MAINTENANCE LAYER ANALYSIS FOR A LEVEE STRENGTHENING USING SANDY SHORES IN A NON-TIDAL ENVIRONMENT

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Abstract

Since there has never been a levee strengthening in a lake like the sandy shores at the Houtribdijk, there are many questions about how a sand nourishment like this evolves. This study aims to seek insight in how the maintenance layer of the sand nourishment develops and for how long it will comply to the safety norms before requiring maintenance.

To test the hypothesis that the currently constructed sandy shores are insufficient for a 10-year period, an analysis on subsidence and morphology was conducted. The results from this subsidence analyses show how subsidence substantially decreases over time and that most of the total subsidence occurs shortly after construction. The analysis on morphology showed an eventual equilibrium in volume gains/losses for the maintenance layer and indicated that the shore-line movement would be the reason for the sandy shores requiring maintenance earlier than the designers 10-year prediction.

The analyses were mostly performed on periodic measurements at four detail locations, therefor the results give an average trend on how the maintenance layer overall evolves over time due to subsidence and morphology. Given the results on the performed analyses it can be predicted that the constructed maintenance layer will most likely not be sufficient for a 10-year period. Most parts of the sandy shores will require maintenance 5 or 6 years after being constructed. Furthermore, there are a few specific locations that require even earlier maintenance.

Contents

1. Introduction

1.1 Context

The “Houtribdijk” also known as “Markerwaarddijk” is a 25-kilometer-long dam in between Lelystad and Enkhuizen. It has kept large parts of the Netherlands safe from flooding for more than 50 years after its construction. The Houtribdijk is part of the Dutch primary water defences. The levee was originally designed for the reclamation of the southern part of the “IJsselmeer” in 1963. In 2003 it was decided to step away from these land reclamation plans and the Houtribdijk became a dam (History HRD, 2020).

In this day and age, the Houtribdijk separates the Markermeer from the IJsselmeer and acts as a road connection between Lelystad and Enkhuizen (figure 1). Two sluice stations are present in the levee to make sure shipping between the two lakes is possible. The main flood risk management function of the Houtribdijk is to break the surge (in case of a storm) between the Markermeer and IJsselmeer and break waves. In this way the Houtribdijk contributes to the safety from flooding for the areas around the Markermeer and IJsselmeer.

Figure 1 Houtribdijk connecting Lelystad and Enkhuizen. Source: Rijkswaterstaat.

In 2006 the Houtribdijk did not comply to the safety norms of the Dutch Water law anymore (Royal Haskoning, 2014). The law describes the standard to which condition the levee should be able to prevent flooding. To make sure the Houtribdijk would meet these norms a strengthening of the levee had to take place.

The strengthening project was already ongoing at the time of a new water law. The design of the strengthening is based on the old norms from 2014. These norms have a standard of high water exceeding the levee 1/10.000 years. In 2017, Rijkswaterstaat started the execution of the levee strengthening project in order to comply to the safety norms again, based on the execution program of the Flood-risk-reduction program (in Dutch: Hoogwaterbeschermingsprogramma - HWBP). In this project the contractors are not only requested to improve the safety but also stimulate to give additional attention to the creation of nature areas. According to the initial planning the project should be completed mid-2020.

The strengthening of the levee near Lelystad was done by the use of rubble mount and between Enkhuizen and Trintelhaven the levee is strengthened on both sides by constructing sandy shores. These sandy shores are supposed to break the waves. Using sandy shores to reinforce a levee in a large lake where tides are absent, has never been done before. Therefore, knowledge gaps are present and there is a lot to discover on how these sandy shores behave and evolve in this situation (Ton, 2019).

1.2 Problem description

When looking at the phenomenon of sandy solutions for flood risk management one can look at the Dutch coast as an example. A good example is the program “Kustlijnzorg” (Suppletieprogramma, 2018), this program shows how the Dutch coastline is strengthened and maintained by sandy solutions. In testing and designing these sand nourishments at the Dutch coast, there are certain standards and calculation methods used in the design and construction process. However, there is a large difference in external factors the sand nourishments have to deal with when comparing sandy solutions at the Dutch coast to a sandy solution in a fresh water non-tidal lake.

There are a few problems that come to mind when comparing a sand strengthening at the Dutch coast to a sand strengthening in a lake. One is that during a storm large amounts of sand at the coast are eroded from the dunes to the beach and shoreface. This loss of sand can later on largely be recovered by tides, waves and wind. These processes are less present in the IJsselmeer and the Markermeer. Next to this, the Dutch coast is mostly straight (at the provinces North-Holland and South-Holland) and has similar hydraulic profile conditions for the whole stretch of coastline. However, the Houtribdijk has multiple gentle curves and nods in its profile and a varying wave condition in terms of different angles in which waves hit the sand body over the whole stretch of the Houtribdijk (Rijkswaterstaat, 2016). Another important aspect is the orientation of the levee relative to the wind which plays a large role in the erosion process.

Figure 2 presents a schematic figure of the sandy shores at the Houtribdijk. The sandy shores consist of different design layers of sand, each with its own purpose. The existing body of the Houtribdijk acts as a base on which the sandy shores were constructed. The largest volume of sand that was added is in the safety-profile layer. This sand body acts as a minimum volume that needs to be present, determined by “DUROS-plus” calculations. These DUROS-plus calculations use multiple different factors that play a role in the erosion of dunes during a heavy storm. Things like: sand particle size, wave characteristics and water depth are all taken into account in the DUROS-plus calculation to determine the total erosion (ENW, 2007). The storm surcharge layer acts as a compensation body for volume losses as a result from longshore-transport and occurring secondary storms. The maintenance layer is present to ensure that the safety-profile and the storm surcharge can deal with structural erosion for multiple years. The heightening volume layer is present to support the maintenance layer and keep it in place. At last, within this existing sand body there is a cunet present. This cunet provides stability to the Houtribdijk and minimizes subsidence from the soil above it.

In 2017 there were new agreements made in the new water law (WBI2017). New norms and regulations were set that are also applicable for the Houtribdijk. Based on the small-scale pilot performed by Rijkswaterstaat and Ecoshape for this type of levee strengthening in combination with this new water law, there are new findings in the way of calculation methods used for the maintenance layer (Arcadis, 2019). Since the design process was already finished before this period, the conservativeness of the design of the sandy shores became unsure with these new norms and standards.

The methods used in designing the sandy shores and thus the maintenance layer are appearing to be less conservative than the designers thought. It appears that the maintenance layer erodes faster than the designers predicted. This conclusion could be drawn from the first few months of monitoring the maintenance layer.

During construction there was some extra robustness created by applying some excess height in the sand body to cope with erosion and subsidence. Next to this, the maintenance layer (marked layer figure 2) is there to maintain a sufficient sand profile. This leads to the question how this lower sand layer develops, keeping in mind the less conservative maintenance sand layer and the excess height that was created. This excess height needs to cope with subsidence. The maintenance layer is present to deal with the partly volume losses of the different sand layers and maintaining a sufficient sand body for ten years. If the development of the maintenance layer turns out to be negatively impacting the safety of the levee, the problem could be that the levee requires more maintenance than in design was prospected.

The storm surcharge is present to act as a buffer in case of a heavy storm so that erosion and the transportation of sand during a storm can be compensated. During construction the storm surcharge just like the maintenance layer, was intended to have no need for maintenance for the upcoming 10 years (Rijkswaterstaat, 2016).

Since the sandy shores appear to be less conservative than calculated, it is likely that earlier maintenance is required.

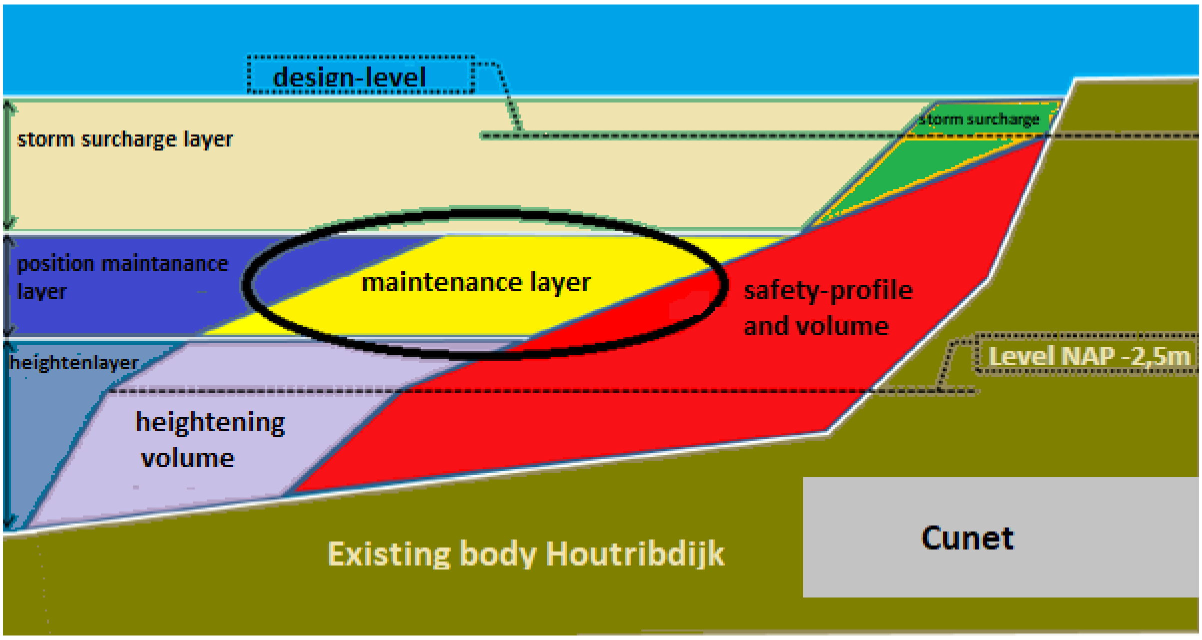

Figure 2 different layers in the sand nourishments (adapted after (Rijkswaterstaat, 2016))

1.3 Study area

The study area of this research will be at the part of the Houtribdijk between Enkhuizen and Lelystad where the sandy shores are present (red circle figure 3). The sandy shores have a total length of 9,6km on the side of the IJsselmeer and 9,2km on the side of the Markermeer (Arcadis, 2019).

These sandy shores are partly above water, however a large part of the sand body lies below water. The maintenance layer lies between NAP -1 and NAP +1 and in this sand layer the main research will be performed (figure 4).

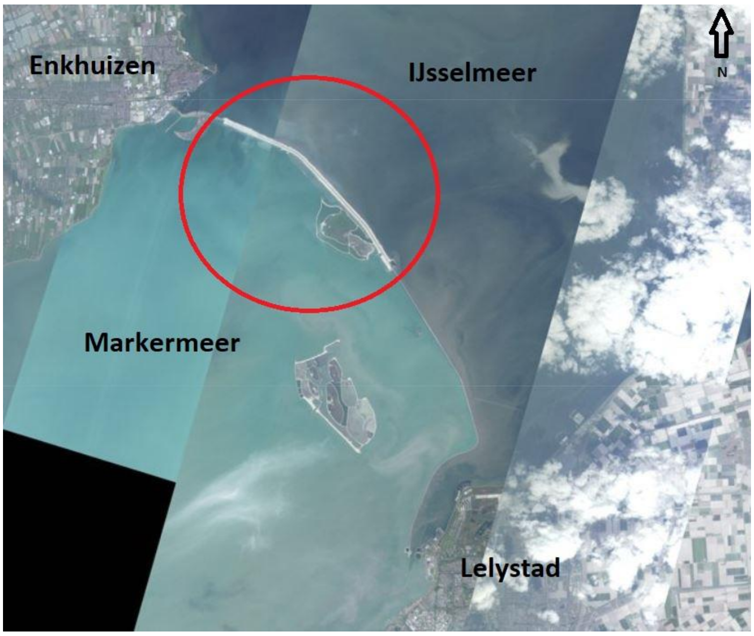

Figure 3 Location of Sandy shores (red circle).

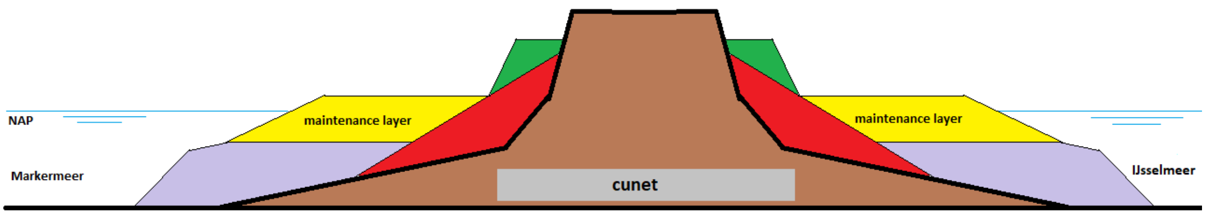

Figure 4 maintenance Layer position to NAP.

1.4 Main research question

- *RQ1: Given the design of the maintenance layer and the first monitored results of morphology and subsidence, what lifetime of the maintenance layer can be expected?*

1.5 Research sub questions

- *RQ1a: In what way does subsidence play a role in the development of the maintenance layer?*
- *RQ1b: What morphological developments play a role in contribution to the development of the maintenance layer?*

1.6 Research relevance

The intention of this research is to analyse the design of the sandy shores and see if the design is working as the designers intended it to. Solving my research questions will better help to understand in how the maintenance layer has evolved for the first 1,5 years after construction. This will help in the maintenance process of the Houtribdijk and to ensure the safety of the levee.

2. Methodology

Figure 5 shows a schematic view on how the research for the sub-questions and main question was performed. Since this research is done for a design that has already been built, it allowed the option to validate design decisions that were made and thus can be partly be validated (or not) by this research. Starting for both sub questions at the top or the circle (identifying research area).

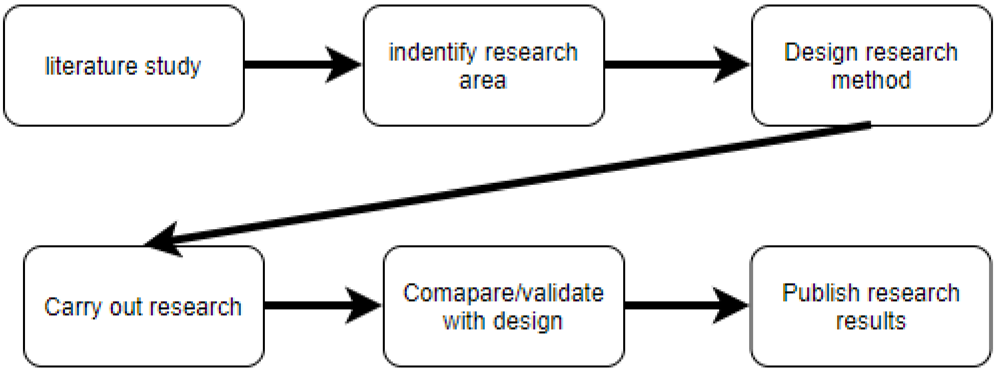

Figure 5 Schematic view of the research process

2.1 Available data

Since this type of levee strengthening is a worldwide premiere, it is interesting to see how the sandy shores develop for the first few years after construction. This is why Rijkswaterstaat finances an ongoing project named “LakeSIDE” executed by the Technical University Delft, and contracted various companies to perform periodic measurements of the sand profile in cross shore direction. This data is obtained by lidar measurements alongshore the Houtribdijk. At four different locations (the detail locations) there are monthly measurements whilst the full Houtribdijk is measured every half year. These measurements provide a clear cross-sectional view in how the profile of the sandy shores develop over time (as well above as below the water line). In general, these measurements are performed every 50 meters in alongshore direction. However, if the Houtribdijk makes a bend every 25 meters is being measured. In cross-shore direction these lidar measurements are performed on a grid for every 25cm by 25cm. These measurements provide lots of data concerning subsidence and morphological developments which makes it possible to do analysis and evaluate design decisions with the current measurements.

2.2 Intervention line (BOL)

To determine when maintenance is required for the sandy shores at the Houtribdijk, a certain intervention criterion is set. This intervention criteria depends on the position of the shoreline represented by the mass balance location of a particular vertical volume layer. The term used for this intervention line is in Dutch: “Basis Oeverlijn” (BOL), which is derived from the Basic Coast Line (‘Basiskustlijn’ in Dutch). The boundaries for this BOL are NAP -1m and NAP +1m. Figure 6 shows an example of a transect where this BOL is defined. For both the IJsselmeer and Markermeer the proposed BOL for which maintenance shall be required can be seen in figures 7 and 8 (solid line for the design BOL, dotted line for the alternative BOL without storm buffer (BOL, 2019). The design intention for the sandy shores is that this BOL line should not be exceeded for the first 10 years.

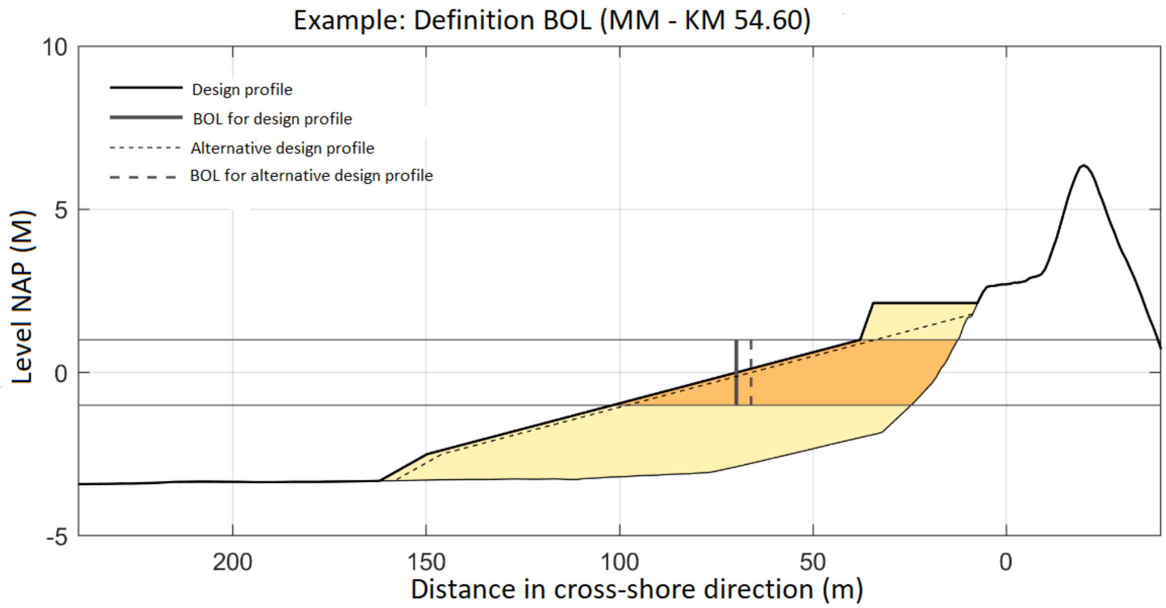

Figure 6 Example how the BOL line is defined for a specific transect (solid line for the design profile, dotted line for the alternative design profile).

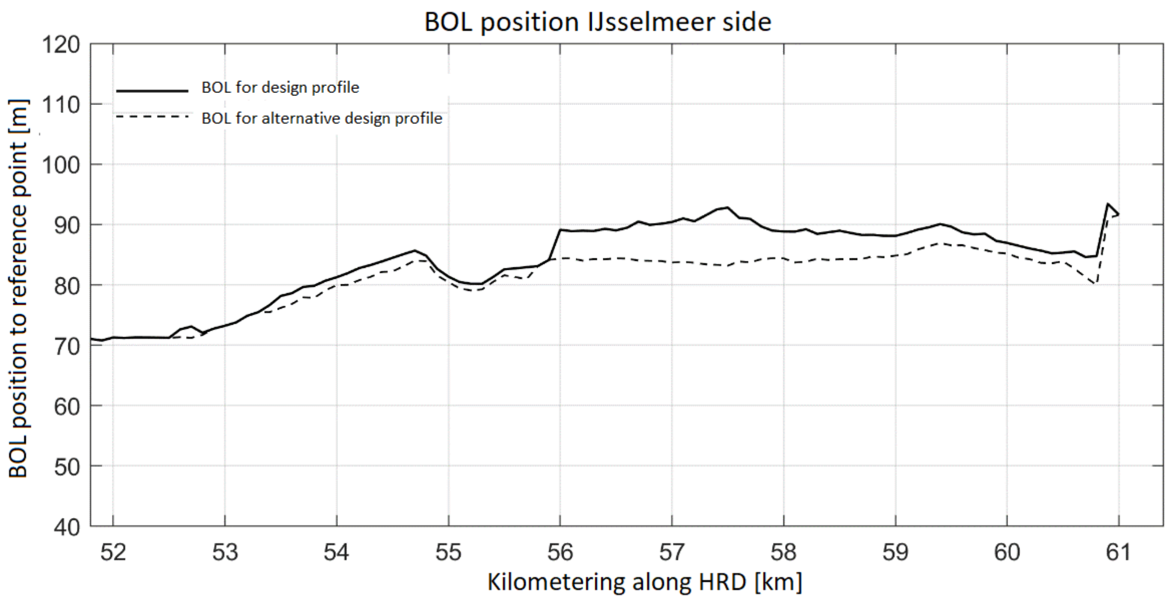

Figure 7 intervention line (BOL) for the IJsselmeer side

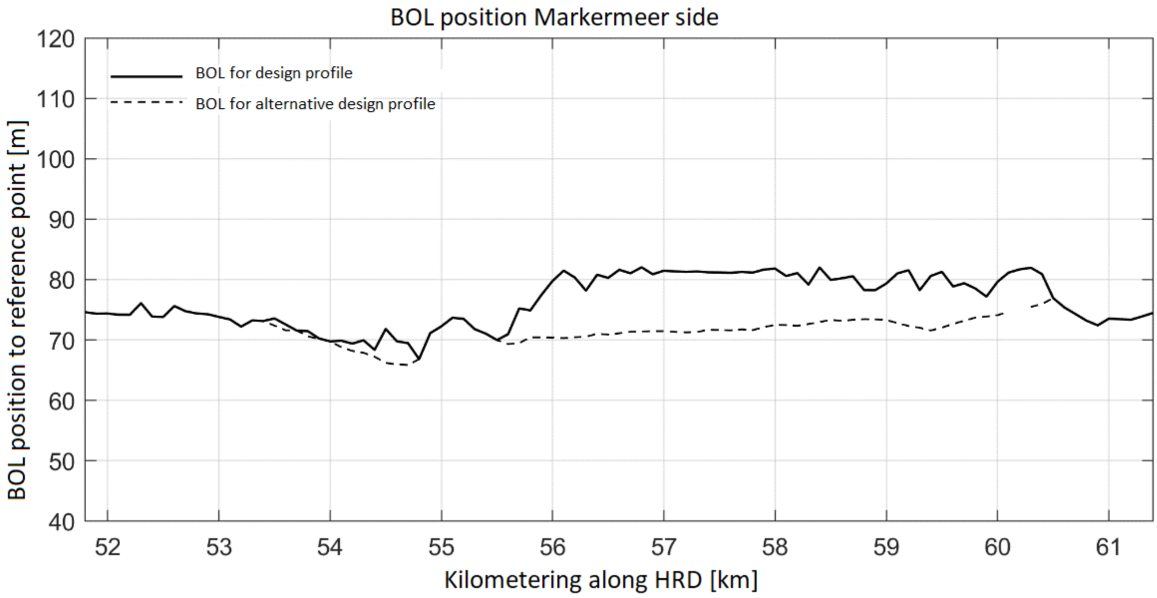

Figure 8 intervention line (BOL) for the Markermeer side

2.3 Subsidence impact on the maintenance layer

For this first sub-question, the impact of subsidence on the maintenance layer is analysed. Determining the impact of subsidence on the maintenance layer, the height data from the periodic measurements at the Houtribdijk have to be analysed. To be able to analyse the subsidence the measurements have to be analysed in such a way so that morphological developments, erosion and the support of a cunet can be excluded as much as possible from the analysis. This should result in a subsidence analysis for the sand layer due to the compaction of subsoils. The subsidence can spatially vary due the present of tidal channels (Red boxes in figure 9), where the subsoil in general is very looser. With this analysis there will also be looked at the difference in subsidence for the first couple of months after the construction of the sandy shore compared with a couple months in a later stage to see if the developments are linear in time or, most likely, generally decaying.

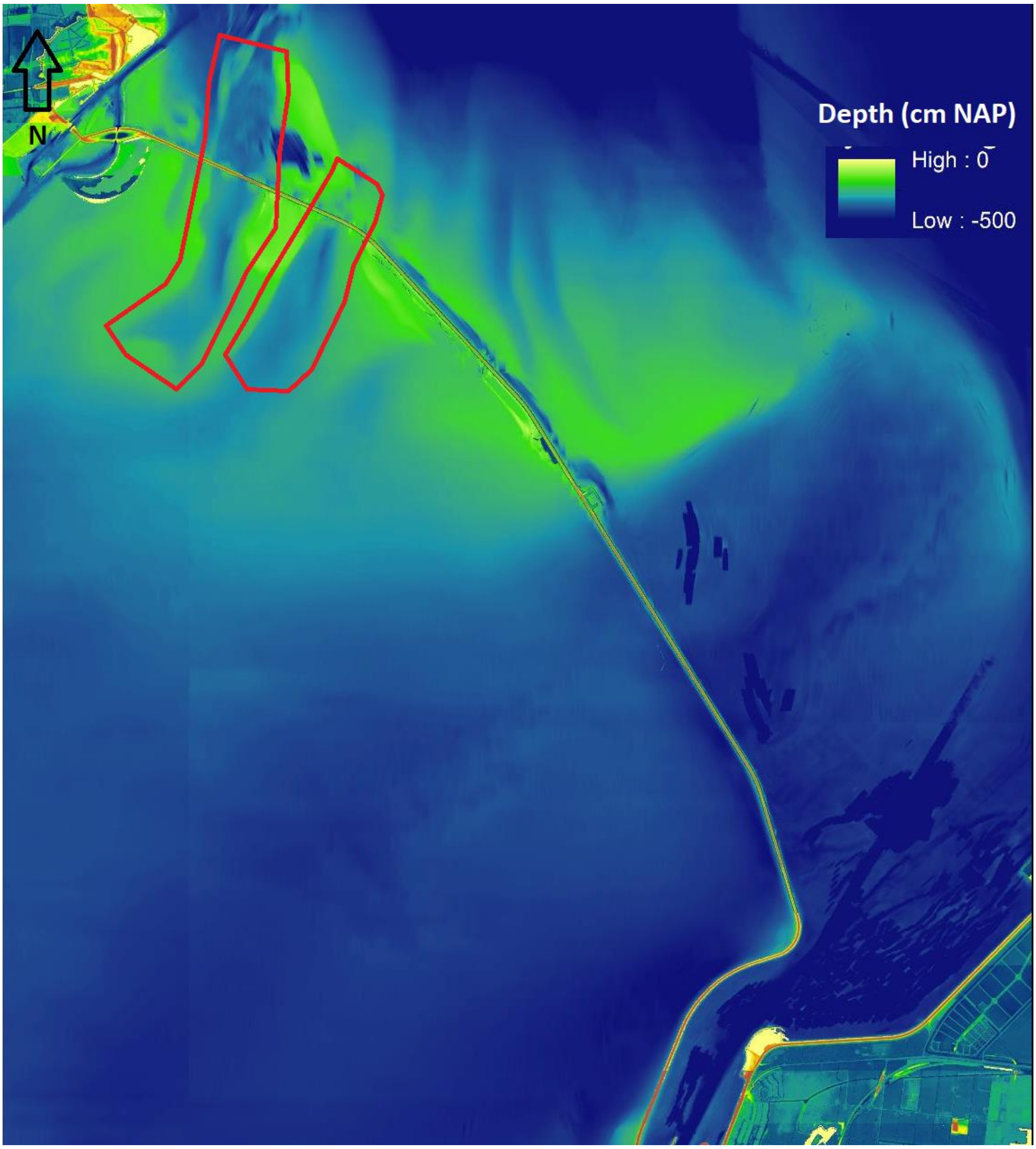

Figure 9 Tidal channels (marked in the red boxes). Retrieved from (Arcadis, 2019).

As a reflection the observed subsidence will be compared with the design predictions. As can be seen in figure 10 a prediction was made in the design for the required subsidence compensation in relation with the thickness of the added sand layer (OntwerpnotaHRD, 2018). There were 2 predictions made for the required subsidence compensation, the red line shows the prediction for a 50-year period after construction and the blue line shows a prediction for a 2-year period after construction. Since these predictions were made at the time of the construction of the sandy shores (2018). At the moment of writing this thesis, almost 2 years have passed since the construction of the dandy shores. This makes it possible to verify this blue line prediction. As verification, this 2-year blue line prediction will be compared to the actual measured subsidence compared with the thickness of the sand layer.

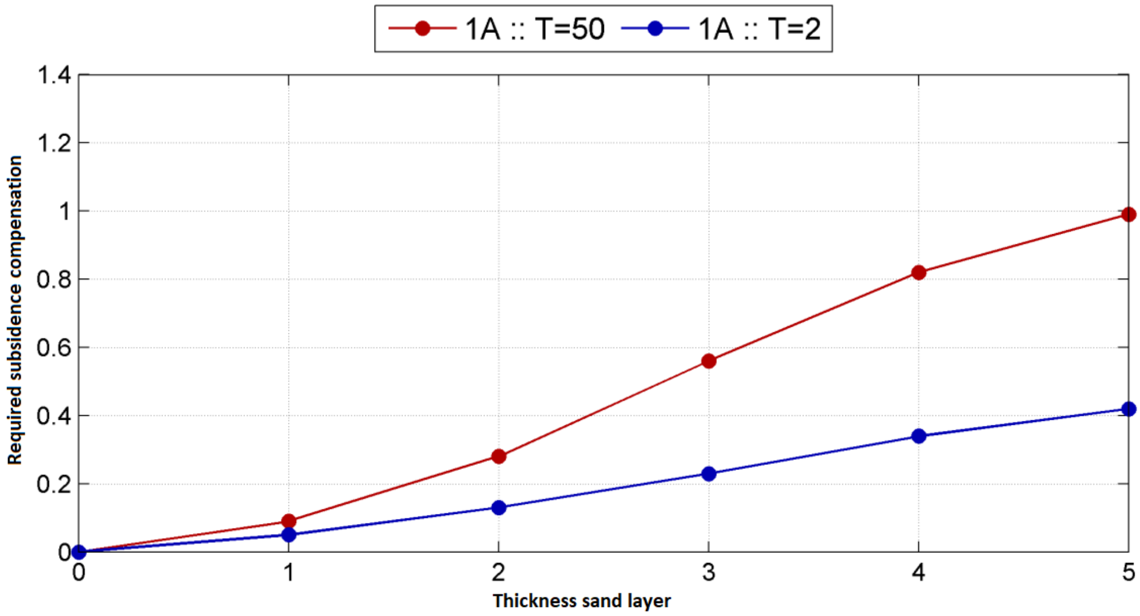

Figure 10 Predicted required subsidence compensation for 50 years(red line) and for 2 years (blue line) (Arcadis, 2019).

Data above NAP +0,5 m and at least 40 m from the dike was used to investigated subsidence. This has to do with for example the supportive presence of a cunet. This cunet causes the first 40 meters from the reference point (centre of the road on the Houtribdijk) to barely have any subsidence in this “cunet supported zone” (left of the vertical red line in figure 11). Furthermore, the area where waves start to impact the sand surface profile between NAP+0,5m and NAP-0,5m (the morphological zone, red circle figure 11) must be excluded. This leaves only a small area where the sand profile (mostly) subsides due to compaction of the subsoils (blue circle figure 11).

These areas differ for both sides of the Houtribdijk. For the IJsselmeer side this location is on average between meters 40 until 75 from the reference point (blue circle figure 11). For the Markermeer side of the Houtribdijk this section is between 30 until meter 100 from the reference point on the Houtribdijk.

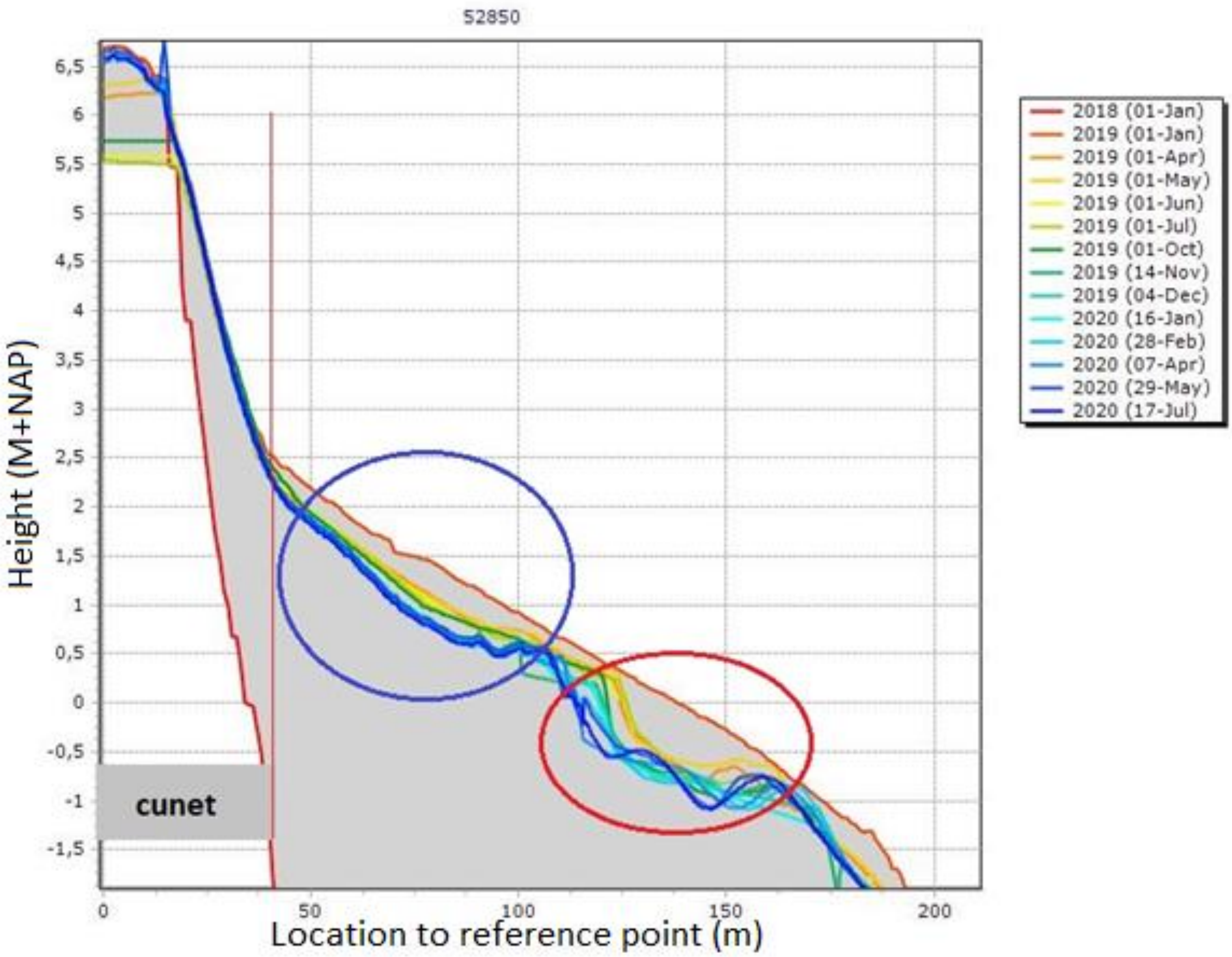

Figure 11 "Cunet supported zone" (left of the red vertical line), subsidence analysis zone (blue circle) and morphological zone (red circle).

There are multiple measurement dates where the surface of the sand profile has been measured. These measurements can be analysed and plotted to see how the sand body subsides over time. A relation between subsidence and sand layer thickness is drawn.

The data points that are analysed are measurements in cross-shore direction of 25cm or 1meter, this varies for the date that the measurements have been performed. In this "subsidence due to compaction of the subsoil" region (blue circle figure 11) all the data are compared. This is done by plotting all these measurements in a scatterplot where the thickness of the sand layer is plotted related to the subsidence on that specific sand layer thickness. In these scatterplots, a trendline with its corresponding formula is drawn to give a gross relation between subsidence and sand layer thickness. The hypothesis for the relationship is that the subsidence will slightly exponentially increase when the sand layer gets thicker. Furthermore, it is predicted that most of the subsidence will occur right after construction and will decrease over time.

Testing this hypothesis, the following scatterplots where made:

- For both IJsselmeer and Markermeer, the construction date until the most recent measurement date (1-Jan-2019 until 17-Jul 2020).
- For both IJsselmeer and Markermeer, the first couple of months after construction (1-Jan-2019 until 1-Jun-2019).

- For both IJsselmeer and Markermeer, the currently last couple of months of measurements (19-Jan-2020 until 17-Jul-2020).
- An overlapping scatterplot of both IJsselmeer and Markermeer data in one figure to compare the two sides with each other.

2.4 Morphological impact on the maintenance layer.

In determining what morphological developments play a role in the contribution to the development of the maintenance layer multiple aspects are important. Figure 12 shows a section from the IJsselmeer side of the Houtribdijk. Having looked at all the data on both the Markermeer side and IJsselmeer side of the Houtribdijk this figure illustrates the trend of shore-line movement for the sand profile at most locations at the Houtribdijk. In figure 12 it can clearly be seen that there appears to be a change in the surface of the maintenance layer. When looking at the sand profile alongshore the Houtribdijk, there appears to emerge a platform with an equilibrium around NAP -0,7m. This height of the platform has to do with the wave height of the waves that are present on the maintenance layer (Ton, 2019). To analyse possible volume losses and the rapidly moving shoreline, analyses about the following topics are performed:

- There is a loss of volume in the morphological zone (red circle figure 12) whereas there appears to be a volume increase in a lower lying location (blue circle figure 12).
- The rapid change in shore-line movement (red circle in figure 12).

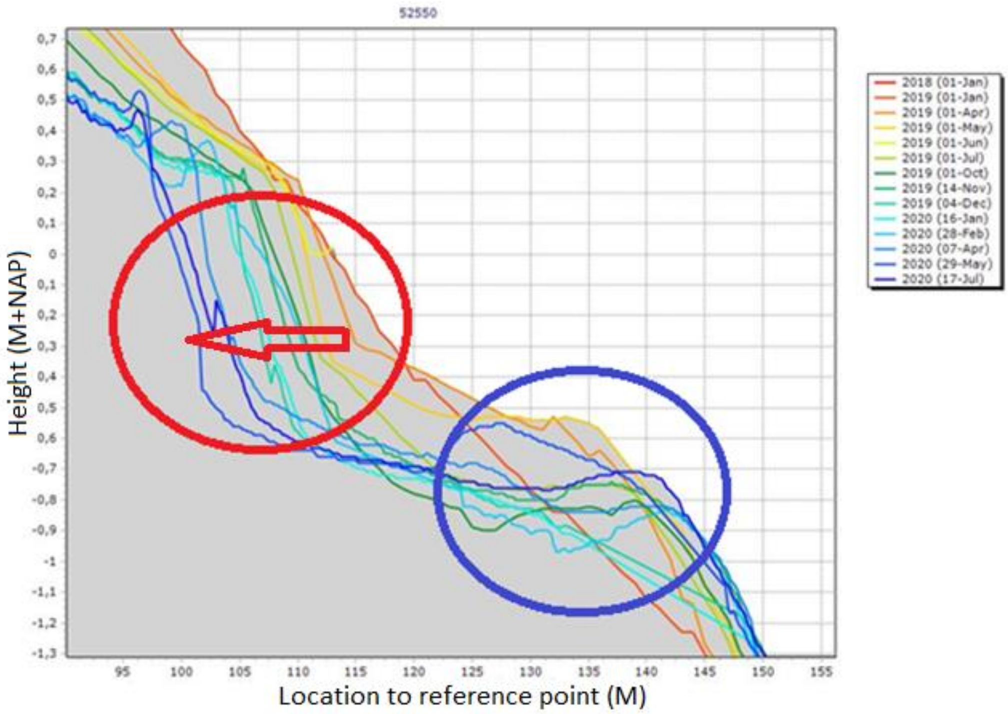

Figure 12 "Morphological zone" from the sandy shores at the Houtribdijk (red circle shore line movement), (blue circle platform equilibrium).

2.4.1 Sand volume losses/gains

To analyse if there are any volume losses in the maintenance layer due to morphological activity, a volume analysis for this part of the maintenance layer is performed. The intention of this volume analysis is to see if the possible loss/gains of sand volume in the morphological zone (red circle in figure 11) can give a prediction concerning the maintenance of this morphological active area. Furthermore, the results from the subsidence analysis will also be taken into account in the conclusion of this volume analysis due to morphological activity.

2.4.2 Shoreline movement

Visually figure 11 shows how the platform appears to have an equilibrium at around NAP -0,7m. However, when looking at the shoreline (red circle figure 11 and red circle figure 12) this seems to move fairly linearly land inwards. By the use of MorphAn and the converted data in Matlab a relation in how the shoreline moves over time can be found and what results this has for the morphology of the maintenance layer.

3. Results

3.1 Results subsidence

3.1.1 Results IJsselmeer.

Figure 13 shows a scatter plot for all the measurements from 01 January 2019 until the most recent measurement 17 July 2020 for the IJsselmeer side of the Houtribdijk. This scatterplot shows a relationship between the subsidence with the thickness of the sand layer. The trendline, a second order polynomial, is weakly quadratic. There are certain outliers in the scatterplot, these can be explained by for example morphological changes that are not taken into account in this plot. In general, the trendline corresponds well with most of the data points.

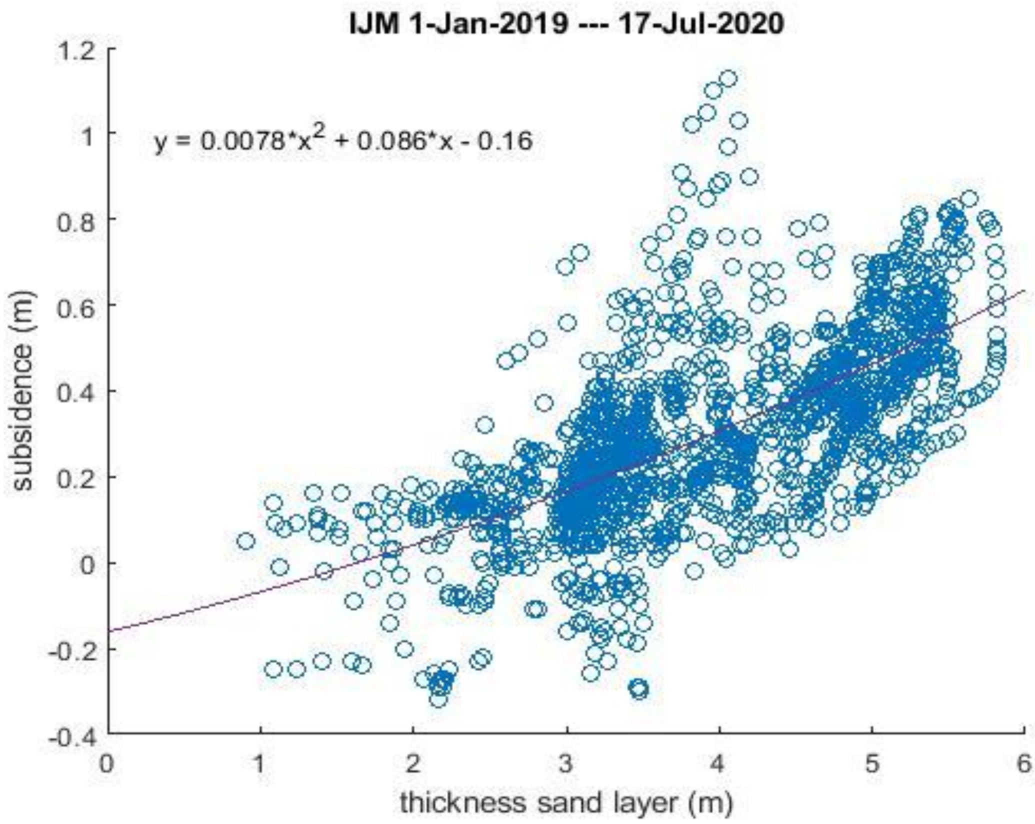

Figure 13 Subsidence scatterplot IJsselmeer side 1-Jan-2019 until 17-Jul-2020

Since it can be expected that the subsidence for a newly constructed sand layer is the largest in its early stages, the subsidence analysis has been split into two periods to test this hypothesis. Figure 14 and figure 15 show the beginning stage and a later stage after construction (01-1-2019 until 01-6-2019 and 16-1-2020 until 17-7-2020) in which data at the IJsselmeer side was collected. Based on figures 13 and 14 it can already be stated that when looking at the y-axis the sand layer subsides substantially more in the beginning stage after construction compared to a later stage. This complies with the logic of a gradually slower subsidence since the sand layer gets more compact over time. As shown in figure 15, the data shows that the sand layer has settled for the most part and that there are minimal differences even over a 6-month period. The data show that the subsidence is substantially larger in the first few months after construction in comparison with a later stage.

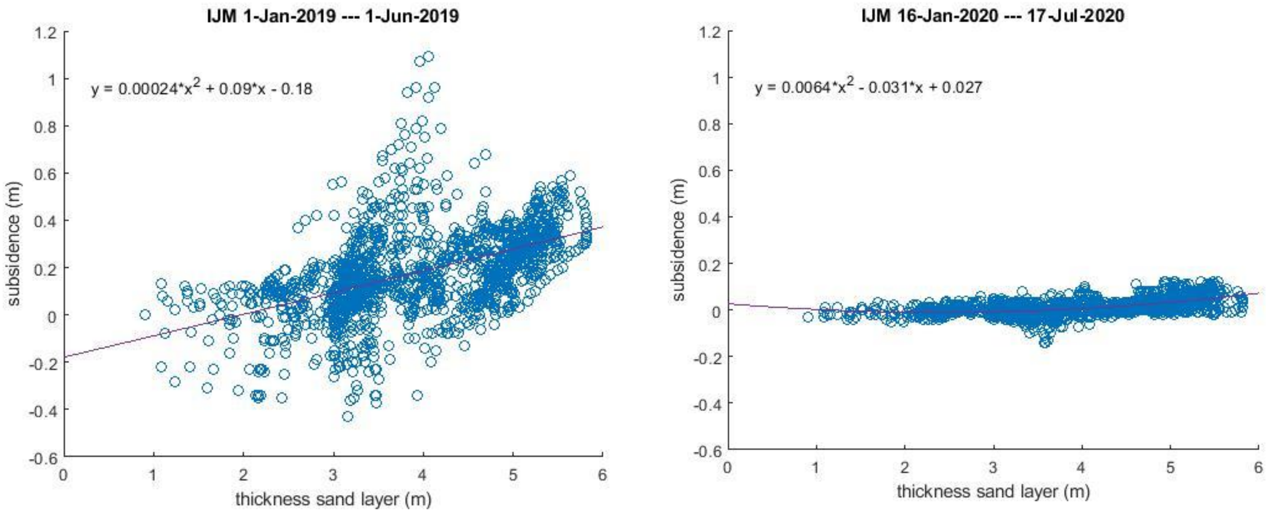

Figure 14 (left) and 15 (right) Subsidence scatterplot IJsselmeer side 1-Jan-2019 until 1-Jun-2019 (month 1-6 after construction) and 16-Jan-2020 until 17-Jul-2020 (month 12-18 after construction)

3.1.2 Results Markermeer.

Analysing the results for the Subsidence scatterplot of the full dataset from 1-Jan-2019 until 17-Jul-2020, the results are shown in figure 16 and seem fairly similar to the scatterplots at the IJsselmeer side. As expected just like the IJsselmeer side of the Houtribdijk the sandy shores on the Markermeer side of the Houtribdijk seem to have a similar relation for the subsidence compared to the thickness of the layer. There seems to be a slight exponential relation for when the sand layer gets thicker, the subsidence increased exponentially.

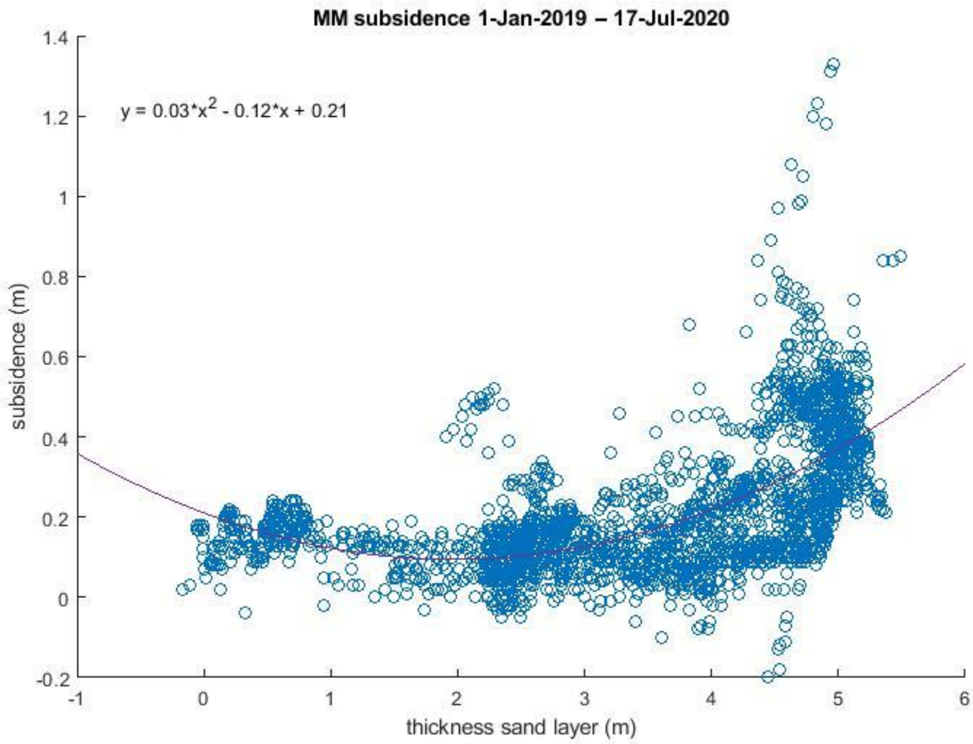

Figure 16 Subsidence scatterplot Markermeer side 1-Jan-2019 until 17-Jul-2020

Comparing figure 17 and figure 18 which represent the first stage of the sand layer after construction and a layer stage as comparison, the figures differ from those of the IJsselmeer side. The subsidence for the first 5 months after construction shows subsidence up to 0,4m which is slightly less but comparable to the values at the IJsselmeer side of the Houtribdijk. Furthermore, the last 6 months show for the Markermeer side a decrease in subsidence. When comparing figure 17 and 14 and figures 18 and 15 which show the same time frames but at the other side of the Houtribdijk it can be said that the figures show very similar x-y relations and it can be stated that the sandy shores subside more in the first stage after construction in comparison with a later stage.

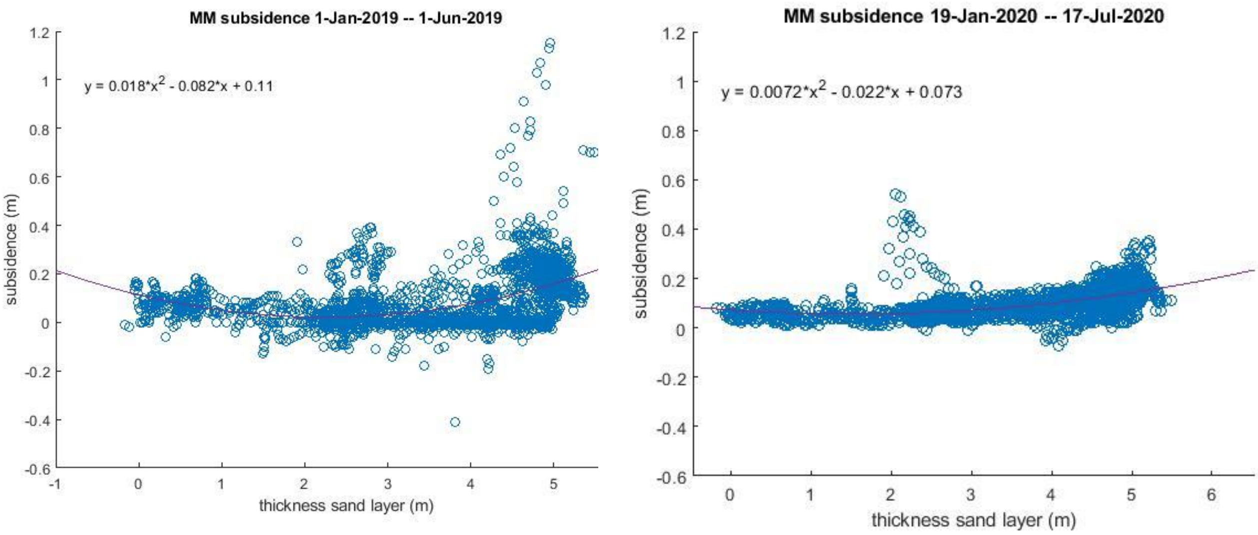

Figure 15 (left) and 18 (right) Subsidence scatterplot Markermeer side 1-Jan-2019 until 1-Jun-2019 (month 1-6 after construction), and 19-Jan-2020 until 17-Jul-2020 (months 12-18 after construction)

3.1.3 Results Markermeer and IJsselmeer combined.

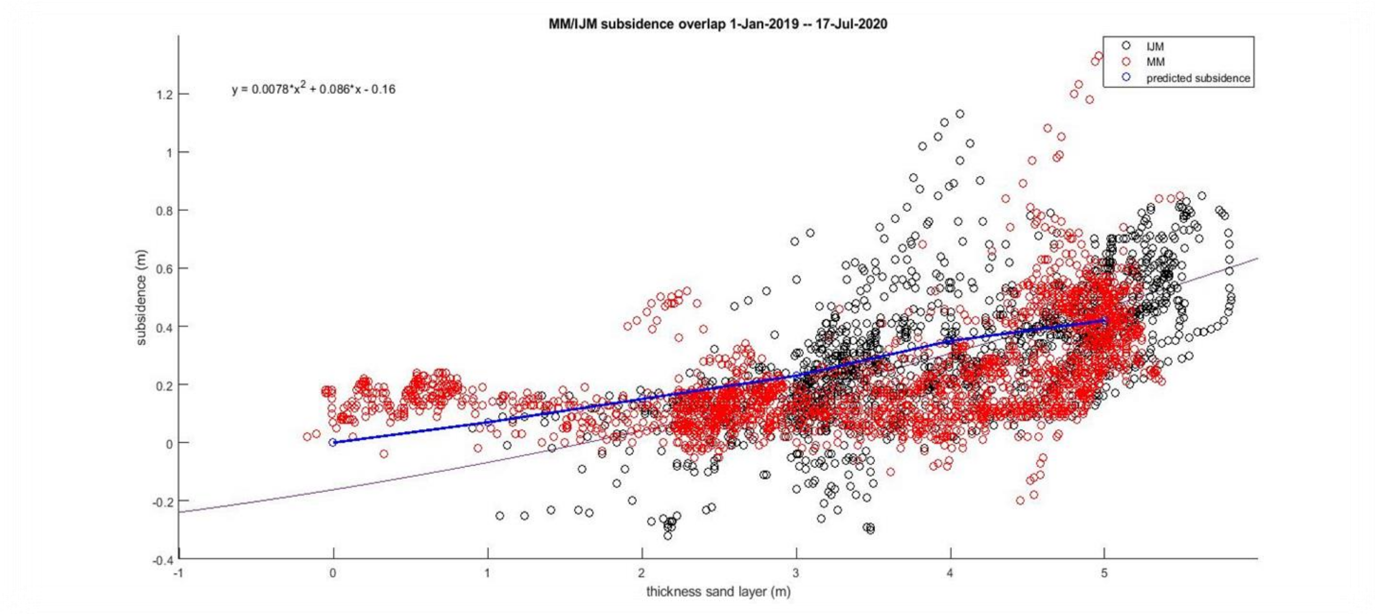

Figure 19 Subsidence combination scatterplot Markermeer/IJsselmeer 1-Jan-2019 until 17-Jul-2020, required 2-year subsidence compensation (blue line) compared to the 1,5-year observed subsidence (purple line).

Figure 19 shows a scatterplot for the subsidence measurements from both the IJsselmeer and Markermeer side. The subsidence shows a clear exponential relation with the thickness of the sand layer and taking an average over all these data points the exponential trendline clearly shows this relationship. Reflecting this trendline back to figure 10, one can see that the prediction for the subsidence compensation over a 2-year period (blue line figure 19) corresponds pretty well with the trendline prediction in figure 10. When for example looking at a 5m sand layer thickness it can be seen that this layer on average subsides 0,4m over an 18-month period.

3.2 Results morphology.

3.2.1 Sand volume losses/gains

Having performed multiple volume analyses for different locations at the Houtribdijk, there appears to be a trend in how the sand profile evolves and the volume loss/gains in cross shore direction. Figure 20 shows an example what the sand profile looks like right after the construction of the sandy shores. The sandy shores have a smooth slope over 140 meters in cross shore location. The volume for this specific alongshore location is 386 m^3/m. This volume has its boundaries in height and cross shore location. The boundaries used for this analysis are in height: NAP -3m and in cross shore direction 45m from the reference point.

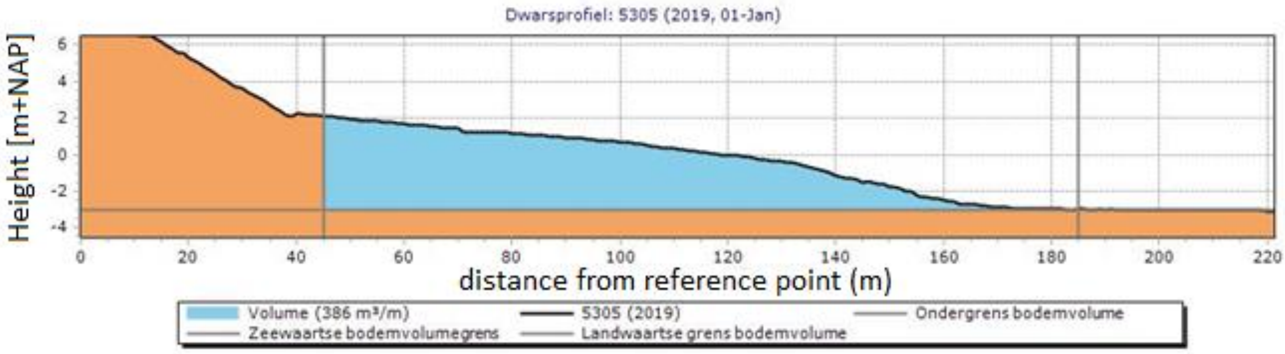

Figure 16 Sand volume and profile in cross-shore direction right after the creation of the sandy shore (1-Jan-2019).

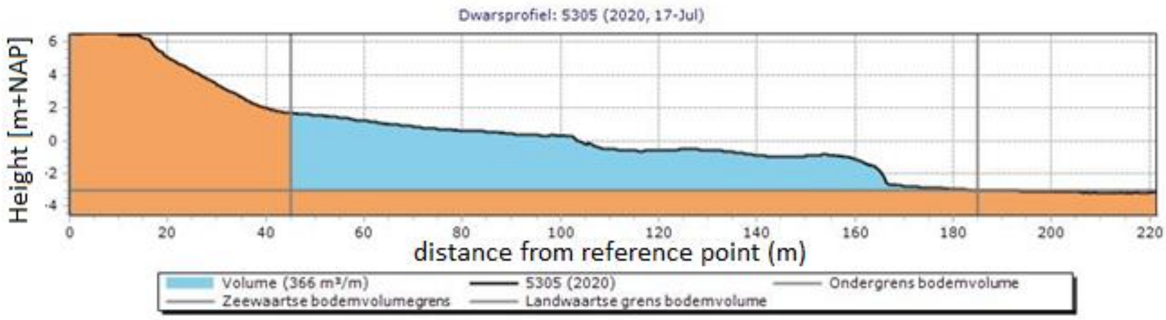

Figure 21 Sand volume and profile cross-shore direction at the latest measurement (17-Jul-2020).

Figure 21 shows the sand profile together with its volume for the same alongshore location at 17-July-2020. It clearly shows the appearance of the platform for the morphological zone. Next to this the total volume is 366 m^3/m which is a volume loss of 20 m^3/m for this specific alongshore location. Having looked at multiple different alongshore locations over the entire stretch of the Houtribdijk

there seems to be a net volume loss between 0 m^3/m and 30 m^3/m over all alongshore locations (X-axis showing the amount of transects this calculation has been performed at) shown in figure 22.

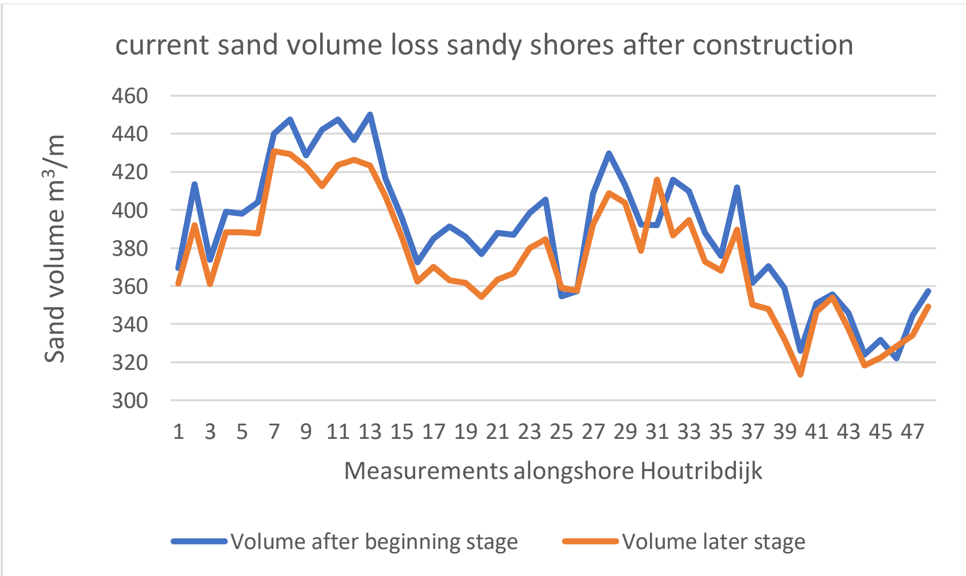

Figure 22 Current sand volume loss sandy shores after construction (18-month period from 01-1-2019 until 17-7-2020).

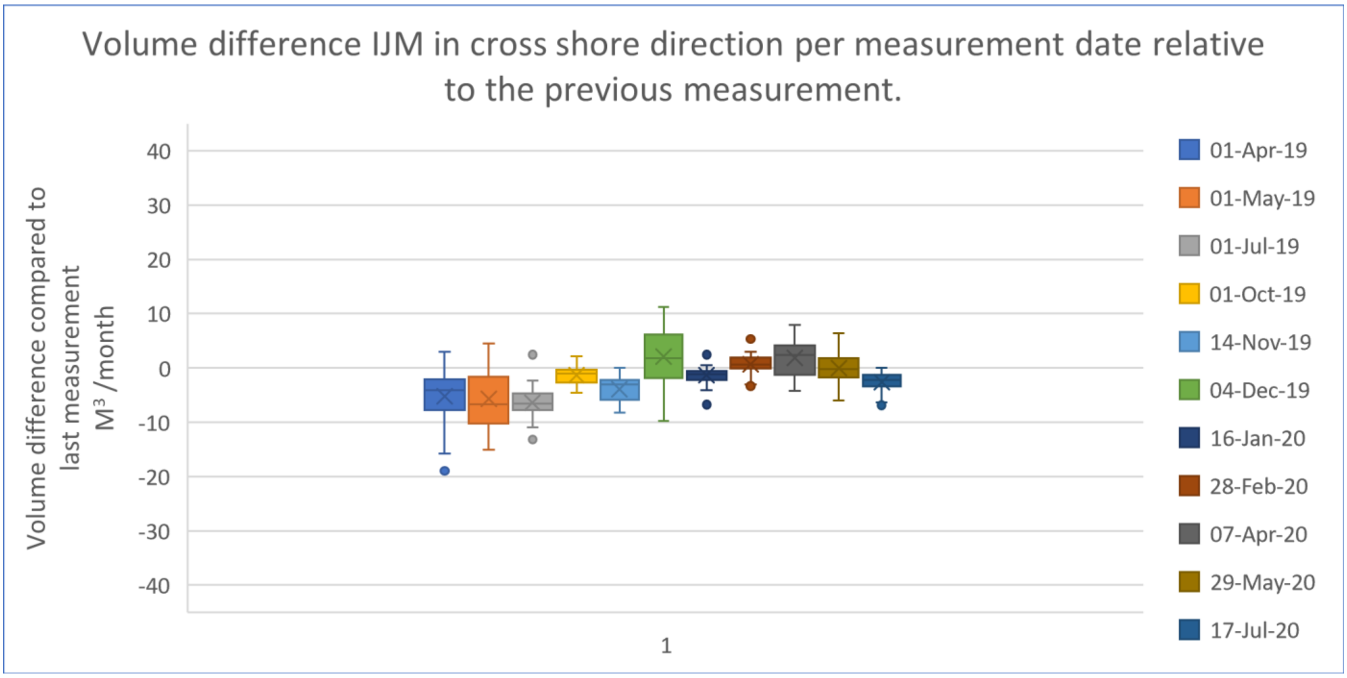

Figure 23 IJsselmeer volume loss M³ /month difference per measurement date.

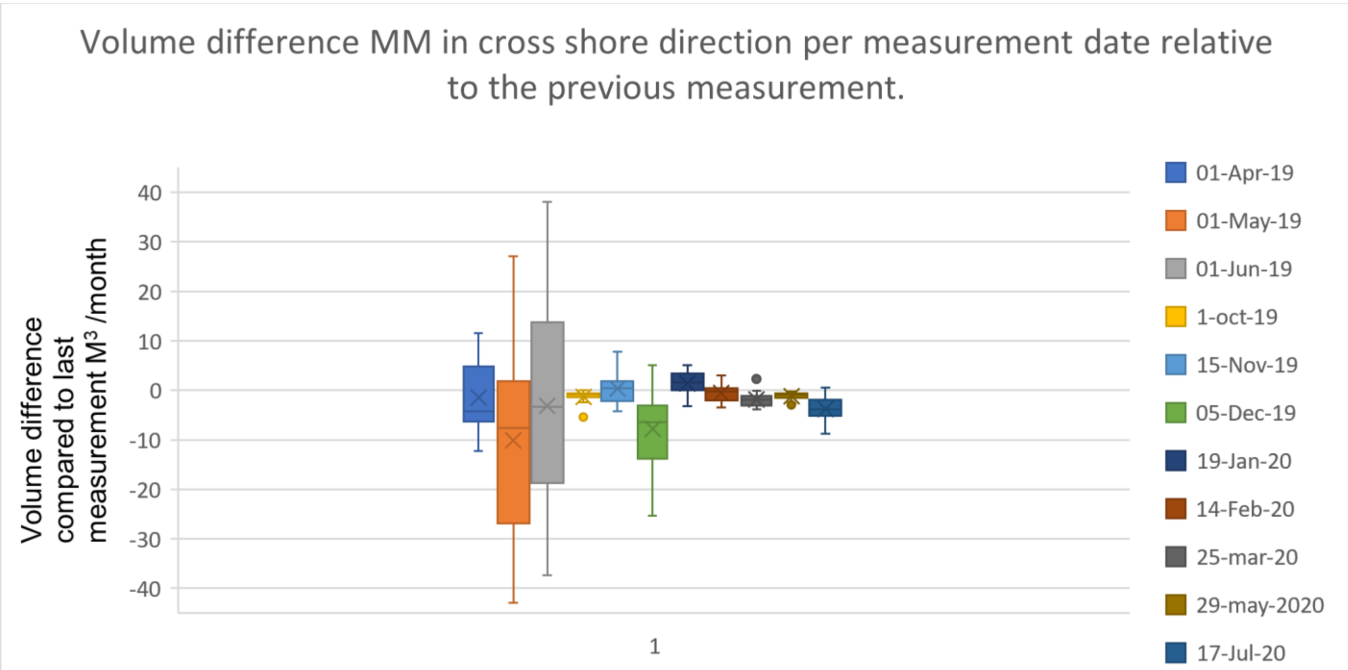

Figure 24 Markermeer volume loss M³ /month difference per measurement date.

Figures 23 and figure 24 show the volume differences for each measurement date compared to its previous measurement on every location at the Markermeer and IJsselmeer side. There seems to be strong decrease in sand volume for the first few months for most alongshore locations. In figures 23 and figure 24 there appears to be forming an equilibrium in sand volume for a later stage of the Houtribdijk.

Most of the sand volume losses appear to occur in the early stage (first few months) after the construction of the sandy shores together with the minimal loss of sand volume in a later stage of the sandy shores. This leads to the conclusion that the subsidence of the maintenance layer is likely to be the main reason for the volume losses in the early stage of the sandy shores. Next to that it can be stated that the differences in the sand profile (appearance of the platform) do not result in major net sand volume losses. Sand is only redistributed over the cross-sectional profile of the sandy shores.

On average there has been a loss of $25m^3/m$ in alongshore direction. This average is decided by taking all detail locations and comparing their total volumes bounded by 40m from the reference point and NAP -3m. The total volumes to get to this average volume loss value can be found in appendix 8.1. The volume calculations where done for a stretch of 140 meters in cross-shore direction on sand profiles that have an average sand thickness of 3 meters in cross-shore direction. Reflection this back to the subsidence results an estimation can be made on how much of this sand volume loss is due to subsidence: On average a sand thickness of 3 meters shows an average subsidence of 0,15 meter (with the assumption that sand under water subsides the same way as it does above water) from the moment of construction until the last measurement (17-jul-2020). In the full cross shore direction this results in $21m^3$ sand loss. This means on average an alongshore sand loss of $21m^3/m$. This shows that the gross part of the volume loss is due to subsidence and only a small part due to morphological developments.

3.2.2 Land inwards moving shoreline

An interesting observation since the periodic monitoring is the shoreline movement (which lies between -0,3m NAP and -0,5m NAP). Although the evolution of the “plateau” in the sand profile (Ton, 2019) seems to find a relatively fast equilibrium, the land inwards shore line movement seems to continue on longer. Figure 25 and figure 26 shows a plot where the shoreline from all periodic measurements for both the Markermeer and IJsselmeer side at all measurement locations have been analysed and compared with its previous periodic measurement. Due to the time in between measurement dates not being consistent, the values are converted in shoreline movement per month. The trend over these measurements show a land inwards shoreline movement for the IJsselmeer side (figure 25). But when looking at the Markermeer side this trend is strongly decreasing over time (figure 26). The difference has to do with the peak for the IJsselmeer side at April-7-2020 and another in july-17-2020. These peaks in shoreline movement cannot be explained by the potential occurrence of any strong storms and remains a questionable observation.

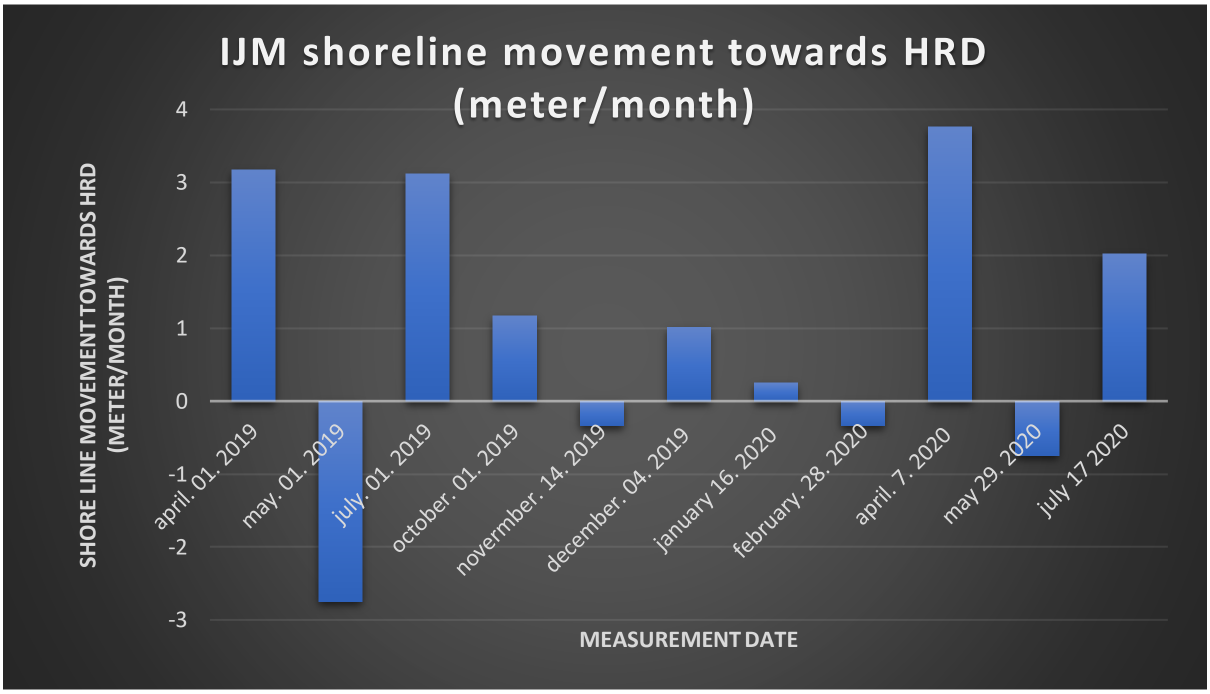

Figure 25 Shore line movement at the IJsselmeer side.

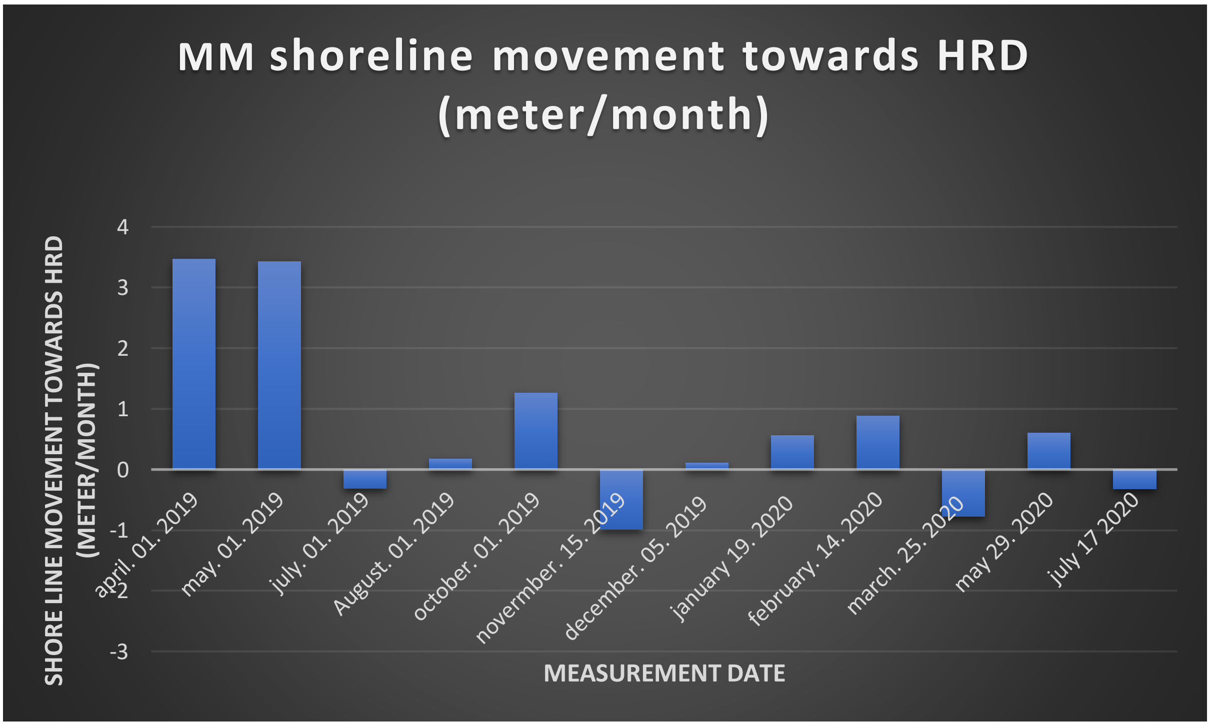

Figure 26 Shore line movement at the Markermeer side

This movement of land inwards shoreline show the natural variability between the two sides of the Houtribdijk. Figures 25 and 26 can help in the prediction when the set intervention line (BOL) will be exceeded. When the shoreline exceeds this line, maintenance to the Houtribdijk is required to stay within the safety regulations that are set for the sandy shores. Looking at figures 25 and 26 it shows that the shoreline at the IJsselmeer side moves faster compared to the Markermeer side. Due to aspect like the angle in which waves hit the sand body, stronger periods of wind and other morphological aspect the differences between the Markermeer and IJsselmeer side could possibly be explained. However, these aspects are not taking into account due to limitation of time for this research. Eliminating the initial subsidence for the first half year and looking at the trend and the values from figures 25 and 26, the BOL will most likely be exceeded in 5 to 6 years for the IJsselmeer side considering my research results.

4. Discussion

For figure 19 it has to be noted that the data in this scatterplot Is for a 1,5-year period whilst the blue line in figure 10 is for a 2-year period (Arcadis, 2019). Considering this fact, it can be explained why the blue line seems to be on the high side compared to the plotted trendline in figure 19. In half a year (when the 2-year period is complete), the blue line will very likely be more in the centre of the scatterplot which would confirm a good prediction for the required subsidence compensation. Having concluded that the gross part of the subsidence takes place in the first few months after construction, the measurements for the exact 2 year period (measurements that will be taken in January 2021) are expected to correspond with those predicted by the blue line in figure 10.

The results obtained by the subsidence sub-question are determined for a “dry” sand body above the shoreline. In answering this subsidence sub-question, the assumption was made that the sand body underwater has a similar subsidence trend as the sand above water. Research for the impact of sand subsidence below water is required to give a more complete answer on what impact subsidence as a whole has on the maintenance layer.

The results indicate that the maintenance layer of the sandy shores at the Houtribdijk are likely not sufficient enough for a 10-year non-maintenance period given the current BOL (BOL, 2019). The main reason for this is the exceedance of the intervention line (BOL). This would mean that earlier maintenance is required to comply to the safety norms of the Houtribdijk. However, the results obtained in this research do not give the complete picture. The results obtained do not take the direction and strength of wind and waves into account which are likely to be an important factor in the erosion process. These factors are important to fully understand the morphological changes and explain the differences between the results for the shoreline movement at the Markermeer and IJsselmeer side.

The morphology results give an answer in the movement of sand and the sand volumes in the morphological zone from the maintenance layer. These results do however not tell us in what exact way waves and or wind (which are the main influencers for the morphological zone) cause the sand to move. A scientific study about the strength of waves and wind and the angle in which they hit the sand body could give a better insight in the developments of the morphological zone.

5. Conclusion

The aim of this research was to answer the following research (sub)questions:

- *RQ1: Given the design of the maintenance layer and the first monitored results of morphology and subsidence, what lifetime of the maintenance layer can be expected?*
- *RQ1a: In what way does subsidence play a role in the development of the maintenance layer?*
- *RQ1b: What morphological developments play a role in contribution to the development of the maintenance layer?*

The results from RQ1a showed the subsidence differences for the sand body in the first 6 months after construction compared to a period for 12 to 18 months after construction. It is very clear that the initial subsidence (first 6 months) is by far larger than the subsidence in a later period (month 12 -18). Reflecting these subsidence result with the subsidence compensation that was added in the design (Arcadis, 2019), one can see that the sand added to compensate for subsidence matches the observed subsidence very well. It can be concluded that the subsidence compensation added to the maintenance layer is thus far sufficient and that the design has dealt with the subsidence aspect properly.

The results from RQ1b showed that most of the lost sand volume happens in the first few months after construction. After these first few months after construction there seems to be an equilibrium in the amount of sand volume present in cross-shore direction. Although, the sand volume reaches an equilibrium over time, the sand is however redistributed. This is due to the forming of a platform (Ton, 2019), and the movement of the shore line. As a conclusion on this sub question and considering RQ1a, it can be said that the loss of sand volume in cross shore direction is caused by the initial subsidence of the sandy shore. Furthermore, it can be concluded that the movement of the shoreline will cause the intervention line (BOL) to be exceeded earlier than the design predicted 10-year period.

Having answered RQ1a and RQ1b, the following for RQ1 can be concluded: By having analysed the subsidence in combination with sand profile changes due to morphological activity, the design is likely to be sufficient for a 5 to 6 year period before maintenance is required with a few outlier locations where currently maintenance is already required. After this 5 to 6-year period, the intervention line (BOL) will be exceeded which indicate that maintenance is required to comply to the safety norms of the Houtribdijk.

6. Recommendations

To better understand how the maintenance layer is affected by subsidence and morphological activity the following research would give an addition to the research in this thesis: A research for subsidence by the sand body located underwater would give a more complete view on what impact subsidence has on the maintenance layer, and if there are any differences in subsidence for sand above and below the water line. Furthermore, a research about the strength and angle in which waves and wind hit the sand nourishment should be conducted to possibly give a better explanation in my findings for morphological changes in the maintenance layer.

Since the data consisted of periodic measurements for a period of 1 month or longer, certain events like a couple days of consistant strong wind from a certain direction can be overshadowed by the other conditions in the same measurement period. To get a more detailed view in morphological phenomena due to wind for example, more frequent measurements should be performed to better understand how specific external factors influence the maintenance layer.

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8. Appendix

8.1 Volumes detail locations HRD

Cross-shore volume m3/m (1-jan-2019)	Cross-shore volume m3/m (17-Jul-2020)	Volume lost m3/m
375.5	355.5	20.0
427.7	366.3	61.4
408.0	360.4	47.6
419.2	360.3	58.9
411.3	360.9	50.4
433.4	373.1	60.3
468.5	380.3	88.2
450.2	367.1	83.1
465.4	388.3	77.1
474.3	404.5	69.8
493.8	418.6	75.3
491.6	420.7	70.8
491.7	424.1	67.6
462.2	409.3	52.9
385.8	366.3	19.5
405.8	374.3	31.5
369.4	361.3	8.1
413.6	392.0	21.5
373.9	361.0	12.9
398.9	388.3	10.7
398.0	388.4	9.6
404.0	387.5	16.5
440.0	430.9	9.2
447.4	429.3	18.1
428.7	422.8	6.0
442.0	412.6	29.4
447.4	423.7	23.6
436.6	426.5	10.1
450.1	423.3	26.9
416.5	407.0	9.5
396.4	386.2	10.2
372.3	362.4	9.9
384.8	370.0	14.8
391.4	363.0	28.5
385.9	361.6	24.2
376.8	354.4	22.4
387.9	363.5	24.4
387.0	366.6	20.5
398.4	380.0	18.4
405.3	384.4	20.9
354.5	359.1	-4.6

357.2	357.7	-0.5
408.4	392.2	16.3
429.8	408.6	21.1
413.1	403.8	9.3
392.4	378.4	14.0
391.9	416.0	-24.2
416.0	386.6	29.5
409.9	394.5	15.4
388.0	372.6	15.3
375.9	368.1	7.8
411.7	389.7	22.0
361.8	350.1	11.7
370.3	348.0	22.3
359.0	332.2	26.8
325.9	313.5	12.4
350.8	346.6	4.1
355.8	353.9	1.9
345.8	337.6	8.2
324.1	318.2	5.9
331.7	322.5	9.2
322.0	328.4	-6.4
344.7	334.2	10.5
357.1	349.2	7.9
Average Volume m3/m (1-Jan-2019)	**Average Volume m3/m (17-Jul-2020)**	**Average volume lost m3/m**
403.4	377.6	24.6