone shaped profile will be created. Figure 5-28 represents the set-up of the deposit method.
When the required layer thickness is deposited, the spray pontoon needs repositioning.

The layer thickness is the height of the cone. The gradient determines the radius of the cone. Once the radius is known the volume of the cone can be calculated.
By dividing the volume of the cone by the in-situ production the duration to fill one cone is determined. Once the desired height is reached, the spray pontoon has to be repositioned by

two times the cones' radius. In this way the horizontal velocity can be determined. In formula form:

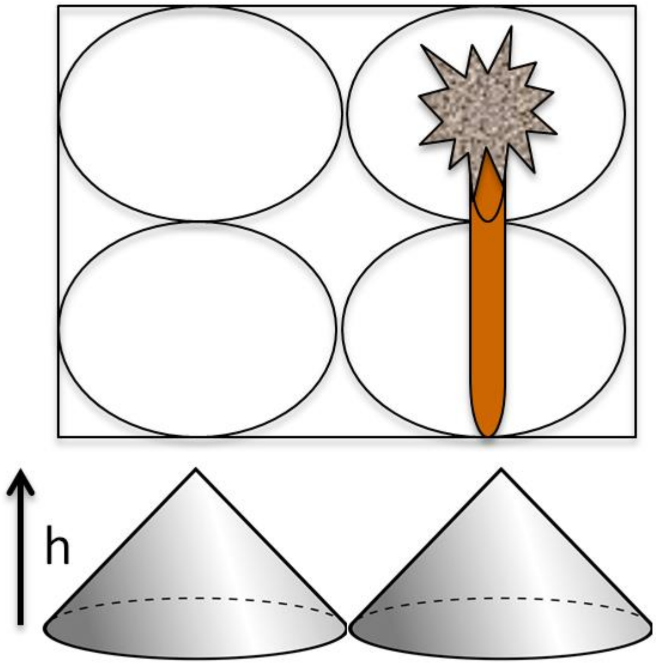


Figure 5-28: Set-up of deposit method.

$$V_{cone} = \pi \cdot \frac{h}{3} \cdot r^2 \tag{43}$$

With

V_{cone}	=	Volume cone	[m^3]
h	=	Layer thickness	[m]
r	=	Radius base conus	[m]

Horizontal velocity spray pontoon is determined by:

$$v_{ASP} = \frac{2 \cdot r}{\frac{V_{cone}}{Q_d}} \tag{44}$$

With

v_{ASP}	=	Horizontal velocity spray pontoon	[m/s]
r	=	Radius base conus	[m]
V_{cone}	=	Volume cone	[m^3]
Q_d	=	Delivering volumetric flow rate of a solids body	[m^3/s]

5.5.5 Conclusion

The required amount of displacement, i.e. the hauling velocity of the spray pontoon, follows from (*Equation 44*). The pipeline system has to be able to follow the spray pontoon, however not the whole pipeline system have to be displaced if there is flexibility available in the pipeline system.

Regarding production a review period of one week will be considered. This period will determine the amount of volume that is available at point A. Together with the deposit slope gradient the total area of one week of production can be determined.
In this way the amount of flexibility needed, and there with the amount of platforms can be determined.

5.6 Pipeline set-up

In this section first an explanation will be given why flexibility have to be created in the pipeline system. Next an elaboration is given how to generate flexibility. Lastly the pipeline set-up is discussed.

5.6.1 Flexibility in the pipeline system along section A-B

When multiple pipeline segments are coupled to each other, this has consequences for the freedom of movement of the pipeline system. For instance the degree of freedom will be reduced.
If a straight pipeline system is applied between point A and point B, and the spray pontoon (= point B) has to be repositioned, the entire pipeline system have to be repositioned because of the rigid setup behavior.
When the deposition area is flooded, the assumption is that the floating rigid pipeline system could be repositioned quite easily. Things changes when no water is present and the pipeline is resting on the soil surface.

In order to decrease the total resistance force to displace the pipeline system flexibility in the pipeline system has to be created. The idea is that instead of displacing the entire pipeline length along section A-B when the spray pontoon has to be displaced but that only the part of the pipeline system located close at/near the spray pontoon needs repositioning.

Figure 5-29 gives a nice representation of the flexibility created along the pipeline system. The dredger is able to move forward and from side to side while the outflow of the pipeline end remains on the same spot. It can be concluded that not the entire pipeline system have to be displaced. The total resistance force is therefore smaller.

Figure 5-29: Example of pipeline flexibility.

5.6.2 Generating flexibility

Generating flexibility in the pipeline system can be created as follows:

- Steel pipelines and their connections are assumed to be rigid. In order to generate flexibility in the pipeline system, ball joints are applied in the pipeline system. These ball joints enable a certain amount of freedom in the horizontal plane as can be seen in Figure 5-33.
- Instead of applying steel pipelines, rubber pipelines could be used (Figure 5-31). These rubber pipelines can offer a degree of freedom in the horizontal x-y plane. The connection between the rubber pipeline segments is assumed to be rigid.

Figure 5-30: Pivot point.
(Source: *dredgingtoday.com*)

Figure 5-31: Rubber pipeline.
(Source: *dredgingtoday.com*)

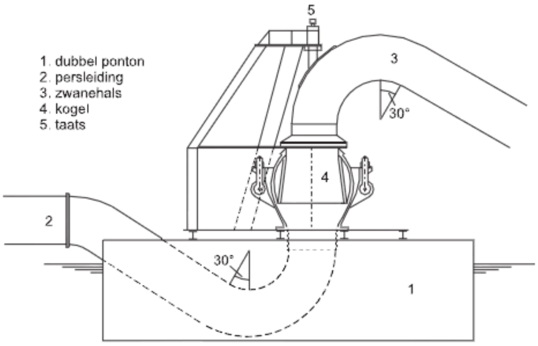


Figure 5-32: A so called 'Swan neck'
(Source: *VOUB, 1998*)

Figure 5-33: Example of a ball joint.

Ball joints such as in Figure 5-33 will allow a maximum rotation of twenty degrees seen from the axial axis of the pipeline between two pipeline segments. If multiple ball joints are placed along the pipeline system, flexibility can be created.
If a larger rotation is required, a 'Swan neck' (Figure 5-32) has to be integrated in the pipeline system. A maximum rotation of almost 360 degrees can be created with this set-up.
The required amount of flexibility of the pipeline system will differ per project. The displacement velocity of the spray pontoon (depends on the in-situ production and required layer thickness), duration flooding of the deposition area, water depth, and construction phase will differ from one project to the other.

By applying a test case the total length of pipeline system is known. Together with the mentioned aspects the required amount of flexibility can be determined. In this way the amount of ball joints and pivot points can be calculated. This will be elaborated in Chapter six.

5.6.3 Pipeline set-up

To determine the set-up of the pipeline the working method of depositing the material into the desired design has to be known. The working method depends amongst others on the available water depth, and when material is available at point A. The availability of material at point A can be extracted from the dredging cycle. The dredging cycle states when and how long it takes to discharge the material from the dredger.
By plotting the water levels (or the water depth) and the dredging cycle in one graph the available water depth during discharge of the dredger is known.

In the figure below an example is given of a possible pipeline set-up.

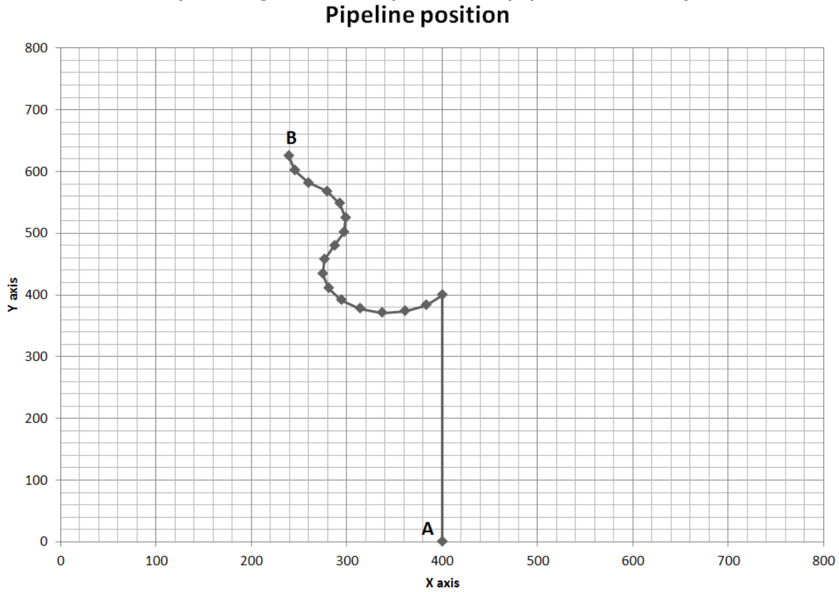


Figure 5-34: Example of a pipeline set-up.

It's desired to minimize the amount of displacement of the pipeline system. In the dredging practice it is common to deposit material in a rectangular shape. I.e. by moving point B in Figure 5-34 from left to right, and vice versa. After each cycle point B has to move in the y-direction in order to deposit the adjacent layer.
During a meeting with Professor van Rhee (*Progress meeting, March 14-th, 2017*) the suggestion was made to take a review period of one week regarding discharging. In this week no adaptation of the pipeline length is allowed. I.e. point B must have the ability to deposit an area that is available from the production of the dredger in a period of one week time.

At first glance the most promising pipeline set-up is to construct a rigid pipeline from point A to half the deposit area in y-direction. At the center point a ball joint will be installed that allows 360 degrees of flexibility (Figure 5-33). From this ball joint towards the spray pontoon (represented as point B in Figure 5-34) the pipeline will be supported by platforms. Reference is made to Chapter four for the platform concepts. The most promising concept regarding the platform has yet to be determined. This will be done in Chapter seven.
To allow for flexibility between the platforms a ball joint will be installed.
In this way the pipeline system will have the properties of an accordion. With this set-up the spray pontoon able to reach every spot during one week of depositing, covering the whole area with material deposits.

The test case will supply numeric input. The amount of displacement needed, and therefore the pipeline set-up will be checked, and optimized further on.

5.7 Tractive effort per amphibious spray pontoon concept

As described in Chapter 3 'Depositing material' the most promising concept for depositing material on the interface of water and land is an amphibious spray pontoon. From Chapter 4 'Delivering material from A to B' the most promising method to deliver material to the spray pontoon is a pipeline. To displace the pipeline, the spray pontoon has to be able to generate a pull or push force. Pushing or pulling comes down to tractive effort.
It should be noted that the required amount of tractive effort is determined by the pipeline set-up and characteristics.

Four concepts regarding the amphibious spray pontoon have been developed. All concepts use different techniques to displace the spray pontoon. The tractive effort for each displacement technique will differ, and therefore needs investigating.
Below per displacement technique for the amphibious spray pontoon the tractive effort to be generated on land is presented.

5.7.1 Track system

There are several empirical methods to existence for evaluating tracked vehicle performance (*Wong, 2010*).
In developing the methods, vehicles were tested in a range of terrains, primarily fine –and coarse grained soils.

If the normal pressure on the track is uniformly distributed, as shown in Figure 5-35, and the

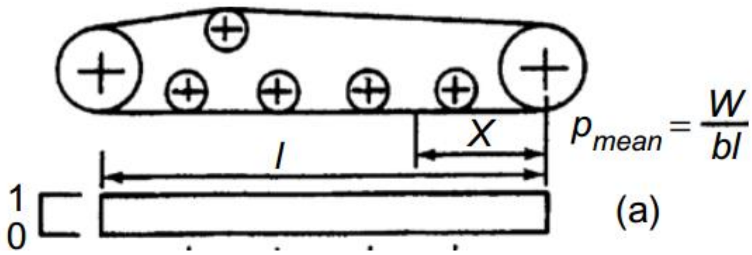


Figure 5-35: Idealized normal pressure under a track. (Source: *Wong, 2010*)

stress-shear displacement relationship is described by the simple exponential equation the tractive effort F of a track with a flat contact surface can be expressed by (*Wong, 2010*):

$$F_{tractive} = A \cdot c + W \cdot \tan(\varphi) \cdot [1 - \frac{K}{i \cdot l} \cdot \left(1 - e^{\frac{-i \cdot l}{K}}\right)] \qquad (45)$$

Where

A	=	Contact area track	[m]
b	=	Contact width track	[m]
l	=	Contact length track	[m]
c	=	Cohesion	[Pa]
φ	=	Angle of shearing resistance	[deg]
K	=	Shear deformation parameter	[m]
i	=	Track slip	[%]
W	=	Normal load on the track	[N]

As a first order estimation of the tractive effort of a track system, a uniform distributed load is assumed.
In Figure 5-36 the effects of a normal pressure distribution on the tractive effort (thrust) of a track on sand are represented. From the figure it can be seen that the maximum tractive effort is reached at high values of slip. The asymptote value is W·tanø.

(Equation 45) reduces to:

$$F_{tractive} = A \cdot c + W \cdot \tan(\varphi) \tag{46}$$

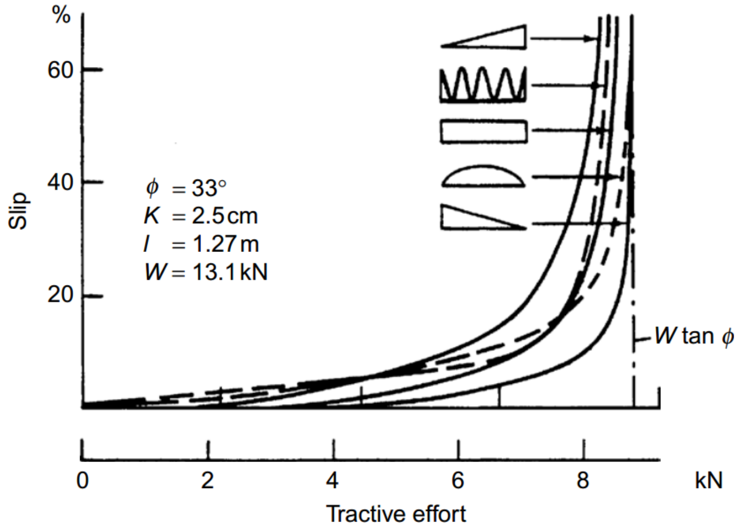


Figure 5-36: Effects of normal pressure distribution on the tractive effort (thrust) of a track on sand. (Source: *Wong, 2010*)

From the predicted tractive effort and the motion resistance encountered during displacement, the drawbar pull as a function of slip and the overall tractive performance of the vehicle can be determined. I.e.

$$F_{pull} = F_{tractive} - R_c \tag{47}$$

The method to calculate the compaction resistance R_c for a track system is already given in section 5.3.1.

5.7.2 Archimedes screws

To determine the jointly tractive effort in x-direction (F_x) of a platform with two Archimedes screws a method is developed by (*Nagaoka et al, 2010*):

$$F_x = \sum sgn(\omega) \cdot F \cdot \cos(\eta) \tag{48}$$

With

$$F = b \cdot R \cdot \sin(\eta) \cdot \int_{\theta_r'}^{\theta_f} (\tau \cdot \cos\xi - \sigma \cdot sin\,\xi) \cdot d\theta \tag{49}$$

Due to the uncertainties (because of the assumptions made) it's difficult to determine the general dimensions of the Archimedes screws. As a result the input arguments of the Equations (*48*) and (*49*) are holding large uncertainties.
The outcome of (*Equation 48*) will therefore have a small meaning.

In this study it's all about determining the most promising concept for displacing the pipeline. It's about indicating the differences between the concepts.
Regarding the aspect of tractive effort this study wants to know which concept is able to generate the largest tractive effort.
Figure 5-37 represents a graph of the maximum tractive effort (= drawbar pull) a tracked vehicle, a Screw Drive Rover, and a wheeled Vehicle is able to generate.

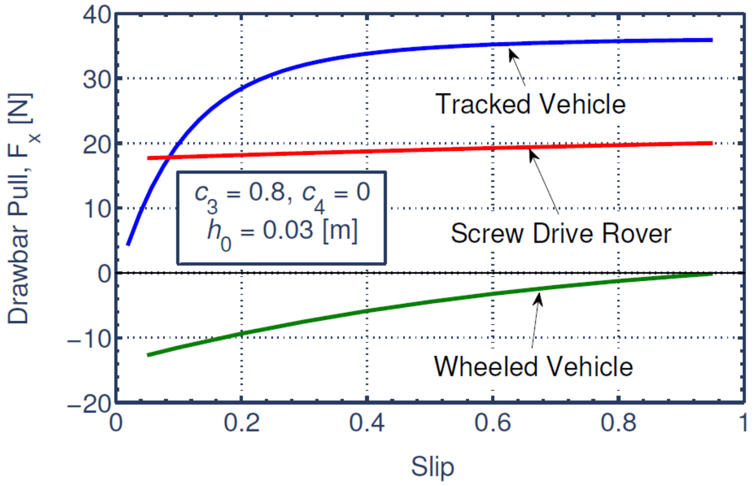


Figure 5-37: Comparative simulation result of Screw Drive Rover model with wheeled and tracked vehicle models. (Source: *Nagoaka, 2011*)

It can be seen that the maximum tractive effort a Screw Drive Rover is able to generate, is smaller compared to a tracked vehicle.
This can be explained since the two installed screws are moving in opposite direction of each other during axial movement of the platform. I.e. the screws are working against each other. The flanges of the screw are mounted with an angle on the circular body. By decomposing the forces it can be noticed that a smaller net force is available for axial displacement.

The difference stated in Figure 5-37 is of importance in the determination of the most promising concept regarding the amphibious technique for the amphibious spray pontoon.

5.7.3 Hoverbarge

During hovering of the hover barge only a very small tractive effort can be generated. Explanation lays in the fact that during hovering, the platform is sort to speak floating. There is only friction present the skirt and the soil surface. When a pull force has to be generated, the opposite force has to come from the soil surface through support.
The hovering pontoon can, so to speak, be displaced by a small push. As a consequence in the opposite direction the pull force is also very small.

To enable a sufficient pull force, an anchor-winch system will be applied. A conventional floating spray pontoon as described in (*De Leeuw et al, 2002*) also uses such a system to enable displacement of the pontoon.
The dimensions of the anchors-winch system follows are amongst others determined by the pipeline system.

This study assumes that the dimensions of the anchor-winch system are such that the system still has acceptable dimensions as this system is often applied in the marine industry.

5.7.4 Watermaster concept

Displacement of the Watermaster concept and therefore tractive effort will be enhanced by a spud pole. A spud pole system is able to generate a push force but question is if this push force is sufficient to displace the spray pontoon, and also the pipeline system. There is big chance that all the push force is required to displace the spray pontoon, and therefore no residual force is left to displace the pipeline.

A large bending moment on the spud pole at the point of penetration into the soil is created. This has consequence for the dimensions of spud pole. It's expected that the spud pole will become too heavy.
An anchor-winch system is needed to generate a big enough tractive force. Regarding the anchor-winch system; the same goes as described in the section above related to the hoverbarge.

5.8 Conclusion

To conclude the theoretical review part; all the aspects regarding the criteria to be used for the multi criteria analysis are reviewed. In this way numeric output values are created.
This output will serve as input for the multi criteria analysis to select the most promising amphibious technique for the spray pontoon.

The most important aspect that follows after the theoretical review is dependency of all the aspects. Choices made for one aspect have a significant effect on the remaining aspects. I.e. this causes large uncertainties in the design process.

Due to large amount of parameters involved and the strong influence of the local conditions on site it will be very hard to determine the most promising concept without the local site conditions.
Therefore a test case will be used. The test case will supply information about the deposit site. In this way numeric input for the theoretical part will be created.
The output of the theoretical part will be used to assign values per criteria for each concept.

In the next chapter a workability assessment will be performed.

Chapter 6

Workability assessment

An approach was chosen to select the most promising method for replenishing material, and to select the most promising concept to displace the pipeline along section A-B.
Numeric values will provide great ease of comparing the scores per criteria for each concept. The multi criteria analysis is able to grade the concepts according to their scores.
Chapter 5 'Theoretical review for pipeline displacement' is holding content to produce numeric output values of the selected criteria. By literature reviews methods are available to produce quantitative values.
However, the literature content is still quite abstract. Therefore a test case will be applied. This test case will provide numerical input for the literature review. The created numerical output will serve as input for the MCA.
It must be stated that the generated numerical output is only applicable for the presented test case. Other projects will have different numeric input values, and as a consequence also different numeric output.

During a progress meeting (*Progress meeting, March 14-th, 2017)* it was decided to apply a test case as suggested by Witteveen+Bos. The selected test case is a sand suppletion project[3] in the Eastern Scheldt estuary, the Netherlands. Arguments for selecting this specific project are the great applicability of the new dredging method, the project is very typical, and the tangibility of the project in The Netherlands. The test case will assess the new dredging method, and allows for checking the increase of workability of dredging projects executed in shallow waters.
Below a short description of the test case is presented.

6.1 Introduction test case

The Eastern Scheldt is an estuary situated in the south-western part of The Netherlands. Since the construction of the Eastern-Scheldt barrier located at the opening of the estuary there is a net deficit of sand because of the restricted flow magnitude. As a result the salt marches in the estuary are eroding, resulting in a decrease of surface area above the mean water level. This will result in a decrease of the aspects ecology and safety; this is an unwanted trend.

The most promising method to compensate for the 'sand hunger' in the Eastern Scheldt estuary is to apply sand depositions in the intertidal region (*van der Werf et al, 2016*). This region is dictated by the area that is between 50% and 80% of the time above water. I.e. the area is between 20% and 50% of the time flooded.
Of all the marches present in the estuary the marsh 'Roggenplaat' is the most affected. This marsh has the most severe erosion of all the marches in the Eastern Scheldt. In Figure 6-1 and Figure 6-2 the location and a top view of the Roggenplaat march is provided.
Due to the erosion the duration of flooding is increased, and this is unfavorable for the flora and fauna on the marsh. In addition the hydraulic loading is increased on the adjacent flood defenses. This may result in a decrease of the safety levels against flooding.
The department of Waterways and Public Works (*Dutch = Rijkswaterstaat*) has therefore decided to apply sand suppletions on the marsh in the period 2017-2018 (*van der Werf et al,*

[3] Execution of the sand suppletion is being planned for 2017-2018 (*van der Werf et al, 2016*)

2016). The total volume of sand to be deposited on the ‘Roggenplaat’ will be around $1.3 \cdot 10^6$ m^3.

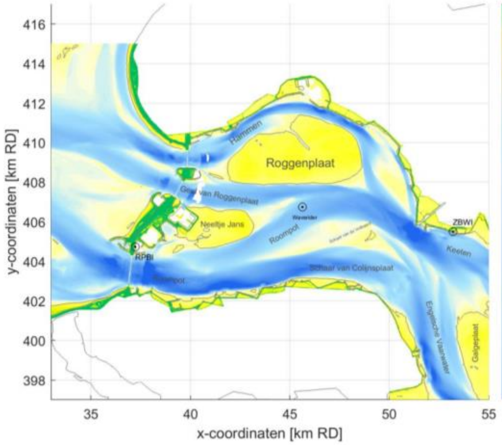


Figure 6-1: Location Roggenplaat. (Source: *van der Werf, 2016*)

Figure 6-2: Aerial view Roggenplaat. (Source: *van der Werf, 2016*)

According to the report ‘Final design Roggenplaat suppletion’ (Dutch: Definitief ontwerp Roggenplaat suppletie) (*van der Werf et al, 2016*) the most promising solution is to replenish sand on the Roggenplaat on six locations, as represented in Figure 6-3. These designated locations are the result of optimizing and balancing all the aspects and values the Roggenplaat is fulfilling. There are two mooring locations where the contractor can discharge the material.

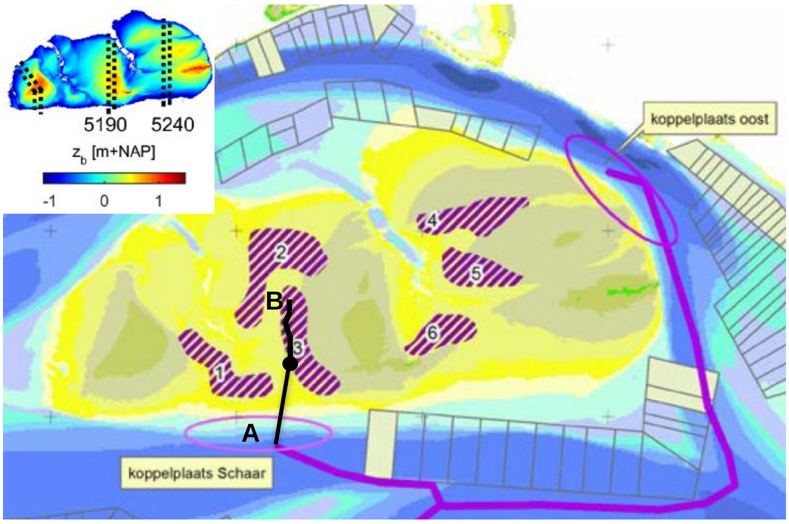


Figure 6-3: Overview suggested deposition areas. (Source: *van der Werf et al, 2016)*

The mooring place located south in Figure 6-3 is point A. A pipeline is running from point A towards the spray pontoon at point B. At the boundary of deposit area number three a ‘Swan neck’ ball joint will be installed to enable the spray pontoon together with the platforms to rotate around the fixed pipeline segments that are lying from A towards the Swan neck ball joint.

6.2 Site conditions

6.2.1 Levels

The water levels at the Roggenplaat vary between -2 m + NAP and 2 m + NAP according to a tide with M_2 characteristics. The Roggenplaat is experiencing high tide twice a day. The same goes for low tide.

The design level height of locations 1, 3, and 6 is 0.67 m + NAP, and for locations 2, 4 and 5 0.30 m + NAP. The locations of the deposit areas are displayed in Figure 6-3.
The cross section profile number 5190 as indicated in Figure 6-3 represents the bed level profile at the deposit areas number 2 and 3.

Figure 6-4 gives an overview of the bed, water, and construction levels at the Roggenplaat at profile 5190.

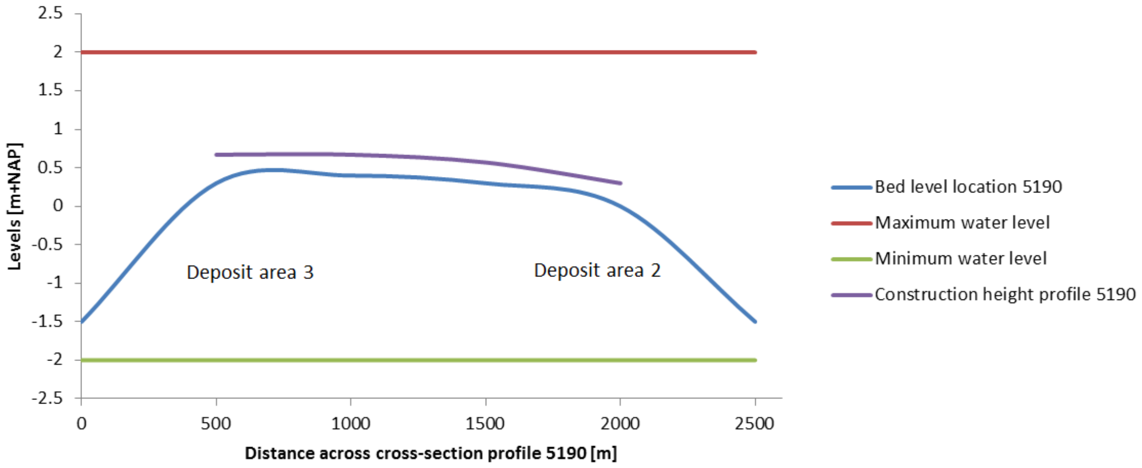


Figure 6-4 Overview bed, water, and construction levels for profile 5190.

Analyzing the initial bed levels and the design bed levels this study assumes that a maximum layer thickness of 0.5 meter have to be deposited.

Due to the limited layer thickness the site equipment have to distribute and level the material over large horizontal distances.
Taking into account the construction height, the water levels and the initial bed levels, it can be concluded that depositing sand is challenging as the construction site is flooded twice per day.

6.2.2 Pipeline length from discharge point to deposit area

According to (*van der Werf et al, 2016*) the maximum distance between the discharge point (i.e. point A) and the deposit point is around 2,200 meter.
This distance is between the discharge point located east of the Roggenplaat and the deposit area number six, see Figure 6-3.
It is assumed that not the entire pipeline length of 2,200 m needs displacing. A review production period of one week is regarded. This period will determine the pipeline length that needs displacing.

6.2.3 Soil properties at the Roggenplaat

The soil surface consists of sand. In this study sand will be used with the following properties:

- Density sand ρ_{soil} of 2,650 kg/m^3
- In-situ density $\rho_{soil\_in\text{-}situ}$ of 2,000 kg/m^3 This corresponds to a porosity of 40%
- Internal friction angle φ is 30 degrees
- Cohesion c is 1,000 Pa
- Shear deformation parameter K of 0.00115 m

The values correspond to sand and are extracted from (*Wong, 2010*).

6.2.4 Hydrodynamic conditions

The hydrodynamic conditions present at or close to the Roggenplaat are as follows:

- The maximum flow velocity u ranges between 0.2 and 0.5 m/s. This study uses 0.5 m/s to check the workability in worst case scenarios.
- The significant wave height H_0 = 0.2 m
- As mentioned in the theoretical review; wind won't be taken into account.

The numerical values are extracted from the report 'T-0 rapportage Roggenplaat Suppletie' (*van der Werf et al, 2016*).

6.2.5 Availability of material at the discharge location

In (*van der Werf et al, 2016*) it is suggested to apply a TSHD with a hopper size of 4,400 m^3. The hopper load per trip inside the hopper is assumed at 3,520 m^3. Arguments for selecting this hopper size are the restrictions that follow from the sluices to access the Eastern Scheldt estuary. This study will apply the same hopper size as suggested by (*van der Werf et al, 2016*).

Details regarding the dredging cycle also follow from (*van der Werf et al, 2016*). The duration to complete one dredging cycle is 250 minutes. Discharging and maneuvering is estimated on 105 minutes. In this study effective discharge duration of 90 minutes will be applied. Reason being is that the effective discharge time dictates the production and as a consequence the amount of displacement of the spray pontoon.
As stated previously a production period of one week will be regarded. This study doesn't account for delays in the dredging cycle due to maintenance, bad weather, breaks downs, and such won't be taken in to account because of the assumptions made together with the uncertainties of the input data. A 24/7 working approach will be assumed. I.e. the amount of production hours per week is 168. Together with the dredging cycle the amount discharges can be calculated.

Regarding the pipeline diameter; an inside diameter of 800 mm will be applied. A mixture density $\rho_{mixture}$ of 1,350 kg/m^3 will be used. This is a reasonable value used in the dredging practice (*VOUB, 1998*).
The pipeline will consist of steel with a wall thickness of 15 mm.

All the remaining numeric values as used in this study are listed in the Nomenclature. Reason being is to improve the readability of the report.

Hereafter the results of the theoretical review are presented.

6.3 Required amount of displacement

To determine the amount of displacement of the pipeline system the following aspects have to be determined:

- Layer thickness
- Working method
- Production
- Periods when pipeline is situated on land together with moment of discharges.

6.3.1 Working method

The spray pontoon will spray the sand-water mixture directly on the soil surface. Once the design level is reached, the spray pontoon needs replacing. The layer thickness to be applied is 0.5 meter.
The behavior of the sand water mixture determines how much displacement of the spray pontoon is required.
Displacement of the spray pontoon doesn't pose difficulties when the pontoon is situated in water. However, in absence of water the required effort to displace the spray pontoon together with the pipeline requires a significant amount of effort. For that reason the behavior of the sand-water mixture in water is not reviewed but the behavior of the mixture above water therefore is.

The behavior of the sand-water mixture on land is nicely shown in Figure 6-5. What can be seen is that the gradient decreases as the sand-water mixture travels from the point of depositing.

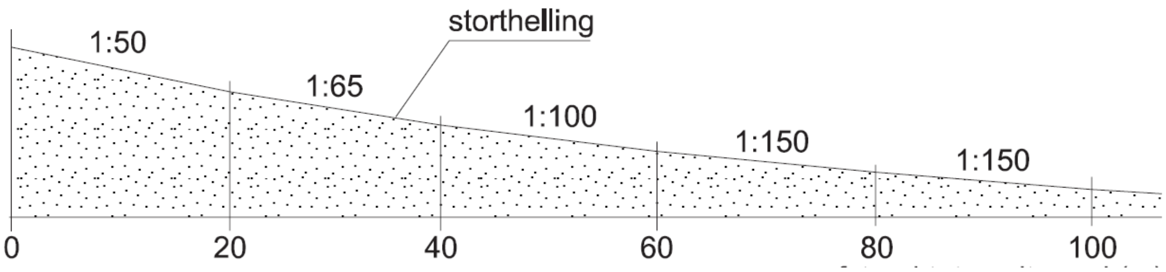


Figure 6-5: Slope gradients with increasing distance from the point of depositing. (Source: *VOUB, 1998*)

The development and the behavior of the slope depend strongly of the characteristics of the sand-water mixture and of the sandy material itself.
In this study an average gradient of 1:80 will be used. This value is obtained from Figure 6-5 as the average gradient.

The following working method will be applied; the spray pontoon starts with depositing the material. The deposited material will assume a cone shape profile. Once the desired height is reached, the spray pontoon has to be displaced (and also the pipeline). Because the layer thickness is relative small, the ASP will move continuously, depositing material in the meantime.
In order to determine the horizontal displacement velocity, the duration to deposit a cone shape volume with a height of 0.5 meter and a gradient of 1:80 has to be determined.

6.3.2 Displacement velocity

The following production figures are applicable with a pipeline diameter of 800 mm. Reference is made to the theoretical review in Chapter five.

Mixture velocity v_m including a safety factor of 10%	=	7.6	m/s
Volumetric flow rate of mixture Q_m	=	3.8	m^3/s
Volume concentration C_v with $\rho_{mixture}$ of 1,350 kg/m^3	=	0.2	-
Volumetric flow rate of solids Q_s	=	0.8	m^3/s
Porosity soil in-situ n	=	0.40	-
Effective volume flow rate of solids Q_{s_eff} (10% loss assumed)	=	0.7	m^3/s
In-situ production Q_d	=	1.1	m^3/s

The in-situ production will be used to calculate how long it takes to deposit one cone shape profile as described in the previous section.

Height cone h	=	0.5	m
Radius cone (follows from height cone & slope gradient)	=	40	m
Volume cone V	=	850	m^3
Duration cone (volume cone / in-situ production)	=	13	min

It can be concluded that during discharging of the trailer suction hopper dredger the spray pontoon have to be displaced frequently.
Conclusion: relative high displacement velocity

6.3.3 One week of production

Reviewing a production of one week and the application of one TSHD with a hopper size of 4,400 m^3 and a dredging cycle of 250 minutes per week 40 discharges could be realized (most optimistic solution; ignoring downtime and such). Per cycle the hopper has a net load of 3,520 m^3 according to (*van der Werf et al, 2016*)

As a check:
The volumetric flow rate of solids in the pipeline Q_s = 0.8 m^3/s. (*section 6.3.2*) After 90 minutes the total volume of solids is 4,100 m^3. Taking into account the start and finishing aspects (flushing the pipeline with water, decreasing the available time for discharging the hopper) a hopper load of 3,520 m^3 seems reasonable.

After one week of production a total *in-situ* volume of 1.1 m^3/s * 90 * 60 s *40 discharges ≈ 250,000 m^3 is realized.
A layer thickness of 0.5 m have to be applied, so in one week a total area of 250,000/0.5 = 500,000 m^2 can be covered. The radius of the corresponding circle after one week of production is theoretically speaking around 400 meter. This is a large area, so a lot of repositioning of the spray pontoon is required. During a production review period of one week the spray pontoon have to be repositioned around 275 times; 40 discharges of 90 minutes each, and it takes 13 minutes to deposit a cone with a radius of 40 meter and a height of 0.5 meter. During each discharge with duration of 90 minutes the spray pontoon has to be displaced 80 meters.

The dimensions of the deposited area are known. Next a method has to be figured out whereby the ASP is able to reach every spot of the deposit area within one week.

Different approaches are available but goal is to find a set up whereby the least amount of pipeline length and movement is needed because repositioning the pipeline on land requires a significant amount of effort.
Assuming a fixed length of the pipeline system (i.e. no pipeline segment are coupled or decoupled to the pipeline system) the spray pontoon must be able to reach every spot. This has consequences for the total pipeline length, and for the flexibility of the pipeline system.

6.3.4 Amount of displacement on land

It's assumed that displacing the pipeline system in water requires (much) less effort compared to displacing the pipeline system when on land. Reason being is the absence of the Archimedes principle when on land.
A M_2 tide is present at the deposit site, and this interferes with the dredging cycle. By plotting the dredging cycle and the available water depth in one graph, the water depth during discharging of the hopper (and also the water depth at the spray pontoon) is presented.
Prof van Rhee suggested (*committee meeting March 28, 2017*) to take a period of one week regarding the production, and determine the required amount of displacement that follows from this.

Figure 6-6 represents the water depth during moments of discharging over a period of fifty hours. A period of fifty hours is represented instead of 168 hours (= 1 week), reason being is the improved clearness of the figure.
In Appendix B a table is representing the water depth for each discharge, both for the start as the end of each discharge, for a period of *one week* (= 168 hours). A side note is placed: delays for maintenance or down time aren't accounted for.

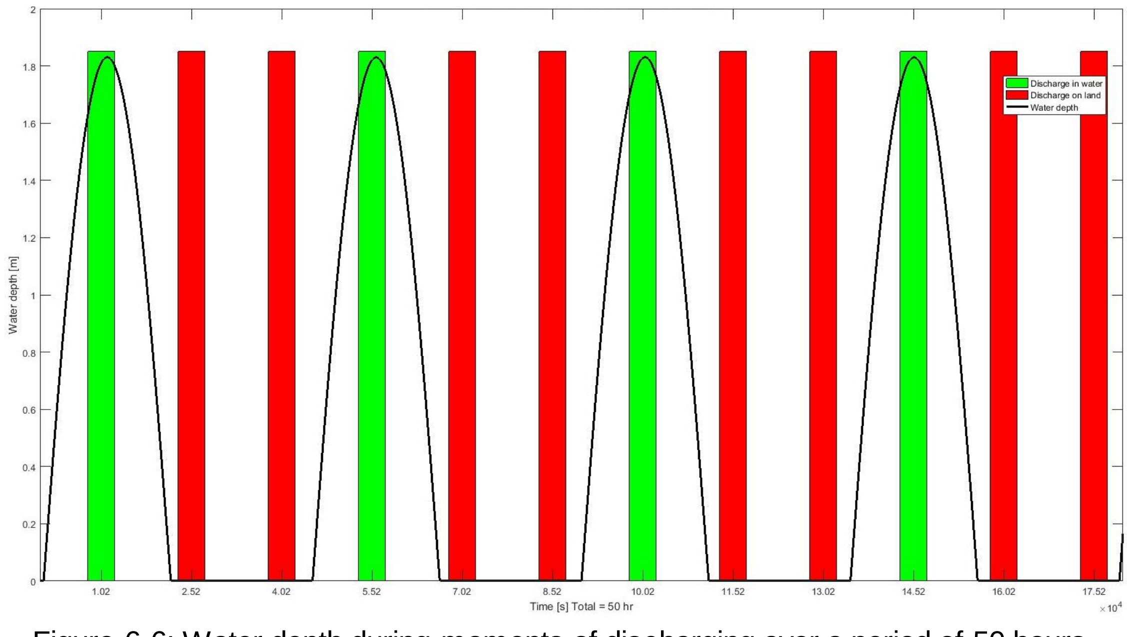


Figure 6-6: Water depth during moments of discharging over a period of 50 hours.

In the periods between the discharges of the TSHD the spray pontoon is not depositing material, and remains stationary.

From the figure can be seen that two discharges take places whereby the pipeline is situated on land, and at discharge number three a (sufficient) water depth is available.
I.e. the pipeline system must allow for a flexibility and/ or reach of the spray pontoon such that two discharges on land can be executed.

6.3.5 Conclusion

After analyzing Figure 6-6 it can be concluded that the spray pontoon and the adjacent pipeline system must have flexibility such that two discharges of a hopper size of 4,400 m^3 could be processed while the spray pontoon and the pipeline are situated on land.

Two discharges on land correspond to an in-situ volume of about 12,000 m^3. A layer thickness of 0.5 meter translates to surface area of 24,000 m^2. Assuming a circular deposit shape in absence of water a radius of about 85 m is created.
When on land the spray pontoon must have the ability to position itself along a radius of 85 m or a diameter of 170 meter.

The radius of influence of the material and the corresponding radius are known. With this info the pipeline set-up can be determined. This will be done hereafter.

6.4 Pipeline set-up

Two questions needs answering when determining the pipeline set up:

1. How much flexibility is required?
2. How to set-up the pipeline system?

6.4.1 Amount of flexibility

<u>Total pipeline length</u>
This study assumes that during the production period of one week no adaptation of the pipeline system is allowed.
By reviewing the area that could be deposited in a weeks' time of production the total pipeline length between the discharge area point A and the spray pontoon is determined.
Assuming a circular deposit shape and layer thickness of 0.5 meter to be deposited a corresponding radius of 400 m is found. Reference is made to section 6.3.3.

<u>Displacement spray pontoon</u>
The most effort is required when the spray pontoon is situated on land. To determine how much displacement the spray pontoon requires section 6.3.4 is stating that the spray pontoon must have the ability to cope with two discharges cycles on land. This corresponds to a radius of 85 meter. I.e. on land the spray pontoon must be able to reach every spot on a circle with a radius of 85 meter.
After these two discharges the deposit area is flooded again allowing for easy displacement of the (total) pipeline system.

6.4.2 Pipeline set-up

The amount of pipeline segments that have to be moved should be reduced to a minimum. By applying a rigid pipeline set up towards the center of the circle, its length will be the radius of the regarded deposit area. To reach the outer circumference of the pipeline, a flexible pipeline set up with ball joints running from the center towards the outer edge. Its length is also the radius of the circle.
In order to reach every spot of the circular area, the ball joint in the center of the circle must be able to rotate 360 degrees. A regular ball joint doesn't allow such a rotation but by changing the orientation of the ball joint the pipeline is able to swing 360 degrees. A so called 'Swan Neck' (section 5.6.2) could be installed in the center of the circle.
By installing a ball joint with a flexibility of 20 degrees (section 5.6.2) after two pipelines segments flexibility in the pipeline setup is created.

The figures below represent the maximum reach of the pipeline system and a random position of the pipeline.

Pipeline length between point A and the ‘Swan Neck’ is 400 meter. The same goes for the remaining pipeline length till the spray pontoon.

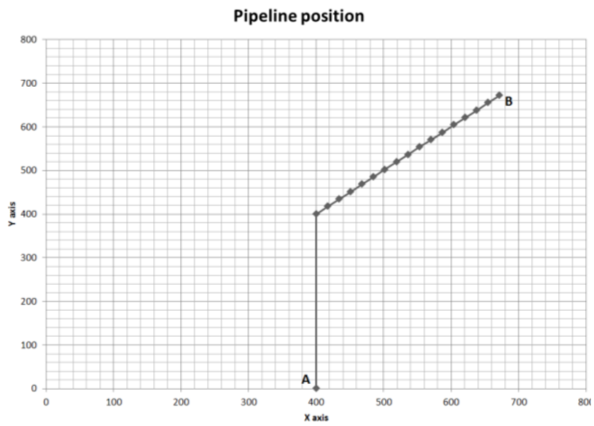


Figure 6-7: Pipeline at maximum reach.

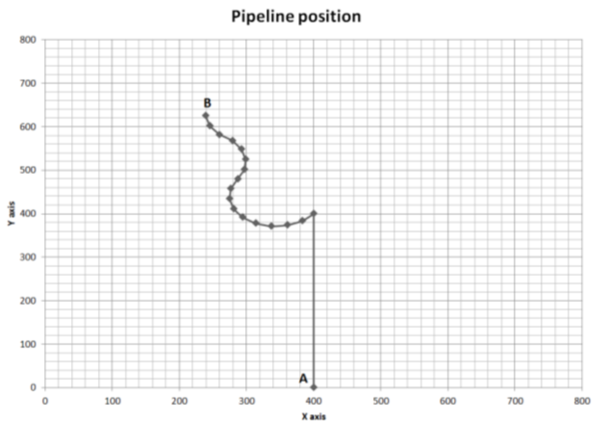


Figure 6-8: Pipeline in random position.

Next question that need answering is how much effort is takes to displace the pipeline system with the suggested pipeline set-up.
By determining the amount of platforms that have to be displaced, the required effort can be determined. This will be done next.

6.5 Pipeline length to be carried per platform

To determine the amount of platforms that have to be applied carrying the pipeline segments, the amount of pipeline length that each platform has to carry must be determined. Below per aspect that determines the amount of platform will be elaborated.

6.5.1 Deflection

To determine the amount of deflection of the pipeline system when it’s supported on platforms the following weight force q of the pipeline in operation will be used:

Weight pipeline		
Body with wall thickness of 15 mm	=	2,940 N/m
Flanges per pipeline element of 600 N	=	50 N/m
Weight mixture		
For $\rho_{mixture}$ of 1,800 kg/m^3	=	8,900 N/m +
Total weight force in operation per meter q	=	11,890 N/m

A pipeline with an internal diameter of 800 mm and a wall thickness of 15 mm has a second moment of area I_{yy} of 0.0032 m^4

The maximum deflection of the pipeline system between two platforms is:

Amount of pipeline segments	Total length between two platforms [m]	Deflection [m]
1	12	0.005
2	24	0.08
3 ←	36	0.39
4	48	1.23

A maximum of three pipeline segments regarding the aspect of deflection can be deployed. Reason being is the amount of deflection; a deflection of more than one meter seems not reasonable because the height of the platforms can be around this value. This is not desired, and in addition too much deflection may have consequences for the flow regime (for example bed formation) inside the pipeline.

6.5.2 Stresses

Deflection of the pipeline and a pulling action (used for displacing the platforms) causes stresses inside the material. These stresses are not allowed to exceed the yield value. Below the stresses are calculated due to deflection and pulling.

A steel pipeline with an outside diameter of 0.83 m and an inside diameter of 0.80 m has a section modulus W of 0.008 m^3.

Deflection

Amount of pipeline segments	Total length [m]	Moment [Nm]	Stresses [N/mm^2]
1	12	210	28
2 ←	24	850	111
3	36	$2.0 \cdot 10^{6}$	250
4	48	$3.5 \cdot 10^{6}$	445

S235 steel is used to construct the pipelines (*VOUB, 1998*). This steel has a yield stress of 235 N/mm^2. From the acting stresses it can be concluded that a maximum of two pipeline segments can be applied. In this way the yield stress is not exceeded.

Pulling
The pipeline will be used to displace the platforms. The maxim pull force that is allowed by the pipeline with a steel cross sectional area of 3.8 cm^2 at yield stress is (without deflection stresses present in the pipeline) is 90 kN. This value will be compared to determine the total pipeline length that can be displaced when the resistance values are known to displace the pipeline system.

If there are deflection stresses present this will have consequences for the total pipeline length that can be displaced.
The deflection stress will be added to the normal stresses. The yield stress of 235 N/mm^2 remains the same so, after subtracting the deflection stress a smaller stress value remains used for pulling. I.e. a smaller pipeline length can be displaced.

The length between each platform is 24 meter. The corresponding deflection stress is 111 N/mm^2. In this way 124 N/mm^2, or 47 kN is left for displacing the pipeline.

6.5.3 Amount of platforms

Deflection limits the distance between de platforms to 36 meter when a pipeline diameter of 800 mm is applied. Stresses due to deflection dictate the pipeline distance between the platforms to 24 meter.
The stresses are normative in the determination of the distance between the platforms. The distance between de platforms is two pipeline segments of 12 m each; 24 meter in total.

In section 6.3.5 it is stated that when the spray pontoon is situated on land the pontoon must be able to deposit a circular area with a radius of 85 m. This corresponds to a diameter of 170 meter.

Dividing 170 m by 24 m will determine the amount of platforms. In total seven platforms have to applied to cover the final 170 m to the spray pontoon. As the spray pontoon accounts for one platform, six more platforms have to be applied. At the adjacent platform a 'Swan Neck' will be installed.

To displace six platforms the required effort has to be known.

6.6 Required effort to displace the pipeline situated on land

To displace 170 meter of pipeline a tractive effort have to be generated by the spray pontoon. For that the resistance force has to be known to displace the six platforms. The generated platform concepts will have different resistance force values. The numeric values are generated below. But this paragraph starts with a calculation to determine the required effort to displace 170 meter of pipeline without any platform or such.

Sinkage
The pipeline segment will be fully supported over the pipeline length by the soil. I.e. the support length is 12.0 m.
The equivalent sinkage modulus of terrain K_s, b = 12.0 m and n = 0.8

	=	912	Pa/m^n
Static sinkage z_0	=	0.05	m

Displacement of the pipeline by:

Rolling

F'_{RC} for one segment of 12 m	=	26	kN
F'_{RC} for 170 m of pipeline	=	370	kN

Sliding axial direction

Wedge formation	=	0.01	kN
Sliding force	=	51.8	kN +
Total for one segment of 12 m	=	51.8	kN

To displace 170 meter in axial direction the wedge formation will be the same as one pipeline segment because only a wedge will be formed in front of the pipeline. The sliding force however, will increase accordingly.

Wedge formation	=	0.01	kN
Sliding force	=	733.8	kN +
Total for 170 m	=	735	kN

Sliding lateral direction

Coulomb friction	=	114	kN
Berm effect	=	22	kN +
Total for one segment of 12 m	=	136	kN

Coulomb friction	=	1,615	kN
Berm effect	=	312	kN +
Total for 170 m	=	2,000	kN

What can be seen from the results is that rolling the pipeline requires less effort than sliding the pipeline, both for axial as for lateral direction.
Analyzing the results raises the question if the wedge formation during axial sliding is not underestimated in the calculation scheme. The hypothesis is that a (significant) wedge will be

developed in front of the pipeline. The calculated resistance to overcome the wedge of 0.01 kN seems in the right order with a static sinkage of around five centimeters.
During displacing the wedge will tends to increase in size, increasing the amount of effort to displace this wedge.
If the pipeline is displaced in a straight line, only one wedge will develop. This wedge will be situated at the front of the pipeline. Even when multiple pipelines are applied, only one wedge will be formed, assuming that no flanges present along the pipeline segments.

In the following section the resistance force to displace each pipeline displacement concept will be presented.

6.7 Resistance force per pipeline displacement concept

In section 4.2.3 concepts have been generated whereby the pipeline is mounted on platforms to decrease the resistance force. In section 6.6 the required force to displace 170 meter pipeline were represented. This set-up consists of multiple pipeline segments. During displacement of the ASP the multiple pipeline segments have to be displaced. According to section 6.5.3 this corresponds to six platforms.

By mounting the pipelines on platforms, the hypothesis is that the required force to displace the pipeline system is reduced, enabling a decreased effort to displace the pipeline system.

From section 6.5 follows that two pipeline segments of twelve meter each will be mounted per platform (stresses due to weight deflection of the pipeline are normative in the determination of the amount of pipeline segments per platform). Taking into account the weight of the two pipeline segments plus adding the estimated weight of the platform, the total resistance force per platform could be determined. It must be mentioned that the weight of each platform serves as an indication. Detailed analysis of each platform will determine the dimensions of each platform and therewith the weight force. However, this is outside the scope of this study.

The resistance values will be used to compare the resistance values between the concepts and used as input for the MCA. Below per platform concept the resistance force is given.

6.7.1 Tracks

Each platform will equipped with two tracks. As a start each track will have the following dimensions:

- Weight 1 track = 49 kN
- Length = 7.5 m
- Width = 1.0 m

} General dimensions of an amphibious excavator track system.

The load per track including 50% of the pipeline weight is 191 kN.

The resistance force per track due to compaction of the soil is 0.2 kN.
This force seems very low. After analyzing the friction inside track system has also to be accounted for. When a friction coefficient of 0.25 is applied to account for the friction present inside the track system, the following friction value is encountered in each track: 48 kN.
A friction coefficient of 0.25 serves as a first estimation: because the track is active in a sandy environment, sand and water will be present inside the track system, increasing the friction value.

Summarizing: a total friction force of 48 kN per track is present. Per platform equipped with two tracks a friction force of 96 kN is encountered.
Six platforms will encounter a resistance force of 576 kN.

6.7.2 Archimedes platform

An Archimedes platform is equipped with two screws. The friction force encountered by the screws consists of bulldozer force and skin friction along the screw. Each screw has the following dimensions as a first estimation (*from the Mudmaster concept*);

- Radius of screw flight edge = 0.5 m
- Radius of screw cylinder = 0.45 m
- Sinkage with slip = 0.10 m
- No cohesion is assumed

Per platform of two screws the bulldozer force = 0.03 kN
The skin friction along the screw is assumed to be the same as the Walnut concept = 122 kN
In total the platform encounters a total friction force of 122 kN.

Six platforms will encounter a resistance force of 732 kN.

6.7.3 Hoverbarge

The hoverbarge is able to lift its entire weight by its hover system. To decrease the loss of over pressure created underneath the hover barge (i.e. to make the hover action more efficient) a skirt is applied at the circumference of the hover barge. During movement of the hover barge this skirt will drag over the soil surface.
To determine the magnitude of the friction during displacement, the following aspects have to be known:

- Net weight force of the skirt. A percentage of the weight of the skirt is lifted by the fans; an estimation have to be made of the weight of the skirt that is actually touching the soil surface
- Friction coefficient rubber skirt and soil
- Total length skirt per hover barge, i.e. the circumference of the hover barge.

The values stated below serve as a first estimation.

- Net weight skirt = 100 N per meter skirt
- Friction coefficient = 0.75
- Circumference = 100 meter

Per hoverbarge a friction force of 7.50 kN is encountered
Six platforms will encounter a resistance force of 45 kN.

6.7.4 Walnut concept

This concept only encounters a friction force due the normal force. Wedge formation is not taken into account; sinkage of this concept is assumed to be negligible due to the large surface area. Also the shape of the concept will minimize the wedge formation in front of the platform if a wedge is created.

As a first estimation the weight force of the wall nut concept itself is assumed at 49 kN. Together with a pipeline weight of 285 kN the total weight force per platform is 334 kN.
An external friction angle of 2/3 times the internal friction angle is applied → 20 degrees.

Total friction force per platform equipped with two Archimedes screws is 122 kN.
Six platforms will encounter a resistance force of 732 kN

6.7.5 Wheeled platform

From the mechanical theory (*Hartsuijker, 2007*) follows that three supports under a platform is from a mechanical point of view stable. In this study a platform with three wheels will be applied as a starting point.

Weight of the platform is estimated at 40 kN. Adding the pipeline weight of two pipeline segments the total weight force of the platform is 324 kN.
Each wheel experiences a load of 108 kN.

As a first order estimation each wheel will have the following dimensions:

- Width: 0.5 meter
- Wheel diameter: 1.0 meter

These are general dimensions of a truck tire.

Each wheel will encounter a resistance force of 12 kN. In total the platform has a resistance force of 35 kN.
Six platforms will encounter a resistance force of 210 kN.

6.7.6 Overview

In Table 6-1 an overview is presented of all the concepts and their resistance forces in order to displace 170 m of pipeline. Also the resistance force to displace the pipeline that is resting on land is represented.

Table 6-1: Resistance force for displacing 170 meter of pipeline.

Pipeline is	**Resistance force**	**Unit**
Rolling	370	kN
Sliding axial direction	735	kN
Sliding lateral direction	1,927	kN
Mounted on		
Platforms with tracks	576	kN
Archimedes platforms	732	kN
Hover barges	45	kN
Walnut platforms	732	kN
Platforms with three wheels	210	kN

An important aspect is the orientation of displacement. The calculated resistance force per concept represents displacement of the platforms in axial direction.
In section 6.5.2 it was stated that the pipeline is able to handle a maximum pull force of 47 kN.
Analyzing the resistance forces in Table 6-1 only the hover barges could be displaced by applying the pipeline but it's on the limit value. Taking into account the uncertainties it's fair to say that the pipeline itself cannot be used to pull the platforms.
Other means have to be found to distribute the pull force.

Further analysis of the results will be performed at the multi criteria analysis in the next chapter.

6.7.8 Strength ball joint

In section 6.4.2 'pipeline set-up' it was elaborated that ball joints with a degree of freedom of twenty degrees will be applied between the platforms.
The pipeline will be used to displace the platforms. As a result a normal force will be present in the pipeline system. The ball joints have to able to transfer this normal force.
The normal force follows from the encountered normal force. Reference is made to Table 6-1 for an overview of the encountered resistance forces.

According to McWane (*fact sheet Ball and Socket Joint Pipe*) a ball joint for a pipeline with a diameter of 30 inch (= 0.76 m; corresponds to the pipeline diameter as used in this study) has a strength of 1,490 kN. This strength is sufficient for the desired application in this study.

6.8 Pull effort per amphibious displacement concept

The resistance force to displace 170 meter of pipeline is known. Question that needs answering is the amphibious spray pontoon able to displace the pipeline system? I.e. how much pull effort is each amphibious displacement concept able to generate. Below for each concept an indication of the pull effort is given.

Material properties follow from (*Wong, 2010*). Sand is considered:

- Cohesion c = 1000 [Pa]
- Internal friction angle φ = 30 [deg]
- Shear deformation parameter K = 0.00115 [m]
- Slip i (maximum slip is assumed) = 100 [%]

6.8.1 Track system

To estimate the maximum tractive effort of the ASP the following dimensions of a two tracked system are used:

- Width 1 track = 1.0 [m]
- Length 1 track = 7.5 [m]
- Weight 1 track = 191,425.52 [N]

The calculated tractive effort per track is 118 kN.
Resistance encountered by 1 track due to soil compaction = 0.16 kN. (from section 6.7.1)
→ Pull force per track is 118 kN.
The ASP has two tracks, so a total tractive effort of 236 kN could be generated.

6.8.2 Remaining displacement concepts

The remaining amphibious displacement concepts are the Archimedes screws, Hoverbarge and the Watermaster concept. The latter two concepts are applying an anchor-winch system.
As described in section 5.7 a track system is able to generate a larger pull effort than an Archimedes screw set-up.
Also it's assumed that an anchor-winch set-up is to existence that is able to generate a force equal to or larger than the resistance forces.

6.8.3 Conclusion

Comparing the pull effort that a track system with the stated dimensions is able to generate, and the resistance force per platform concept, it can be concluded that an amphibious spray pontoon with tracks is only able to displace 170 m of pipeline when these are mounted on hover barges or wheeled platforms.

To displace the other platform concepts, the track system dimensions of the spray pontoon have to be increased.

6.9 Required effort to hold position in water

6.9.1 Hydrodynamic forces on the pipeline

Each of the hydrodynamic forces could have a different direction of approaching. This study assumes the worst case scenario, i.e. all the hydrodynamic forces have the same orientation. In this way all the forces can be added to each other.

		Due to currents
$u = 0.5$ m/s	$C_d = 0.7$	Drag force per meter = 0.9 kN/m

Due to waves

Distance floating pipeline to bottom ≥ diameter pipeline/4

Inertial force	$C_i = 2$	6.2 kN/m
Drag force	$C_D = 0.7$	1.7 kN/m
Lift force	$C_L = 0$	0 kN/m +
	Total	7.9 kN/m

Adding the hydrodynamic forces caused by the current flows, and by wave action a total hydrodynamic force of ≈ 9 kN/m is experienced by the floating pipeline.

It should be mentioned that when the pipeline is mounted on platforms, the pipeline is not in contact with the water body. I.e. there are no hydrodynamic forces acting on the pipeline itself. Instead, the hydrodynamic forces are acting on the platforms.

6.9.2 Impulse force caused by orientation change of the pipeline

The maximum angle the ball joint can reach seen from the axial axis of the pipeline is twenty degrees. This angle is creating an impulse force as the mixture is forced into a different direction. As a consequence the mixture with a density of 1,350 kg/m^3 at the maximum angle amplitude of 20 degrees will create a force of 13.4 kN per ball joint.
To displace one pipeline segment of twelve meter a force between 52 kN and 273 kN is required to displace the pipeline (reference is made to section 5.3.2). The impulse force is not sufficient to displace the pipeline system when on land.

When the pipelines are floating, the impulse of the mixture might cause the pipeline system to move. Together with hydrodynamic forces acting on the pipeline a holding force has to be generated to prevent uncontrolled movement of the pipeline system.
It depends on the directions of the hydrodynamic forces, the position and orientation of the pipeline if the impulse force of the mixture enables (local) movement of the pipeline system.

6.9.3 Overview

To create an overview of the consequences of the hydrodynamic forces on the pipeline system three scenarios will be described. The area reviewed in one week of production is reviewed. Reference is made to section 6.3.3. The radius of this area is 400 meter. 170 meter of pipeline will be mounted on platforms at the pipeline end towards the spray pontoon. 230 meter if pipeline is situated on the soil surface.

No water present at deposit area
During low tide no water is present on the deposit area. Only the impulse force caused by the mixture inside the pipeline is present. This impulse force is not sufficient to displace the pipeline system.

Deposit area is party flooded

In this scenario the platforms are operating on land and the 230 meter of pipeline is situated in water. The weight of the pipeline during operation is 12 kN per meter. This value is applicable for a pipeline on land.

A pipeline in water situated on the bottom is only experiencing forces due to currents. The drag force is 0.9 kN per meter pipeline. The weight force of the pipeline in water is decreased slightly due to the Archimedes' Principle but is still ten times bigger than the drag force. It's not expected that the pipeline will be displaced by the drag force.

The same goes for the impulse forces generated by the sand-water mixture. A calculated impulse force of 13.4 kN per ball joint corresponds to 1.1 kN per meter pipeline. This force is also about ten times smaller than the weight force of the pipeline.

Deposit area is flooded

The deposit area is flooded from the discharge area up to the position of the spray pontoon. The pipeline and the platforms will be situated in water.

There are drag forces present due to currents on the pipeline section of 230 meter, there are wave forces and currents forces acting on the platforms, and there are impulse forces acting caused by the sand-water mixture inside the pipeline.

As already described the pipeline section of 230 meter and the impulse force won't induce movement of the pipeline system.

The weight of the platforms is supported by the soil surface as there is contact between soil surface and the platform. It's expected that this weight force (consisting of 24 meter of pipeline in operation and the weight of the platform itself) produce a friction/holding force that is much bigger than the hydrodynamic forces. I.e. no movement of the platforms enhanced by the hydrodynamic forces is expected in this study.

Chapter 7

Most promising total concept

Goal of this chapter is to determine the most promising concept to displace the pipeline system and to determine the most promising amphibious technique for the spray pontoon.

First the most promising platform concept is determined by applying a multi criteria analysis. Next the most promising amphibious technique is determined. Following the total concept is described.
It must be noted that the used numeric values are based on the workability assessment as performed in the previous chapter.

7.1 Most promising platform concept

7.1.1 Criteria

In Chapter 4 'Delivering material from A to B' five platform concepts have been developed whereby the pipeline will be mounted on. Idea is that the required effort to displace the pipeline is decreased compared to displacing the pipeline that is situated on the soil surface.
Also in Chapter 4, eleven criteria were presented to select the most promising platform. Four criteria were selected to be elaborate further on. Reference is made to section 4.3.2 for arguments why this study selected these four criteria.
The selected criteria were elaborated by a theoretical review and a workability assessment.

Each concept can score a value between 0 and 4 per criterion whereby zero is the lowest score and 4 the highest score.
The scores for the criteria forces, repositioning, and flexibility will be based on the numeric output. Results of the workability assessment will be used as input to assign values to the selected criteria for each platform concept.
The criterion operation will attain scores based on the criteria listed in section 4.2.1.

Below a short recap of each selected criterion is stated:

<u>Forces</u>
The required force to displace the pipeline system is of importance because when the pipeline is situated on land, the force to displace the pipeline is significant. The method that will result in the lowest required force will be assigned with the highest score.

<u>Reposition</u>
The spray pontoon has to be able to move to a different spot when the required thickness is applied. The platform concepts have to be able to follow the spray pontoon in any x and y direction.

<u>Flexibility</u>
The pipeline system and the ASP have to be able to work both on land (soft soil) as in water (varying water depths). The deposition area could be flooded for any period of time. Also during construction the deposition area will increase in height. The concepts have to be able to cope with this aspect.

Operation

This criterion covers the aspects on how well each concept will work in the dredging practice. Aspects are like: resistance against wear and tear, fuel consumption, maintainability, general dimensions, reliability, CAPEX and OPEX values, supply of energy, environmental impact, remoteness, and obstacles.

7.1.2 Overview scores per platform concept

In Table 7-1 the attained scores per concept per criterion are stated.

Table 7-1: Obtained scores per criterion per concept.

Concepts	Criterion Weight factor	**Forces**	**Repositioning**	**Flexibility**	**Operation**	Total	Score %
	Weight factor	2	1	2	1		
Pontoon on tracks		1	0	1	2	6	25
Archimedes platform		0	2	3	2	8	33
Hover barge		4	4	4	0	16	67 ←
Walnut concept		0	4	2	1	9	38
Wheeled platform		2	3	1	3	12	50
Ideal		4	4	4	4	24	100

Below the scores per criterion will be elaborated.

7.1.3 Elaboration criterion forces

Table 7-2 represents the resistance values to displace 170 meter of pipeline (*from section 6.7.6*). The platform concept that has the smallest amount of resistance during displacement will attain the highest score, and the concept that has the most effort during displacement scores the lowest score.

Table 7-2: Overview resistance force to displace 170 meter pipeline.

Pipeline is	**Resistance force**	**Unit**
Rolling	370	kN
Sliding axial direction	735	kN
Sliding lateral direction	1,927	kN
Mounted on		
Platforms with tracks	576	kN
Archimedes platforms	732	kN
Hover barges	45	kN
Walnut platforms	732	kN
Platforms with three wheels	210	kN

The hover barge requires the least amount of effort. The Walnut and the Archimedes have the highest resistance. The difference between hover barge and the other concepts is significant. This difference must be visible in the obtained scores in the MCA. That's why the scores jump from a two for the wheeled platform to a four to the hoverbarge.

7.1.4 Elaboration criterion repositioning

The platforms will be dragged along by the amphibious spray pontoon. The platforms have to be able to follow the spray pontoon in x and y direction. The platform concept that provides the best degree of freedom in the x-y plane will attain the highest score.

Platform with tracks
Very capable in moving in axial direction but movement in lateral direction translates in large turning radius. When the spray pontoon is located perpendicular to the track platform, movement of the platform isn't possible. I.e. a platform on tracks doesn't allow for easy repositioning in the x-y plane.

Archimedes platform
Allows for easy repositioning to move in x and y direction but angles between the x and y are difficult to cope for this system. First the platform have to be turned such that the platform is in a straight line in x or y direction.

Hover barge
Excellent capabilities to reposition in the x-y plane because the platform is afloat. In addition the resistance force is small.

Walnut concept
Displacement of the walnut concept goes by sliding. Because of the shape of the walnut the resistance force is equal in any direction of the x-y plane.

Wheeled platform
Since the platforms are equipped with wheels with a caster set-up the platforms can be positioned in any x-y direction. When the pull force has an offset towards the axial direction of the platform there is a turning resistance present in caster wheel set-up. The amount of offset, the distance between the king pin, wheel sinkage into the soil, and the wheel axis determines the magnitude of this turning resistance.

7.1.5 Elaboration criterion flexibility

Platform with tracks
Tracks will be in contact with soil surface all the time. The hydrodynamic forces and the impulse forces don't have a large impact on the platform. Requirement is that the height is sufficient. As a consequence the platform is dependent of the water depth. I.e. the water depth is not allowed to exceed the height of the platform.

Archimedes platform
In water the concept will be afloat. The screws are able to generate traction in water but this force will be small. This force will probably not be sufficient to displace the pipeline system when in water and in case of strong currents. But this concept is independent of the water depth provided that the spud pole is sufficient.

Hover barge
The hoverbarge has floating capacity. On land it just can rest on the soil surface or it will be on hover, independent of the state of the soil surface or the water surface. For that reason the hover barge will obtain the maximum score.

Walnut concept
The walnut shape provides floating capacity. Due to the weigh force the dimensions of the walnut platform could be such that it becomes very large. Soft soil might pose problems as

the platform will sink significantly into the soil. In that case berm formation does play a role, increasing the resistance force to displace the concept.
If the spud pole is sufficiently strong, the walnut shape platform is independent of the water depth.

Wheeled platform
Idea behind this platform concept is that the wheels stays in contact with the soil surface at all times. As a consequence the platform must have a height such that it is larger than the water depth. This limits the application range regarding the water depth this platform concept is still able to operate.
Besides in absence of water together with a soft soil surface will enhance significant sinkage of the wheels. As a result the resistance force to displace the wheeled platform is also increased significantly. On firm soil this concept works well.

7.1.6 Elaboration criterion operation

Platform with tracks
Displacement by a track system is a proven technique. The system is a bit more complex and needs maintenance. Could cope with obstacles quite well.

Archimedes platform
Screws are also a proven technique. High wear rates of the screws due to the movement in sandy material.

Hover barge
Huge fuel consumption. High environmental impact because of the high fuel consumption. High capex and opex values. Hover craft technology is complex and vulnerable. Not ideal in remote locations.

Walnut concept
Wear rate is high but simple set-up. Obstacles are difficult to overcome.

Wheeled platform
Simple set-up, low capex and opex values. Obstacles may cause difficulties because if one wheel gets stuck, this has consequences for the rest of the pipeline system.

7.1.7 Most promising platform concept

According to the multi criteria analysis the most promising platform concept is to apply a hover barge. Seconds place goes to the wheeled platform.

7.2 Most promising amphibious technique for the spray pontoon

This study came up with four amphibious techniques to displace the spray pontoon:

- Hovercraft technology with an anchor winch system
- Track propulsion system
- Archimedes screws
- Spud-pole system

To determine the most promising amphibious technique focus is on maximizing the tractive effort to displace the platform concept.
Besides the amphibious technique must enable mobility such that the material could be deposited according to the design.

7.2.1 Pull effort

According to (*Nagoake, 2011*) a tracked vehicle is able to generate a larger drawbar pull than an Archimedes Screw vehicle or a wheeled vehicle. See Figure 7-1.

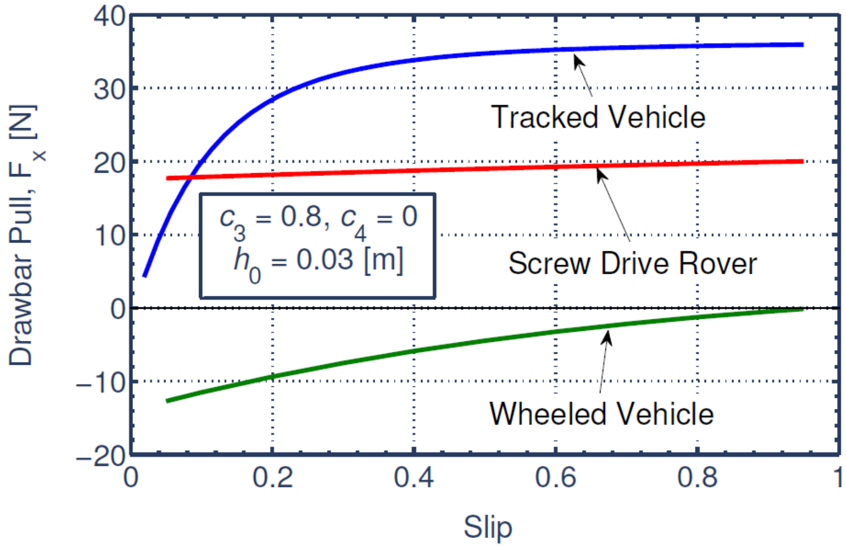


Figure 7-1: Comparative simulation result of Screw Drive Rover model with wheeled and tracked vehicle models. (Source: *Nagoaka, 2011*)

An anchor-winch system is able to generate a large pull effort. This all depends on the dimensions of the anchor. Determining the dimensions of the anchor system is outside the scope of this study.
Also a spud-pole system won't be considered any more regarding the pull effort as described in section 5.2.4. Assumption is that the pull effort might be too small but main objection is the very limited mobility of the spud-pole system.

In section 6.8 the pull effort for a spray pontoon on tracks is determined. The total pull force to can be generated is 236 kN.
Analyzing the resistance forces in Table 7-2 the spray pontoon is only able to displace the 170 m pipeline system when it is mounted on hover barges and the wheeled platforms.

7.2.2 Mobility

The most promising amphibious technique is now only between the track system and the hoverbarge with an anchor-winch system.
By looking at both concepts for the ability to move, a preference could be made for one concept.
Compared to a tracked vehicle an anchor winch system with four anchors has bigger mobility values. But the anchors have to placed and a have a limited length, compromising the mobility.

As stated previously a tracked vehicle has great mobility in axial direction, but in lateral direction the mobility is not as large as in axial direction. But by moving the tracks in opposite direction the spray pontoon is able to create mobility. In addition a track platform is able to operate independently of anchors as such.

7.2.3 Most promising amphibious technique

The most promising amphibious technique for the spray pontoon is a track system.

7.3 Visualization most promising total concept

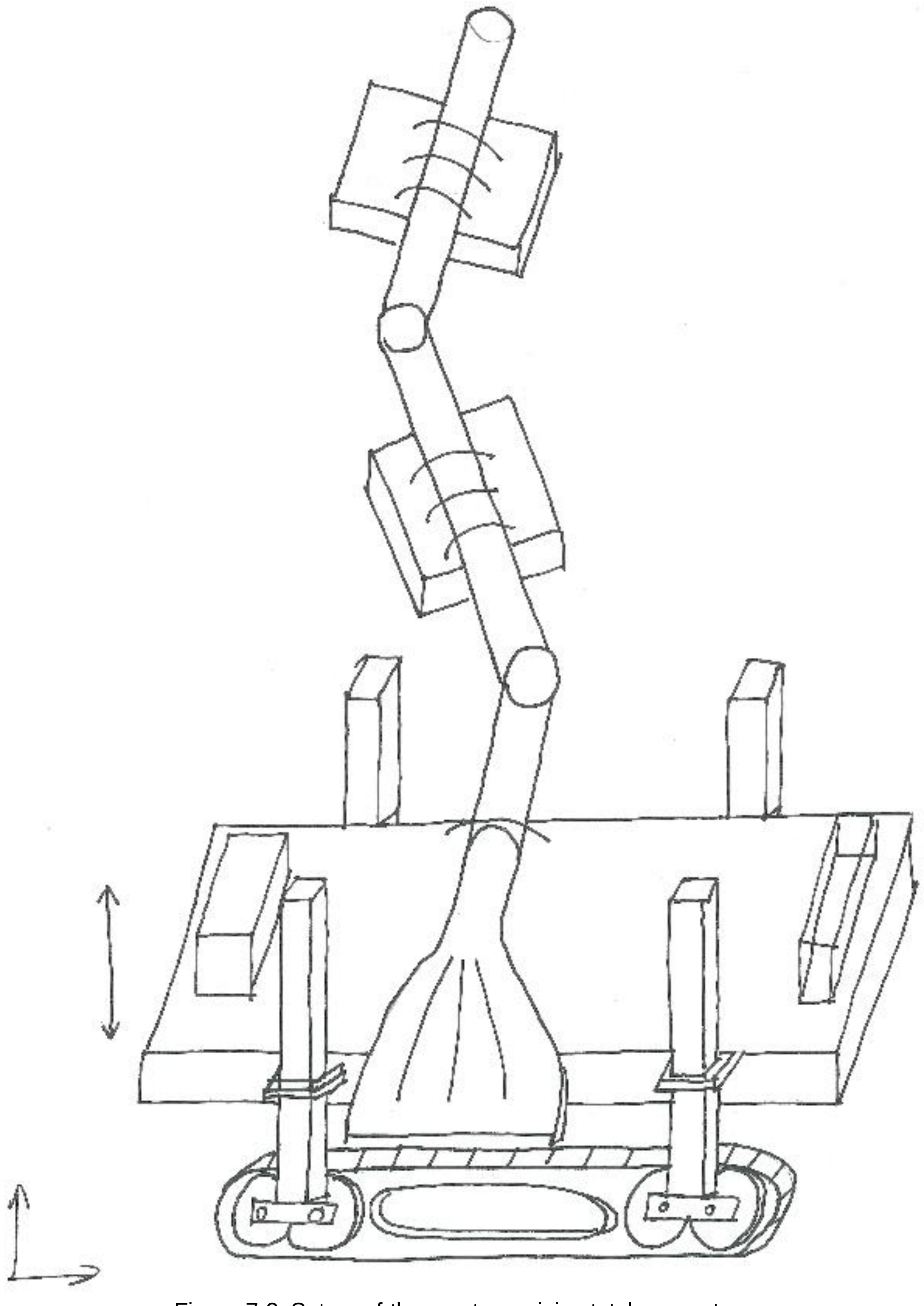


Figure 7-2: Set-up of the most promising total concept.

(A part of) the pipeline system will be mounted on hover platforms or platforms equipped with three wheels and a caster set-up. Both platforms can be displaced 360 degrees in the x-y plane.
Along the pipeline section flexibility is created by applying ball joints which enable a degree of freedom in the x-y plane. Also a ball joint have to be placed at the first platform seen from the dredger that allows for a 360 degree of freedom in the x-y plane. The spray pontoon and the platforms can swing around this ´Swan neck´ ball joint.
Each platform will carry 24 meter of pipeline. This determines the amount of platforms to be installed for each project. For the project as used in the workability assessment there are six platforms needed. Reference is made to section 6.5.

The spray pontoon will be equipped with a track propulsion system. The orientation of the tracks is perpendicular to the pipeline segments. Reason being is that spray pontoon will deposit the material while displacing in axial direction. With this set-up the smallest amount of pipeline length has to be displaced enabled the swinging action around the 'Swan neck' ball joint while a large surface area could be reached by the spray pontoon.

The total concept has to be able to continue depositing material in limited water depths. The spray pontoon has the capability of jacking the pontoon above the water surface. In this way the spray pontoon is able to continue depositing material in limited water depths.
Regarding the hoverbarge, a full floating capacity is present. No limitations regarding the water depth are present.
The platforms equipped with wheels must have a height such that it reaches above the water surface as the wheels will remain in contact with the bottom surface.

Chapter 8

Conclusion and recommendations

8.1 Conclusion

The most promising amphibious propulsion technique for the spray pontoon is to apply a track system. Main reason for selecting a track system is being that a track system is able to generate the largest amount of tractive effort compared to the other suggested propulsion techniques.
In addition a track system is able to operate independently of an anchor winch system. This is beneficial from a mobility point of view. Analyzing the test case the spray pontoon have to be displaced a lot during discharging of the dredger, so allowing easy movement of the spray pontoon is necessary in order to deposit the material in small layers.

The pipeline segment will be mounted on platforms. The platforms have to fulfill two important aspects:

1. The platforms must be able to follow the spray pontoon when the pontoon is displaced. I.e. in any orientation and location in the x-y plane the platforms have to able to follow the spray pontoon.
2. The required force required to displace the platforms must be at a minimum. In this way the dimensions of the propulsion system of the spray pontoon is also at a minimum. This is desired as the amount of tractive effort to be generated by the spray pontoon is related to the dimensions of the propulsion system.

The most promising concept regarding the platforms is, according to the performed multi criteria analysis, a hoverbarge. Second place goes to a wheeled platform.

However, there are more criteria which determine the most promising platform concept. In Chapter four a selection was made regarding which criteria would be elaborated. The remainder of those criteria still holds value in the determination which platform is the most promising.
Below an overview of these remainder criteria is listed:

- Reliability
- CAPEX and OPEX
- Wear
- Remoteness
- Supply of energy
- Environmental impact
- Obstacles

Dredging operation takes place in a marine environment; this is an aggressive environment due to salt water and the scour effect of the dredged material. Ideally the platform concept must have the simplest possible set-up. In this way a low risk of failure to minimize downtime and to create small capex and opex values is ensured. Regarding this aspect the wheeled platform is preferred.

Main objection against the wheeled platform is that the platform is dependent of water levels and accordingly with the water depth as the wheels need to stay in contact with the soil surface. At the other hand, the water depth won't be that large as otherwise the ordinary floating equipment will be deployed.
When obstacles are encountered wheels may require very high pull forces to overcome those obstacles. A hoverbarge has a superior behavior regarding handling obstacles.

Downside is the expected fuel consumption of the hover barges when on hover. It could be stated that the wheeled platforms requires much less fuel. This has consequences for the OPEX values, and also for the environmental impact.
In addition it is expected that the CAPEX values for a hoverbarge (due to its complex technique) are bigger than a wheeled platform.
But a hoverbarge has superior capabilities to operate on the interface of water and land.

Summarizing: it depends on the type of project, and the regarding conditions which type of platform have to be applied. On project locations were a small variation of the water levels is to be expected, and the soil surface has a high bearing capacities values the wheeled platform can be applied.
However, on soft soils with low bearing capacity values the wheels will experience significant sinkage; the resistance force to displace the wheeled platforms can possible not be generated by the spray pontoon. In addition on soft soil the pull force is probably smaller compared when the spray pontoon is on firm soil.
On (very) soft soils hoverbarges are advantageous compared to wheeled platforms.
In addition the pipeline cannot be used to distribute the pull force generated by the spray pontoon to displace the platforms. Other means have to be found.

Concluding: a uniform concept doesn't exist because there is a large amount of parameters and aspects involved, resulting in complexity in the determination of the most promising total concept. More investigation is needed to state the most promising solution with more confidence.

8.2 Recommendations

This study is still in the orientation phase, and as a result a lot of assumptions have been made. As a consequence (large) uncertainties are present in the outcome of the calculations. The numeric output following from the workability assessment serves as an indication in order to determine the most promising concept.

As stated in the conclusion a uniform concept doesn't exist for replenishing material in intertidal areas. More investigation is required to determine when to apply a hoverbarge and when a wheeled platform is more advantageous. Both platform concepts have their pros and cons but a distinction have to be made to determine for which conditions one platform concept is favorable to the other.
More investigation is required into the site conditions and especially on the interaction of soil surface and the wheeled platform concepts, together with the tractive effort of the spray pontoon as these aspects have a strong relationship with each other.

Next the behavior of the pipeline system needs investigation. Ball joints will enable the desired degree of flexibility but can this degree of freedom be generated?
A method has to be found on how to mount the pipeline segments on the platforms, and how to distribute the pull force to displace the platforms. Focus must be on the pipeline connection to the platforms and on the ball joints (friction in the ball joints).

The dimensions of the track propulsion system and the dimensions of the platforms have been determined quite roughly. These dimensions have to be determined in more detail.

Finally the influence of the deposited material on the track system of the spray pontoon and the wheels of the platform needs more attention as the deposited material may influence the soil compaction resistance in front of the track system and the wheeled platform.

8.3 Discussion

By discussing the approach to determine the most promising concept a statement could be made regarding the feasibility of the most promising concept.

A multi criteria analysis was chosen. A disadvantage of this approach is that the outcome of this analysis could be steered by the user by selecting certain criteria. By calculating the weight factors for each criterion the steering effect can be decreased. But assigning scores to the concepts for each criterion is mainly a subjective process and is controlled by the user. As a consequence the outcome of the multi criteria analysis holds a value such that the user has been assigned to.
In this study a multi criteria analysis have been applied such that it gave guidance in the process to determine the most promising concept. During the process the user was pushed to analyze what's involved regarding the problem identification, to come up with concepts to answer the main research question, and how to determine the most promising concept.
In addition the outcome of the analysis holds a value such that the most promising concept is the most promising with the state of the art techniques in mind. When in the (near) feature new techniques are being invented, it might well be that those techniques or concepts are more promising than for the time being stated the most promising concept.

In the process to determine the most promising platform concept, the concepts have been assigned scores based on the numeric output following from the workability assessment. The numeric output heavily depends on the numeric input from the test case. The numeric input holds a lot assumptions and corresponding uncertainties. As a result the assigned scores in the analysis are not very accurate. If the relative difference between the concepts is still correct, the analysis also still holds a significant value.
I.e. the outcome of the analysis has to be approached with a critical view in mind.

The most promising total concept, a spray pontoon on tracks and by pulling platforms on wheels or hoverbarges, is applicable if the soil surface consists of sand and the material to be deposited is also sand.
A soil surface of sand will have as a consequence that the track system and the wheeled platform performs well due to a small sinkage into the soil surface. A limited sinkage will result in relative low resistance forces during displacement of the spray pontoon and wheeled platforms.
It seems realistic that the soil surface consists of sand because of the following arguments:
The floating equipment will deposit sand by dumping when there is a sufficient water depth available. When the available water depth decreases, a hopper could switch to rain bowing, depositing the material. When the rainbow is not able to reach the deposit spot any more the amphibious spray pontoon will be applied.
As a result it's very likely that there is already a sandy soil surface present when the spray pontoon is applied.

Answering the question as stated in the beginning of this paragraph: 'Is it technical feasible to apply an amphibious spray pontoon?'
From the test case follows that following aspects have major influence on the spray pontoon:

- Water levels and corresponding the water depth
- Pipeline length that needs displacing
- Soil conditions
- Creating flexibility in the pipeline system.

All of those mentioned aspects could be dealt with by suggested most promising concepts, so the application of an amphibious spray pontoon seems feasible. However, a lot need still investigating, especially regarding the soil interaction and the spray pontoon. Reference is made to section 8.2 'Recommendations'.

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Nomenclature

$r_{outside}$	Outside pipeline radius	0.415	m
r_{inside}	Inside pipeline radius	0.400	m
b	Width support pipeline	12	m
n	Sinkage exponent of terrain Bekker for soft terrain	0.8	-
L_{pipe}	Length of 1 pipeline segment	12	m
t_{wall}	Thickness wall pipeline	0.15	m
W_{flange}	Weight flanges per pipeline segment	600	N
k_c	Cohesive modulus of terrain in Bekker's model	16,500	Pa/m^{n-1}
k_φ	Frictional modulus of terrain in Bekker's model	911000	Pa/m^n
φ	Internal friction angle	30	deg
$\rho_{soil\_in\text{-}situ}$	Density soil in-situ	2,000	kg/m^3
ρ_{soil}	Density soil	2,650	kg/m^3
μ	Friction coefficient lateral pull pipeline	0.8	-
μ_{track}	Friction coefficient in track system	0.25	-
g	Gravitational constant	9.81	m/s^2
$\rho_{mixture\_max}$	Maximum density mixture in pipeline	1,800	kg/m^3
$\rho_{mixture}$	Density mixture in pipeline	1,350	kg/m^3
ρ_{steel}	Density steel	7,800	kg/m^3
E	Young modulus steel (for pipeline)	210˙10^9	N/m^2
σ_{yield}	Yield stress S235 steel	235	N/mm^2
σ_m	Maximum stress S235 steel	360	N/mm^2
b	Width of track	1.0	m
l	Contact length track	7.5	m
R_0	Radius of screw flight edge	0.5	m
r_0	Radius of screw cylinder	0.45	m
d	Steady sinkage with slip	0.10	m
c	Cohesion	0	N/m^2
W_s	Weight skirt per meter	100	N/m
L_s	Length skirt	100	m
μ_r	Coefficient of friction	0.75	-
n_{wheels}	Amount of wheels per platform	3	-
w_{wheel}	Width wheel	0.5	m
D_{wheel}	Diameter wheel	1.0	m
C_D	Drag coefficient	0.7	-
C_L	Lift coefficient	0.85	-
ρ_{water}	Density water	1,025	kg/m^3
u	Velocity tide	0.5	m/s
ν	Kinematic viscosity of water	10^{-6}	m^2/s
C_i	Inertial coefficient	2	-
C_D	Drag coefficient	0.7	-
C_L	Lift coefficient	0	-
H_0	Wave height on deep water	0.2	m
T_0	Wave period on deep water	2.5	m
d_{water}	Water depth	2.0	m
a	Wave particles amplitude in orbit at the bottom (= $0.5 \cdot L_0$)	1	m
α	Angle between wave's speed direction and pipeline	90	deg

ø	Maximum angle between pipeline segments	20	deg
C_{v_eff}	Effective volume concentration	0.9	-
T_{M2}	Wave period M_2 tide	44,700	s
K	Shear deformation parameter	0.00115	m
c	Cohesion	1,000	Pa
i	Track slip	1	-

Acronyms

ASP	:	Amphibious Spray Pontoon
TSHD	:	Trailer Suction Hopper Dredger
CSD	:	Cutter Suction Dredger
CD	:	Chart Datum
GDP	:	Gross Domestic Product
CAGR	:	Compound Annual Growth Rate
PSI	:	Pounds per Square Inch
CAPEX	:	Capital Expenditure
OPEX	:	Operational of Operating Expenditures

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Appendix A

A-1 MCA for depositing material

Weight factors

The boundary conditions as listed in paragraph 2.3 will be used as input arguments for the MCA. Some arguments are more important th an other arguments. To highlight this difference this study will apply weight factors per argument.
The weight factors are determined as follows:

1. First the arguments are written down on both on the first column as the first row and in the same order.
2. On the location of the same arguments an x will be written down. This will result in line of x's diagonally over the table.
3. Next starting with the first argument stated in the column number 1, this argument is rated against the arguments stated in the first row. If the argument is more important than the argument above, an 1 is written down. If the argument in the row is more important a 0 is written down. Next argument number 2 is rated against the arguments in the first row. In this way the whole table could be filled in. Per row the scores are added up.
4. After calculating the total scores an one is added up to the total score per argument. In this way the least important argument doesn't get assigned with a zero weight factor resulting in deleting the argument in the MCA. The least important argument now has weight factor of one and the most important argument a weight factor of 14.

Table A-1: Weight factor calculation.

	Weight factors	Continuous production	Reliability	Safety	CAPEX and OPEX	Remote areas	Flexibility	Dosable	Different subsurfaces	Forces	Environment	Availability of power supply	Crew	Flowrate	Total	**Weight factor**
1	Continuous production	x	0	0	1	1	1	1	1	1	1	1	1	1	10	**11**
2	Reliability	1	x	0	1	1	1	1	1	1	1	1	1	1	11	**12**
3	Safety	1	1	x	1	1	1	1	1	1	1	1	1	1	12	**13**
4	CAPEX and OPEX	0	0	0	x	1	0	0	0	0	1	0	1	0	3	**4**
5	Remote areas	0	0	0	0	x	0	0	0	0	1	0	0	0	1	**2**
6	Flexibility	0	0	0	1	1	x	0	0	0	1	0	1	0	4	**5**
7	Dosage	0	0	0	1	1	1	x	0	0	1	0	1	0	5	**6**
8	Different sub surfaces	0	0	0	1	1	1	1	x	1	1	1	1	1	9	**10**
9	Forces	0	0	0	1	1	1	1	0	x	1	0	1	0	6	**7**
10	Environment	0	0	0	0	0	0	0	0	0	x	0	0	0	0	**1**
11	Availability of fuel	0	0	0	1	1	1	1	0	1	1	x	1	0	7	**8**
12	Crew	0	0	0	0	1	0	0	0	0	1	0	x	0	2	**3**
13	Flowrate	0	0	0	1	1	1	1	0	1	1	1	1	x	8	**9**

MCA

A Multi criteria analysis (MCA) is a scientific evaluation method in order to make a rational decision between several discreet alternatives based on more than one criterion. The criteria have been assigned with weight factors; these have been determined in
Table A-1.

In the first column the methods are listed. In the first row the criteria and in the second row the weight factors are summed up. Next the methods are rated for each criterion and will be assigned with a discrete value ranging between 0 (bad score) and 4 (good score). If a method scores a zero the power of veto will be applied. I.e. this method will be excluded in the analysis. In this way the design process is sped up and the most promising method will be (much) more realistic.

Next the score is multiplied with the weight factor. Per method the received scores for each criteria/argument are added up. The total score is divided by the maximum score to be obtained. As a result a percentage is known and in this way the methods could be compared to each other in order to determine the most promising method.

Below the results of the MCA are presented.

Table A-2: Multi criteria analysis with weight factors batch 1.

	Method / Criteria	Continuous production	Reliability	Safety	CAPEX and OPEX	Remote areas	Flexibility	Dosable	Different subsurfaces	Forces	Environment	Availability of power supply	Crew	Flowrate	Total	**Percentage**
	Weight factor	11	12	13	4	2	5	6	10	7	1	8	3	9		
1	ASP Hovercraft	4	2	4	1	3	4	3	4	1	1	1	3	4	269	**73,9**
2	ASP Tracks	3	3	4	3	3	2	3	3	3	3	3	3	3	281	**77,2**
3	ASP Screws	3	3	3	3	3	2	3	2	2	3	3	3	3	251	**69,0**
4	ASP Watermaster	3	3	4	2	3	3	3	3	2	3	3	3	2	266	**73,1**
5	Adjustable rainbow	0	4	4	3	4	1	2	1	1	4	4	4	3	0	**0,0**
6	Amphibious bulldozer	2	1	4	2	2	4	2	1	3	2	4	4	1	216	**59,3**
7	Amphibious excavator	2	3	1	2	2	3	1	3	2	3	4	4	1	204	**56,0**
8	Equipment elevated platform	2	3	2	2	2	3	1	2	3	2	4	4	1	213	**58,5**

Table A-3: Multi criteria analysis with weight factors batch 2.

	Method / Criteria	Continuous production	Reliability	Safety	CAPEX and OPEX	Remote areas	Flexibility	Dosable	Different subsurfaces	Forces	Environment	Availability of power supply	Crew	Flowrate	Total	**Percentage**
	Weight factor	3	3	3	1	1	2	2	3	2	1	2	1	2		
1	ASP Hovercraft	4	2	4	1	3	4	3	4	1	1	1	3	4	76	**73,1**
2	ASP Tracks	3	3	4	3	3	2	3	3	3	3	3	3	3	79	**76,0**
3	ASP Screws	3	3	3	3	3	2	3	2	2	3	3	3	3	71	**68,3**
4	ASP Watermaster	3	3	4	2	3	3	3	3	2	3	3	3	2	76	**73,1**
5	Adjustable rainbow	0	4	4	3	4	1	2	1	1	4	4	4	3	0	**0,0**
6	Amphibious bulldozer	2	1	4	2	2	4	2	1	3	2	4	4	1	62	**59,6**
7	Amphibious excavator	2	3	1	2	2	3	1	3	2	3	4	4	1	60	**57,7**
8	Equipment elevated platform	2	3	2	2	2	3	1	2	3	2	4	4	1	61	**58,7**

A-2 Calculation of weight factors for delivering material

Table A-4: calculation of weight factors per criterion for delivering material.

	Criteria	Forces	Reposition	Flexibility	Operation	Reliability	CAPEX & OPEX	Wear	Supply of energy	Environmental impact	Obstacles	Remoteness	**Outcome calculation**
1	Forces	x	1	0	1	1	1	1	1	1	1	1	**9**
2	Reposition	0	x	0	1	1	1	1	1	1	1	1	**8**
3	Flexibility	1	1	x	1	1	1	1	1	1	1	1	**10**
4	Operation	0	0	0	x	1	1	1	1	1	1	1	**7**
5	Reliability	0	0	0	0	x	0	0	0	1	0	1	**2**
6	CAPEX & OPEX	0	0	0	0	1	x	1	1	1	1	1	**6**
7	Wear	0	0	0	0	1	0	x	1	1	0	1	**4**
8	Supply of energy	0	0	0	0	1	0	0	x	1	0	1	**3**
9	Environmental impact	0	0	0	0	0	0	0	0	x	0	1	**1**
10	Obstacles	0	0	0	0	1	0	1	1	1	x	1	**5**
11	Remoteness	0	0	0	0	0	0	0	0	0	0	x	**0**

Appendix B

Water depths during discharging of the TSHD at Roggenplaat for a review period of one week

Discharge number	Time start [hr]	Water depth start [m]	Time end [hr]	Water depth end [m]
1	2.08	1.57	3.58	1.77
2	6.25	0.00	7.75	0.00
3	10.42	0.00	11.92	0.00
4	14.58	1.61	16.08	1.75
5	18.75	0.00	20.25	0.00
6	22.92	0.00	24.42	0.00
7	27.08	1.65	28.58	1.72
8	31.25	0.00	32.75	0.00
9	35.42	0.00	36.92	0.00
10	39.58	1.68	41.08	1.70
11	43.75	0.00	45.25	0.00
12	47.92	0.00	49.42	0.00
13	52.08	1.71	53.58	1.66
14	56.25	0.00	57.75	0.00
15	60.42	0.00	61.92	0.00
16	64.58	1.74	66.08	1.63
17	68.75	0.00	70.25	0.00
18	72.92	0.00	74.42	0.00
19	77.08	1.76	78.58	1.59
20	81.25	0.00	82.75	0.00
21	85.42	0.00	86.92	0.00
22	89.58	1.78	91.08	1.55
23	93.75	0.00	95.25	0.00
24	97.92	0.00	99.42	0.00
25	102.08	1.80	103.58	1.50
26	106.25	0.00	107.75	0.00
27	110.42	0.00	111.92	0.00
28	114.58	1.81	116.08	1.46
29	118.75	0.00	120.25	0.00
30	122.92	0.00	124.42	0.08
31	127.08	1.82	128.58	1.40
32	131.25	0.00	132.75	0.00
33	135.42	0.00	136.92	0.17
34	139.58	1.83	141.08	1.35
35	143.75	0.00	145.25	0.00
36	147.92	0.00	149.42	0.25
37	152.08	1.83	153.58	1.30
38	156.25	0.00	157.75	0.00
39	160.42	0.00	161.92	0.33
40	164.58	1.83	166.08	1.24

Appendix C

Drag and lift coefficients for a pipeline situated in water

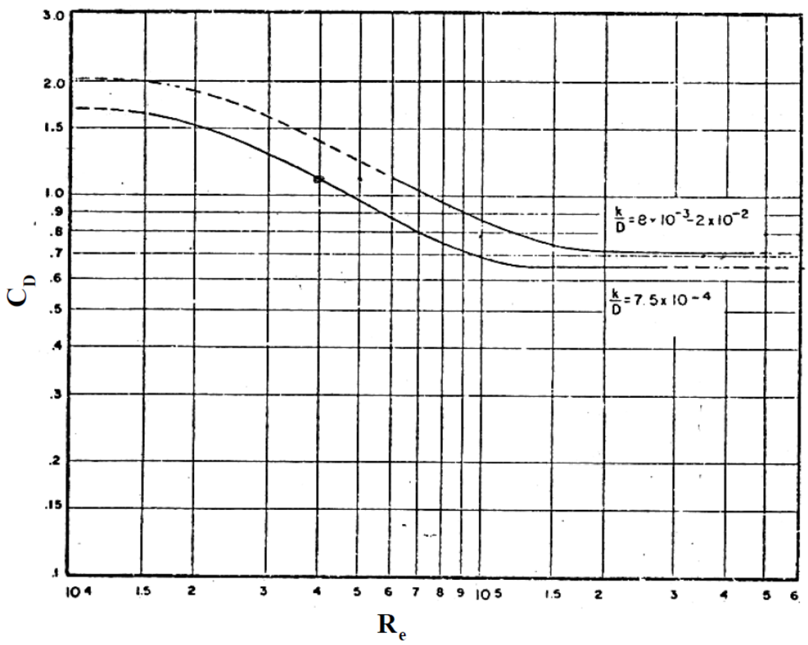

Figure C-1: Drag coefficients. (Source: *Pipelife Norge AS, 2002*)

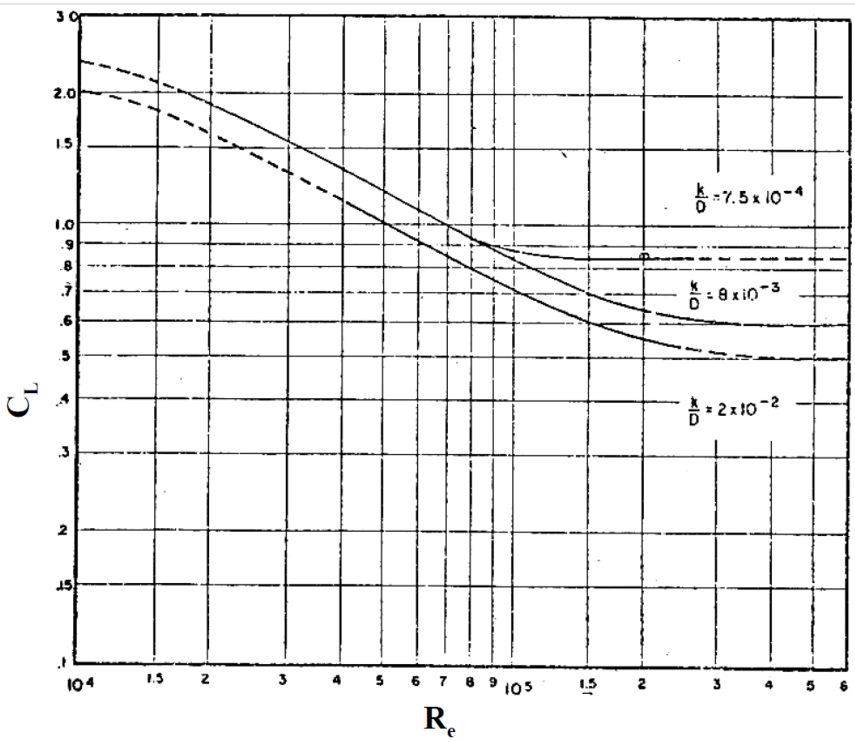

Figure C-2: Lift coefficient. (Source: *Pipelife Norge AS, 2002*)