Construction variants for a Sandbar breakwater in a dynamic coastal area

Master Thesis

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Preface

Six years ago, on the 30th of August 2012, my first lecture in Civil Engineering took place. The more I got into the field of Civil Engineering; it became clear that water is my subject. Choosing the track Water Engineering and Management, flooding, flood protection, flood risks, drought, water policy and standards, propagation of water and sediment, measurements and data analysis, physics, design and engineering, all subjects passed by.

After I finished all Master courses I started with my master thesis at CDR International. Dirk Heijboer, director and founder of CDR offered me an interesting subject concerning the construction of a Sandbar breakwater, which was being built by the time I was searching for a graduation project. Since Royal Boskalis Westminster N.V. has executed the actual construction of the Sandbar breakwater, this company was introduced as second party for my research. I want to thank Dirk Heijboer and Jaap van Thiel de Vries for giving me the opportunity to graduate here.

Next, I would like to use this opportunity to thank the people who contributed to my Master Thesis.
At first I want to thank Bart-Jan van der Spek at CDR and Antoon Hendrik at Boskalis for their supervision, useful discussions, answering questions and providing feedback. I also want to thank Anne Waij, an intern at Boskalis who was also working on the Sandbar breakwater topic, for the cooperation in the beginning of my research. Besides, I would also like to thank my colleagues and fellow graduate student at CDR International and Boskalis. They also supported me, helped me out when I got stuck and inspired me for this research.

At the university I would like to thank chairwoman Kathelijne Wijnberg for her critical reviews and discussions of my work. A special thank goes to Johan Damveld, my super visor from the university of Twente for this moral support and the very detailed (textual) feedback he gave me.

Special thanks go out to my parents and my girlfriend, Ilse for their unconditional support, trust and patience.

William Wilbrink

Abstract (not fully completed yet)

Conventional breakwaters are often built by rocks or concrete elements. Recently, CDR-International designed a new constructing philosophy for a portal breakwater. Using the concept of 'Building with Nature' the idea is to develop a so-called 'sand breakwater'. CDR-International has implemented this new concept of a breakwater for a port project at Lekki, Lagos State Nigeria. The construction of this Sandbar breakwater has been completed in the summer of 2018.

The Sandbar breakwater is constructed in a highly morphodynamic area. Significant sediment losses during construction of the breakwater have been occurred due to wave and current impacts on the breakwater. Since this concept. For the construction of the Lekki Sandbar breakwater a certain method and sequence is devised which was on forehand seen as the most practical and financial profitable. However due to the lack of experience, an analysis of the construction process of the Lekki project regarding the occurred conditions, the executed construction method and the accompanying sediment losses would be useful.

Since the Sandbar breakwater is a new concept and due to the fact that during the construction process certain moments significant nourished sand volumes was naturally moved outside the design profile, the idea arose that apart from the Lekki project construction method it would be useful to also investigate other construction methods or sequences. Based on the experiences and the large amount of data which have been collected during the Lekki project, CDR and Boskalis first want to analyse the construction process of the Lekki Sandbar breakwater project regarding the observed conditions and the occurred sand losses. Then, this Lekki project can be compared to other construction alternatives regarding not only morpho-dynamic behavior (sediment losses) but also on costs and feasibility by investigate what the best construction method is for the Sandbar breakwater concept.

In order to be able to assess the morphodynamic behaviour of different construction variants for the Sandbar breakwater a morphodynamic model XBeach has been used. Before the assessment of the construction variant, first the performance of the model in the dynamical coastal system at Lekki is investigated. Then the sediment losses and the naturally accreted sediment into the design profile is quantified for all construction variants, followed by a financial cost and practicability assessment of these variants.

The results are for the assessment of the XBeach model are as follows:

Based on the rapid morphodynamic development observed at the Sand Engine located at the east side of the Sandbar breakwater a XBeach model performance analysis was carried out. After various model adaptations and optimisations the following conclusions can be drawn on the XBeach model performance:

- None of the model simulations predict the morphodynamic development of the Sand Engine very accurately. The observed erosion at the Sand Engine (210,000 m^3) is after extensive model calibration still underestimated (65,000 m^3).
- The best performance was obtained by using the lower MorFac (=10) alpha (=), gammax () and wet slope () parameter settings and higher facua (=) and gamma (=) parameter settings than the default settings. This resulted in small improvements of the model morphological prediction accuracy: the erosion rate from the Sand Engine improved by somewhat more than 10,000 m^3 as it is compared to the actual bathymetric survey data while the cross-shore development prediction of the model almost remains the same (Brier Skill Score=0.51, considered as good by van Rijn et al et al (2003)). After an extensive calibration process, the results can be satisfactory since the morphodynamic assessment of the construction variants is aimed for the relative comparison of the sediment losses. Absolute erosion and sedimentation value may differ from reality, although this margin of error is present in all assessed variants.

The used model is developed for the simulation of storm events at a typical Dutch coastal system which has different characteristics than the Lekki coast. The slope of the beaches in the Netherlands are much milder, the wave height peaks are higher and no swell conditions are presented (long wave periods).

This study has shown that the (near) optimal morphodynamic predictability of the XBeach application is not possible for this reflective, swell dominated coastal system.

The results of the assessment of different construction variant leads to the following recommendations for an optimal construction method for the Sandbar breakwater:

This is discussed on the basis of the optimal construction sequence, method, start moment, the (number) of operational dredging vessels, the impact of the hydrodynamic conditions on the construction phase and the whether the implementation of temporary groynes is desired.

- *Regarding the moment of execution of the reclamation work:* From the Lekki project analysis appears that the start of the reclamation works was relatively late in the calm season. The start of the construction of the submerged bund is advised in October/November. This consequently mean that the critical sand nourishments at the Mean Sea Level (such as the expansion perpendicular to the coast of the Sandbar Road and the Sandbar reclamation) can be executed during the calmest moths of the year. This will result in less sediment losses and minimises the possible risk as project delay or a breakthrough of the Sandbar during the construction phase.
- *Regarding the dredging vessels for the reclamation work:* To further ensure a smooth and durable construction process the use of two hopper dredgers (TSHDs) and one cutter dredger (CSD) is recommended. This number of vessels is the optimum between a safe and quick construction and the financial cost. The chance that is sand nourishments have to be executed during rough wave conditions is minimal and the production rates of about 400,000 m^3 per week to ensure enough progress to exclude a Sandbar breakwater breakthrough during the construction process.
- *Regarding the sequence of the reclamation works:* the construction of a submerged bund for all possible area with sufficient depth (below -5 m) is recommended since all the results for all criteria as cost, morphodynamic behaviour and practicality state that this is the most optimal start of the reclamation of the Sandbar breakwater.
  The Sandbar breakwater reclamation above the water level should not be applied over de full width of the design as horizontal progress is recommended to have early access to the Sandbar Groyne and contribute to a rapid closure of the Sandbar (the main land with the Sandbar Road).
  The next recommended step after the submerged bund is to reclaim the Sandbar Road from the (east side of the) coast. This is the most direct way and rapid way to the Sandbar Groyne tip and enables an early start of the construction of this groyne in order to prevent sand from eroding to the east.
  The next stage in the construction phase two main assessed criteria are in conflict: the morphodynamics and the financial cost. The reclamation of the Sandbar along the inner shore side of the design profile (Variant 0/1) is significant cheaper than the offshore sea side expansion of the Sandbar (Variant 2 and 3). Although the sediment losses are larger for variant 0 and 1, the total cost for the reclamation works (mainly rainbowing) is still significant lower due to less sand which has to be pumped ashore.
- *Regarding the actual conditions during the reclamation works:* As critical reclamation are planned to be executed, it is recommended to let the best sequence and execution method depend on the expected wave conditions on forehand. In case strong swell from a deviant wave direction is predicted it is not advisable to start with the reclamation of the inner slope of the Sandbar (Road).
  - *Regarding the implementation of the (temporary) groynes in the Sandbar design:* from the financial assessment the temporary groynes proved not to be financial feasible. However, the cost depend highly on the specific situation. In case the cost for production or transportation appear to be lower and due to the fact that is a promising Building with Nature concept than the construction of one or two temporary groynes is certainly recommended.

Table of content

Nomenclature

Acronyms

The acronyms which are used in this research are summarized in Table 1.

Table 1: Acronyms which are used for this research.

Acronym	Definition
CDR	CDR International B.V.
Boskalis	Royal Boskalis Westminster N.V.
DPRP	Dangote Petroleum Refinery and Petrochemicals Free Zone Enterprise, client of the project
DORC	Dangote Oil Refining Company; client of the project
RoRo Jetty	Roll on/Roll off Jetty
TSHD	Trailing Suction Hopper Dredger
CSD	Cutter Suction Dredger
BwN	Building with Nature concept
ITCZ	Inter-Tropical Convergence Zone
LST	Longshore Sediment Transport
AD	Active Depth
MBES	Multibeam Echo Sounder
MorFac	Morphological Acceleration Factor
MSL	Mean Sea Level
LAT	Lowest Astronomical Tide
CD	Chart Datum

Glossary

The definitions which are used in this research are summarized in Table 2.

Table 2: Glossary explaining various definitions which are used for this research.

Definition	Description
Accropode	Concrete armour elements which can be placed in a single armour layer on a breakwater with a steep slope
Bed load transport	Sediment which is transported along the bed level
Breaker zone	Subset of surf zone. Zone in which wave approaching the shore start breaking
Breakwater	Human made coastal structures for coastal mitigation measures or protection of ports
Diffraction	Changing of waves from direction towards areas containing lower amplitudes due to amplitude changes along the wave crest (Holthuijsen, 2007)
Groyne	Human made coastal structure constructed for coastal mitigation measures constructed in and around the breaker zone
In-survey	Initial bathymetry of the seabed as observed at the start of the works
Littoral transport/drift	See Longshore Sediment Transport
Longshore Sediment Transport (LST)	Transport of sediment along the coast parallel to the shoreline caused by oblique incoming waves
Method Statement	Document which describes the scope of work, the method and equipment which is used for the Lekki project
Overwash	Flow of water over dune & dry beach slope

Refraction	Change of wave direction due to changes in water depth underneath (Bosboom and Stive, 2012)
Storm surge	Rise in sea water level caused solely by a storm due to low air pressure
Surf zone	Area of breaking waves
Suspended sediment transport	Sediment which is transported in suspension
Swell	Waves originating in distant storms which have travelled for large distances and have been subjected to frequency and directional dispersion of which uniformity in direction, period and height is developed over travelled time and distance
Wave train	Groups of swell waves
Wind set-up	The vertical rise in the still water level in front of a structure caused by wind stressed on the surface or the water (Bosboom and Stive,2012)
Wind sea waves	Waves caused by the shear stress of wind.

List of Symbols

The symbols which are applied in this research are summarized in Table 3.

Table 3: Clarification of used symbol for this research

Symbol	Units	Description
x	*[m]*	Alongshore position
y	*[m]*	Cross-shore position
z_b	*[m]*	Bed level
$z_{b,i}$	*[m]*	Initial bed level
$z_{b,c}$	*[m]*	Modelled bed level
$z_{b,m}$	*[m]*	Measured bed level
S	*[m^3/year]*	Longshore Sediment Transport
φ/θ	*[°]*	Angle of wave incidence
E	*[]*	Wave energy
D_w	*[J/m^2]*	Loss of organised wave motion due to breaking
D_r	*[J/m^2]*	Dissipation due to the roller
D_{50}	*[μm]*	Median grain size
D_{90}	*[μm]*	90^{th} percentile grainsize
BSS	*[-]*	Brier Skill Score
MSESS	*[-]*	Mean-Squared Error Skill Score

Conventions and Definitions

Terminology Sandbar

In this section the terminology regarding the different elements of the Sandbar Breakwater design are stated in Table 4 and Figure 1.

Table 4: Relevant terminology of the Sandbar breakwater design

Term	Description
Sandbar Breakwater	Breakwater construction which functions as protection of the port and provides shelter for incoming waves with components mainly made out of sand
Lekki project	Project name of Sandbar Breakwater at Lekki, Nigeria
Method Statement	Document which describes the scope of work, the applied work method, the used equipment and the safety plan for the Lekki project.
Sandbar Road	Sandy bend from land to south-eastern tip of design profile
Sandbar body	Sandy part of Sandbar Breakwater
Inner Lake	Lake within Sandbar design which will not be reclaimed as is supposed to remain 'empty'
Basin	Area which needs to be dredge for (un)loading of vessels
Sandbar Groyne	The large, sand retaining groyne at the south-eastern tip of the Sandbar Road
North Groyne	Small groyne along turning basin
Access Road	Temporary road used to be able to construct the Sandbar Groyne from the shore
Turning Basin	Area which needs to be dredge used for the turning of vessels
Access Channel	Area which needs to be dredge to deepen the approach route for the vessels
Sandbar Leeside Revetment	Revetment on leeside of Sandbar Breakwater
Basin Revetment	Revetment adjacent to basin
Onshore reclamation of the Sandbar	The reclamation of the Sandbar from the Sandbar Road at the onshore side of the Sandbar breakwater design profile (Inner Lake side).
Offshore reclamation of the Sandbar	The reclamation of the Sandbar from the Sandbar Road at the offshore side the Sandbar breakwater design profile.

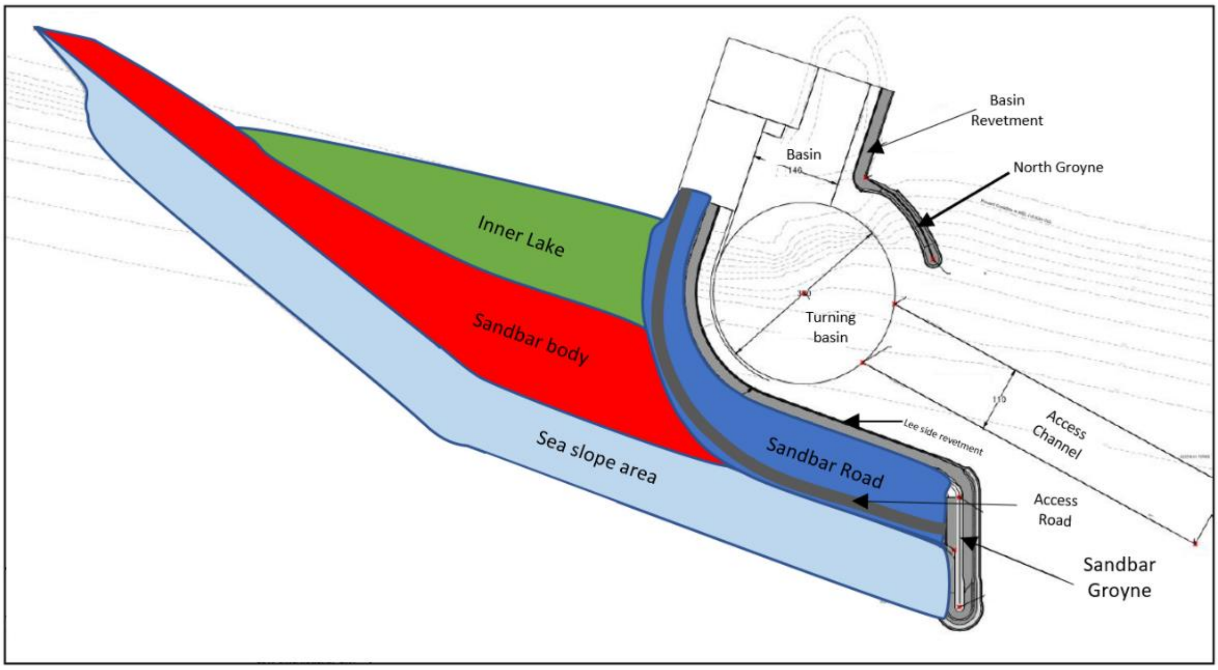


Figure 1: Overview of different components in the Lekki Sandbar breakwater design

Beach orientation and wave angle incidence

For clarity, an overview of the different beach- and incoming wave angle orientations is presented in Figure 2.

Figure 2: An overview of the initial equilibrium beach orientation (100°) , the Sandbar breakwater orientation (110°), the average incoming wave direction (ϑ) and the scatter in incoming wave direction (ϑ) data obtained from the wave buoy. All orientations are expressed relative to the North (0°).

Interpretation of water levels

A relation between Mean Sea Level (MSL) and the presented modelling results need to be clarified. The local datum is the Lekki Chart Datum (CD). Bathymetric data from different sources has been adapted to match the projection and the model datum, see Figure 3. MSL is used as standard datum in this study.

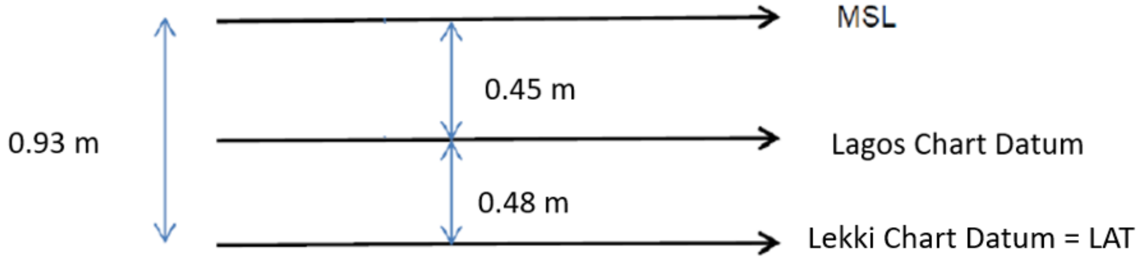


Figure 3: Local vertical datum (LAT) and MSL relation

1. Introduction

1.1. Sandbar breakwater concept

In recent years, the coastal zone of Nigeria has been subjected to an increase in economic activities, primarily driven by seaport activities and oil exploration and exploitation (Orupabo, 2008). In the Lekki Free Trade Zone in Nigeria, currently a Petroleum Refinery and Polypropylene Plant is under construction. In order to allow for further development of these facilities, material is planned to be transported by seagoing vessels. To transfer the material to the construction site, recently a new harbour is constructed along the coastline of Lekki. In this new port, a quay wall with a Roll-on-Roll-off (RoRo) facility is developed for unloading of project cargo. In addition, facilities will be created to accommodate tugs, auxiliary craft and other supporting vessels. In order to protect the RoRo Jetty facility, the approach channel and the turning basin, a breakwater is designed and constructed. The design and supervision of the project has been the responsibility of CDR International B.V. (CDR) while the actual construction is executed by Royal Boskalis Westminster N.V (Boskalis).

Recently, CDR developed a new concept for a breakwater along the Nigerian coast at about 8 kilometres east of Lekki: the 'Sandbar breakwater'. The construction of the Sandbar breakwater has been completed in the summer of 2018. The complete construction consists of components which are made out of sand and hard structures at some locations. The Sandbar breakwater concept is based on the Building with Nature concept (IADC, 2015). It uses the dynamics of nature such that it is expected that the stability of the breakwater will only increase over time (van der Spek, 2017). The philosophy of the Sandbar breakwater is that due to longshore sediment transport, sand will accumulate against the breakwater and as result new land on the updrift (west) side will be created. This natural accretion reduces the necessity of hard construction materials as they lose their function over time as these structures are covered by large quantities of sand from the longshore sediment flow. Moreover, this leads to the reduction of costs. In Figure 1, a plan-view of the design of the Sandbar breakwater is presented.

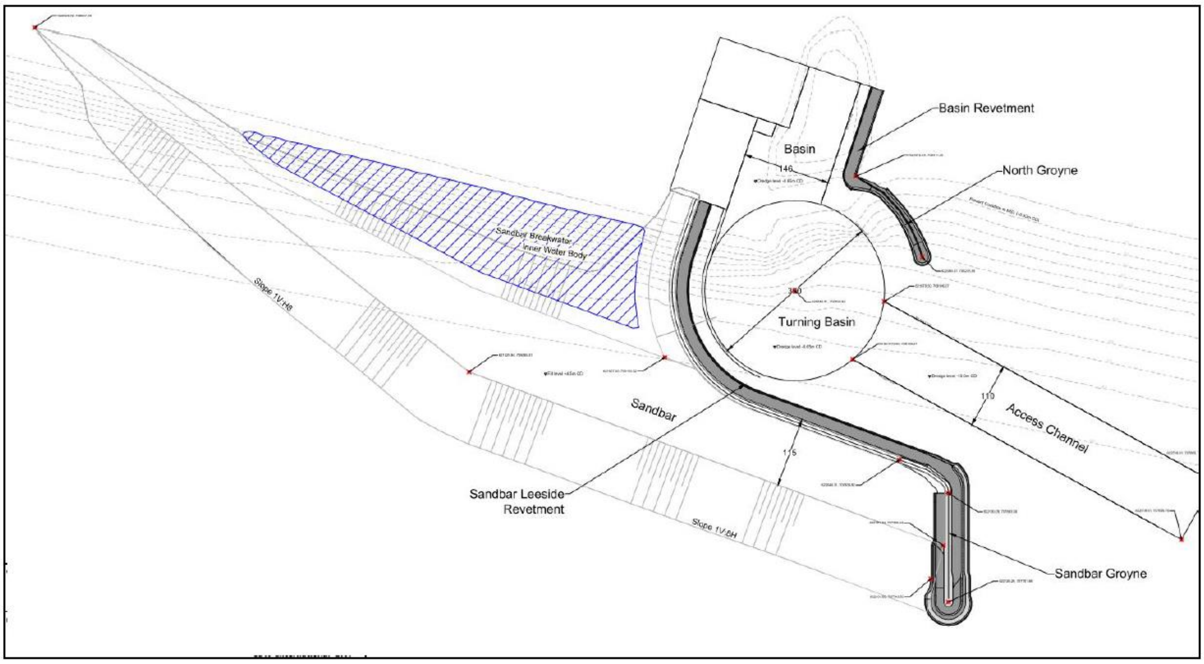


Figure 1.1: Plan-view of the Sandbar breakwater (excluding the Sand Engine at the east side (CDR International, B1609-05-A-405-Topviews)).

1.2. Problem description

As stated above, the design of the Sandbar breakwater consist of hard and soft materials. Apart from the hard structures (groyne), a large amount of sand is needed in the design. The combination of soft (sand) and hard measures in such a highly dynamic environment (much wave action, large sediment transport rates) makes it complex to develop a robust, but time and cost efficient construction methodology. Since this concept is fairly new, the optimal construction method is still unknown (yet).

For the construction of the Lekki Sandbar breakwater a certain method and sequence is devised in the Method Statement (Boskalis, 2018) which was on beforehand seen as the most practical and profitable. However, due to the lack of experience, an analysis of the construction process of the Lekki project regarding the occurred conditions, the executed construction method and the accompanying sediment losses would be useful. On forehand it was known that the area is highly morphodynamic, although the exact quantities of the sediment being lost during the construction stages were unknown. No detailed studies were executed on the morphological development during the construction phase. Sediment losses were roughly estimated by the morphological study of Svasek Hydraulics carried out 2017, which was done for only two static situations of the construction stage (Svasek, 2017). During the project it became clear that at some locations large amounts of nourished sand were naturally transported outside the design profile.

At Boskalis a data analysis was carried out in order to investigate the quantities and the locations of sand being placed or (naturally) transported outside the design (Boskalis, 2018). The conclusions of this analysis were that indeed significant sediment losses have occurred during the construction process at certain moments during the project. This turned out to be mainly caused by natural processes: sand being placed correctly in the design profile and transported outside the profile and sand accretion from longshore sediment transport located around and outside the design. Also inaccuracies in sand placement contributed to some sand being located outside the design profile. This analysis also concluded that it is hard to attribute the reason of sand quantities being located outside the design profile.

Since the Sandbar breakwater is a new concept and due to the fact that during the construction process certain moments significant nourished sand volumes was naturally transported outside the design profile, the idea arose that apart from the Lekki project construction method it would be useful to also investigate other construction methods or sequences. Based on the experiences and the large amount of data which have been collected during the Lekki project, CDR and Boskalis first want to analyse the construction process of the Lekki Sandbar breakwater project regarding the observed conditions and the occurred sand losses. Then, this Lekki project can be compared to other construction alternatives regarding not only morphodynamic behaviour (sediment losses) but also on costs and practicability. An optimal construction method regarding the morphodynamics does not automatically mean that the construction strategy is financially more attractive or feasible to build. Therefore an assessment of these criteria gives a good insight of the different construction methods, from which lessons can be learnt.

In order to gain more knowledge on the morphological development during the construction phase parts of different construction variants a hydro- and morphological model is required. First, it should be investigated to which extent a model is able to predict morphological evolution for a reflective, longshore transport dominated coastal area during the nourishment for the construction of a Sandbar breakwater. Furthermore, to assess the morphodynamic behaviour during the construction process of a Sandbar breakwater different stages should be assessed, since the continuously nourishments during the project constantly a new morphological situation will occur. Normally modelling studies are carried out for static situation where no sand is nourished or removed during the simulation period. No model studies on nourishment processes have been executed before.

Since the promising Sandbar breakwater concept probably will be implemented in future project, the investigation of different construction strategies and the assessment on how well a model can predict the morphodynamics in such an area during the construction phase, is very useful.

1.3. Research objective

The objective of this thesis is to improve the understanding for the optimal construction method of a breakwater mainly built out of sand in a highly dynamic coastal area which is assessed by evaluating different construction strategies for a Sandbar breakwater.

This research has the objective to contribute to the practical knowledge on the relation between the morphodynamics (losses), the practicability of the construction process and the total project costs to be able to decrease the complexity of decision-making and make a better trade-off between these criteria.

The objective from the modelling part of this study is to identify and understand the constraints of the morphological modelling application and also to define the best settings to improve the model performance for a reflective, uniform swell dominated beach.

In this study the focus is on the Lekki Sandbar breakwater constructed at the Nigerian coast. The different construction scenarios that are developed in this study are based on the specific site conditions and characteristics. However, the results and conclusion will be generalized such that it can be useful for the construction of a future comparable Sandbar breakwater.

1.4. Research questions

The thesis process will be guided by the following main research question:
Which construction strategy for the Sandbar breakwater concept are optimal regarding the morphological behaviour, project practicability and cost?

Five sub-research questions are formulated in order to answer the main research question:

a. *How does the actual construction project of the Lekki Sandbar breakwater project compare to the design details and the planned construction execution method regarding the sand nourishments methods, the wave conditions and the morphological behaviour?*
b. *What is the performance of the XBeach model application regarding morphological modelling of the Lekki Sandbar breakwater in a typical swell dominated reflective coastal system?*
c. *Which construction strategy is most optimal by only considering or the morphological behaviour or the project cost or the construction practicability?*

1.5. Methodology

To accomplish the main objective to investigate different construction strategies for the Sandbar breakwater first the sub-questions require investigation. In this section the methodology which is applied to answer the different sub-research questions is briefly stated followed by an overview of the data which is used for this research (section 1.5.2). Further description of the methodology for the data analysis, the model study and the assessment of the different construction variants is descripted in the introduction section of each corresponding chapter. An overview of the steps of the research approach (i-v) is presented in a road map (section 1.5.3)

1.5.1. Research approach

The process of the comparison of the actual construction method at Lekki to other construction strategies requires an iterative approach. The approach can be roughly schematised in five main phases (i-v) described below and summarized in Figure 1.2.

i. **Analysis of Lekki project regarding wave conditions, nourishment methods and sediment losses (Chapter 3).**

The first step in the research is to analyse the project process comparing the expected and observed wave conditions, the actual nourishment works with the on forehand made Method Statement and the expected sediment losses with the actual occurred sediment losses. This analysis is useful to determine at the locations and moments during the project significant sediment losses due to wave action or the misplacement of sand has occurred. Furthermore, the lessons learnt from this project will be drawn and these aspects are used for the development of new Sandbar breakwater construction alternatives (Chapter 4). The different steps in the project analysis which are executed for each construction stage are briefly discussed in the sections below.

a) **Analysis and comparison of the Method Statement (planned execution) and the actual construction method (practise) regarding the execution of the sand nourishments.**

The analysis of the Lekki construction method is executed by using the Method Statement and the (site) expert appraisal. In the Method Statement which was developed on forehand the project method execution planning is detailed described (Boskalis, 2017). The planned construction strategy will be compared to bathymetric survey data and ship logs (see section 1.5.2). During the site visit at Lekki in May 2018 Cees van Laarhoven, resident engineer for CDR and Gert-Jan Rodenburg (project engineer for Boskalis) provided details on the actual construction execution which is been used for the project analysis.

b) **Determination and comparison of the expected and observed wave conditions during the Lekki project.**

The expected wave conditions during the different construction stages are obtained from the representative wave conditions data set. The actual wave condition during the construction period is obtained from the wave buoy data. These wave characteristics are compared to each other. This results are related to the statistical long-term wave climate.

c) **Determination and comparison of the expected and actual sediment losses during the Lekki project.**

In order to assess the efficiency and accuracy of the sand nourishments during the Lekki project, the sediment losses during the project need to be quantified. The study area is highly dynamic induced by several natural processes -as longshore sediment transport flow and wave action, see chapter 2) causing sediment losses during the construction process. It is needed to determine a clear definition of the term ‘sediment loss’. Boskalis executed an analysis on the quantities of nourished sand that ended up outside the design. This Boskalis analysis and the definition of a sediment loss will be used to determine the sediment losses during the Lekki project. Next, these quantities are compared to the on forehand estimated sediment losses due to natural processes. Furthermore, there is investigated what the wave conditions were as large quantities of sand was naturally transported outside the design profile and whether this is physically can be explained.

ii. **Development of construction alternatives (Chapter 4).**

In order to assess different construction methods for the Sandbar breakwater concept, the second step in this research is to develop three construction alternatives apart from the Lekki construction execution (variant 0).

a) Implementation of different concepts in construction alternatives

For the different construction variants conceptual designs are made being distinctive on the aspects of construction sequence, reclamation work equipment, construction speed and the implementation of (hard) structures. The alternatives are based on the knowledge of the morphodynamics of the coastal system (Chapter 2) and furthermore on the finding of the Lekki project analysis (Chapter 3). Due to time limitations only some cases can be implemented in the construction alternatives. Most important is to investigate the impact of the construction speed and sequence as well as to which extent sand can be naturally accreted by hard structures ('additional' groynes) into the design profile. Therefore are in the variants different numbers of operational vessels (variation between 2-4) implemented as well as additional groynes in the Sandbar breakwater design (none additional groynes, 1 or 2 groynes).

b) Determination of construction variants details

The characteristics of the scenarios will be determined in detail regarding the construction method, duration, nourishment discharge volumes, reclamation vessels, production rates and hard structures component details. The assumptions, estimations and calculations for this step is detailed elaborated in Chapter 4 and Appendix B.

iii. Assessment of XBeach modelling performance (Chapter 5).

In order to gain knowledge of the morphodynamic behaviour of the different construction variants first several model analysis have been performed of an existing XBeach model. Therefore first a general model analysis is executed followed by a sensitivity- and calibration analysis. The steps are briefly explained below and detailed explanation on the model set-up, the approach and the steps in the model study are further elaborated in the corresponding chapters (Chapter 5, Appendix C).

a) General model analysis

A suitable case from the Lekki project is selected and the observed morphological development is compared to the model simulations. Furthermore, the impact and the optimal adjustment of several non-calibration parameters is investigated (such as MorFac, spin-up, roller-equation: since it is assumed that this process is hardly present in the study area this is not a calibration parameter).

b) Execution of sensitivity analysis

The sensitivity of the model for different calibration parameters is investigated in order to gain knowledge in the performance of the XBeach model for the area of interest and to better understand the impact of specific model parameters and settings. The selected parameters is explained in Chapter 5.

c) Execution of calibration analysis

In order to obtain the most realistic results for the morphological development assessment of the construction scenarios, the model is calibrated as optimal as possible.

iv. Assessment of construction variants (Chapter 6).

Now the construction variants are developed and the model performance study is executed, the assessment of the construction variants for the different criteria is carried out.

a) Determination of morphological behaviour scenarios

The morphological development of a construction scenario will be assessed by using the best calibration simulation of the XBeach model. Sand transported by natural processes to areas where it is considered as a loss and volumes of sand which are naturally accreted into the design profile are quantified for different stages in the project.

b) Determination of costs and practicability scenarios

The costs of the different scenarios will be determined based on estimation of required reclamation works equipment, discharge method, materials, volumes of sand (losses/accretion). Therefore standardized costs for dredging works are used based on the Lekki project data, literature (see chapter 4) and expert appraisal. Cost assumptions are agreed by Bas van der Sande (project engineer at CDR, Bas Vellekoop, manager Tender Design Boskalis and Steff Stevense, senior Marine Rock Engineer at CDR.

v. **Comparison and conclusion on the different construction strategies of the Sandbar breakwater (Chapter 7 and 8).**

After the assessment of the different variants (0-4) on the criteria morphological behaviour, costs and execution, the best strategy for each criteria is stated. In order to answer the main research question these (sometimes contradictory) criteria are combined by weighing these to each other. This will result in a list of recommendation for the strategy of a future Sandbar breakwater project.

1.5.2. Overview of data

In order to answer the different research questions various data sets, bathymetries and vessel data is required. In the study area much wave and bathymetry data has been acquired by Boskalis and CDR. This data was beneficial for the Lekki project analysis as well as for the accurate set-up, sensitivity- and calibration analysis of the XBeach model. In Table 1.2. a summary of the gathered data is shown. For more explanation, see the corresponding chapter and Appendix A.1.

Table 1.1: Overview of used data for this research

Description of used data	Instrument/source	Type of data	Data period
Wave buoy data nearshore Sandbar breakwater	Directional Wave Rider Boskalis	Hourly wave data (Hs, Tp, θ)	December 2017-July 2018
Wave climate used for the model assessment of the construction variants	SWAN model (Svasek, CDR)	Wave conditions (10), with separate weight (Hs, Tp, θ)	2005-2016
Bathymetric data in the area of interest before the start of the construction of the Sandbar breakwater	Multi-beam/drone footage (obtained from CDR)	Bathymetric data	From before construction (May, 2016)
Weekly surveys bathymetry Sandbar breakwater area during construction	Multi-beam/drone footage acquired by Boskalis	Bathymetric data	December 2017-July 2018
Hopper nourishment details operating at Sandbar breakwater project	Ship logs Boskalis	Nourishment data: vessel sailing-, (un)loading time and capacity	December 2017-February 2018, (only first months of project)

Table 1.2: Overview of expert consulted for this research

Name expert	Role in the Lekki project	Consulted for:
B.J.T. van der Spek	Project engineer and modelling expert CDR	Model study support and acquirement of data
C. van Laarhoven	Resident Engineer Nigeria, CDR	Construction execution details Lekki project, practical knowledge on nourishment works and bathymetric surveys
B. van de Sande	Project engineer CDR	Assumptions and determination for cost assessment
S. Stevense	Senior Marine Rock Engineer at CDR	Assumptions and determination for groynes dimensioning and in construction alternatives cost for these hard structures
A.J.H. Hendriks	Project engineer Boskalis	Model study support, development construction alternatives
G. Rodenburg	Project manager Nigeria, Boskalis	Construction execution details Lekki project, practical knowledge on nourishment works
Bas Vellekoop	Manager Tender Design Boskalis	Assumptions and determination for cost assessment

1.5.3. Roadmap

The roadmap for this study, as illustrated in Figure 1.2, gives an indication of the major processes which are important in this study. Most activities are sequential, since they depend on the outcomes of previous operations. The main operations are the Lekki project analysis, the XBeach model performance analysis and the development and assessment of different scenarios followed by an comparison and conclusions.

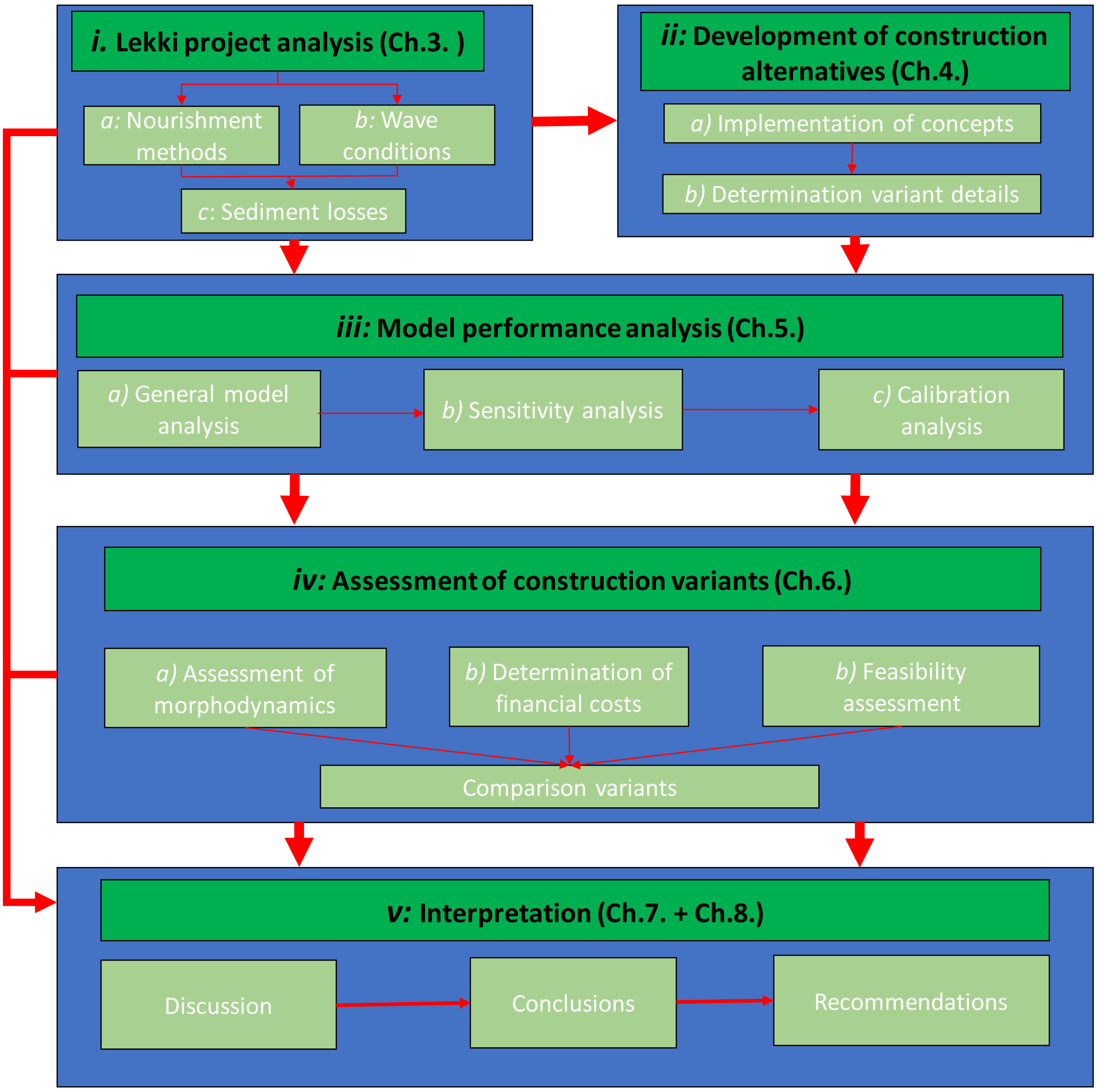


Figure 1.2: Roadmap for research methodology

2. Description of the coastal system near Lekki and the Sandbar breakwater concept

The Sandbar breakwater is an unique concept which is based on several specific coastal system characteristics. Only in coastal systems with these specific conditions are be implemented at certain locations where the coastal system has several specific characteristics and conditions. For the construction process of a Sandbar breakwater and the assessment of other construction alternatives a thorough understanding of the morphodynamics of the system is required. In this chapter, an overview of the most important characteristics and major physical forcing of the coastal system at Lekki, Nigeria is provided. A description of the Sandbar breakwater concept is given and the design details as well as the stability is discussed. This chapter is based on the literature study which was drafted before the start of this research (Wilbrink, 2018).

2.1. Topography study area

The Sandbar breakwater is constructed along the Nigerian coastline at Lekki which is located 80 kilometres east of Lagos. The coastal system is part of the Gulf of Guinea which stretches from Liberia in the West up to Gabon at the South (Figure 2.1).

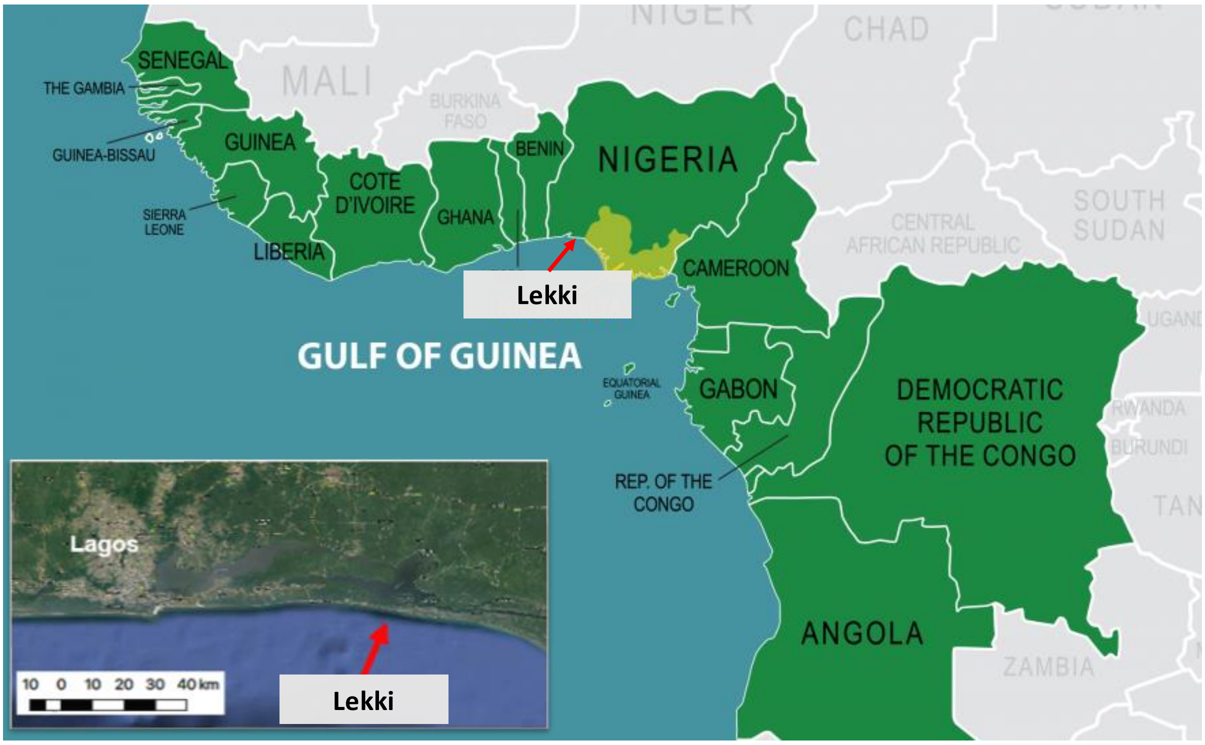


Figure 2.1: Coastal system of the area of interest Lekki, Nigeria (Toritseju, 2017). The red arrow indicate the location where the Sandbar breakwater is constructed.

The Nigerian coast can be classified in multiple morphological zones. The area of interest can be characterized as the barrier-lagoon coastal zone. The coastal stretch consists of a lot of interconnected lagoons, creeks, lakes, rivers and channels. The coastal area is mainly low-lying with heights that do not exceed 3 meters above sea level and is backed by a large lagoon named as the Lekki Lagoon.

The shore at Lekki can be described as a sandy reflective beach (Short, 2018). The beach profile has a steep slope: the first 30 meters into offshore direction is steep (slope 1:6) and decreases to 1:25/1:30 further offshore (between CD -6 m to CD -10 m) and becomes even more gentle further offshore. Due to this steep beach slope the surf zone is narrow which consequently means that coastal processes which only occur in the surf zone (such as littoral drift) take place at a small bandwidth along the coast.

Another characteristic of this coastal area is the huge availability of coarse sediment. The sediment grain size varies between 300-750 µm and is moderately well sorted. Based on sand sample grading analysis the average grain size (D_{50}) turned out to be 600 µm. (Copline Engineering Services., 2016) (CDR International, 2017). Sieve analysis tests were conducted on the retrieved sand samples on both the low waterline and high water line respectively at Lekki beach. An impression of the beach at Lekki and a top view of the area of interest with dept contour lines is presented in Figure 2.2.

Figure 2.2: (a): Bathymetry and topography at the site location before the construction of the Sandbar breakwater. (b): Impression of beach at Lekki (CDR International, 2017).

2.2. Dominant coastal dynamics study area

In this section the most important hydrodynamic (section. 2.2.1) and morphodynamic processes (section 2.2.2) are briefly discussed.

2.2.1. Wave climate

Swell waves

Along the Nigerian coast the wave energy is dominated by very uniformly directed swell from the southwest. Swell waves develop during storms with strong winds generating long and high ocean waves. These swell waves don't lose their energy even when the wind forces are not present anymore. These swell waves can propagate over large distances (Holthuijsen, 2007). The swell waves arriving at the Nigerian coast are generated by storm far away in the southern part of the Atlantic Ocean and travel over a distance of thousands of kilometres which is visible in Figure 2.3-a,b. Seasonal modulation of swell waves is weak, with H_s peaking at 1.6 m during (northern hemisphere) winter at the Nigerian coastline (see colour bar Figure 2.3). The larger the distance to the origin of the swell wave the larger the uniformity of the wave field is. Figure 2.3 also shows that the wave direction is rather uniform within the Gulf of Guinea and particularly along the open coastline of the Bight of Benin where the coastal zone of Nigeria is located.

Wind waves

The impact of wind waves in the area of interest is small. As depicted in Figure 2.3-c,d the annual average wind wave H_s is smaller (0.4 m) and the direction is more oriented from the west (215° clockwise from north). Wind waves also show larger day-to-day and monthly variations. Contrary to the swell waves, wind waves are driven by local tropical winds. Since strong winds are rare at the Nigerian coast the generation of wind wave is limited and the wave energy is significant lower having almost no impact on the Lekki wave climate.

Nearshore conditions

As a result of the SWAN wave analysis done for the Sandbar breakwater design (Svasek, 2017), it can be stated that the average wave heights are in the order of H_s=1.4 m and the average wave period is approximately 12 seconds at a depth of approximately 10 m (Figure 2.4). The average wave direction, which plays a key role in the design of the Sandbar Breakwater concept, is between 200° and 202° clockwise from the north (S-SW direction). These conditions are presented in the nearshore wave height and wave period rose (Figure 2.4).

Waves in the surf zone dissipate their energy and nourished sand in the Active Depth (AD) will be transported onshore by overwash. When a wave approaches the shore and it breaks sediment is taken into suspension, due to the energy, which waves have in themselves. There is onshore sediment transport by the swash and deposition as the swash peters out. Strong shoreward velocities of waves move sediments shoreward. There is a net onshore movement of sediment because the backwash is weaker than the swash (Maddux, 2007).

Another aspect of the waves nearshore is the way of breaking: the waves almost immediately collapse after breaking. This type of wave breaking occurs at beaches with a steep beach slope and relatively large wave length (L) and periods (T). Waves almost immediately collapse and dissipate most of their energy at that moment. Svendsen (1984) suggested that normally in most coastal systems the large amount of potential energy lost in the transition zone is converted to forward momentum flux, which can be described as 'surface roller'. In other words wave energy is not dissipated immediately, but first converted to roller energy. Since this is hardly the case in the area of interest the wave energy dissipation will take place further from the shore at Lekki.

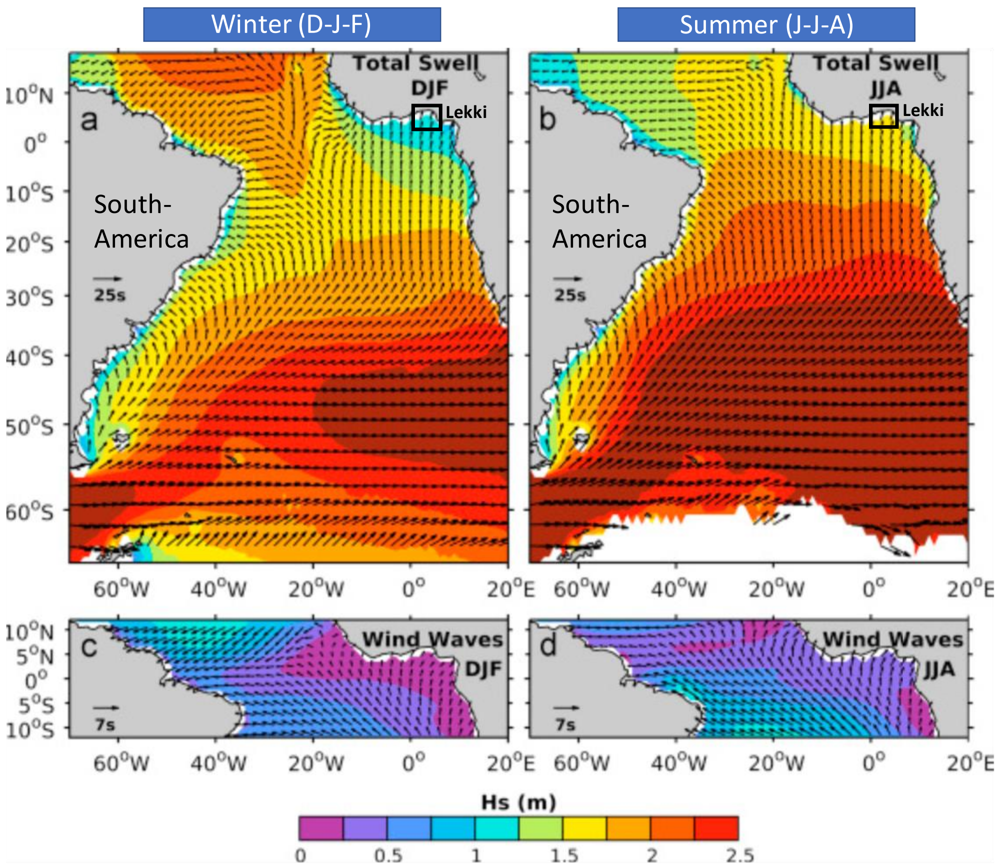


Figure 2.3: Average swell wave conditions during the northern hemisphere winter (D-J-F) and summer (J-J-A) in the South Atlantic Ocean (a and b) and the averaged wind waves conditions in the Equatorial Atlantic Ocean (c and d). For the swell wave and wind wave conditions the significant wave height (H_s, colour bar), period (T, length wave arrow) and direction (ϑ) are indicated (Markina, 2008).

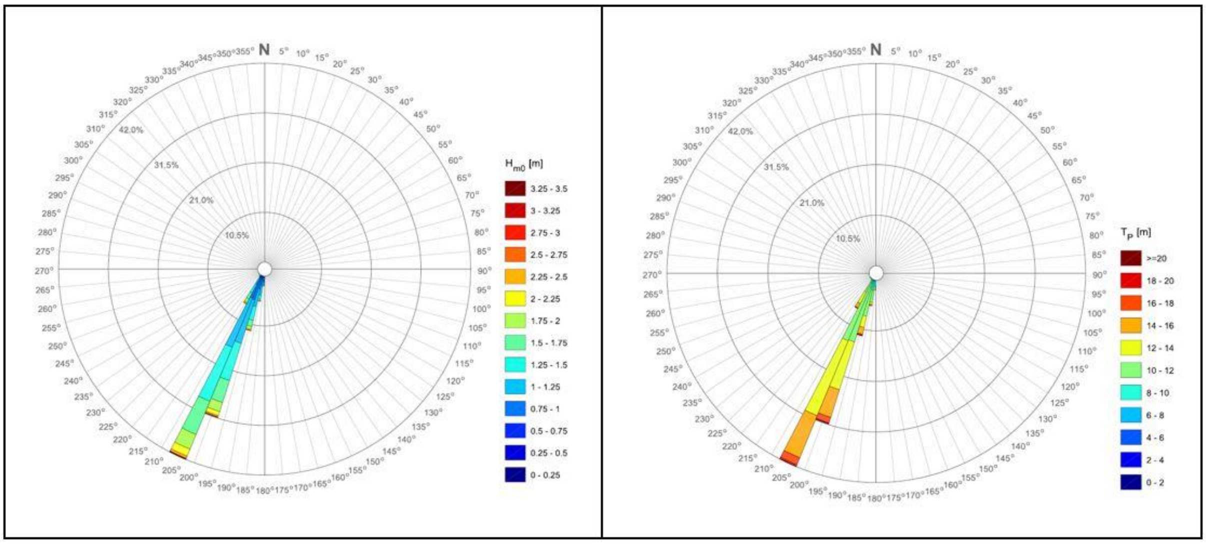


*Figure 2.4: (*a, left): Nearshore wave rose at the site location at an approximate depth of 10 m. (b, right): Nearshore period rose at the site location at an approximate depth of 10 m (CDR International, 2017).

Tides

The tidal signal in Nigeria can be described as a semi-diurnal tide with an average range of 1 m which implies that it can be classified as a micro-tidal coastline (Austin, 2007). The longshore tidal current is small (0.5 m/s, Allersma, 1993) and the impact is neglectable concerning the morphodynamics compared to the littoral drift (section 2.2.2). However, the tidal range is relevant for the coastal system and for the execution of the sand nourishments during the construction of the Sandbar breakwater: at high water spring (MHWS) morphodynamic processes are taking place further onshore than at low water spring (MLWS) and concerning the reclamation works: vessels can reach areas closer to the shore at high tide than at low tide.

2.2.2. Longshore sediment transport

The Nigerian coastline is known for its large Longshore Sediment Transport (LST) rates. LST refers to the cumulative movement of beach and nearshore sand parallel to the shore by the combined action of tides, wind and waves and the shore-parallel currents produced by them (Seymour, 2005). Since the shore-parallel (tidal) currents and winds are weak and a strong uniform swell wave climate prevails, a strong literal drift to the east exist in the order of magnitude of 900,000 m^3 annually from west to east (Tilmans, 1993). This comes down to 12,500-17,500 m^3 per week depending on the time of the year and the occurring wave conditions. At calm conditions (October-March) the LTS is smaller compared to rough conditions (April-September).

The longshore sediment transport strongly depends on alongshore variation in orientation of the coastline. This relationship between sediment transport (S) and the angle of wave incidence relative to the coastline orientation (φ) is a central concept in coastal engineering and can be best explained by the (S,φ)-curve (

Figure 2.5-a). The incoming wave direction at Lekki is measured in relation to the North, which is clarified at the Conventions and Definitions in Figure 2. For the (S,φ)-curve concept these directions need to be transformed to angles relative to the shore.

The (S,φ)-curve indicates that perpendicular incoming waves relative to the shoreline orientation will not lead to LST. As waves enters the coastline obliquely after some time a literal sand drift will arise. The more oblique the waves approach the shore, the larger the longshore sediment transport rate is. The maximum longshore transport occurs at an angle a bit smaller than φ_0= 45°. The transport in longshore direction reduces to zero if φ_0=0° resulting in normally incident waves at the breaker line and only wave stirring and no longshore current (Bosboom, 2012).

The longshore sediment rate for different angle of incidence at the Lekki coast is calculated by using the CERC longshore transport formula. The results are presented in

Figure 2.5-b. These calculations show indeed that the averaged angle of incoming wave trains relative to the coast (12°) induce a large yearly sediment transport. From this analysis it can also be stated that especially if the waves are arriving almost perpendicular to the coast a small change in incoming wave angle has larger impact on the littoral drift rate. In such case a deviation of only 2 to 5 degrees may already lead to a (theoretical) increase of the sediment transport magnitude of more 50%, regardless the significant wave height or wave period (see

Figure 2.5-b). However since the wave climate is highly uniform, the longshore sediment transport drift is almost always easterly directed relative to the initial Lekki coastline. Short period that waves arrives from other direction will have impact on the longshore sediment transport rates in- or decreasing the eastern littoral current. In case the wave direction is from the (south)east for some time this will even lead to a western longshore sediment transport current.

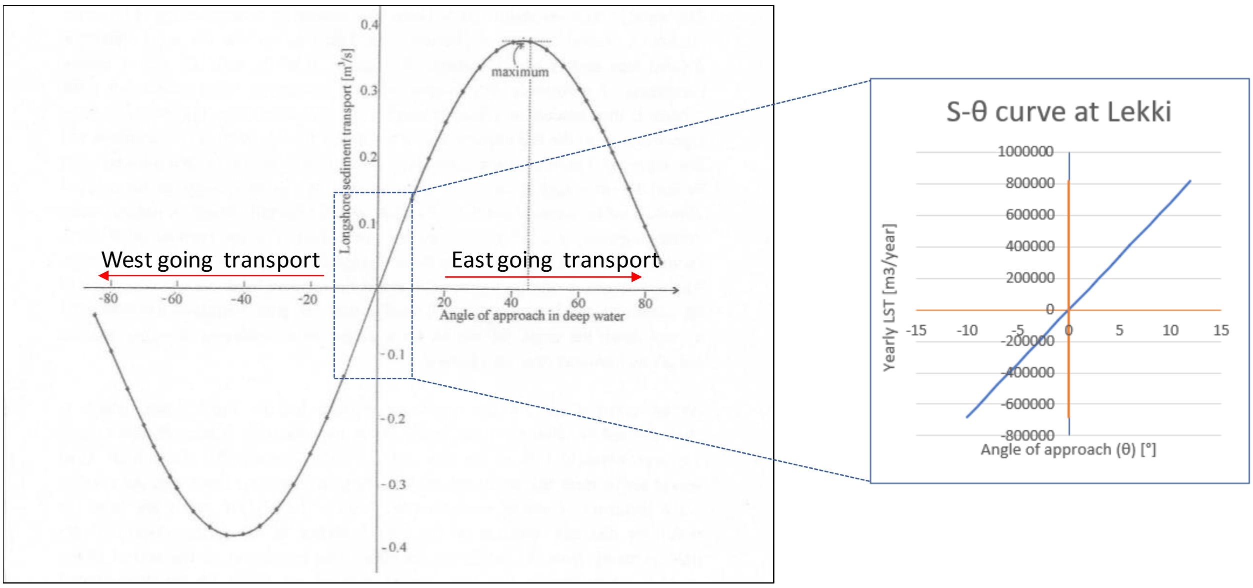


Figure 2.5: (a, left): (S,ϕ)-curve representing an example of the relationship between the longshore sediment transport rate [m³/s] and the angle of the approaching waves relative to the coastline orientation (ϕ_0) (Bosboom, 2012). (b, right): steepest part of the (S,ϕ)-curve determined for the conditions at the coast at Lekki, Nigeria. At an angle of 0° (perpendicular incoming waves at the coast orientation), the longshore sediment transport is equal to zero.

Due to the fact that the surf zone is relatively narrow, the bandwidth over which LST takes place is small. This is confirmed by a modelling study from Svasek (2017) which showed that hardly any longshore sediment transport below the CD -6 m depth contour exists.

2.3. Sandbar breakwater concept and design details

2.3.1. Effect of breakwater at coastline

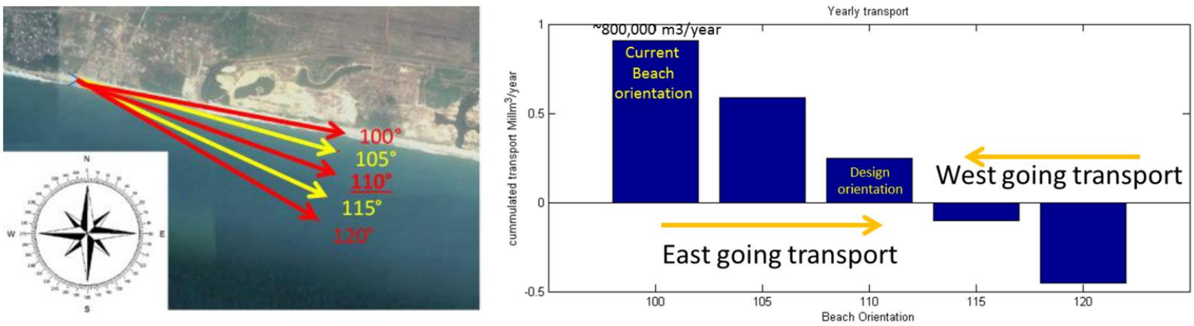
Even though the presence of the large LST current, the Nigerian coastline is more or less in equilibrium. However a coastline intervention as a breakwater will disrupt the equilibrium shoreline. It will (partly) block the net longshore sediment transport in the surf zone which leads to accretion of sand on the west side ('updrift') and erosion of sand on the east side ('down drift') of the intervention. Subsequently, siltation of the access channel or the (turning) basins will take place.

Since the LST is strong along the Nigerian coast, this will have an impact on hydraulic structures such as breakwaters. The morphological coastal evolution after a breakwater intervention is clearly visible at different constructed breakwater along the Nigerian coast. In the Sandbar breakwater design this effect is used since sand is accumulating at the sandbar from the west and the stability of the breakwater will only increase over time.

2.3.2. Breakwater orientation and design

The design of the Sandbar breakwater is based on the LST concept explained above in section 2.2.2. the coast orientation at which almost no eastern longshore sediment transport is taking place (110° w.r.t. the North) is implemented into the design of the Sandbar Breakwater (see

Figure 2.5 and Figure 2.6). This in order to prevent erosion along the Sandbar breakwater itself and to



allow sand to flow into a sand trap for the purpose of replenishment of the beach east of the port. As mentioned before different wave conditions for shorter or longer period will influence the morphodynamics significantly. A more detailed overview of the final design of the Sandbar breakwater is presented in Figure 1.1.

Figure 2.6: (a): Different beach orientations. (b): Effect on LST for different Sandbar breakwater orientations (CDR International, 2017).

The morphological development of the final design over time is assessed by the morphological model 'FINEL' over a period of four years. The results show that in the beginning the sandbar part of the Sandbar breakwater becomes thinner, although this development stagnates after circa two years and is nearly stable after three years. On the other hand, the foreshore expands and accretion takes place west of the Sandbar breakwater. The model results of the Sandbar breakwater at the start of the *simulation and after four years is presented in*

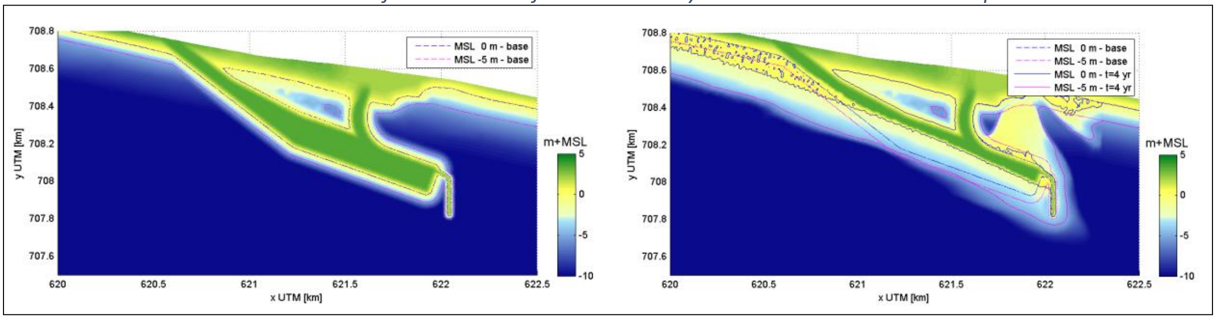


Figure 2.7.

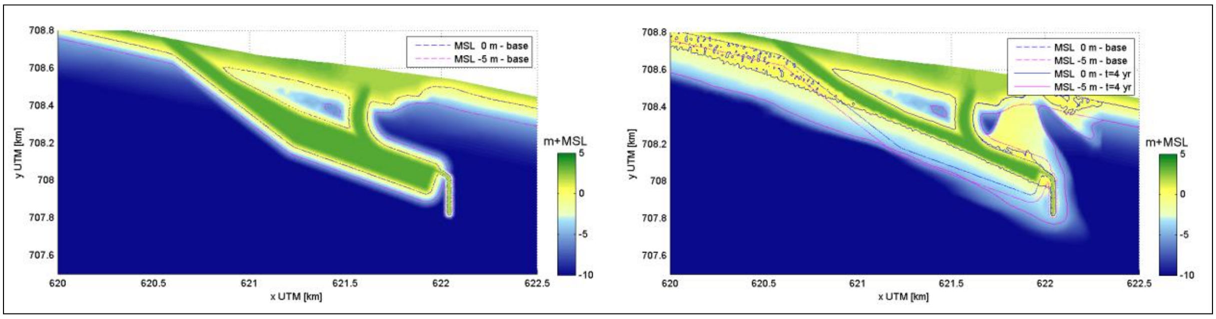


Figure 2.7: (a): Bed level after construction of the sandbar breakwater (final design) as the start bathymetry for the durability assessment modelling study. (b): Bed level after 4 years of morphological simulation for the final design (CDR International, 2017).

Based on the modelling results, it was concluded by CDR that the investigated final design is a durable and that no breaching of the sand body is expected. A volume of about 4 Mm^3 of sand is required for this design. A design with a smaller sand bar (and thus less sediment) will not suffice (CDR-International, 2017).

2.3.3. Sandbar breakwater stability and sediment losses

The Sandbar breakwater is developed in such a way that the required sand nourishment volumes are minimized in order to save costs. Therefore an Inner Lake is implemented into the design, since reclaiming this area does not contribute to the strength and stability of the Sandbar Breakwater.

Due to the hydro- and morphodynamic processes during the construction process, certain amounts of nourished volume will end up outside the design. Since for the Lekki project analysis and the assessment of the construction alternatives the sediment losses are quantified, first a clear definition of a sediment loss is drafted:

A sediment loss is a quantity of sand which is nourished inside the design profile but is moved/transported outside the design profile by natural processes to locations where it does not contribute to the stability and strength of the Sandbar breakwater.

Locations where nourished sand does not contribute to stability of the Sandbar breakwater and is considered as a loss are Inner Lake and the east side of Sandbar breakwater. This is visualised in Figure 2.8.

Figure 2.8: Locations in the area of interest where sediment nourished inside the design profile but is moved/transported outside the design profile by natural processes is considered as a sediment loss: the Inner Lake and at the East side of Sandbar Breakwater which is indicated by the black-yellow polygons.

2.4. Summary Chapter 2

This chapter is briefly summarized by the following statements:

- *The Lekki coastline can be described as a straight and sandy, reflective beach, with a steep slope resulting in a narrow, active surf zone.*
- *Due to the prevailing uniform swell wave climate a strong longshore sediment transport current to the east exist of about 850.000 m^3 per year.*
- *The Sandbar breakwater design is based on these concepts: natural accretion west of the breakwater prevents the necessity of hard construction materials as they lose their function over time and an appropriate Sandbar orientation based on the dominant incoming wave direction ensures a durable design.*
- *The definition of a sediment loss in this study is a quantity of sediment which is nourished inside the design profile but is moved/transported outside the design profile by natural processes to locations where it does not contribute to the stability and strength of the Sandbar breakwater.*
- *The areas where nourished sand is considered as a loss are the Inner Lake and the east side of the Sandbar breakwater.*

3. Lekki Sandbar breakwater project analysis

In this chapter the analysis of the Lekki Sandbar breakwater project regarding the nourishment strategies, the wave conditions and the sediment losses is presented. For this analysis the applied nourishment methods, the observed wave conditions and the actual occurred sediment losses during the Lekki project are determined. These aspects are compared by the planned construction strategy (Method Statement), the expected hydrodynamic conditions and the estimated sediment losses. This analysis reveals to which extent the actual construction strategy corresponds to the Method Statement, assesses the accuracy of the nourishments and indicate the impact of the hydrodynamic conditions on the morphology during the construction process. Altogether, it contributes to a better overall understanding of the construction process of a Sandbar breakwater and the conclusions are used for the development of Sandbar breakwater construction alternatives in this research (Chapter 4) and may be helpful for future comparable projects.

This chapter is structed as follows: first a general explanation regarding the project stages, the duration and the dredging vessels for the execution of the sand nourishments is stated, followed by the analysis of the nourishment execution methods, the observed wave conditions and the occurred morphodynamic behaviour with the focus on sediment losses and natural accreted sand at the Sandbar breakwater.

3.1. General Lekki project details

3.1.1. Project stages and duration

The Lekki project is executed in a number of distinct phases. Some stages are executed parallel and others sequential. Prior to the operational phase preparations have been made. This included the arrangement of site offices and accommodation, the acquisition of the in-survey and the removal of the existing groynes (see Appendix A, Figure A.X). Once this was completed, the dredging operations and rock installation works commenced. These works are divided in six main stages, which are summarized below. In Figure 3.1 a clarification of the different components in the construction stages is presented.

- Stage 1: Nourishment of an offshore submerged bund
- Stage 2: Reclamation of the Sandbar Road
- Stage 3: Construction of the Sandbar Groyne
- Stage 4: Reclamation of the Sandbar to the west from the Sandbar Road
- Stage 5: Further widening and heightening of Sandbar breakwater up to design requirements
- Stage 6: Reclamation of the Sand Engine, the construction of the Lee side Revetment and the installation of the Geo tubes.

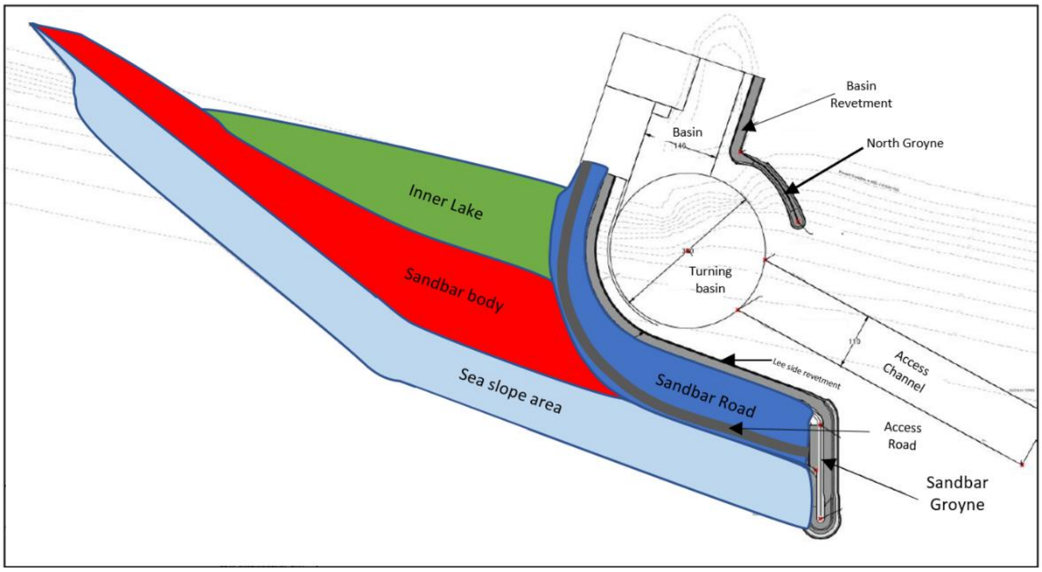


Figure 3.1: Overview of the different components in the Lekki Sandbar breakwater design

The duration of the nourishments was 16 weeks in total (end of December 2017-April 2018) of which the first 12 weeks were used for the nourishment of 4 Mm^3 sand in the design profile of the Sandbar breakwater and the last 4 weeks for the reclamation of the Sand Engine. These durations corresponds to the estimated project duration. An overview of the duration of the different construction stages is presented in Table 3.2.

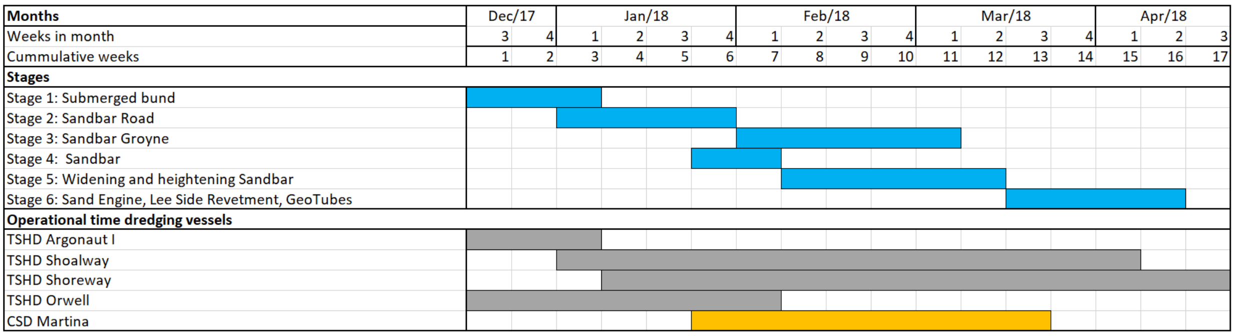
3.1.2. Dredging vessels

The sand nourishments for the construction of the Sandbar and the Sand Engine are executed by four Trailing Suction Hopper Dredgers (TSHD) and one Cutter Suction Dredger (CSD) (Table 3.1.). The TSHDs are used to dredge sand material at a nearby offshore borrow area and to transport this to the reclamation location. For unloading the sand several nourishment methods are applied: discharging by bottom door dumping (unloading the sand through the bottom doors), discharging by rainbowing (unloading the sand by pumping it overboard through a jet nozzle at the bow of the TSHD) or discharging by pumping the sand ashore (unloading by pumping it ashore by pipeline(s), abbreviated as PASH). The hopper capacity of dredger vessels is shown in Table 3.1.. This table also shows the operational time at the project of each ship, which is also shown in the time table overview of the project (Table). In Appendix B, more explanation on the used dredging vessels and the applied nourishment methods is given.

Table 3.1: An overview of the operational time and the maximum and actual averaged load capacity of the dredging vessels during the Lekki project of the hopper dredgers (TSHD) is presented. For the cutter Martina (CSD) the capacity does not apply.

Dredging vessel	**Operational time at project**	**Maximum capacity**	**Actual averaged capacity during project**
TSHD 'Argonaut I'	12/22/2017 - 01/07/2018	2,500 m^3	2,030 m^3
TSHD 'Shoalway'	01/05/2018 - 04/09/2018	4,500 m^3	3,325 m^3
TSHD 'Shoreway'	01/06/2018 - 05/06/2018	5,600 m^3	3,800 m^3
TSHD 'Orwell'	12/19/2017 - 02/01/2018	2,575 m^3	2,080 m^3
CSD 'Martina'	01/28/2018 - 03/20/2018	*n/a*	*n/a*

Table 3.2: Construction period overview of different stages during the Lekki Sandbar breakwater project.



3.2. Nourishment and rock installation work execution

In this section the planned construction strategy (Method Statement) is compared to the actual nourishment and the rock installation work execution. An overview of the Sandbar construction stages according to the Method Statement and the actual execution which is presented by bathymetric surveys is shown in Figure 3.2.. The Sand Engine construction stage is presented in Figure 3.3.. In Appendix A all the bathymetric (week) surveys from before, during and after the construction phase are presented, which gives a good chronologic overview of the project execution. The construction details and the differences between the Method Statement and the actual execution is discussed in section 3.2.1 (Stage 1 and 2), section 3.2.2 (Stage 3,4 and 5) and section 3.2.3 (Stage 6). In stage 6 the Sand Engine is construction and since this is not the focus of this study this stage is briefly discussed.

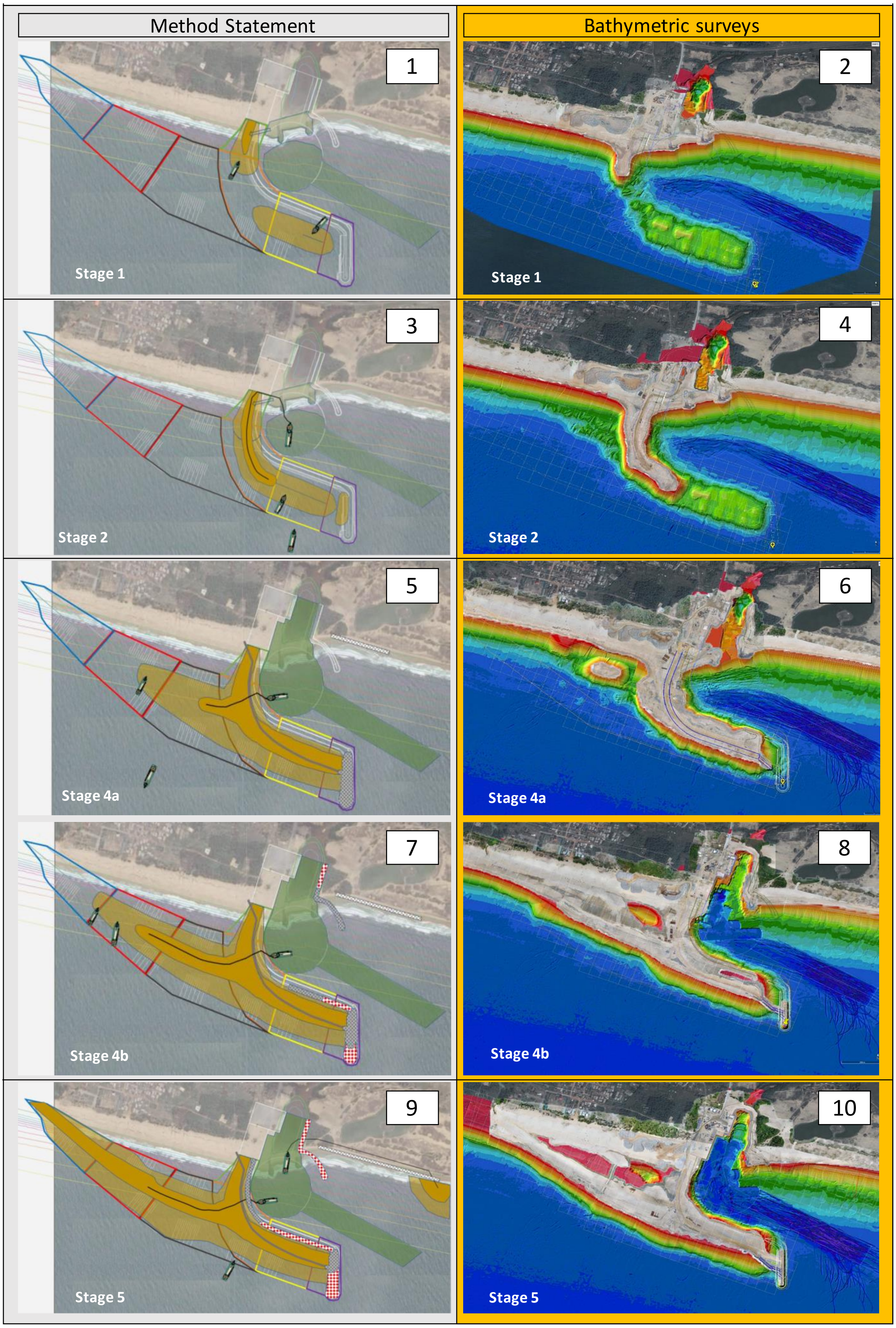


Figure 3.2: Sandbar construction stages overview of the Lekki project. The left figures represent the stages according to the Method Statement (Boskalis, 2017) and the right figures represent the actual construction stages (Boskalis, 2018). Image 1 and 2 show construction stage 1: (offshore submerged bund), image 3,4 show construction stage 2 (coastal expansion Sandbar Road) and image 5-8 show stage 4 (reclamation of the Sandbar) and image 9 and 10 show stage 5 (widening and heightening of the Sandbar).

3.2.1. Stage 1 and 2

The start of the reclamation of the Sandbar was the construction of an offshore submerged bund to a bed level of about CD -5 meter (Figure 3.2-2). The start date of the nourishment works was 22 December 2017 and had a duration of about 2 weeks (22 December - 4 January). The submerged bund was constructed at the south-east part of the Sandbar breakwater design profile and was mainly executed by the TSHD Orwell applying the discharge method 'bottom door dumping'. The nourishment production rates during stage 1 was approximately 20,000 m^3 per day. The bund was initially supposed to have a volume of 350,000 m^3 (Figure 3.2-1), however it has become larger than planned (approximately 400 x 100 m with a volume of 550,000 m^3). This deviation from the initial plan was executed because of two reasons. The TSHD Orwell suffered from a technical problem such that it only could discharge the load by bottom dumping. Secondly, the submerged bund turned out to be very stable and little morphological development was noticed (section 3.4.1).

After the construction of the submerged bund, the Sandbar Road was being build out from the coast (Stage 2). This is clearly visible at the bathymetric surveys of 8 and 14 January (Figure 3.2-2,4). During this stage, two or three TSHDs were executing the sand nourishments with a duration of about 3 weeks. The production rate during stage 2 was approximately 45,000 m^3 per day, much larger than in the beginning of the project in order to speed up this stage and lower the sediment loss risks.

The Sandbar Road is constructed a little westward from the design profile, since there were concerns of large erosion of nourished sand to the east by longshore transport. This aspects and the consequences are further described in section 3.3.3.

After sufficient progress of the Sandbar Road, the plan was to use a TSHD to pump sand ashore (PASH) which was drawn in the Method Statement. This was not possible since the pipelines were not available in time on site. This meant that the CSD Martina could not been used yet and the TSHDs could only applied the rainbowing and bottom door dumping method. Therefore more dry extraction of the harbour quay wall was executed which is visible at the bathymetric surveys of 8 and 14 January (Figure 3.2-2,4). This excavated sand was brought on the Sandbar Road coastal expansion from land by Articulated Dump Trucks (ADT).

3.2.2. Stage 3, 4 and 5

After reaching the south-eastern tip of the Sandbar Road (Survey January 22th; Appendix A, Figure A.5-c), stage 3 commenced: the construction of the Sandbar Groyne at the tip of the Sandbar Road. The plan was to start as soon as possible with the construction of the Sandbar Groyne to prevent erosion of sand to the east. This was supposed to take place before and during the reclamation of the Sandbar, illustrated in Figure 3.3-a. The actual construction of the Sandbar Groyne started at the same time as the Sandbar nourishments, however the first part of the Groyne was only finished in half February as the Sandbar was already almost constructed (**Fout! Verwijzingsbron niet gevonden.**Figure 3.3-b).

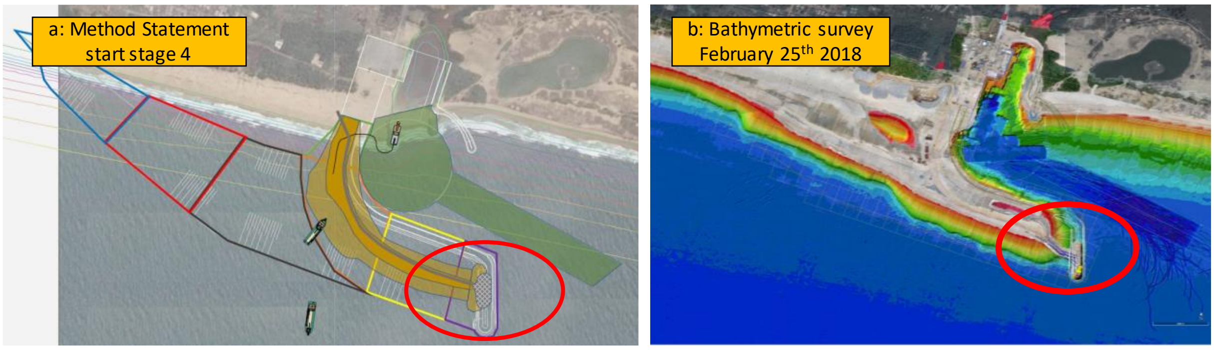


Figure 3.3: (a): Situation at the start of stage 4 according to the Method Statement showing that the construction of the Sandbar Groyne (red circle) has already started. (b): Bathymetric survey from February 25th 2018 (stage 5) showing the reclaimed Sandbar while still only a small part of the Sandbar Groyne (red circle) is constructed, implying that the construction of the Sandbar Groyne was delayed.

Another difference regarding the Method Statement was that the access road to the Groyne was constructed more towards the south tip of the Sandbar Groyne than was planned in the original design (visible in Figure 3.3-a and b, red circles). This was done due to optimise rock volume during execution. In this design this access road was consciously designed more northern in order to prevent easy bypassing of sand to the east. CDR has advised that the temporary access road has to be removed as this will disrupt the formation of a natural beach profile. It is of utmost importance that the reshaping of the profile can take place, as this contributes to a stable Sandbar. The access road is later on removed in order to meet this design requirements and the reshaping of the profile could take place, as this contributes to a stable Sandbar. The construction of the Sandbar Groyne was finished on March 4th 2018 with a duration of almost 5 weeks.

Stage 4, the construction of the Sandbar was planned to be executed from east to west from the Sandbar Road (Figure 3.2-6,8). During this stage there were two or three TSHDs executing the sand nourishments by applying the bottom door dumping and the rainbowing method. The construction period of this stage was almost 2 weeks with a production rate of about 45,000 m^3 per day.

In the fourth stage the actual execution of the project was quite different from the Method Statement. On the project site it was decided that the nourishments will be executed on shoreside side in order to be able to discharge more nourishment volumes by rainbowing and bottom door dumping instead of pumping ashore. Pumping dredged sand ashore is a more expensive method (see Appendix B). Next to that, the morphological development of the nourished sand in stage 1 and 2 was very little so the expectation on site was that this decision would not have much impact on the nourishments of the Sandbar. The combination of the applied nourishments at the shoreside of the design profile and the occurred wave conditions at that moment (discussed in section 3.3.2), a large volume of sand ended up in the Inner Lake visible on the surveys in Figure 3.**Fout! Verwijzingsbron niet gevonden.**2-d and the bathymetric surveys January/February in Appendix A.

Another deviating aspect was that the nourishments were not strictly executed from east to west but also at the centre and the westside of the Sandbar. The start of the Sandbar expansion was initiated by the construction of an island, west of the Sandbar Road section clearly visible in Figure 3.2-6. Later on nourishments at the west and east side of the Sandbar design profile were executed (Appendix A, Figure A.6-b,c: *survey February 11th/18th*).

Furthermore, the plan was to start with the construction of the Lee side Revetment and the North Groyne during stage 4 (Figure 3.3-b). However in practise this commenced later namely directly after the completion of the sand nourishments (April). This was done since the main priority was to nourish the 4 Mm^3 of sand as quick as possible to minimise sediment losses.

The objective in the final stage of the sand nourishment for the Sandbar (stage 5) was to further widen and heighten the Sandbar up to design requirements (up to CD +4.5 m). This stage was executed by two or three TSHDs by rainbowing and pumping sand ashore. The construction period of this stage was approximately 5 weeks with a production rate during stage 5 of approximately 30,000 m^3 per day.

Later on in the project the client Dangote (DPRP) delivered an extra stockpile of sand which was been used to further increase the height of the Sandbar locally and to fill the Inner Lake. This filling of the Inner Lake was decided for practical reasons after negotiations of the local community near the Sandbar breakwater.

3.2.3. Stage 6

The main objective of stage 6 was to construct a Sand Engine at the east of the sandbar breakwater to mitigate coastal erosion at the east side of the construction site which caused by the obstruction of the longshore transport by the sandbar breakwater (chapter 2.3.1). The construction of the Sand Engine started at the 15th of March and was finished almost one month later (13th of April) and was executed by two TSHDs (Shoreway and Shoalway). The total volume of the Sand Engine was designed to be approximately 900,000 m^3 based on the original coastline, which is the equivalent of roughly one year of longshore transport. The production rate during stage 6 was 30,000 m^3 per day. The plan is to renourish the Sand Engine once every year. The design of the Sand Engine at the east side of the Sandbar and the actual survey just after the completion (15th of April) of the construction is shown in Figure 3.4.

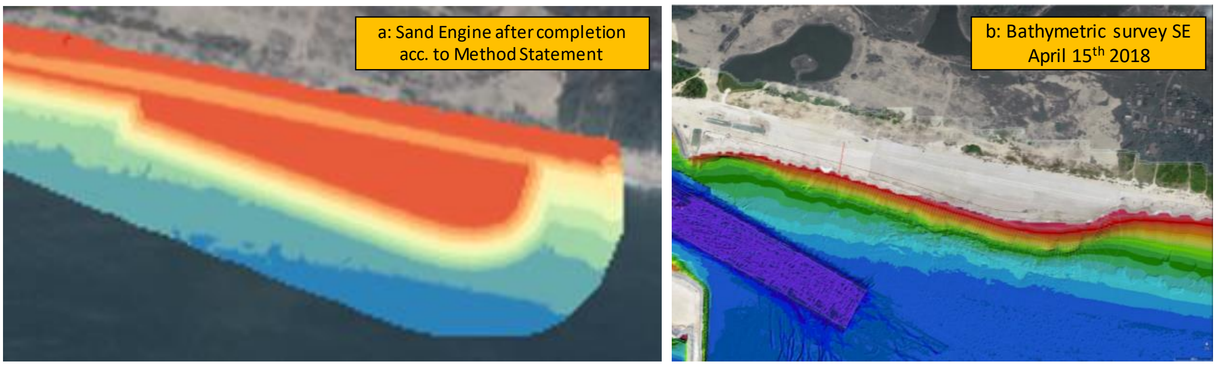


Figure 3.4: a): The design profile of the Sand Engine at the east side of the Sandbar breakwater according to the Method Statement (b): Bathymetric survey of the Sand Engine just after the completion of the Sand Engine (April 15th 2018).

Furthermore, the rock installation works for the construction of the Lee side Revetment and the North Groyne have been executed. Furthermore, the Geo Tubes were installed at the Sand Engine. The duration of this work was a bit longer than planned.

3.3. Wave conditions

In this section the expected and the actual observed wave conditions regarding the significant wave height (H_s), the wave peak period (T_p) and the wave angle (θ) are compared for all stages. The expected wave data is based on a large scale SWAN model which is calibrated against the local measurements. The SWAN data provides wave data for 10 years over the period 2005-2015.

3.3.1. Stage 1 and 2

The wave conditions from the wave buoy for the first two stages are analysed and presented in Figure 3.5. The averaged wave height, wave period and direction over the period is summarized in Table 3.1.

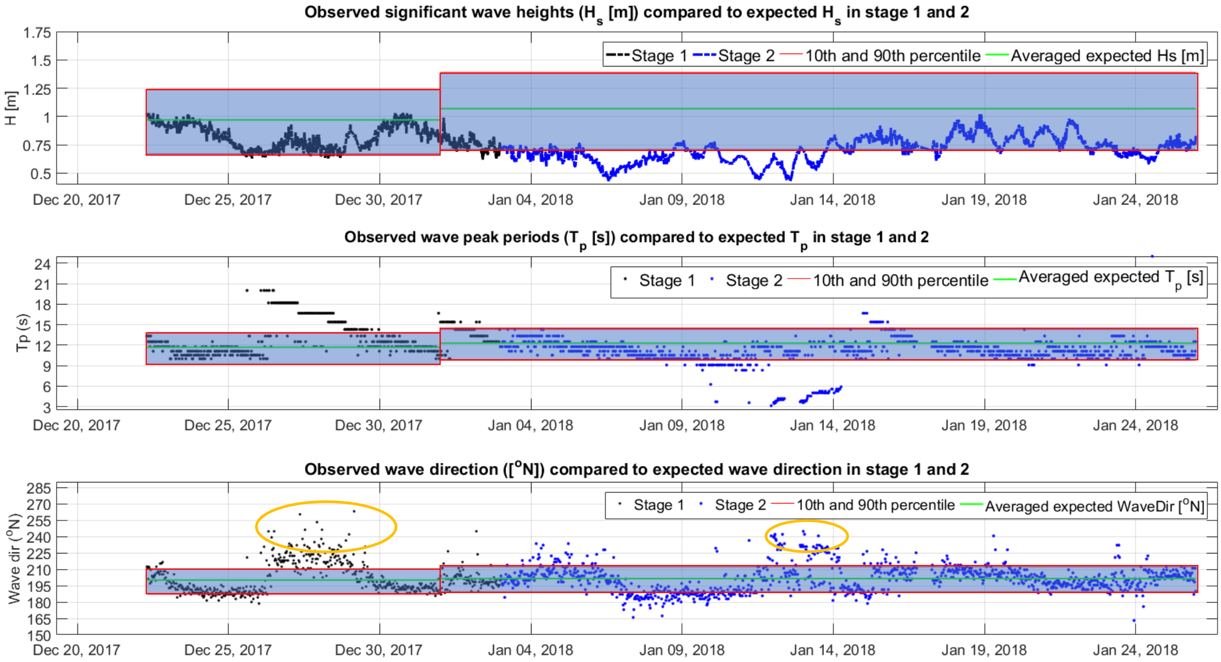


Figure 3.5: Wave conditions of stage 1 (construction of submerge bund) and stage 2 (reclamation of the Sandbar Road) during the construction phase of the Lekki project: (a): wave height (Hs), (b): wave period (Tp) and (c): wave direction (ϑ)). The green line indicates the averaged expected wave condition for the specific month, the red box indicate the 10th to 90th percentile for the wave conditions for the specific month. The yellow circles indicate peaks in the wave direction data meaning that the wave direction is more from the west, see for further explanation section 3.3.1..

Table 3.1: The averaged expected wave data versus the averaged observed wave data in stage 1 and stage 2 of the Lekki project.

	Significant wave height (H_s)		Peak period (T_p)		Wave direction (θ)	
Stage	**Stage 1**	**Stage 2**	**Stage 1**	**Stage 2**	**Stage 1**	**Stage 2**
Averaged expected	0.98 m	1.07 m	12.5 s	12 s	201 °	201.2 °
Averaged observed	0.80 m	0.71 m	13.1 s	10.9 s	202.1 °	201.5 °

For the first two stages of the reclamation works different remarks can be drawn as the observed wave conditions are compared by the expected wave climate:

- The wave heights were significantly lower than expected in the period December/January. The wave height varies between half a meter to a bit more than a meter. The averaged wave height is 30% lower than the averaged expected H_s. Especially at the end of stage 1 and at the start of stage 2 the wave conditions were calm (40% lower H_s and 7% lower T_p) while the waves approaches from the expected south-western direction (Figure 3.5).
- The observed wave conditions in December are less calm (larger H_s, T_p) than in January while in it was expected that December would have been the calmest month. Furthermore, the averaged wave period in December is higher than the expected value (Table 3.1). This is a

deviation from the expected annual variability in wave conditions based on the 10 years wave data obtained from the SWAN analysis.

- The averaged wave direction was a bit more from western direction than expected (201.7° versus 201° over first two stages). This difference is in these stage quite small, however at some short-term periods the waves direction was much more coming from the west exceeding the 240° w.r.t. the North (indicated by the yellow circles in Figure 3.5.). This enhances strongly the eastern directed longshore transport.
- Generally, it can be stated that the scatter in wave data is larger than expected. This means that the wave climate during the first two stages is less uniform than determined by the SWAN wave data analysis implying that this is a deviant period. Most eye-catching is the large scatter in incoming wave direction which differ between 170 and 250° w.r.t. the North (see for clarity Figure 2). This deviation can be probably explained by the yearly variance since the deviation periods are relatively short. Furthermore the SWAN model takes only 10 years of wave data into account and the average range of the expected wave data is small especially for the wave direction so these deviations are not very particular or rare.

3.3.2. Stage 4 and 5

The (averaged) wave conditions for stage 4 and 5 (26 January to 13 March 2018) are presented in Figure 3.6 and Table 3.4.

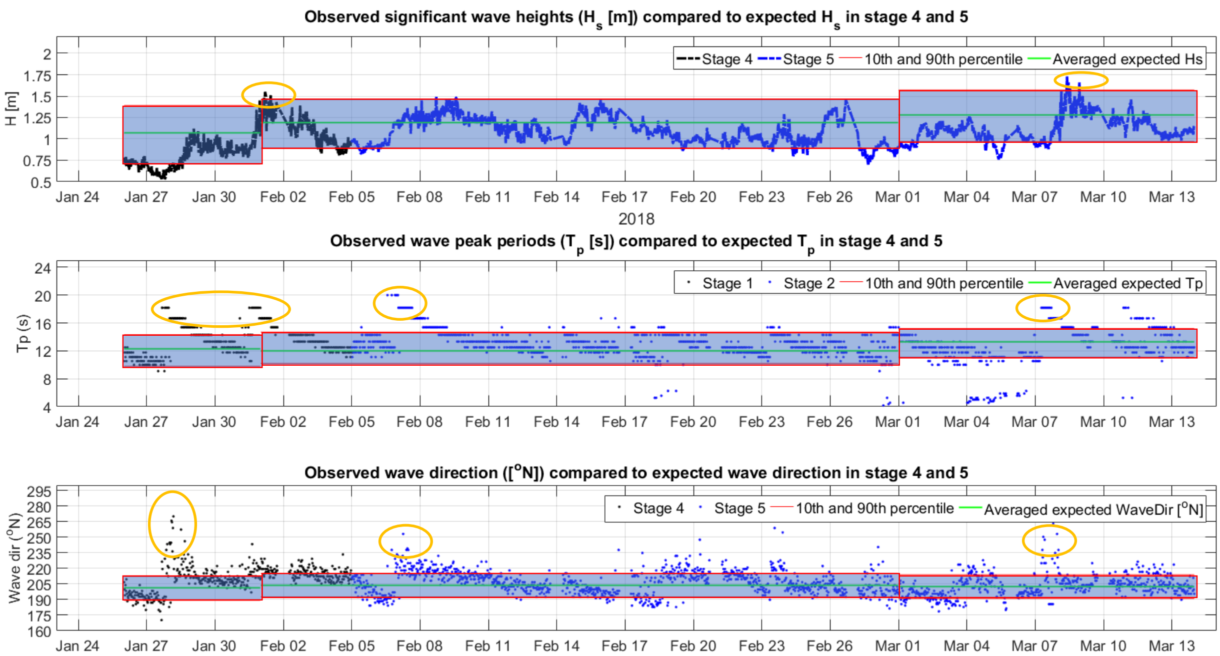


Figure 3.6: Wave conditions of stage 4 (Reclamation of the Sandbar-part) and stage 5 (Further widening and heightening of Sandbar-part) of the construction phase of the Lekki project: (a): wave height (Hs), (b): wave period (Tp) and (c): wave direction (ϑ)). The green line indicates the averaged expected wave condition for the specific month, the red box indicate the 10th to 90th percentile for the wave conditions for the specific month. The yellow circles indicate peaks in the wave data which are further explained in section 3.3.2..

Table 3.2: The averaged expected wave data versus the averaged observed wave data in stage 4 and stage 5 of the Lekki project.

	Significant wave height (H_s)		Peak period (T_p)		Wave direction (θ)	
Stage	**Stage 4**	**Stage 5**	**Stage 4**	**Stage 5**	**Stage 4**	**Stage 5**
Averaged expected	1.19 m	1.28 m	12.2 s	12.4 s	203°	202.4°
Averaged observed	0.92 m	1.10 m	13.6 s	13.0 s	210.9°	205.7°

- The average wave height and period during these stages were almost equal to the expected values (5% lower) while the wave direction is deviation is relatively large (8° for stage 4 and 3° for stage 5). As already noticed for stage 1 and 2, the overall spread in the wave data is larger than expected, which is even more the case for stage 4 and 5.
- Although the observed average values are not very different from the expected values, during several short-term periods the wave conditions do strongly deviate from the expected wave date (e.g. 28 Jan-2 Feb, 7-9 March, see yellow circles in Figure 3.6.) The data shows that more western approaching waves are often accompanied by larger peak periods and higher wave height, which indicate the occurrence of strong swell conditions. Especially the period end January/start of February is significant different leading stronger morphodynamics affecting the construction process. This period will be briefly further discussed below.
- The main striking observed phenomenon in the period 28 Jan-2 Feb is that the waves are approaching more from the west. The wave direction varied from 200 up to 270 ° w.r.t. the North. The wave direction of 270° at January 28th is one of the most deviant angles measured during the entire Lekki project. The wave period exceeded the 90th percentile of the expected wave period resulting in an average wave period of 17.3 seconds. Furthermore, the wave height increased much up to 1.55 m. As stated in the chapter 2.2 a change in wave conditions especially the wave direction have a large impact on the morphodynamics in the area. The relation between the conditions and the morphodynamics during this period is further elaborated in section 3.3.3.

3.3.3. Stage 6

The observed wave conditions during the construction of the Sand Engine are comparable to stage 4 and 5: averaged lower significant wave heights (<10%), higher peak periods (>6%) and more western originated waves (about 5° more SW) than averaged expected from the SWAN analysis.

3.4. Morphodynamics

In this section the morphodynamic behaviour during an just after the construction stages is discussed regarding the sediment losses (erosion) and the natural accretion of sediment (sedimentation). Next, it is compared to the estimations made before the construction phase.

3.4.1. Stage 1 and 2

Sediment losses

In stage 1 very little morphological development was noticed. This can be explained by the observed wave conditions as well as the location of the nourishments. The wave conditions at the start of stage 1 were relatively calm (low H_s, T_p and perpendicular incoming waves). Even though in the second part of stage 1 the peak periods were higher and the wave direction was coming more from the West, the morphological behaviour was still little. This can be explained by the fact that the nourishments took place outside the surf zone at relatively large depth (below CD -5 m).

At the start of stage 2 as the Sandbar Road was reclaimed from the shore, which is a critical point regarding sand being lost from the design profile. Fortunately, for the progress of the project the observed wave condition were calm (below averaged H_s and T_p and averaged θ values most of the time) during this stage which leaded to only 4,000 m^3 of sediment losses to the east which can be mainly attributed to the longshore sediment transport current.

Naturally accreted sediment

In stage 1 no significant natural accretion of sediment into the design profile was noticed because of the reasons explained in the section above: the occurred wave conditions and the location of the nourishments.

In stage 2, already natural accretion at the westside of the Sandbar Road was clearly visible. This sedimentation has occurred due to the 'blockade' of the LST current. Due to the fact that the Sandbar Road was constructed a bit more western (section 3.2.1.), sand from LST was rapidly trapped into the inner lake, which is outside of the design profile (red circle, Figure 3.7). In case the Sandbar Road was positioned a little more to the east, sand from the alongshore current would have ended up into the design profile which is 'free' sediment. However, this also involves more project risks: in case the waves direction was more western orientated during this stage, it would have resulted in much more erosion of nourished sand from the Sandbar Road towards the east side of the design profile being a loss.

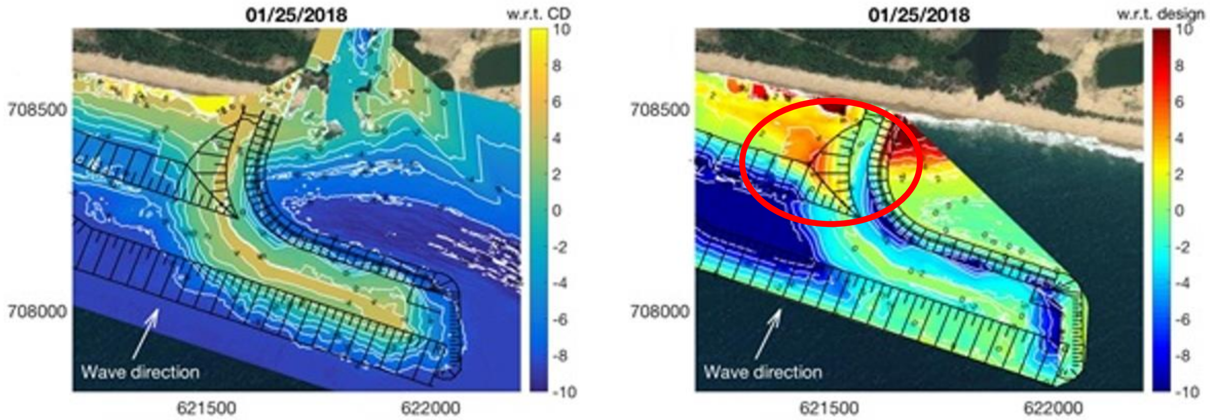


Figure 3.7: The Sandbar Road section at the 25th of January. (a): The bathymetric survey of the road section at the 25th of January, (b): the bathymetric survey of the 25th of January relative to the design profile. The blue colours represent areas that are still below design and have to be filled to reach design requirements. The red colours represent areas that are above the design and therefore outside design, showing accretion at the westside of the Sandbar Road due to the LST current which is indicated by the red circle (Boskalis, 2018).

3.4.2. Stage 3, 4 and 5

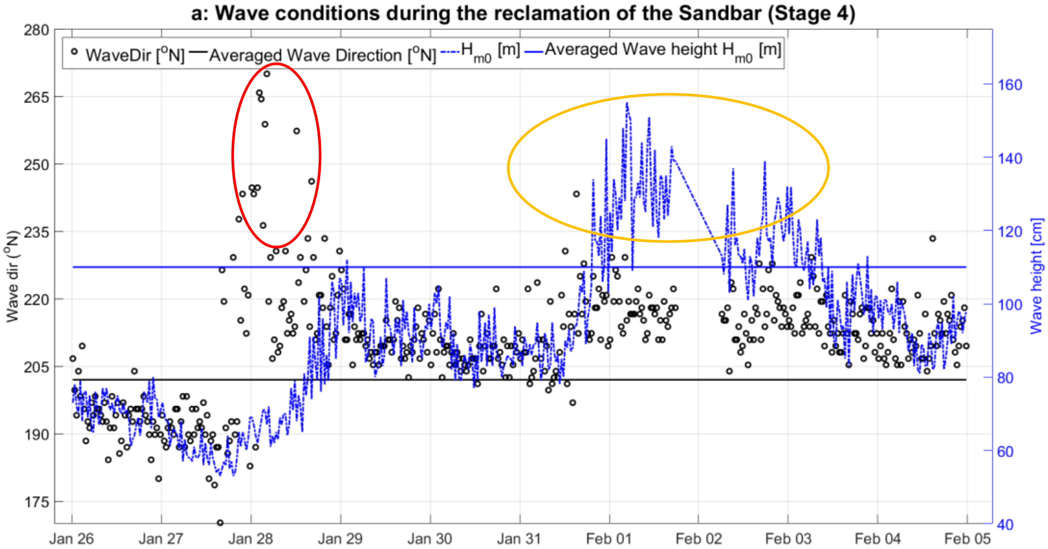
Sediment losses

In contrast to the first two stages, during the reclamation of the Sandbar (Stage 4) large morphodynamic changes were observed. As already mentioned in section 3.2.2. during the nourishments of the Sandbar a large amount of nourished sand has ended up into the Inner Lake. The sand entering the Inner Lake is a combination of nourished sand moved into the design profile (1), sand nourished directly into the Inner Lake (2) and sand naturally accumulated from the longshore sediment transport current (3). Although this separation between these three phenomena is a complex process estimations have been made estimation to split these different volumes (Boskalis, 2018). Based on this analysis the total of nourished sand which was naturally transported into the Inner Lake and which can be considered as a sediment loss is estimated to be almost 200,000 m^3.

Further zooming into the period that most sediment losses into the Inner Lake have occurred (28 Jan-2 Feb) the following conclusions can be drawn from the bathymetric surveys and the wave data.

- Based on the obtained bathymetric data, the island -which is nourished around the 28th of January sand was naturally transported both onshore and eastward towards or even into the Inner Lake which was supposed to remain 'empty' (Figure 3.2-6 and Appendix A Figure A.5-d and Figure A.6-a). This was due to natural morphodynamic processes and the fact that sand was nourished at the 'onshore side' of the design profile in the shallow regions directly into the active transport zone.
- The morphodynamic development during this period were a lot stronger than average. This is due to the strongly deviant hydrodynamic conditions in this period (and Figure a): angles up to 270° w.r.t. the North (wave direction from south-west; indicated by a red circle in Figure

3.8-a) and wave height larger than 1.5 m (indicated by a yellow circle in Figure 3.8-a). These conditions has strengthen the longshore transport current due to much more western orientated wave direction (1) and the overwash of waves (2) inducing sand transport shoreward (Chapter 2). Based on Boskalis analysis (Boskalis, 2018) the sediment losses for the period 28 Jan-02 Feb are quantified and this is compared to the average sediment loss quantity per day during the Lekki project (3100 m^3/day, Figure 3.8-b). This analysis proves that much larger sediment loss quantities than average occurred during this period. Especially during more western orientated waves direction the sediment losses are much larger (27-30 January) which is in agreement with the coastal dynamics theory explained in Chapter 2 on LST.



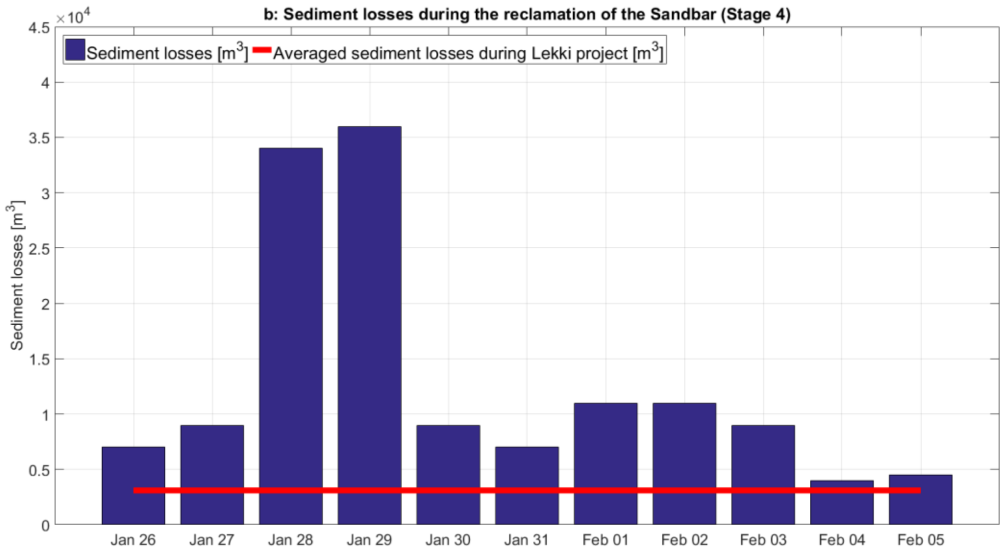


Figure 3.8: (a): Wave conditions (wave direction (ϑ) & height (Hs)) during the period 26 Jan-05 Feb as significant sediment losses occurred. The red circle shows the peak in wave direction indicating more western directed waves. The yellow circle show the peak in wave height increases the wave energy (b): Occurred total sediment losses (Inner Lake and eastside) during this period of which almost all sand ended up in the Inner Lake. The red line indicates the average daily losses during the Lekki project.

During stage 5, the further widening and heightening of the Sandbar, no significant losses have occurred anymore. This is due to the fact that the Inner Lake was 'closed' (the sandbar was connect to the westside shore of the design) and the construction of the Sandbar Groyne was completed, preventing the sand from the Sandbar to be transported to the east.

Naturally accreted sediment

During the construction of the Sandbar also a large volume of sediment from LST is accreted into the Inner Lake and after the 'closure' of the Sandbar at the sea side slope of the Sandbar during stage 4 and 5. Based on the Boskalis analysis 100,000 m^3 of sand in the Inner Lake is trapped from LST in this area (Boskalis, 2018).

3.4.3. Stage 6

The Sand Engine was built as a buffer with the objective to mitigate coastal erosion due to the blockade of the LST current. A yearly erosion rate of roughly the longshore sediment quantity was expected. However, the erosion process went much faster than expected just after the construction of the Sand Engine. Because of this strong morphological development over a relatively short period of time at the Sand Engine, this area is been used for the XBeach model testing and calibration (Chapter 5).

3.4.4. Sandbar dynamics after construction

As stated in Chapter 1, the Sandbar breakwater is highly dynamical throughout the time. This is clearly visible at a survey obtained on July 2018 several months after the completion of the Sandbar breakwater nourishments (Figure 3.9-b). In Figure 3.9-a the design of the Sandbar is shown according to the design requirements just after completion. Compared to Figure 3.9-a the natural accretion due LST which leaded to the growth of the length of the Sandbar over a relatively short period of time is clearly visible (Figure 3.9-b, yellow circle). This morphological development proves the physical concept of the Sandbar. Furthermore, in the period after the completion the width of the Sandbar is dynamic, decreasing after rough swell conditions and growing as a result of strong literal drift due to waves coming from the south-west. During the coming years the development of the Sandbar will be monitored and more knowledge on the development of the Sandbar breakwater will be gained.

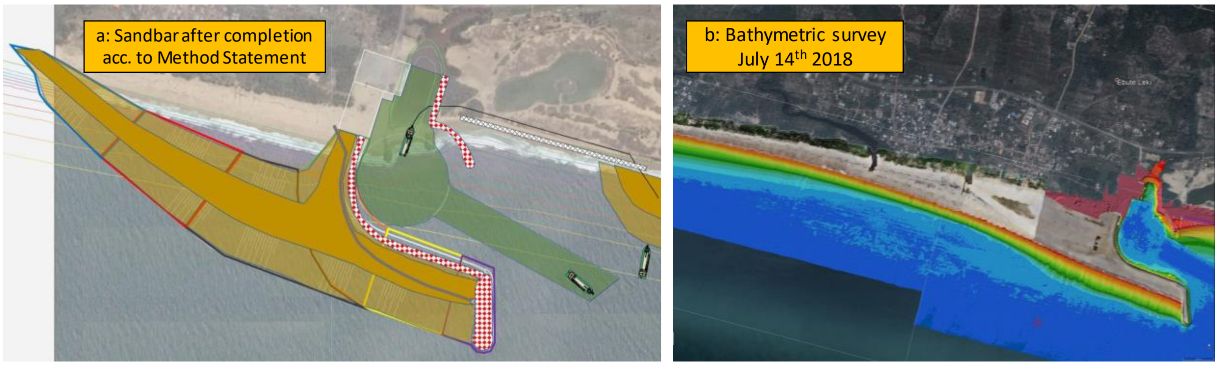


Figure 3.9: (a): Situation of the Sandbar breakwater according to the Method Statement after completion (Sand Engine excluded) (Boskalis, 2017). (b): Bathymetric survey of the Sandbar breakwater some months after completion (July 14th 2018) (Boskalis, 2018).

3.4.5. Overall sediment losses

In Svašek Hydraulics (2017) the sediment loss for a certain stage during construction of the Sandbar Breakwater is determined by means of an online coupled hydro-morphological FINEL-SWAN model. The sediment losses are investigated for calm conditions (December-February) and rough conditions (July-August). The assumptions being made are rough estimations of only one static situation of a nourished sand body at stage 2 in the project. No hard elements (rock) are present in this sand body. The results of these computations are presented in Table 3.4.

Since the sand nourishments for the Sandbar are mainly executed during the calm season with a total duration of 2.6 months the total expected sediment loss during the construction of the Sandbar breakwater (expect the Sand Engine) was estimated to be 150,000 m^3 (Table 3.4). In practise approximately 250,000 m^3 of nourished sand is lost from the design profile due to natural processes, from which the main part ended up in the Inner Lake (about 200,000 m^3). The other losses were naturally transported to the east side of the design. It can be stated that the sediment losses during the project are underestimated of about 100,000 m^3.

Table 3.4: Summary of expected and actual quantified sediment loss volumes during the construction of the Lekki Sandbar breakwater, Nigeria.

Sediment losses during construction phase Lekki project	
Expected sediment losses during calm conditions	14,000 m^3/week
Expected sediment losses during rough conditions	50,000 m^3/week
Total sediment losses	
Total expected sediment losses	150,000 m^3
Total actual sediment losses	250,000 m^3

3.5. Summary Chapter 3

Nourishments execution

In order to protect a RoRo Jetty facility which is developed at the Nigerian coast at Lekki, a Sandbar breakwater is constructed by Boskalis. This new breakwater concept mainly built out of sand (4Mm^3) is invented by CDR. The nourishment works for the construction of the Sandbar breakwater was completed in time (six construction stages in 16 weeks). The nourishments for the Sandbar were executed mainly during the hydrodynamic calm season (October - March). Only the nourishments for the Sand Engine that is constructed at the east side of the Sandbar took place in April. During this months the wave conditions are considerably stronger than in January (approximately 20 to 25% larger than in December and January).

Wave conditions

The wave conditions at Lekki coast were estimated based on SWAN analysis over the period 2005-2015. The observed wave conditions has a larger variance than the expected wave climate. During the construction period the average observed wave height (H_s) was significant lower than expected (20%), the wave period (T_p) was almost the same (2% higher) and the wave direction was 3.7° more from the (south)-west than expected. It can be concluded that the observed wave data is considerably different from the expected values especially during some short-term periods (during the reclamation of the Sandbar). This difference between the expected and the observed wave conditions can be explained by the yearly variance.

Morphodynamics

Nourished sand quantities that are lost (located/ended up outside the design profile) during the construction phase turned out to be a combination of nourished sand transported out of the design profile (1), sand nourished directly into the Inner Lake (2) and sand naturally accumulated from the longshore sediment transport current (3). The total sediment losses during the Lekki due to hydrodynamic processes project (250,000 m^3) were higher than expected (150,000 m^3). This difference can be explained by the fact that the on beforehand assumed sediment losses are very roughly estimated and the sediment loss quantities strongly depend on the actual wave conditions (mainly the wave direction). Especially during the construction of the Sandbar (Stage 4) different wave conditions occurred (larger wave heights and peak periods and more oblique directed waves from the west) resulting in about 200,000 m^3 of sand transported naturally into the Inner Lake. This natural transport is mainly caused sand by (the overwash of) waves towards the shore and the enhanced western longshore sediment transport current.

4. Development construction alternatives

In order to answer on the main research objective to assess different construction scenarios as stated in section 1.4, in this chapter three different construction alternatives apart from the Lekki construction project are developed. The total of four construction variants are later on quantitatively assessed regarding the morphological behaviour, the cost and the practicability (Chapter 6).

For the development of the different construction variants various decisions and assumptions had to be made. Therefore first specifications and assumptions of the nourishments methods, production rates and the use of resources are drawn (Section 4.1.). Next, the various elements which have been implemented in the construction variants are listed (Section 4.2.). Then, the details of construction variants regarding the construction execution, the duration and the required volumes are presented in Section 4.3.

4.1. Nourishment methods

The major task for the construction of a Sandbar breakwater is the nourishment of 4 Mm^3 of sand in the design profile. For this reclamation project different nourishment methods and equipment can be used. The assumptions, estimations, calculations and (technical) details on the different nourishment methods and equipment are detailed elaborated in Appendix B and in this section briefly summarized:

Dredging vessels details

It is assumed that for the main reclamation works two types of vessels have been used: a Trailing Suction Hopper Dredger (TSHD) type 'Shoalway' and a Cutter Suction Dredger (CSD) type '350'. More specifications and an images of the vessels are given in Appendix B.

Nourishment method details

The locations and depts to apply a certain nourishment method is based on comparable studies (Bak (2017), Hauer (1998)), experiences of the Lekki project and expert appraisal. The details are presented in Table 4.1.

Table 4.1: Nourishment method specifications: bed level to which a specific nourishment method is applicable for the Sandbar breakwater design.

Bed level to which a nourishment method is applicable	Bed level
Level to which bottom door dumping method is applicable	- 5 m
Level to which the rainbowing method is applicable	+ 1 m
Level to which the pumping ashore method is applicable	+4.5 m (design requirements)

Based on these nourishment specifications the volumes of sand nourished by a certain nourishing method have been determined for each construction variant specifics (see section 4.3.) by using volume balance calculations.

It is assumed that the dredging works will be conducted during 24 hours per day and 7 days a week during the nourishments phase which was also at the Lekki project. The production rates per week for the hoppers (TSHDs) and the cutter (CSD) for the different nourishment methods bottom door dumping, rainbowing and pumping ashore are determined data from the Lekki project and based on studies regarding sand nourishments (Bak (2017), Hauer (1998)). The production rates for dumping, rainbowing and pumping ashore for the hoppers (TSHDs) and cutter (CSD) are determined by quantifying the loading and unloading time, the sailing time to the borrow area, etc. which is obtained from the logs of the ships operating at the Lekki project. This analysis is further explained in Appendix B and summarized in the Table 4.2 below.

Table 4.2: Production rates for different discharge methods of a TSHD and a CSD used in the construction variants.

Sand nourishment method	Cycle time	Averaged production per hour	Cycles per week	Production rate
Bottom door dumping TSHD	135 minutes	1400 m^3	75	230,000 m^3/week
Rainbowing TSHD	180 minutes	1050 m^3	56	175,000 m^3/week
Pumping ashore TSHD	210 minutes	900 m^3	48	150,000 m^3/week
Pumping ashore CSD	*n/a*	1100 m^3	*n/a*	205,000 m^3/week

4.2. Concepts implemented in the construction alternatives

Considering the strong morphological development at the Sandbar, several lesson learnt from the Lekki project and new ideas are conceived. These ideas are investigated to reduce the sediment losses or to make use of the dynamics to gain naturally accreted sediment into the design profile during the construction phase. The ideas are implemented in the three construction variants and are stated in this section.

Morphodynamics

Based on the experiences of the Lekki Sandbar breakwater project and the knowledge of the coastal dynamic system it can be stated that sand placed at deeper locations further offshore is less sensitive for morphodynamic changes. It became clear that during the construction process of the Lekki Sandbar breakwater project sand which was placed sand below -5 m level hardly moved on the short-term. Therefore a larger submerged bund compared to the Lekki project is implemented in the three construction alternatives with a nourishment volume by bottom door dumping of about 1,000,000 m^3.

Based on the system analysis and the experiences of the Lekki Sandbar breakwater project, the wave conditions are very important for the quantity of sediment losses. During the calm season (October-March) when the wave energy is the lowest and no significant swell storms occur, the least sediment losses occur. Therefore it is decided that all construction variants (also the Lekki reference scenario) will start at the beginning of November, which is at the start of the relatively 'calm' hydrodynamic season.

Dredging vessels and nourishment methods

In order to investigate the impact of construction speed or progress and to assess the use of more or less dredging equipment on the total sediment losses during the project, the construction alternatives have different numbers of operating hoppers. This has also impact on the project cost which will also be assessed.

For the same reason different nourishment methods are applied such as bottom door dumping rainbowing, pumping ashore are implemented. The production rates and nourishment cost deviate for the different nourishment methods which is being assessed in Section 6.4..

From the system analysis and the experiences of the Lekki project it became clear that significant natural sand movement into the Inner Lake has occurred. At Lekki the Sandbar was reclaimed at the onshore side of the design profile which makes this nourished bund sensitive for movement into the Inner Lake. Therefore in (some) variants the impact of the reclamation of the Sandbar from the offshore side is investigated since the assumption is that this will lead to less sediment losses during the construction process. On the other hand, this means than more sand has to be pumped ashore instead of rainbowing increasing the construction cost (see 4.3).

Groynes

As observed from the Lekki project, the Sandbar Groyne is crucial for keeping the sand in the design profile. This means that the focus is first on reaching the Eastern tip of the Sandbar breakwater instead of supplementing the bund on full width in the different variants in order to minimize sediment losses.

During the Lekki Sandbar breakwater project significant natural accretion mainly caused by the longshore sediment transport flow (LST) is observed. In two construction variants it is attempted to naturally 'capture' sediment by accretion into the Sandbar breakwater profile by (a) additional groyne(s). The groynes will only have a major function during the construction execution although one groyne will become part of the Lee side Revetment (Eastern Groyne, see Variant 3, section 4.3.4.). The groynes will be covered by sand and become part of the Sandbar breakwater design.

4.3. Construction variants details

The drafted remarks and conclusions and the system analysis in section 4.2. led to three construction alternatives which are compared them to the Lekki Sandbar breakwater construction method (construction variant 0).

The different construction variants will be executed in a number of distinct phases, which are explained by text and figures in the next sections. The phases in the variants may run parallel or alter in sequence depending on the specific scenario. The first variant (0) represents a schematised execution of the constructed Lekki Sandbar breakwater. The differences between the construction alternatives (1-3) and the Lekki project (0) are listed at the start of each scenario. The three construction alternatives are explained by figures showing the construction execution, the specific production rates, the volumes for the different nourishment methods and the time planning overview. It is remarked that the figures of the different construction stages scenarios give an indication of a moment in time of a certain construction stage. The figures are followed by explanation on the execution of the construction variants.

4.3.1. Variant 0: Lekki project [reference case]

Variant 0 represents a schematized scenario of the executed construction method for the Lekki Sandbar breakwater by which the other construction variants can be compared.

The different construction stages are generalized in order to be able to simulate this construction process. The morphological modelling study is executed on how the work is executed in practice without taking into account the inaccuracies in sand nourishments. Since the stages of the Lekki project are already discussed in Chapter 3 the schematized stages of this variant is not explained here again. However, there are some difference in this variant compared to the actual Lekki project execution. The main differences are that this scenario starts in November instead of the end of December and that only two TSHDs are operating the nourishments instead of four TSHD working on different parts of the project as it was the case in the Lekki project. The total average production rate of the TSHDs during the Lekki project was almost equal to the production rate of two TSHDs type Shoalway as being operational during the entire project. More explanation and figures on this schematized variant is elaborated in Appendix A.3.

4.3.2. Variant 1: Reclamation Sandbar from west + westside Groyne

In this section the first construction alternative is described. In Table 4.3 the elements implemented in this variant which are different relative to the Lekki project (Variant 0) are summarized.

Table 4.3: Construction element of variant 1 which are different to the reference variant 0 (Lekki project).

Construction variant elements variant 1 differences relative to variant 0	Reason
Construction of a larger submerged bund	Promising idea from Lekki project analysis; quick and relatively easy construction method
Construction of a temporary groyne at Westside of the design profile	To assess the natural capturing of sediment into the design profile and investigate the financial feasibility
Sandbar reclamation from the westside of the design profile	To assess the morphological behaviour and financial cost for this construction sequence
Only 1 operational hopper for the construction of the submerged bund; for the rest of the project: 2 active hoppers	To assess the morphodynamic - and financial impact
Sandbar Road (partly) reclaimed by pumping ashore method	Practical reason: due to the reclamation of the Sandbar from the West, the Sandbar Road is more difficult to reach
Access Road Sandbar Groyne via Sandbar	Practical reason: Sandbar Road not yet reclaimed, early start of construction Sandbar Groyne required to minimize losses

The construction process for the first variant can be best described by eight different main stages. The duration of this construction variant is 16 weeks in total and 11 weeks regarding the sand nourishment for the Sandbar Breakwater.

In Figure 4.1. the stages are illustrated and in Figure 4.2-a a detailed overview of the time planning and the durations of the different stages is presented. The details of the stages are further explained in the section below the figures. The nourishment volumes for the different nourishment methods and the production rates during the stages is summarized in Figure 4.2-b,c.

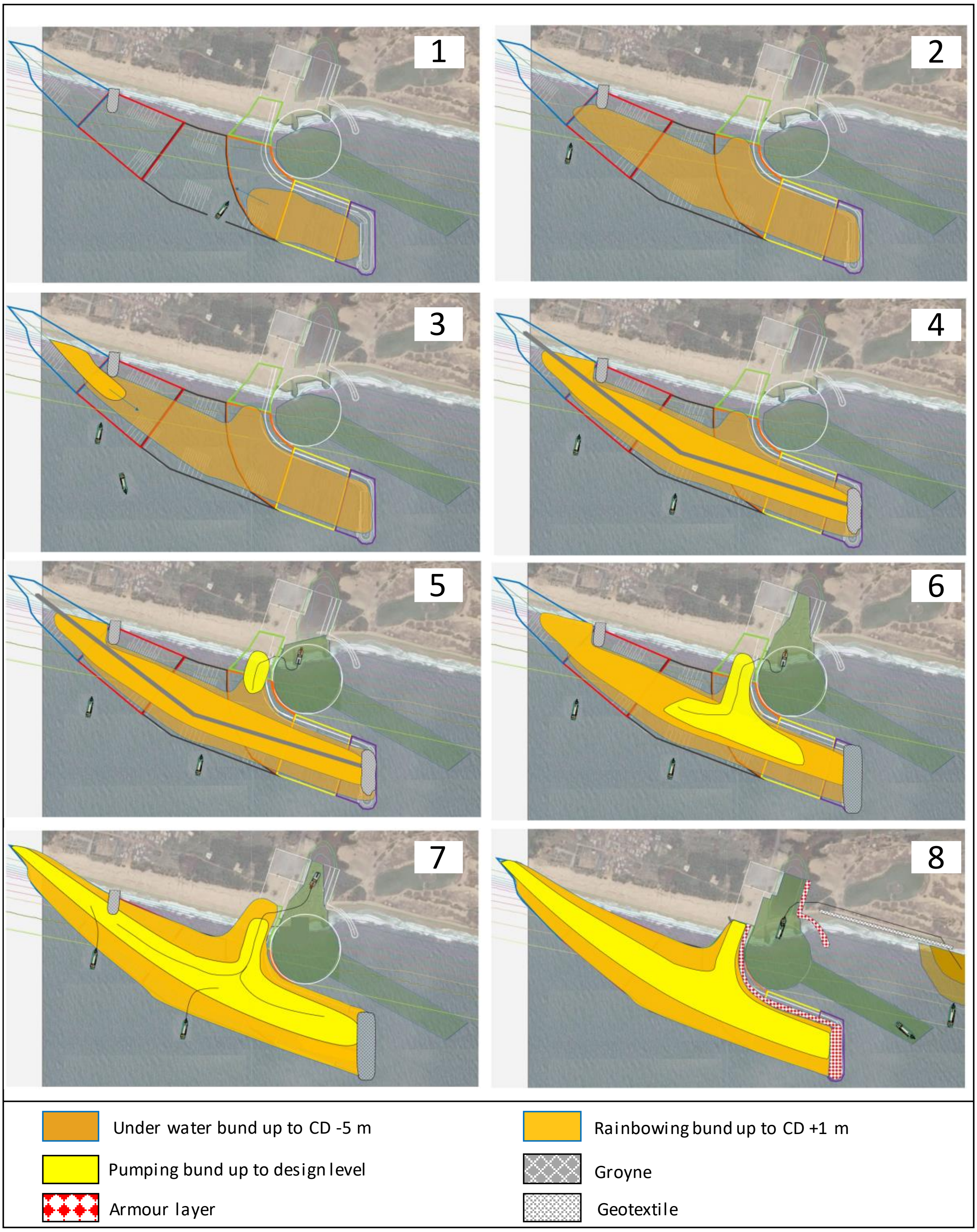


Figure 4.1: An overview of the eight stages for construction variant 1, starting with the nourishment of a submerged bund and a temporary groyne at the West side of the design profile (1,2) followed by reclamation of the Sandbar from the West (3,4). Next to that the Sandbar Road is reclaimed by a CSD (5) and subsequently the profile is further brought up to design requirements (6,7,8).

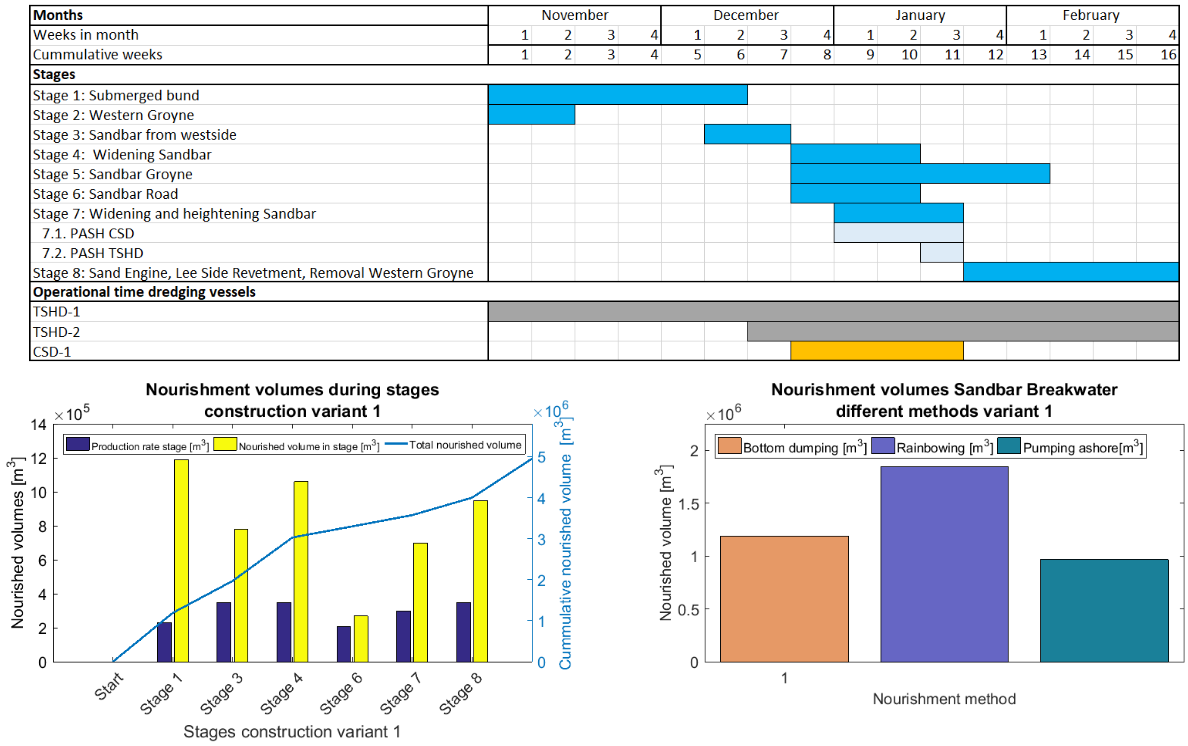


Figure 4.2: Construction variant 1 details: (a, top): Time planning of different stages in scenario (b, left): Nourishment volumes during different stages (c, right): Nourishment volumes of applied nourishment methods in scenario based on volume calculations.

Description of the construction stages variant 1

In this section the construction stages illustrated in Figure 4.1 above are further explained.

Stage 1: Submerged bund up to -5 m by bottom door dumping for full design profile

In the first stage of this scenario for all area within the Sandbar breakwater design profile below -5 m a submerged bund up to -5 m will be nourished. The nourishment of the submerged bund will start at the south-eastern part of the design profile and elaborate towards the coast which is indicated in Figure 4.1-*1,2.*

Stage 2: Construction of Western Groyne

At the same moment the nourishments of the submerged bund take place, a groyne at the West side of the Sandbar breakwater will be constructed which is specified as the 'Western Groyne' from now on. Although this groyne will lose it function over time as it will be covered by sand the groyne will not be removed since this it is a complex and expensive process and it will become part of the Sandbar breakwater design. The orientation of this groyne is perpendicular on the coast and has a length of 50 meter in cross-shore direction. The exact location and dimensions of the Western Groyne in the Sandbar breakwater design is drawn in Figure 4.1 and summarized in Table 4.4.

Table 4.4: Specifications of Western Groyne implemented in construction variant 1 (and 3).

Western Groyne specification	**Quantity**
Length	50 m
Slope	1:1.5
Toe/crest width	23/4 m
Volume	2875 m^3
Weight	8,000 ton

The construction time of the Western Groyne will take approximately 2 weeks and the start at the same moment as the nourishments for the submerged bund will commence (see Time Planning scenario 1:

Figure 4.2-a). This is a conscious construction choice: during and after the completion of the Western Groyne already sand is accumulating into the design profile. In the three weeks when the construction of the groyne is finished and the nourishments of the submerged bund are still in progress the sediment trapping process will continue. The situation after the completion of the full submerged and the Western Groyne is indicated in Figure 4.1-*2.*

Stage 3: Reclamation of Sandbar from the west side

After finishing the submerged bund and the Western Groyne the sand nourishments will continue starting from the coast in the utmost west side of the Sandbar breakwater profile just at the west side of the Western Groyne visible in Figure 4.1. The rainbowing nourishments will be expanded to the East, 'filling' the Sandbar profile up to +1 m. Since the losses are expected to be much higher than for the submerged bund, this project stage is executed by two TSHDs so the production rates increases.

This process will continue up to the utmost south-eastern tip of the sandbar design profile. The rainbowing of sand up to -1 m from the west to south-east tip of the Sandbar will first not be applied over the full width of the design profile which is visualized in Figure 4.1-*3,4.*

Stage 4: Further widening Sandbar

The further widening up to design requirement will be executed as soon as the south-east tip is reached and the construction of the Sandbar Groyne can be started (see stage 5). This will be done by two TSHDs rainbowing the profile up to +1 m which is illustrated Figure 4.1-*7.* The further widening of the Sandbar will executed from the east side, in order to maximize the accretion of sand volume into the Sandbar breakwater profile from the LTS at the westside of the design profile.

Stage 5: Construction of Sandbar Groyne

Once the Sandbar tip can be reached from land, a temporary access road from the westside is developed in order to be able to reach the Sandbar tip with the necessary materials for the construction of the Sandbar Groyne (Figure 4.1-*4*). The Sandbar Groyne has the same dimensions as in the Lekki project.

Stage 6: Reclamation of Sandbar Road from Turning Basin

A CSD will be used in this stage of the project for two aspects: firstly for the connection of the Sandbar constructed from the West to the coast which is indicated as the Sandbar Road and secondly the further heightening of the Sandbar by pumping sand ashore (see stage 7). The reclamation of the Sandbar Road up to +1 m will start right after the reclamation of the small Sandbar bund (stage 3) and thus will take place simultaneously with stage 4. The CSD will dredge sand from the Turning Basin and the Access Channel deepening this area and to reach the quay wall according to the design.

Stage 7: Further widening and heightening up to design requirements

After stage 6 the CSD will continue with pumping sand ashore to the Sandbar design profile areas where the rainbowing method is no longer applicable. This will start from the Sandbar Road and will elaborated in two directions: west and east side of the Sandbar (see Figure 4.1-*6*). The maximal volume of sand which is available from the Turning Basin and the Access Channel is 700,000 m^3. The remaining 300,000 m^3 of the total volume of sand which must be pumped ashore in this scenario is discharged by the two operating TSHDs once these vessels are finished with their rainbowing activities in stage 4.

Stage 8: Reclamation of the Sand Engine and construction of North Groyne and Leeside Revetment Sandbar breakwater

The last phase is the same as the last stage of the Lekki project (Variant 0) the reclamation of the Sand Engine at the east side of the Sandbar breakwater, the construction of North Groyne and the Leeside

Revetment. After the completion of this stage the construction of the Sandbar breakwater for this construction variant is fully completed. An illustration of the situation after the completion of this last stage is given in Figure 4.1-*8.*

4.3.3. Variant 2: Offshore side reclamations Sandbar design; Sandbar reclamations from two sides (east and west)

In this section the second construction alternative is described. In Table 4.3 the elements implemented in this variant which are different relative to the Lekki project (Variant 0) are summarized.

Table 4.5: Construction element of variant 2 which are different to the reference variant 0 (Lekki project).

Construction variant elements variant 2 differences relative to variant 0	**Reason**
Construction of a larger submerged bund	Promising idea from Lekki project analysis; quick and relatively easy construction method
Sandbar reclamation from two sides: west- and east side of the design profile	To assess the morphodynamic behaviour and financial cost for this construction sequence
Western Sandbar reclamation from the offshore side of the design profile	To assess the morphodynamic behaviour and financial cost for this construction sequence

The construction process for the second variant is described by six main stages. The total duration of this variant is 17 weeks and 12 weeks regarding the sand nourishments.

In Figure 4.3. (next page) the stages are illustrated and in Figure 4.4-a a detailed overview of the time planning and the durations of the different stages is presented. The details of the stages are further explained in the section below the figures. The nourishment volumes for the different nourishment methods and the production rates during the stages is summarized in Figure 4.4-b,c.

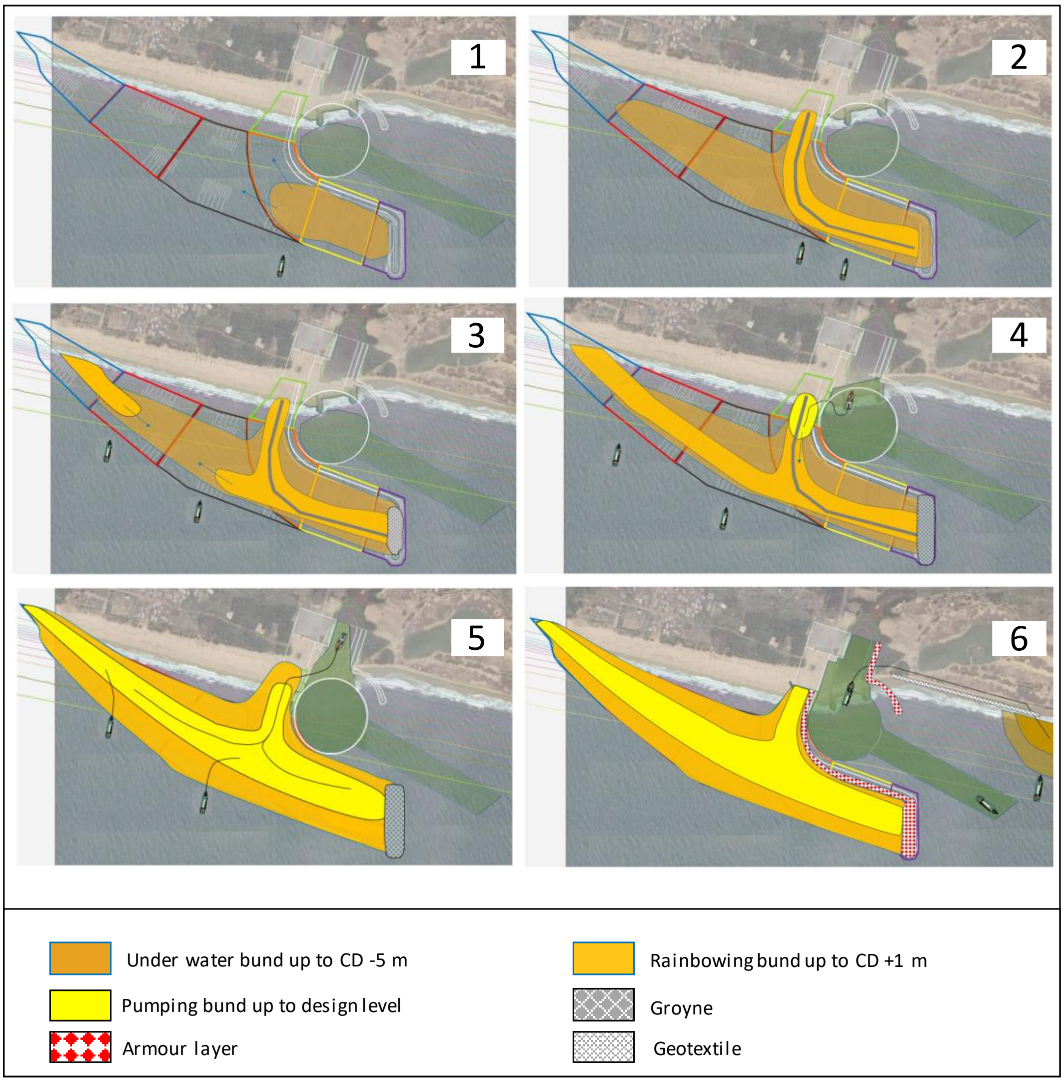


Figure 4.3: An overview of the six stages for construction variant 2, starting with the nourishment of a submerged bund and an the reclamation of the Sandbar Road followed by the 'offshore expansion' of the Sandbar from the East (3,4). Next to that the Sandbar Road is further heightened by a CSD (4) and subsequently the entire profile is further brought up to design requirements (5,6).

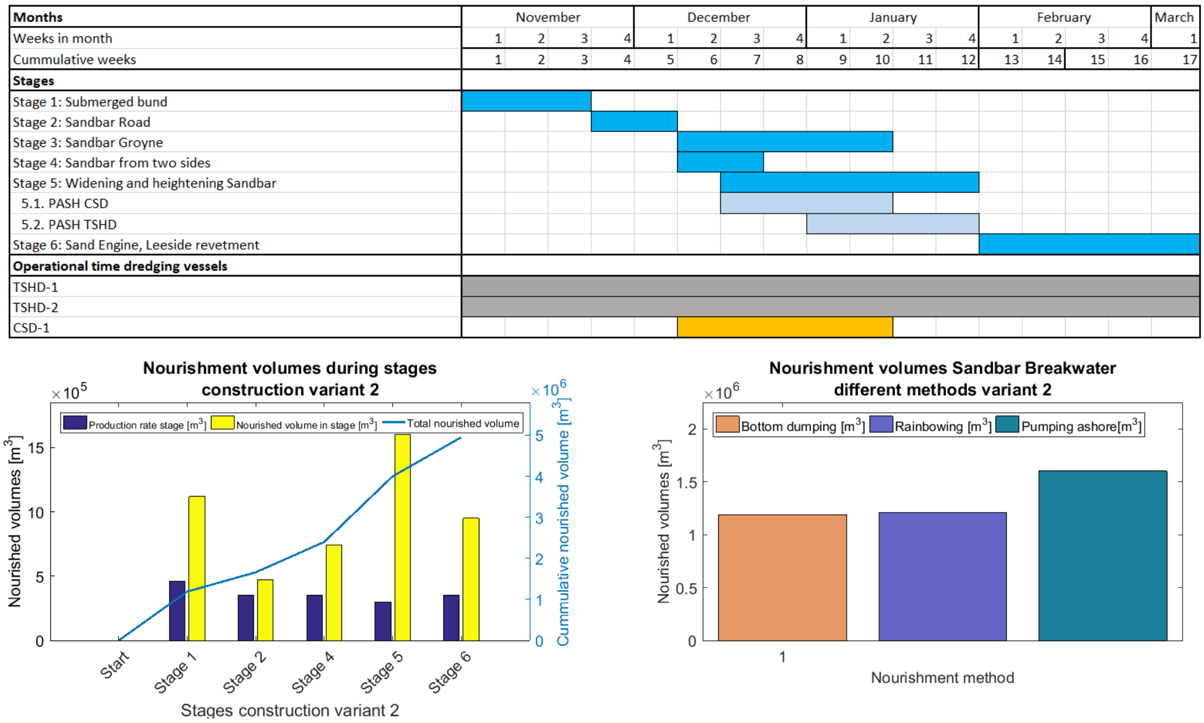


Figure 4.4: Construction variant 2 details: (a, top): Time planning of different stages in scenario (b): Nourishment volumes during different stages (c): Nourishment volumes of applied nourishment methods in scenario based on volume calculations.

Description of the construction stages variant 2

In this section the construction stages illustrated in Figure 4.1 above are further explained.

Stage 1: Submerged bund up to -5 m by bottom door dumping for full design profile

The first stage of this scenario is executed almost identical to the first stage of variant 1: all area within the Sandbar breakwater design profile below -5 m is nourished up to -5 m. The only difference compared to stage 1 of scenario 1 is the used dredging equipment. In this stage two TSHDs will be executing the submerged bund nourishments instead of only one TSHD in stage 1 scenario 1 illustrated in Figure 4.3-*1,2.*

Stage 2: Reclamation of Sandbar Road

After the completion of stage 1, the reclamation of the Sandbar Road will commence. Two TSHDs will nourish a bund in the offshore direction by applying the discharge method rainbowing. This process will continue to the south eastern tip of the Sandbar Road. The bund expansion is not applied over the full width of the Sandbar design profile as horizontal progress is preferred to access the Sandbar Groyne.

Stage 3: Construction of the Sandbar Groyne

As soon as the Sandbar Groyne is been accessed from land an access road will be created to start the construction of the Sandbar Groyne.

Stage 4: Reclamation of Sandbar from west- and east side

The next step in this scenario is to reclaim the Sandbar by reclamations from two sides: both the Sandbar Road 'offshore side' and from the west coast side expanding to the East (Figure 4.3-*3*). This will also be done by two TSHDs. The inner-lake will be 'closed' somewhere at the middle of the Sandbar Breakwater (Figure 4.3-*3,4*).

Stage 5: Further widening and heightening up to design requirements

During the reclamation of the Sandbar with the two TSHDs by discharging sand by rainbowing, a CSD, starts dredge the Turning Basin and the Access Channel. The sand will be pumped ashore to heighten the Sandbar Road up to the design level. The CSD will start to deepen an area at the east side of the Turning Basin to make this area accessible for the TSHDs to be able to reclaim the leeside of the Sandbar. The CSD will pump 700,000 m^3 sand ashore from the Turning Basin and the Access Channel. The total volume to heighten and widen the Sandbar and Sandbar Road is 1,670,000 m^3. So 970,000 m^3 of sand will be pumped ashore by the two operating TSHDs which will finally results in the situation drawn in Figure 4.3-*5*.

Stage 6: Reclamation of the Sand Engine and construction of lee side revetment Sandbar breakwater

The last phase for this scenario is the same as stage 6 of the Lekki project having a duration of 5 weeks. An illustration of the situation after the completion of stage 6 is given in Figure 4.3.

4.3.4. Variant 3: Offshore island + Western & Eastern Groyne

In this section the third construction alternative is described. In Table 4.6. the elements implemented in this variant which are different relative to the Lekki project (Variant 0) are summarized.

Table 4.6: Construction element of variant 3 which are different to the reference variant 0 (Lekki project).

Construction variant elements variant 3 differences relative to variant 0	Reason
Construction of a larger submerged bund	Promising idea from Lekki project analysis; quick and relatively easy construction method.
Construction of two temporary groynes: at west- and east side of the design profile	To assess the natural capturing of sediment by two groynes located close to each other and investigate the financial feasibility.
Start of the reclamation of the Sandbar Road by an offshore island, working towards the coast	To assess the morphodynamic behaviour and financial cost for this construction sequence.
Sandbar reclamation from the offshore side of the design profile	To assess the morphodynamic behaviour and financial cost for this construction sequence.
Three hoppers operational during entire project	To assess the morphodynamic- and financial impact.

The construction process for the second variant is described by eight main stages. The total duration of this variant is 12 weeks and 8 weeks regarding the sand nourishments.

In Figure 4.5. the stages are illustrated and in Figure 4.6-a. a detailed overview of the time planning and the durations of the different stages is presented. The details of the stages are further explained in the section below the figures. The nourishment volumes for the different nourishment methods and the production rates during the stages is summarized in Figure 4.6-b,c.

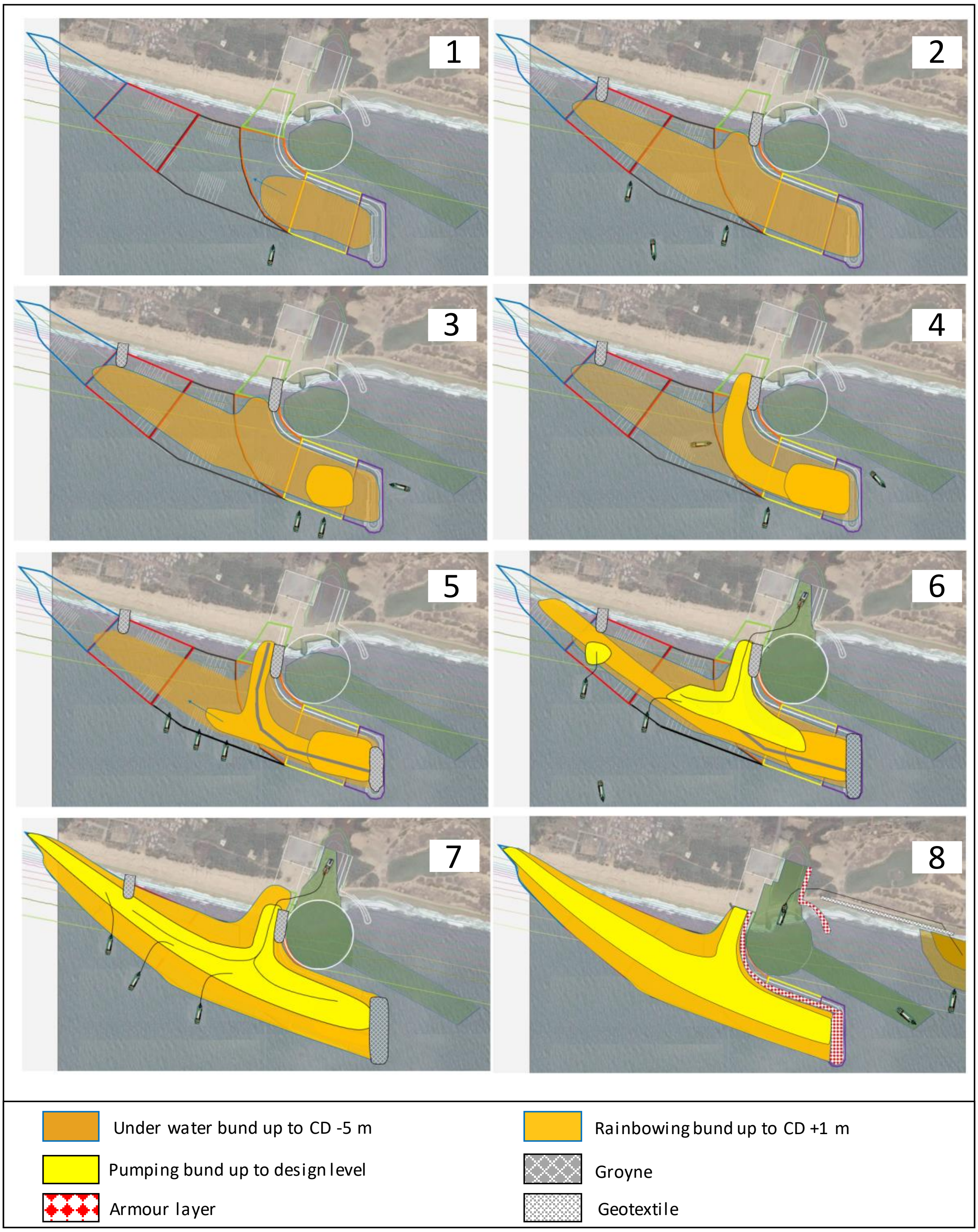


Figure 4.5: An overview of the eight stages for construction variant 3, starting with the nourishment of a submerged bund and the construction of two groynes (1,2) followed by the reclamation of an offshore island (3). Next to that the Sandbar Road is reclaimed by the TSHDs (4) and subsequently the profile is further brought up to design requirements (6,7,8).

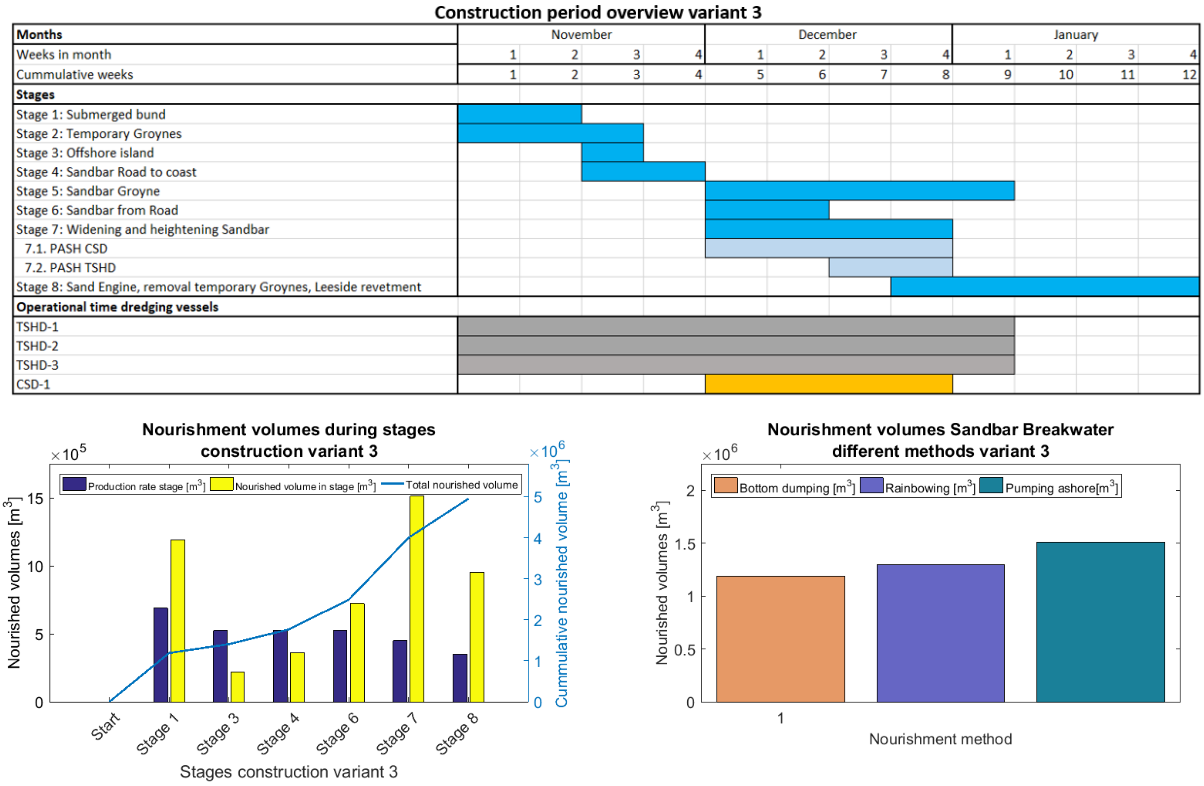


Figure 4.6: Construction variant 3 details: (a, top): Time planning of different stages in scenario (b, left): Nourishment volumes during different stages (c, right): Nourishment volumes of applied nourishment methods in scenario based on volume calculations.

Description of the construction stages variant 3

In this section the construction stages illustrated in Figure 4.5. above are further explained.

Stage 1: Submerged bund up to -5 m by bottom door dumping for full design profile

The first stage of this scenario is executed almost identical to the first stage of variant 1. The only difference is the use of three TSHDs for the reclamation of the submerged plateau (Figure 4.5-*1,2*).

Stage 2: Construction of Western and Eastern Groynes

At the same moment the nourishments for the submerged bund take place, the construction of two groynes will commence. At the west and east onshore side of the design profile two short groynes will be built. The choice to implement the two groynes in this construction scenario is that in this variant the nourishments starting offshore. During the offshore nourishments longshore sediment transport will accumulate against the westside of the groyne which is part of the design profile. The period that sediment can be trapped behind the breakwaters is the longest in this variant compared to the other alternatives.

The groyne at the west side of the Sandbar breakwater design is called the 'Western Groyne' and has the same specifications as stage 2 in scenario 1. The groyne at the east side of the design is named as the 'Eastern Groyne'. The orientation of this groyne is perpendicular on the coast and has a bit larger length than the Western Groyne which is 75 meter in cross-shore direction. The other specifications and materials used for the construction of this groyne are the same as the Western Groynes which is already described in scenario 1. The choice to implement the Eastern Groyne with a larger length than the Western Groyne is twofold: the design profile at this location is for a longer distance directed in cross-shore direction and secondly this Eastern Groyne will not be removed as it becomes a part of the Leeside Revetment (see stage 8). The exact location and dimensions of the Western and Eastern

Groyne in the Sandbar breakwater design is drawn in Figure 4.5-*2* and summarized in Table 4.4 and Table 4.7.. Based on the dimensions the required volumes and weights have been determined.

Table 4.7: Specifications of the Eastern Groyne implemented in construction variant 3.

Eastern Groyne specification	Quantity
Length	75 m
Slope	1:1.5
Toe/crest width	25 m / 4 m
Volume	5050 m^3
Density	2650 kg/m^3
Weight	13,000 ton

The construction time of the groynes will take approximately almost 3 weeks which will start at the same time as stage 1. The situation after the completion of stage 1 (submerged sand plateau) and stage 2 (groynes) is indicated in Figure 4.5-*2.*

Stage 3: Reclamation of offshore island

The next step in this construction scenario is the reclamation of an offshore island (south-east of Sandbar breakwater profile, close to the location where the 'Sandbar Groyne' will be constructed) up to +1 m by applied by three TSHDs discharging the load by rainbowing (Figure 4.5-*3*).

Stage 4: Reclamation of Sandbar Road from the offshore island towards the coast

From this offshore island, land will be reclaimed towards the coast via the Sandbar Road in the design profile and to the end of 'Sandbar Road' using the same equipment and nourishment methods.

Stage 5: Construction of Sandbar Groyne

After stage 4, the tip of the Sandbar Road is accessible from land and thus the construction of the Sandbar Groyne can be started in order to prevent sediment from eroding/bypassing from the design profile.

Stage 6: Reclamation of Sandbar in western direction offshore side design profile

The next step in this scenario is to reclaim the Sandbar by nourishing it from the 'offshore side of the design profile' from the Sandbar Road, which is the same concept as in stage 5 in scenario 2. The three TSHDs will nourish a small offshore sandbar bund up to +1 m, see Figure 4.5-*5.*

Stage 7: Further widening and heightening up to design requirements

During the reclamation of the Sandbar by the TSHDs a CSD will start with the dredging of the Turning Basin and the Access Channel to raise the bottom level in the design profile up to +4.5 m (Figure 4.5-*6,7*). The total volume to heighten and widen the Sandbar and Sandbar Road up to the required height is 1,700,000 m^3 from which 700,000 m^3 is dredged by the CSD. The other 1,000,000 m^3 of sand is required to be pumped ashore by the three operating TSHDs which will finally results in the situation drawn in Figure 4.5-*7.*

Stage 8: Reclamation of the Sand Engine and construction of Leeside Revetment Sandbar breakwater

In the last stage the reclamation of the Sand Engine and the construction of the Leeside Revetment is executed. After the completion of this stage the construction of the Sandbar breakwater is fully completed (Figure 4.5-*8*).

4.4. Summary construction variants details

In this section the differences between the developed construction alternatives and the reference case (Lekki project) are summarized. Multiple different construction methods, sequences and materials have been implemented in in the variants. The aim of the construction variants is to investigate the impact of the construction speed and sequence as well as to which extent sand can be naturally accreted by hard structures ('additional' groynes) into the design profile. Therefore are in the variants different numbers of operational vessels (variation between 2-4) implemented as well as additional groynes in the Sandbar breakwater design (none additional groynes, 1 or 2 groynes). In Table 4.8. a comparison regarding the dredging equipment, production rates, construction duration and other construction variant specifics are given.

Table 4.8: Overview of the different aspects of the construction variants regarding dredging equipment, nourishment methods and sequences, durations, production rates and other construction component details.

Construction variant	**Variant 0 [Reference variant]**	**Variant 1**	**Variant 2**	**Variant 3**
Dredging vessels operational in construction variants				
Hopper dredger (TSHD)	4 TSHDs operational part of the project*	2 TSHDs operational entire project	2 TSHDs operational entire project	3 TSHDs operational entire project
Cutter dredger (CSD)	1 CSD	1 CSD	1 CSD	1 CSD
Reclamation volumes and production rates construction variants				
Volume discharged by bottom door dumping	550,000 m^3	1,190,000 m^3	1,190,000 m^3	1,190,000 m^3
Volume discharged by rainbowing	2,350,000 m^3	1,845,000 m^3	1,210,000 m^3	1,298,000 m^3
Volume discharged by pumping ashore	1,100,000 m^3	965,000 m^3	1,600,000 m^3	1,512,000 m^3
Minimum production rate	300,000 m^3	230,000 m^3	300,000 m^3	450,000 m^3
Maximum production rate	460,000 m^3	350,000 m^3	460,000 m^3	690,000 m^3
Construction specifics of construction variants				
Sandbar Road reclamation	From the coast towards south—east tip of design	From the Sandbar towards the coast	From the coast towards south—east tip of design	From offshore island towards the coast
Sandbar reclamation	From Sandbar Road starting at the leeside of design	From the west side of design	From Sandbar Road and the west starting at the seaside of design	From Sandbar Road and the west starting at the seaside of design
Construction of additional groynes	None	Western Groyne	None	Western Groyne, Eastern Groyne
Duration of construction variants				
Durations variant	15 weeks	16 weeks	17 weeks	12 weeks
Duration sand reclamation works	11 weeks	11 weeks	12 weeks	8 weeks

* *The total average production rate of the four TSHDs which were all not operational during the entire Lekki project is almost equal to the maximum production rate of two TSHDs type Shoalway as being operational during the entire project. Therefore, a production rate comparable to two TSHD type Shoalway is assumed. For the (mobilisation) cost four TSHDs has been retained.*

5. Model performance analysis

In order to be able to assess the morphodynamic behaviour of different construction variants for the Sandbar breakwater the morphodynamic model XBeach (Roelvink et al., 2015) has been used. For the design of the Sandbar breakwater already a XBeach model was set-up and therefore this existing model is used for this research. For more explanation on this model we refer the reader to Wilbrink (2018).

5.1. Modelling analysis method approach

This XBeach model set-up by CDR was first meant to assess the morphological development of the Sandbar breakwater after completion (CDR International, 2017) and is also used for this study. It is a 2D XBeach model which is used in stationary mode. In the stationary model the wave-averaged equations are solved efficiently. Infra-gravity waves are neglected. A wave group (such as infra-gravity waves) which consists out of different wave components with different wave lengths and frequencies, can not implemented in the stationary mode, since in stationary mode solitary waves enter the domain (Roelvink et al., 2015). This mode is mainly used for moderate, uniform wave conditions and since this is the case in the study area, this mode is selected. The model has a variable rectangular grid (dx=2-20 m, dy = 10-50 m, with a total of 228 x 307 grid cells), with smaller grid cells in the zone of interest. The hard part of the breakwater, the Sandbar Groyne is included in the model as hard structures (non-erodible layers).

Before the assessment of the construction variants by executing a modelling study, the performance of the model in the dynamical coastal system at Lekki is investigated. This is useful for to gain knowledge on the performance of the XBeach application in the area of interest as well as the know the reliability of the morphological simulations.

The model performance study consists of a sensitivity analysis for non-calibration parameters (named as the 'General model analysis') and calibration parameters which is carried out by a calibration analysis.

The general model analysis is executed to verify in which extent the physical processes and characteristics for in the Lekki system are represented by the XBeach model. In addition, the analysis contributes to further model optimisation regarding simulation time. For this general model analysis the following parameters are assessed:

- Grain size of sediment (D_{50} and D_{90})
- Wave roller effect (roller=1 (switched on), roller=0 (switched off)
- Modelling Morphological Modelling Factor (MorFac)
- Moment that model morphodynamic computations start which is called the spin-up time of the model (Morstart)

The sensitivity analysis is useful to check whether certain parameters have impact on the reliability of the model which can be later on used for the calibration analysis. For this sensitivity analysis seven calibration parameters have been assessed which are specified (see section 5.4 and Appendix C.6) After the optimised and calibrated model, the morphodynamic behaviour study of the construction variants can be carried out (Chapter 6).

In this Chapter a summary of these analysis is given consisting of a description of the case which is used for the calibration process as well as the results for the assessment of different (non-)calibration parameters. The detailed description of the model, the methodology of the analyses as well as the applied boundary conditions and more explanation on the evaluation area and period is presented in Appendix C.

5.2. Evaluation area, period and criteria model performance analysis

5.2.1. Evaluation area and period

In order to execute the model performance study with the XBeach model first an suitable calibration case is deliberately selected. Just after the completion of the construction of the Sandbar breakwater, strong dynamical development at the Sand Engine (east side of the Sandbar) was observed. After 13 April 2018 when the reclamation works at the Sand Engine were completed erosion of sand to the east was clearly visible. On account of that, the Sand Engine is selected as location for the model performance. The bathymetry and a cross-section through the Sand Engine at the start and the end of the evaluation period is presented in Figure 5.2.

Due to this strong morphological development and the and lack of more data at the start of the model performance analysis, it was decided that for the model performance analysis a period of 20 days would be investigated (13th of April-3rd of May 2018).

The bathymetry of the survey of 13th of April is used as initial bed level in the model (Figure 5.1). The Sand Engine evaluation area is indicated by a red polygon.

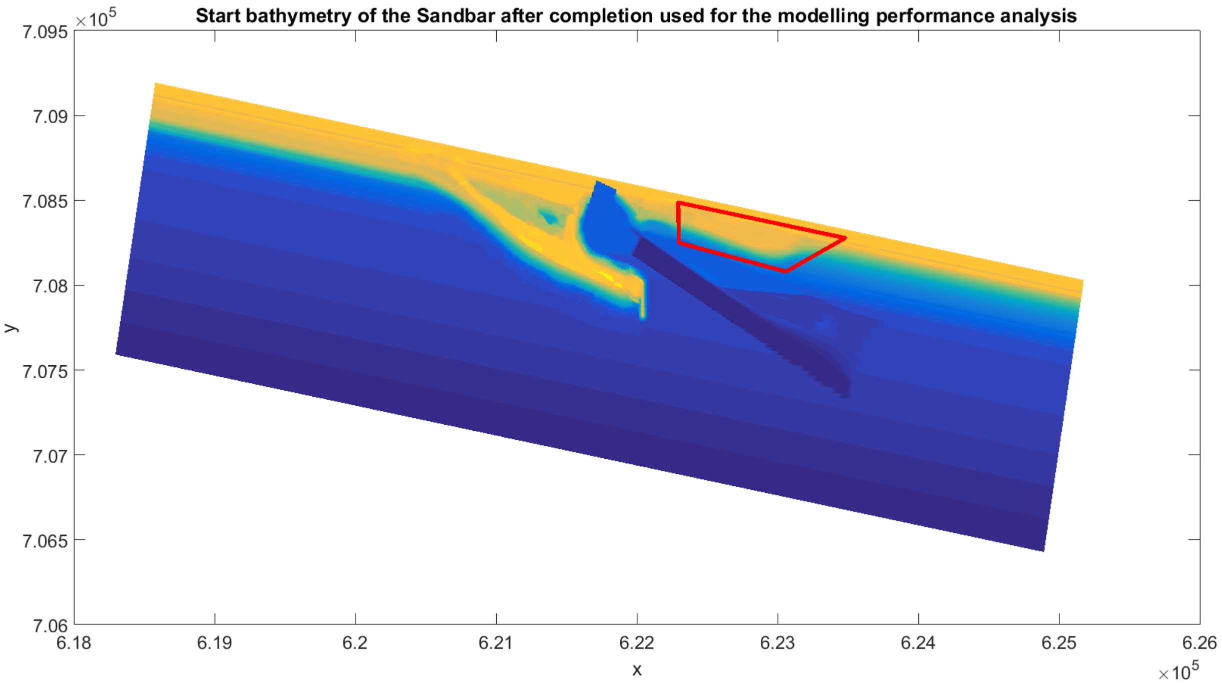


Figure 5.1: The situation of the Sandbar and Sand Engine after the completion of the Sandbar. The Sand Engine is located eastwards of the Sandbar breakwater, which is indicated by a red polygon. This area is used for the model performance study.

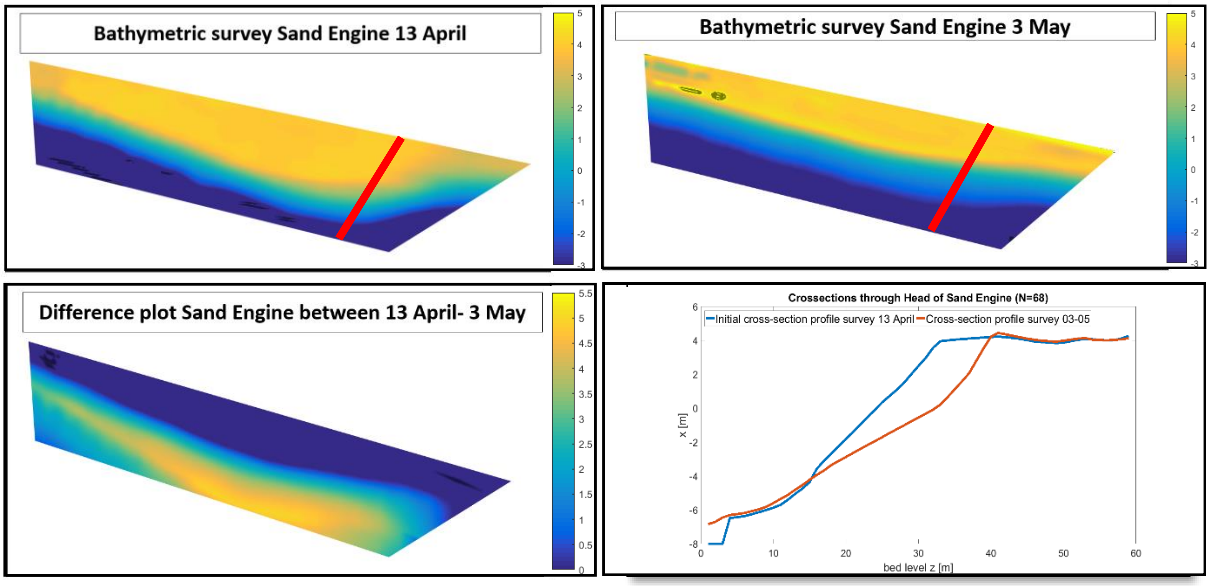


Figure 5.2: (a, top left): Top view of bathymetry survey of the Sand Engine at 13 April 2018 (b, top right): Bathymetric survey of Sand Engine at 3 May 2018 (c, bottom left): Difference plot between start and end of calibration period (d, bottom right): A cross-section through the head of the Sand Engine (located at the Sand Engine at the red line indicated in figure a, b) at start and end of calibration period (20 days, 13 April-03 May).

5.2.2. Evaluation criteria model performance analysis

The model simulations will be evaluated is based on the following criteria:

- The coastal retreat at MSL [m] as a first indicator;
- The volume changes (erosion and accretion) in the Sand Engine profile [m^3] to assess the morphodynamic performance of the simulations;
- The agreement of the bed level changes using the Brier Skill Score method [-] (Bosboom et al., 2014a). This is a score between 0 and 1: perfect agreement gives a skill score of 1 and lower scores indicate worse modelling results and in case the model simulation result is exactly the initial bathymetry the BSS gives the value 0;

The first indication is only used to check whether the results are reliable at the first sight. This is done by visualizing the bathymetric bed level output to check whether instabilities or unrealistic phenomenon have occurred. The second and third assessment criteria are quantitatively determined and are further explained in Appendix C.

5.3. Results general model performance analysis

The general model analysis is executed for the non-calibration parameters grain size, wave dissipation in the coastal system (roller equation), the morphological acceleration factor (MorFac) and the spin-up time. An overview of the general model analysis parameters, the aim of the analysis and the results of the model settings (which are used for further model analysis) are presented in Table 5.1.

Table 5.1: Overview of analysed parameters for the general model performance analysis.

Description parameter	Analysis aim	Assessment tools	Value in the model, resulting from model analysis
Grainsize of sand nourishments	To check to have correct D_{50} and D_{90} in the model	- Sieve analysis - Expert appraisal	**D_{50} = 600 μm** **D_{90} = 1,100 μm**
Roller model	Impact of roller model on model simulations compared to surveys	-Volume balance -Brier Skill Score	**Roller = 0**
Morphological Acceleration Factor	Speeding up simulation time without significant inaccuracies	-Volume balance -Brier Skill Score	**MorFac = 10**
Spin-up time	Speeding up simulation time without significant inaccuracies	-Volume balance -Brier Skill Score	**Morstart = 259,200 seconds (3 days)**

From the general model performance analysis it is decided to switch off the roller equation. This alteration improves the representation of the conditions in the coastal system. In addition, the best settings for the grain size, MorFac and spin-up time are determined. However, the impact in variation of these non-calibration parameters appeared to be low (Appendix C.5).

5.4. Sensitivity analysis

Since XBeach is developed for 1-D modelling of beach erosion during storm conditions and the calibration parameters are calibrated for a specific coastal system (such as the Dutch coast) the question is which calibration parameters settings are best suitable for model simulations in the Lekki coastal system, which has different characteristic than the Dutch system. The default settings do not necessarily result in the best performance of the model of the Sandbar breakwater at Lekki, Nigeria. Therefore a sensitivity analysis has been carried out to identify and understand constrains of the model application which forms the basis for model improvement (calibration process). According to Van Geer et al. (2015) and other calibration studies (Vousdoukas et al., 2014) seven specific XBeach parameters are important calibration settings. Vousdoukas et al. (2014) used these parameters for a calibration study for a coastal system in Portugal with comparable coastal characteristics reflective beaches, moderately well sorted sands). The role of these parameters in the model is described in Appendix C (Table C.10. These parameters are assessed on their sensitivity. The settings of the parameters used for the sensitivity analysis, their default setting and the simulated test settings are presented in Table 5.2.

Table 5.2: Overview of parameters analyzed in sensitivity study

Keyword	Default setting	Tested settings	Relative to default setting	Deviation from default (%)
facuA	0.1	**0.05** **0.15**	0.05	50.0
wetslp	0.3	**0.25** **0.35**	0.05	16.7
lws	1	**lws= 0**	-	-
wci	0	**wci=1**	-	-
alpha	1	**0.8** **1.2**	0.2	20.0
gamma	0.55	**0.4** **0.9**	0.15	27.3
gammax	2	**1.7** **2.3**	0.3	15.0

The results of the model sensitivity analysis regarding the erosion rate (volume flux from the Sand Engine) and the cross-shore development (Brier Skill Score) is presented in Figure 5.3, where the deviation relative to the reference simulation (default calibration parameter settings). More detailed quantitative results and figures of cross-sectional development are presented in Appendix C.6.2. From the sensitivity analysis several conclusions can be drawn:

- Unless the range in the tested calibration parameters is relatively large compared to other XBeach calibration processes, the improvement in the predictability of the simulated erosion from the Sand Engine is very significant. The parameters facuA, alpha and gamma appear to be the most sensitive parameters.
- Furthermore, a pattern is observed: as a specific calibration parameter scored better on the prediction of the beach profile (BSS criteria), it scored worse on the prediction of the erosion rate (volume flux criteria). Based on the one criteria it may concluded that the model performance is improved while this is not the case for other one. From this analysis it can be stated that no optimal simulation would be found for both criteria, which is useful for the calibration process (see section 5.5).
- From the cross-sectional assessment (Figure C.4.) it can be stated that the sensitivity to the varying calibration parameters appeared to increase with an increasing beach slope.

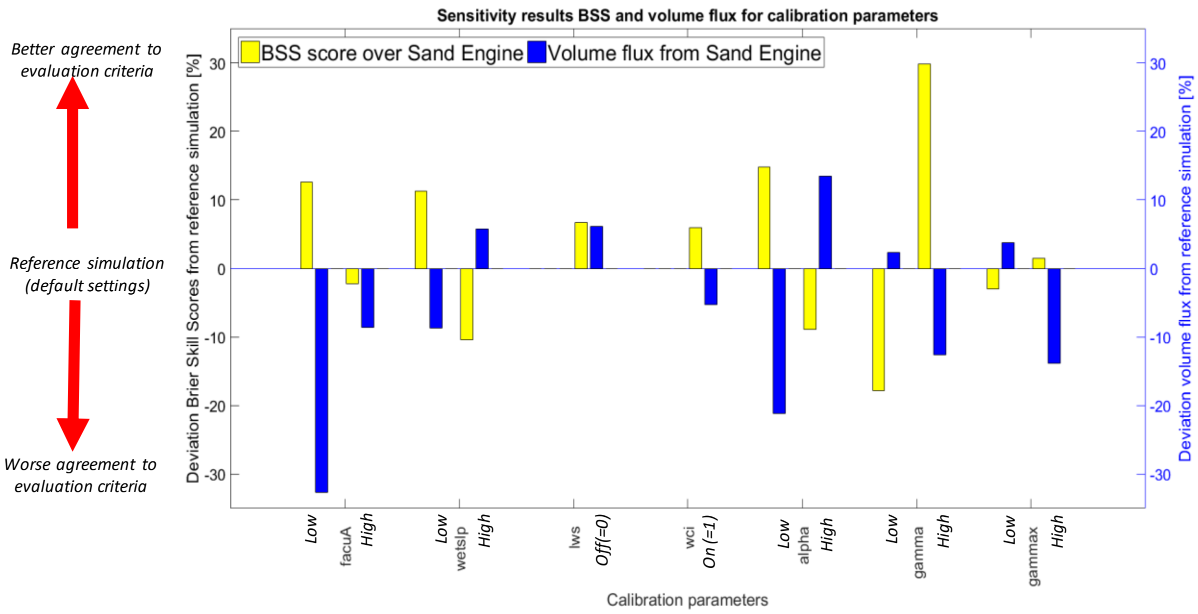


Figure 5.3: Results of the sensitivity analysis for the 7 investigated XBeach calibration parameters facuA, wetslp, lws, wci, alpha, gamma, gammax with decreased (indicated by 'Low' in the figure) and increased values (indicated by 'High' in the or on (0)/off (1) compared to the default setting. The results are presented relative to the reference model simulation: the deviation from the default simulation is indicated in terms of the evaluation criteria (1): the Brier Skill Scores (BSS) and (2): the volume balances method (erosion from Sand Engine). Negative values indicate worse results (deterioration of the result for that criteria) and positive values indicate better results (improvement for that criteria) than the reference simulation.

5.5. Calibration analysis

The final step in the model performance analysis is the execution of a calibration process in order to optimize the XBeach model for the area of interest. The aim of the calibration analysis is to find settings which score 'good' for the volume balance method as well as the Brier Skill score method.

For the calibration process various model simulations have been performed based on the information obtained from the sensitivity analysis. Results of the calibration process show that none of the reference or optimised models gave a (near) perfect prediction. After the assessment of various calibration simulations, the model simulation which scored the best regarding both criteria is selected.

The results for the best calibration run regarding the net volume flux (erosion) and Brier Skill Score for the Sand Engine are presented in Table 5.3 and compared to the actual bathymetric survey data of the Sand Engine.

Table 5.3: Results for the erosion rate and the Brier Skill Score for the Sand Engine from the bathymetric survey data after the general model analysis.

	Erosion from Sand Engine [m^3]	BSS [-]
Calibrated model simulation	**145,000 m^3**	**0.51**
Actual bathymetric survey data	210,000 m^3	1
Difference between surveys and model simulation	65,000 m^3	0.49

The calibration resulted in a better prediction of the erosion flux from the Sand Engine of 10,000 m^3 (135,000 m^3 for reference default run compared to 145,000 m^3 after calibration). The Brier Skill comes down to 0.51 which can be considered as a 'good' value according to van Rijn et al (2003) (section C.4.2.). The settings for the most important parameters for the final simulation run are shown in Appendix C.7. The results of the final simulation run regarding the bathymetry (top-view and cross-shore) is presented in Figure C.5.4.

The best calibration simulation which is selected for the assessment of the morphodynamic behaviour of the construction scenarios, still underestimation the erosion from the Sand Engine of about 65,000 m^3 and the Brier Skill Score did not improve compared to the default settings simulation.

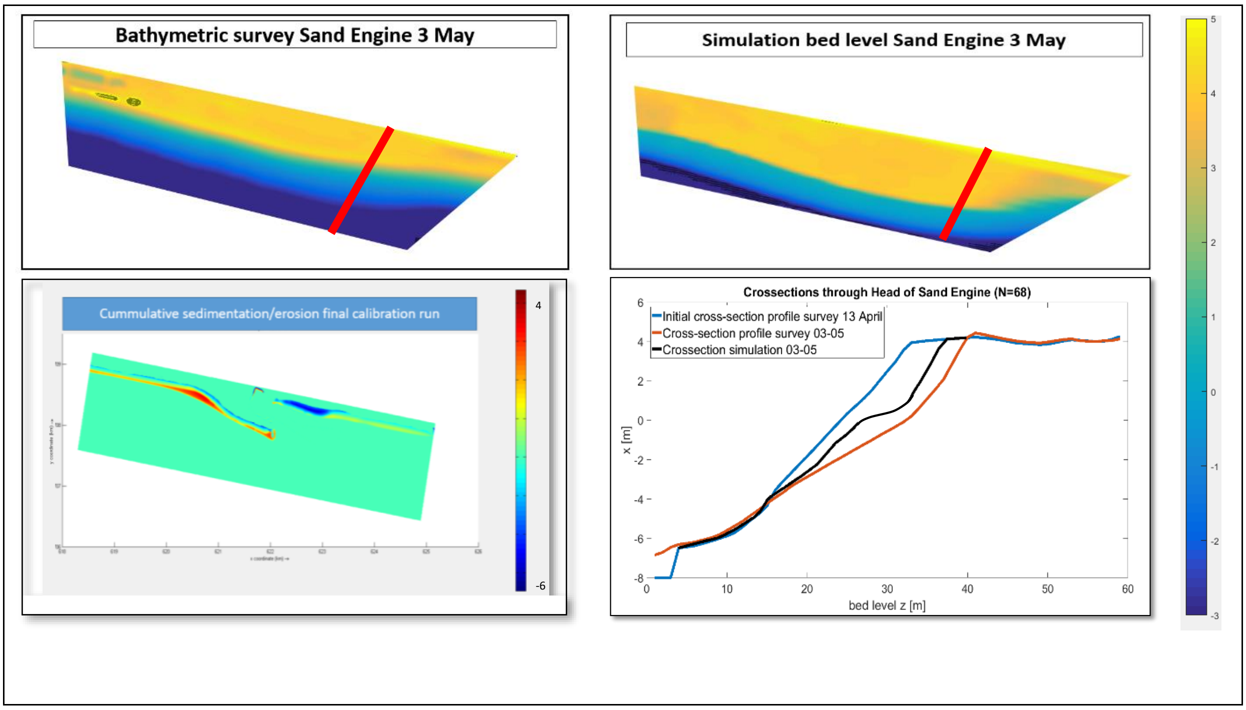


Figure C.5.4: (a, top left): Top view of bathymetry survey of the Sand Engine at 3 May 2018 (end calibration period) (b, top right): Simulated bathymetry of the Sand Engine at 3 May 2018 (end calibration period) final calibration run (c, bottom left): Cumulative sedimentation and erosion pattern final calibration run (d, bottom right): A cross-section through the head of the Sand Engine (located at the Sand Engine at the red line indicated in figure a, b) at start and end of calibration period (from bathymetric survey and final calibration run).

5.6. Summary chapter 5

Regarding the model performance analysis in this chapter and Appendix C the following statements can be drawn:

Based on the rapid morphodynamic development observed at the Sand Engine located at the east side of the Sandbar breakwater a model performance analysis is carried out. The main adaptations which have been made in the model regarding the non-calibration parameters are:

- Enabling the roller model (roller=0) implies wave energy dissipation a bit further offshore resulting in less erosion from the Sand Engine, which better represents the physical processes in the area. Due to the steep beach slope a narrow surf zone exist, resulting in the fact that the wave roller aspect is almost absent.
- The model was also optimised regarding other non-calibration parameters: the MorFac (=10) and the spin-up time (Morstart= 3 days) without accepting large inaccuracies in the model.

The model was calibrated for a set of calibration parameters. From the model analysis it can be concluded that none of the model simulations predict the morphodynamic development of the Sand Engine totally accurate. The erosion from the Sand Engine (210,000 m^3) is after extensive model calibration calculated as 145,000 m^3.

The best model performance was obtained by using the lower MorFac, alpha, gammax and wet slope parameter and higher facua and gamma parameter settings than the default settings. XBeach performed better with higher facua and wet slope values at the reflective parts of the study area and with lower values at the less steep ones. Model sensitivity to calibration settings appeared to increase with beach slope.

The calibration analysis improvements were as follows: the erosion rate improved by somewhat more than 10,000 m^3 compared to the actual data while the Brier Skill Score almost remains the same (BSS=0.51, considered as 'good' by van Rijn et al et al. (2003)).

After an extensive calibration process, the results can be satisfactory since all dominant hydrodynamic processes are included in the model, as has been observed for the general trends of the Sandbar and Sand engine. There will always be an inaccuracy in numerical morphological models, since the results are very sensitive to its input parameters. Any (natural) variability of the parameters will lead to significant different results. The actual sediment transport rates might be higher in reality compared to the expected modelled rate at the Sand Engine. Other morphological models will not give significant better results. Another aspect which cannot be taken into account by morphological models is the initial sediment loss from the Sand Engine due to adaptation effects (such as washing out of finer sediments, consolidation of material, different packing of nourished sand (CDR International, 2018).

Overall, it can be concluded that the XBeach model is able to predict the general morphological trends in the Lekki coastal system, which is swell dominated and characterised by a steep, reflective beach. Although the absolute morphodynamics quantities (such as erosion and sedimentation rates) may differ from reality. Since the model study for construction variants is aimed for the relative comparison of the sediment losses and sedimentation quantities to each other, the XBeach model is satisfactory for the morphological modelling of the swell dominated reflective Lekki coastal system.

6. Assessment construction variants

In this chapter the results for the morphodynamic behaviour (6.1. and the cost (6.2.) analyses is presented. The results regarding morphodynamics and costs are introduced by the applied (modelling) method. After the presentation of the quantitative results, the practicability of the different variants is discussed (6.3.). Finally, an overall summary of the variant specifications and results is presented (6.4).

6.1. Results morphodynamic behaviour variants

6.1.1. Modelling approach construction scenarios

For the assessment of the morphological development a modelling study for four cases is executed: the reference scenario (Variant 0) and three construction alternatives (Variants 1-3).

In this modelling study the stages in the scenarios are simulated for each week. In reality, the sand reclamation works are executed continuously 24 hours per day, 7 days per week. In the morphological model study of the different variants, these reclamations are schematized by adding once per week a volume of nourished sand into the model. The executed steps for this modelling study are briefly presented in Figure 6.1. More explanation on the approach of the simulations of different construction stages and the model settings is elaborated in Appendix C.8.

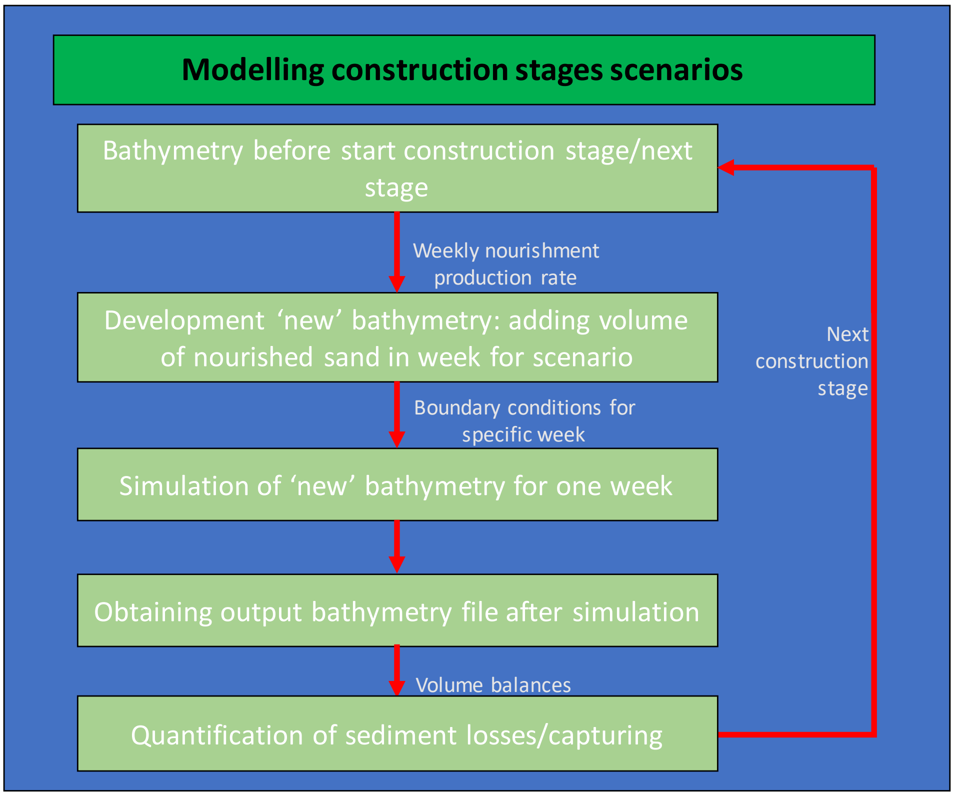


Figure 6.1: Scheme of the modelling study for the assessment of the morpho dynamic behaviour during the stages of the construction variants .

The wave boundary conditions for the assessment of the sediment losses is derived from the existing wave climate for the area of interest. This wave climate with nearshore representative wave conditions is developed based on a large scale SWAN model and calibrated against local measurements, resulting in a limited set of wave conditions for each month. Since the scenario simulations take place on weekly basis the durations of these conditions are scaled from monthly to weekly durations.
Regarding the tide data, this is used from the existing tide input file after adaptation of the tide lengths and correct period.

Since the simulation of the different construction stages is time consuming, it is decided that the morphodynamic behaviour of the construction variants is not assessed for the stage when the Sandbar is only further widened and heightened. The morphodynamic development is low so this will not significantly affect the results. The quantification of natural accretion of sand into the design profile stops at the moment the area is reclaimed by the dredging equipment.

The morphodynamic behaviour results are presented regarding the sediment losses which are specified for the Inner Lake and the east side of the Sandbar design profile. Furthermore, the natural accretion of sand into the design profile as a result of the temporary groynes (Western and Eastern Groyne) for variant 1 and 3 is presented. These results are presented for each construction variant by a figure and are summarized in Table 6.1. The cumulative losses and natural 'captured' sediment during the construction phase of the variants is presented on the right y-axis of these figures.

6.2. Morphodynamic behaviour variants

6.2.1. Variant 0 [Lekki project]

The results of the generalized construction execution of the Lekki project for the investigated stages is presented in Figure 6.2. and summarized in Table 6.1 and Figure 6.6. Based on the results the following remarks can be drawn regarding the reference scenario:

- The morphodynamic development at the start of the construction phase (submerged bund) appeared to be low. This resulted in little movement of the nourished sand into the Inner Lake and to the east side of the design profile (week 1 & 2). This is in agreement with the observations during the Lekki project. The observed losses are also small during these weeks (bit more than 10,000 m^3) and can be mainly explained by a eastern longshore sand transport current.
- Due to predominantly western wave incident angle of the wave climate, nourished sand starts to move to the east side of the Sandbar profile during the reclamation of the Sandbar Road of about 50,000 m^3 (weeks 3-5). This is a bit more than observed in the actual Lekki project which can be explained by the fact that observed conditions during this stage were below average than the applied wave climate in the modelling study.
- After week 5 (reclamation of the Sandbar to the West onshore design side of the design profile) large volumes of sand has been eroded (west) shoreward into the Inner Lake (110,000 m^3). This is less than noticed during the actual project. This can be explained by more oblique incoming waves in the model wave climate than that actually occurred during the execution.
- The total loss obtained from the model study is 220,000 m^3 from which 145,000 m^3 ended up in the Inner Lake and 75,000 m^3 at the east side of the design profile. This is comparable to the losses observed during the Lekki project (250,000 m^3).

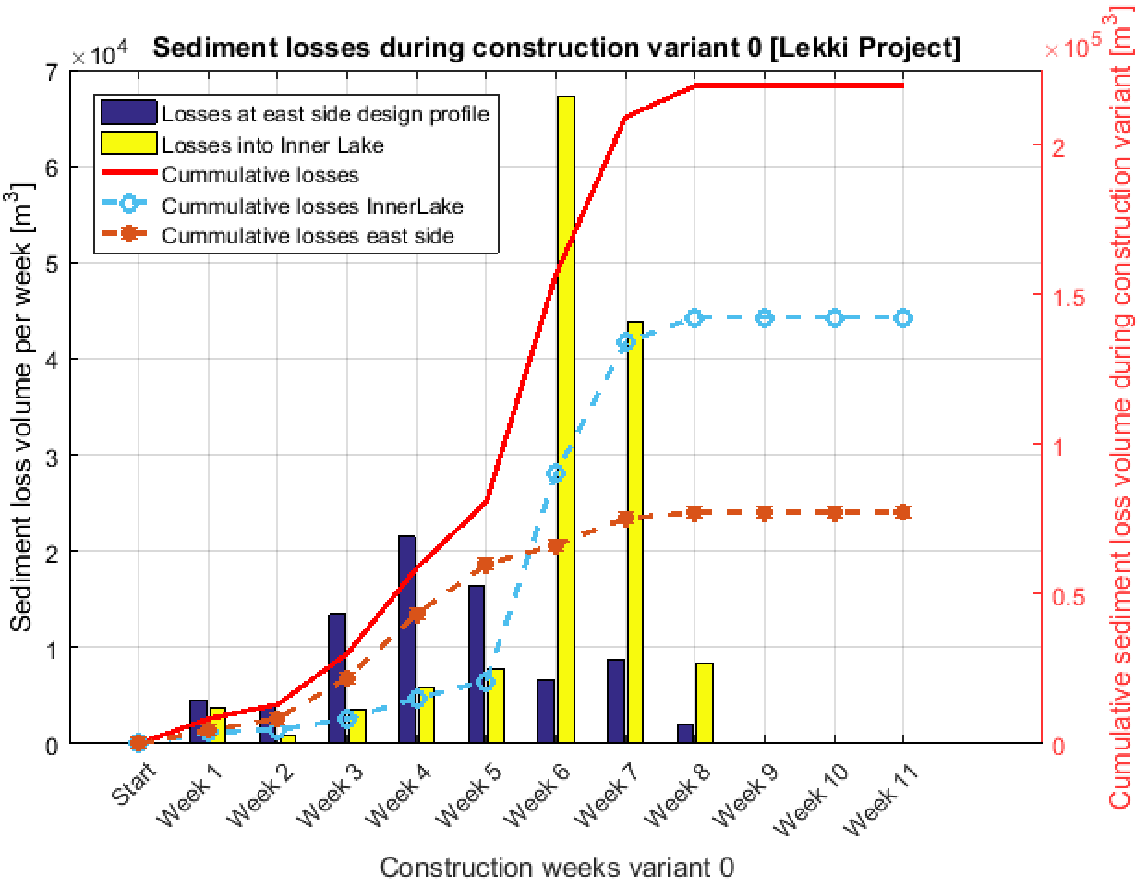


Figure 6.2: The sediment losses located outside the design profile resulting from the modelling study for the reference scenario [variant 0]. The bar chart represents the sediment losses [m³] per week. On the right y-axis the cumulative sediment loss during the construction weeks is presented.

6.2.2. Variant 1

For construction variant 1, the morphological results are presented in Figure 6.3 and summarized in Table 6.1 and Figure 6.6. In this variant the morphodynamic impact of reclaiming the Sandbar from the west as well as the accretion of sediment into the design profile by the Western Groyne is investigated. Based on these results, the following remarks can be drawn regarding the obtained losses and naturally captured sediment into the design profile:

- This variants starts with a larger submerged bund than the reference scenario (first 5 weeks). From this can be learnt that enlarging the submerged bund the losses remain little (20,000 m^3 towards the east during the first 5 weeks) and that a larger volume of sand (1,190,000 m^3 versus 550,000 m^3) can be nourished without significant morphodynamic changes and thus without large losses.
- One week after the start of the construction the Western Groyne, sand starts to accumulate into the design profile 'behind' the breakwater at the westside. Also erosion at the east side (leeside) of the Western Groyne became perceptible. The natural accretion continues until the moment the Sandbar is nourished with a naturally accreted volume up to 16,000 m^3 per stage with a total of 55,000 m^3 (Figure 6.3-b).
- Strong morphological development is noticed during the reclamation of the Sandbar from the west side which resulted in losses of about 115,000 m^3 into the Inner Lake (week 6,7) and 30,000 m^3 to the east side of the design profile (week 7-9). The losses into the Inner Lake are almost the same, however the losses to the east side are larger compared to variant 0.

- The total losses for construction variant 1 are almost 200,000 m^3 while approximately 55,000 m^3 of sand is naturally accreted by the Western Groyne into the design profile.

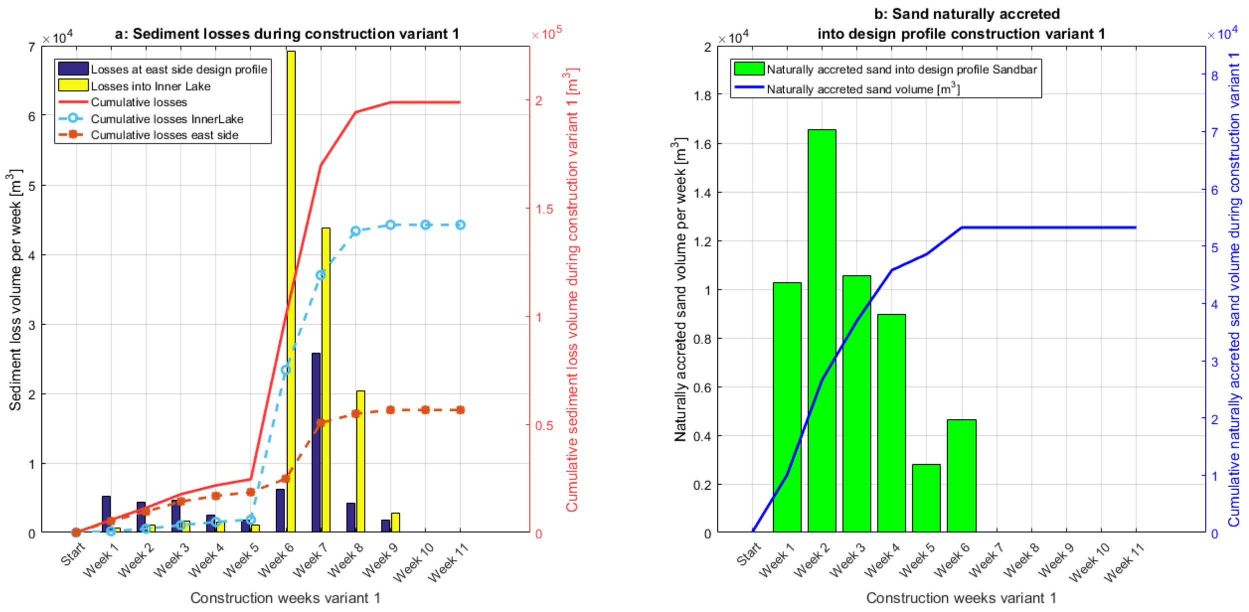


Figure 6.3: Sediment losses outside the design profile and naturally accreted sediment into the design profile resulting from the modelling study for construction variant 1. The bar chart represents the sediment losses per week in Figure (a) and the naturally accreted sand volume in Figure (b). On the right y-axis the cumulative sediment losses (a) and the cumulative naturally accreted sediment volume (b) is presented for all construction weeks.

6.2.3. Variant 2

The morphological results of construction variant 2 are presented in Figure 6.4 and summarized in Table 6.1 and Figure 6.6. In this variant the morphodynamic impact of reclaiming the Sandbar from two sides as well as the offshore expansion of the Sandbar from the Sandbar Road is investigated. Based on the results of this variant the following remarks are drawn:

- During the reclamation of the Sandbar in this scenario, the sand also for the construction strategy sensitive for losses into the Inner Lake. However, the Inner Lake losses are much lower (75,000 m^3 (week 6 and 7) compared to 135,000 m^3 into the Inner Lake at variant 0).
- Losses regarding the east side of the design profile are comparable to the Lekki construction variant.
- The total losses comes down to 164,000 m^3 of which 78,000 m^3 ended up in the Inner Lake and 86,000 m^3 at the east side of the design profile.

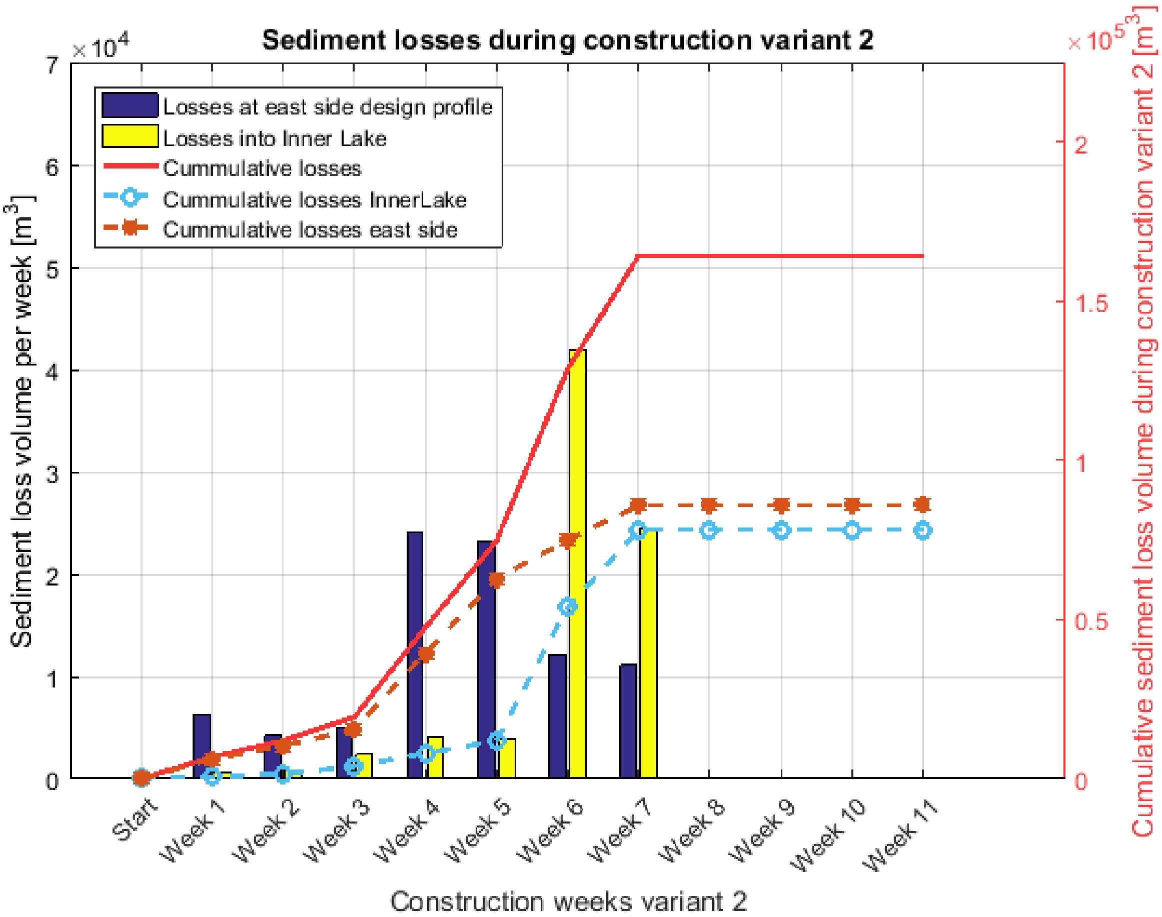


Figure 6.4: Sediment losses outside the design profile resulting from the modelling study for construction variant 2. The bar chart represents the sediment losses per week. On the right y-axis the cumulative sediment losses is presented for all construction weeks.

6.2.4. Variant 3

The morphological results of construction variant 3 are presented in Figure 6.5 and summarized in Table 6.1 and Figure 6.6. About this construction variant the following aspects stand out:

- The Sandbar Road reclamation phase appears to be sensitive for losses to the east side of the Sandbar design profile (Week 3/4) resulting in losses up to more than 80,000 m^3, which is the most of all variants in this stage.
- The losses into the Inner Lake during the Sandbar expansion from the Sandbar Road are lower than the for the other construction variants (almost 55,000 m^3). This is due to a different work method (higher production rates etc., see Appendix B.2).
- One week after the start of the construction of the Western and Eastern Groyne sand starts to accumulate into the design profile 'behind' the breakwater at the west side and at the east side (leeside) erosion is perceptible. The total naturally accreted volume for the Western Groyne is 45,000 m^3 (into Sandbar) and for the Eastern Groyne is 27,000 m^3 (into Sandbar Road, Figure 6.5Figure 6.3-b).
- The total losses for this scenario comes down to 180,000 m^3 from which 73,000 m^3 ended up in the Inner Lake and 108,000 m^3 at the east side of the design profile.

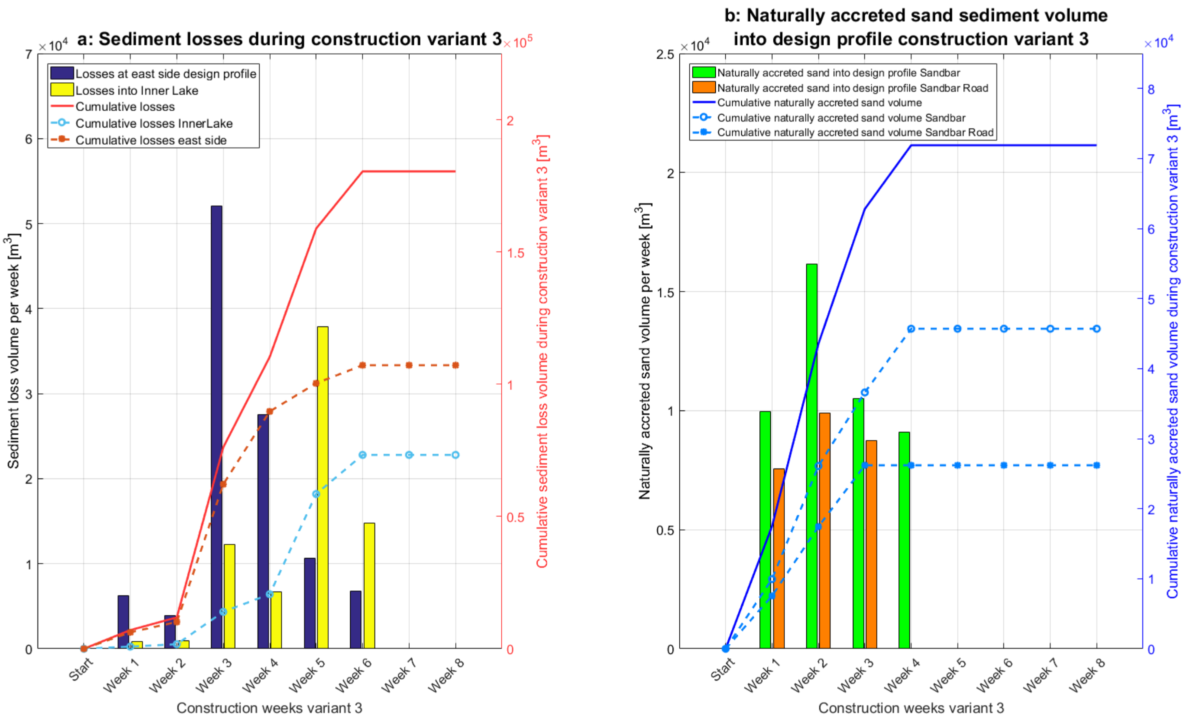


Figure 6.5: Sediment losses outside the design profile and naturally accreted sediment into the design profile resulting from the modelling study for construction variant 3. The bar chart represents the sediment losses per week in Figure (a) and the naturally accreted sand volume in Figure (b). On the right y-axis the cumulative sediment losses (a) and the cumulative naturally accreted sediment volume (b) is presented for all construction weeks.

6.2.5. Morphological behaviour variant comparison

In this section, the cumulative results of the morphodynamic behaviour is presented in Table 6.1. The comparison of the construction alternatives to the reference scenario (Lekki project) is given in Figure 6.6.

Table 6.1: Overview of morphodynamics during the construction phase of the reference variant 0 and the three construction alternatives (Variant 1-3). The colour scale indicate the magnitude of the sediment losses (green indicate less losses, red indicate larger losses) and naturally accreted sediment (bright green indicate more accretion than less bright green colours) relative to each other.

	Variant 0 [Lekki]	**Variant 1**	**Variant 2**	**Variant 3**
Sediment losses				
Inner lake	139,000 m^3	143,000 m^3	78,000 m^3	73,000 m^3
East side	77,000 m^3	57,000 m^3	86,000 m^3	107,000 m^3
Total	**220,000 m^3**	**199,000 m^3**	**164,000 m^3**	**180,000 m^3**
Natural accretion in design profile by groynes				
Western Groyne	n/a	53,000 m^3	n/a	46,000 m^3
Eastern Groyne	n/a	n/a	n/a	26,000 m^3
Total	**n/a**	**53,000 m^3**	**n/a**	**72,000 m^3**

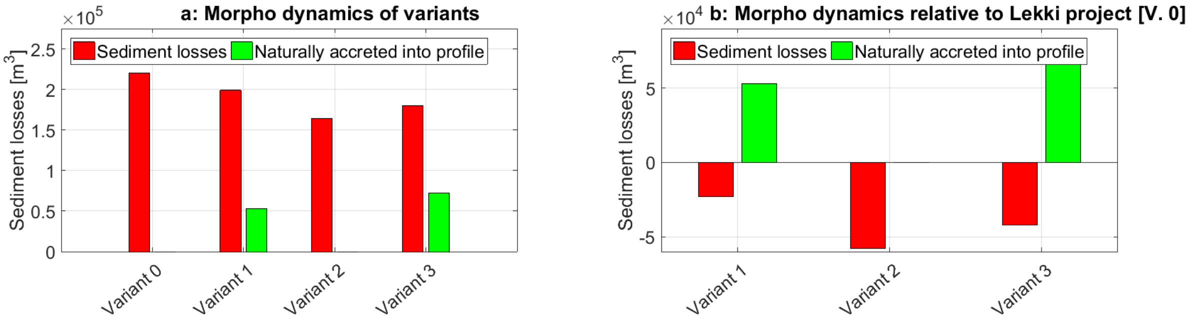


Figure 6.6: Overview of the morphodynamics (sand losses, natural accretion) during construction phase of Variant 0 (Lekki project) and the three construction alternatives (Variant 1-3). (a): Total sediment losses and naturally accreted sand into the design profile for all construction variants. (b): Total sediment losses and naturally accreted sand into the design profile compared to the reference scenario (Lekki project).

Based on the results of the morphological study the following remarks can be stated:

The sediment losses for all variants are lower than the losses occurred during the actual construction of the Lekki project. In particular, the natural movement of sand to the east side of the design profile is lower. This can be explained by the incoming wave angle, which was more perpendicular at December/January 2018 than the conditions applied in the model study in the wave climate. Furthermore, the uncertainty in the model contribute to a deviation in the results.

The total sediment losses for the construction variants have a maximum difference of almost 60,000 m^3 (Variant 2 relative to Variant 0). The total losses for Variant 2 are almost 25 % lower compared to Variant 0 (Figure 6.6). However, this is just 1.5 % of the total nourished volume of sand (4,000,000 m^3). The differences in sediment losses for the construction variants have occurred due to various reasons:

- The statement that sediment losses from the submerged bund are very little is proven by the model simulations, also when a larger submerged bund is applied further towards to coast.
- The reclamation of the Sandbar is sensitive for natural (eastern) sand movement into the Inner Lake. This can be explained by the physical processes overwash by the waves, a strong longshore transport current and due to the fact that sediment is added at a shallow water depth, directly into or close to the active transport zone. However, Variant 2 and 3 shows that reclamation of the Sandbar from the Sandbar Road at the offshore site lowers the sediment losses into the Inner Lake up to 50,000 m^3. This can be explained by less impact of the morphodynamic processes taking place in the active transport zone since sand is placed at larger dept further away from this area.
- The sediment losses into the Inner Lake for Variant 0 (Reclamation of the Sandbar from the east side) are not significant different from Variant 1 (Reclamation of the Sandbar from the west side).
- The results of Variant 3 show that the creation of an offshore island and the reclamation of the Sandbar Road towards the coast lead to more sediment losses at the east side of the design profile than variant 0.
- The temporary groynes have proved that sand from longshore sediment transport is accreted into the design profile. The Western groyne is able to capture about 50,000 m^3 of sand and the Eastern Groyne a bit less than 30,000 m^3 (due to a shorter time that sand accumulation can take place (Variant 3)).

6.3. Cost assessment variants

In this section the cost for the different construction variants are determined. Now the different variants are investigated on their morphodynamic behaviour, this can be coupled to cost. Less sediment losses during the construction phase mean less sand which is required to be nourished, which saves cost. However, this does not automatically imply that when a variant is morphodynamic more beneficial the total project cost are reduced. Different aspects determine the costs of a construction variant. Major other cost components are: (de)mobilization of dredging equipment, the execution of the nourishments by different discharge methods and the cost for the construction of the hard structures in the design such as groynes and the leeside revetment.

For the determination of the these costs various cost assumptions and calculations needed to be executed. First various bulk- and unit prices are estimated for the required materials and reclamation works. By knowing the volumes (determined in Chapter 4) and the unit prices, the costs for the sand reclamations (6.3.1.) and the construction of the hard structures being part of the conceptual designs of the different construction variants (6.3.2.) can be calculated resulting in the total costs for the different construction variants. In order to assess the costs of the different variants, the costs are compared to the Lekki project (Variant 0) as well as to each other (6.3.3.).

6.3.1. Cost component determination

Reclamation costs

In order to quantify the costs for the sand nourishment, first the cost price per m^3 for the different nourishment methods are determined. Based on experiences from the Lekki project, literature (Bak (2017), Hauer (1998)) and benchmarks within CDR and Boskalis, the cost price of all applied nourishment methods, the (de)mobilization of the dredging vessels and the naturally accreted sediment and lost sediment during the construction phase are determined. The schematized unit prices are presented in Figure 6.1 and further explained in Appendix B.

Table 6.1: Cost unit prices for sand reclamation works.

Cost component	**Unit price**
Mobilization cost	
Mobilization Hopper (TSHD)	*$1,000,000*
Mobilization Cutter (CSD)	*$ 950,000*
Reclamation work cost	
Bottom dumping reclamation works	*$ 3/m³*
Rainbowing reclamation works	*$ 4/m³*
Pumping ashore (PASH) reclamation works	*$ 5/m³*
Financial losses/gains morphodynamics	
Sand naturally accreted into design profile	*$ 3.5/m³*
Sand losses	$ 5/m³

6.3.2. Cost hard structures

General

In this section, the cost for the hard structure components in the Sandbar breakwater variants are determined. The cost components of the Sandbar Groyne, the temporary groynes (Western Groyne and Eastern Groyne), the North Groyne and the Leeside Revetment are specified. Therefore, first estimations and calculations regarding the production, the transport and the placement of the hard materials have been made (Appendix C.3). Since this research is on the Sandbar only, the construction cost for the Sand Engine (sand nourishments, installation of Geo Tubes) have been left out of consideration.

The main material which is been used for the construction of the hard structures in the design is Quarry Run (QR 1-500 kg & QR 10-500 kg). Furthermore, in the Sandbar Groyne, the Leeside Revetment and the North Groyne also other construction materials as Backside Protection, granular filter, rocks and concrete elements (Accropode 1) have been used. This is detailed explained in Appendix C.3..

Cost Temporary Groynes

In the construction variant 1 and 3 respectively one or two temporary groynes are implemented (Western Groyne and Eastern Groyne). As described in the design of the construction variants, the required weights of Quarry Run for the construction of the temporary Groynes are respectively 8,000 and 13,000 ton. As the costs per ton are known (Appendix C.3.), the total costs for the temporary groynes are calculated which is presented in Table 6.2.

Table 6.2: Cost of the temporary groynes implemented in the construction variants 1 and 3.

Cost component			
Groyne component	**Weight of Quarry Run [ton]**	**Cost per ton [$/ton]**	**Total cost**
Western Groyne	8,000	27.50	***$225,000***
Eastern Groyne	13,000	27.50	***$400,000***

Other hard structure components cost

The other hard structure components which are part of the Sandbar breakwater as the Sandbar Groyne, the North Groyne and the Leeside revetment are implemented in all construction variants and consequently does not differentiate between the variants. The placement cost for these components were obtained from involved construction site experts. These obtained numbers does not include the production and transportation cost. These cost are determined based on the assumptions on production and transportation and are added to the placement cost which is presented in Table 6.3Table B.10.

Table 6.3: Cost of several hard structural design components part of the Lekki Sandbar Breakwater design

Design component	Placement cost	Material production cost	Transportation cost	Total cost
Sandbar Groyne	*$ 4,000,000*	*$ 1,600,000*	*$ 3,500,000*	***$ 9,100,000***
North Groyne	*$ 300,000*	*$ 520,000*	*$ 670,000*	***$ 1,490,000***
Leeside revetment	*$ 1,000,000*	*$ 810,000*	*$ 1,050,000*	***$ 2,860,000***

6.3.3. Cost comparison construction variants

In this section the cost of several aspects within the construction variants are presented as well as the total cost. To accomplish a valid comparison, unit prices are combined with the total estimated volumes for each component. The component which differentiate within the construction variants are described and visualized in Figure 6.8. The results are put into perspective by comparing it to the reference variant 0 which is summarized in Figure 6.7. In Appendix B more total cost specifications for all variants are described. The coupling between the morphodynamic and the cost results is elaborated in Chapter 8.3.

Total cost

The total cost for the Lekki project for the construction of the Sandbar breakwater including the hard structures as the Sandbar Groyne, the Leeside Revetment and the North Groyne are determined to be $ 34,050,000 (Table 6.5), which is in the same order of magnitude to the actual cost of the Lekki project. The cost specifications regarding the sand reclamation works are presented in Table 6.4. The total cost for all variants are stated in Cost of the construction variants specified for the reclamation work methods, the hard structure components and the total cost.Table 6.5 and Figure 6.8.

The total cost for variant 2 appears to be financial the most beneficial due to the fact that a large part of the volume is nourished by the relatively cheap method bottom dumping and rainbowing. In addition, almost $ 200,000 is gained due to natural accreted sediment in the design, although the cost for sediment losses are relatively large. More description on the differentiating cost components results is elaborated in the next section.

Table 6.4: Cost of different methods of sand reclamation, extra cost due to sediment losses and profit (lowering the project cost) due to natural accretion of sand into the design profile for the construction variants.

	Variant 0	**Variant 1**	**Variant 2**	**Variant 3**
Reclamation cost by bottom door dumping	*$ 1,375,000*	*$ 2,975,000*	*$ 2,975,000*	*$ 2,975,000*
Reclamation cost by rainbowing	*$ 8,225,000*	*$ 6,457,500*	*$ 4,235,000*	*$ 4,543,000*
Reclamation cost by pumping ashore	*$ 4,950,000*	*$ 4,342,500*	*$ 7,200,000*	*$ 6,804,000*
Extra cost sediment losses	*$ 1,100,000*	*$ 1,000,000*	*$ 825,000*	*$ 900,000*
Gains by naturally accreted sand	*n/a*	*- $ 193,000*	*n/a*	*-$ 252,000*

Table 6.5: Cost of the construction variants specified for the reclamation work methods, the hard structure components and the total cost.

	Variant 0	**Variant 1**	**Variant 2**	**Variant 3**
Total cost reclamation work	*$ 15,650,000*	*$ 14,582,000*	*$ 15,235,000*	*$ 14,970,000*
Cost hard structure components	*$ 13,450,000*	*$ 13,675,000*	*$ 13,450,000*	*$ 13,915,000*
Total cost	***$ 34,050,000***	***$ 31,207,500***	***$ 31,635,000***	***$ 32,835,000***

Cost relative to variant 0

From the cost analysis several significant differences can be noticed. In order to know how the construction alternatives 1-3 relate to the actual Lekki project execution, the cost differences for different components are described in this section below and shown in Figure 6.7.

For different construction variants ideas are implemented to investigate whether this is morphological more beneficial. However, this also implies that the practical execution of the variants results into difference in reclamation methods and consequently different costs. The impact of these different methods on the cost is listed as follows:

- For the three construction alternatives, a larger submerged bund is applied. This increases the absolute reclamation cost for bottom dumping while it decreases the absolute cost for other reclamation methods (Figure 6.8-b). The construction of a larger submerged bund means that almost 600,000 m^3 more sand can be nourished by bottom dumping than variant 0 which is cheapest method ($3).
- Another impacting aspect is the reclamation of the Sandbar at the offshore side of the design profile (variant 2 and 3). This means that much more sand has to be pumped onshore at the onshore side of the profile since the rainbowing method is at these locations not any longer applicable. Therefore, the reclamation cost for the application of pumping sand ashore for variant 2 and 3 is much higher (Figure 6.8-d). This method is relative expensive and increases the total cost for the reclamation works of variant 2 and 3.

As we consider the cost regarding the sediment losses, it can be noticed that the maximum total cost difference for the construction alternatives compared to variant 0 is almost $ 300,000 (Variant 2), which is only 1 % of the total cost of the project (Figure 6.8-e). The impact of sediment losses on the total project cost appears to be low.

For the variants with three or four hoppers (variant 0 and 3) the mobilisation cost are respectively 1 and 2 million more than compared to the variants with 2 hoppers. More dredging equipment lead to faster project execution. However, the cost increases significantly and do not weigh up against the reduction in sediment losses (Figure 6.8-c,e).

The cost for the construction of the temporary groynes are a bit more than the profit which is gained by the natural accretion of sediment into the design profile (Figure 6.8-e, Figure 6.7-d).

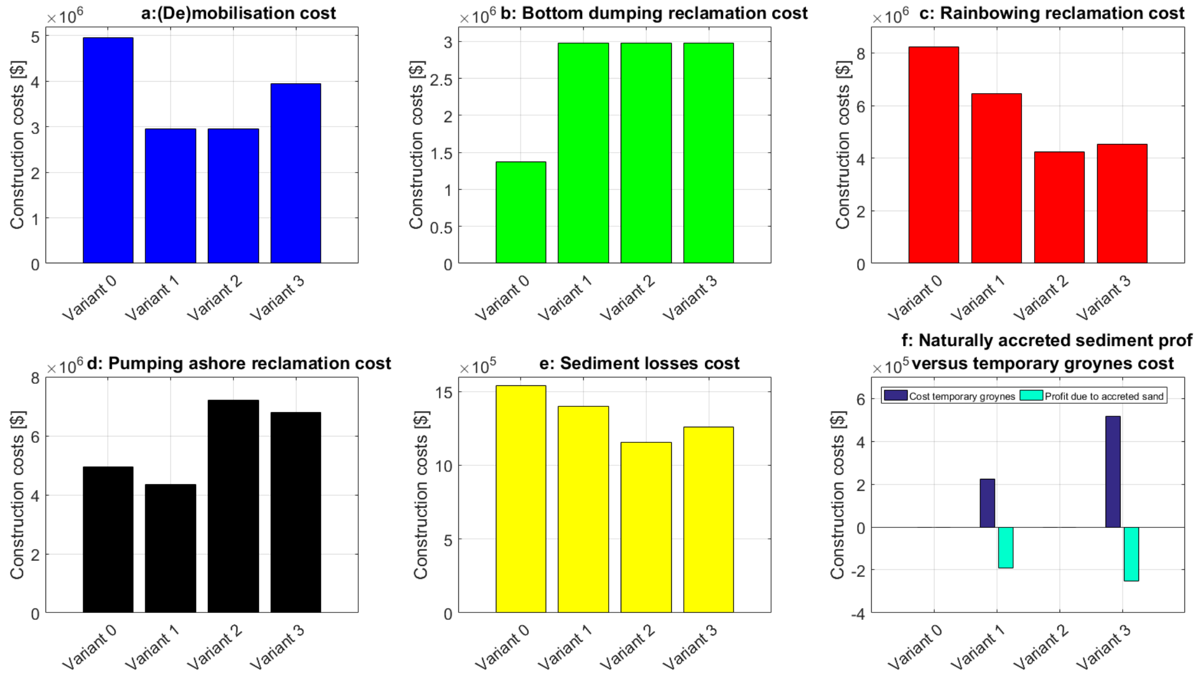
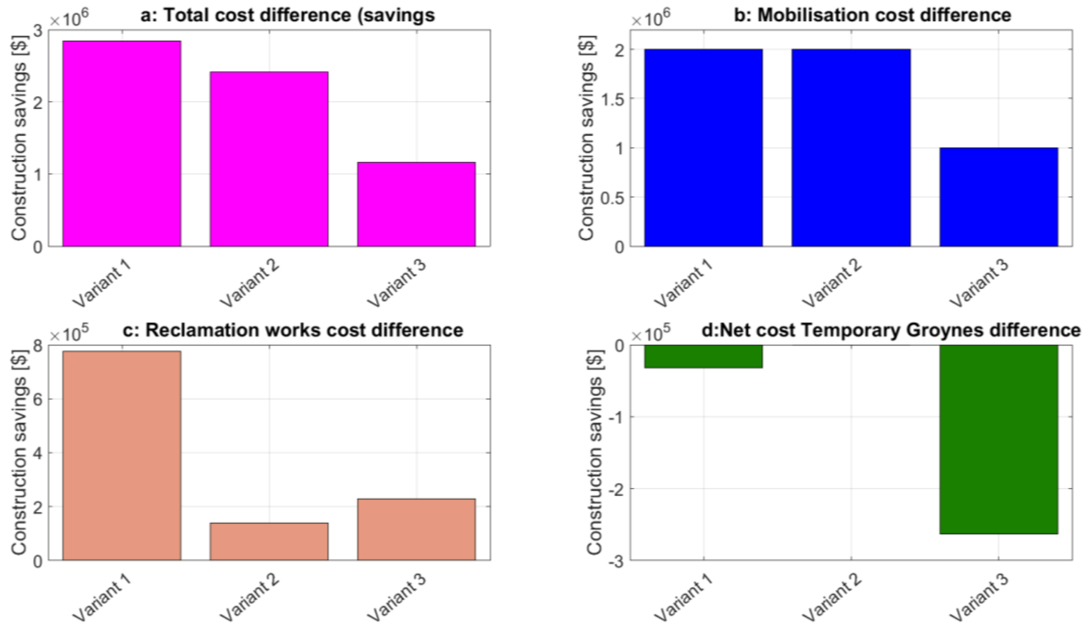


Figure 6.8: Overview of cost components which are different for the construction variants (a): (De)mobilisation costs (b): Cost for the reclamation of sand by applying the bottom dumping method (c): Cost for the reclamation of sand by applying the rainbowing method (d): Cost for the reclamation of sand by applying the pumping ashore (PASH) (e): Extra cost for sediment losses occurred during construction phase (f): Cost for temporary groynes implemented in variant 1 and 3 (dark coloured bars) and the gains from it by naturally accretion into the design profile due to these groynes (light coloured bars).



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6.4. Construction practicability

In this section the construction execution practicability of the variants is qualitatively assessed regarding the reclamation work methods and the project duration.

6.4.1. Nourishment methods practicability

The construction practicability of the variants depend on in which extent sand can be placed by an efficient and straight-forward nourishment method. For a detailed method description, see Appendix B.1.2.. The methods are assessed by the following criteria:

- The way the dredged sand is discharged from the TSHD;
- The production rate of the nourishment method;
- The accuracy of placement and the tendency of sand migration during the discharge process;
- The number of other required dredging equipment apart from the dredging vessels;

Bottom dumping

Bottom dumping can be considered as a very straight-forward method being most preferable method regarding practicability. By opening the bottom doors no sand has to be pumped overboard and no jet nozzle or suction lines are required. The discharging of sand can be done within 15 minutes, which enables a large number of cycles per day resulting in a high production rate (230,000 m^3/week, Table 4.2). Sand can be placed relatively accurately by positioning the vessel at the correct location. However, since for this method the sand is placed at deep locations, the sand can migrate during the settling process to the bed.

Rainbowing

For the rainbowing method sand is being pumped overboard by a so-called 'rainbow' installation. This self-discharging system includes a dredge pump which is connected to a suction line along the hopper length and a bow coupling unit with rainbow nozzle at the bow. Therefore, the discharge time is longer than for bottom dumping resulting in a bit lower production rate (175,000 m^3/week, Table 4.2). In the morphodynamic assessment, it is assumed that the all the sand is placed correctly into the design profile. However, for this method the sand has some tendency to migrate during the nourishment. The TSHD produce a powerful jet of sand and water. This jet causes a current directed from the ship and may result in the fact that sand is being placed not at the location where is was intended. This may lead to some inaccuracy of the sand placement.

Pumping ashore

For the reclamation area which is not reachable by the vessel the pumping ashore method is applied. A (floating) pipeline connects the TSHD with the shore and a pumping system on board is used to discharge the sand. The execution of the construction method is rather complex. Extra work as installation and dismantling of the required pipelines, the making of pipeline road crossings and weir boxes. Additional equipment as excavators, wheel loaders and bulldozers is needed. Due to this complex construction method the production rate is much lower which was estimated to be 150,000 m^3 /week (Table 4.2) for the construction variants. However, the accuracies of this method is very high since sand can be placed very precisely at the desired locations by moving or extending the pipelines.

Variants

From the analysis of variant 1 appears that the most volume of sand can be placed by bottom dumping and rainbowing (≈3,000,000 m^3, Figure 4.2) and is regarding the most optimal nourishment method the most preferable. In variant 0 a bit less sand can be discharged by bottom dumping, but the total volume of nourished sand by bottom dumping and rainbowing is comparable with variant 1 (≈2,900,000 m^3). However, the part of sand being rainbowed is larger for variant 0, which means less straight-forward and lower accuracies regarding the sand nourishment than for bottom dumping. For the variants 2 and 3 large quantities of sand have to be pumped ashore making these variants more complex and time consuming to construct although the accuracy of the sand placement for this method is high.

6.4.2. Duration

The construction variants have different total duration regarding the sand nourishments. From the point of view to minimise the risks of the project a short duration of the projects is desired. A huge, complex project which the construction of the Sandbar breakwater is, is always subjected to the chance of project delay. The lower the project duration, the shorter the period natural sand transport outside the design can take place and the smaller the chance is that the nourishments have to be executed during more rough wave conditions (May-October), when morphodynamics are much stronger resulting in more sediment losses. A maximal construction process can be accomplished by 3 or 4 hoppers. Less hoppers will reduce the production rates much, while more hoppers will result that the vessels are in each other's way. Regarding the accretion of sand into the design: a shorter construction period decreases the amount of sand which is natural accreted in the design (by temporary groynes).

The duration of variant 3 is the shortest (12 weeks) since the number of operational hoppers is the largest (3). However, this means that the time sand can natural accrete in the design profile at the implemented Western and Eastern Groyne is limited. Construction variant 2 last the longest (17 weeks) and is least suitable for this aspect (2 hoppers). Variants 1 and 2 (respectively 15 and 16 weeks) have a slightly shorter duration although it does not differ much compared to variant 2.

7. Discussion

In this chapter the liability of multiple aspects and the most important assumptions on which the study is based are discussed. Aspects of liability of both the model as the construction variant assumptions and results are elaborated on. Another topic that will be discussed is whether the results of this study are only valid for the Lekki context, or could also be used for other locations. The different topics are discussed by chronological structure of this research, starting with the (data) analysis of the Lekki project and the results of the model performance analysis followed by the interpretation of the results for the different construction variants.

7.1. Data analysis and model (calibration) analysis

- Examination of this wave data set obtained from the wave buoy reveals several gabs and outliers (as unrealistic peaks). Explanation for this might be a technical failure of the measuring device(s). Another reason might be that water levels during those gaps where too high so that the buoy would be pulled under water. To determine this, more background research on the wave data needs to be done. These 'missing' values are corrected by linear interpolation, however the number of these filled values was little.
- The bathymetric survey data has some uncertainties, since the bathymetry of a part of the surf zone cannot be reached by the multibeam and the drone (see Appendix A). Bed levels for this area is interpolated. This means that in the highly morphodynamic surf zone inaccurate in the data may exist which might have impacted the calibration process.
- Furthermore, the period for which the model is calibrated is short (20 days after the completion of the Sand Engine). Especially just the completion of the Sand Engine the erosion rate were large, which decreased after the period of 20 days. It would have been better to calibrate the model over a larger period, which would probably have led to a better calibrated model. Due no more available data by the time the calibration was executed, this was not possible.
- The roller model is switched off which impacts the location of wave dissipation in the XBeach model. However, the onshore wave energy 'roller' effect is almost not present in the Lekki coastal system, it is not completely absent. This is an assumption which has impact on the erosion rates in the surf zone leading to an underestimation of the actual erosion in the area. However, by using the roller model, the inaccuracies are much larger.
- Due to limited the model simulation time, some additions regarding non-calibration parameters are made in the model, which lowers the accuracy of the model a bit.
- The XBeach model is developed for a typical Dutch coast, which has different characteristics than the coast at Lekki. The slope of the Dutch beaches are more gentle with a small grain size and the hydro- and morphodynamic conditions are really different. Formulations within XBeach are based on the effects of wave interaction on gentle slopes and small grain sizes subjected to wave climates known to be prevailing at the Northern American coast and the Dutch coast (source). In additions, the calibration area (Sand Engine) is more dynamic and since it is a nourished site, it is also further from the equilibrium profile and the packing of nourished sediment is different. These are all factors that contribute to a faster erosion of the Sand Engine than the XBeach model shows. Further research on modelling both (1) for the area with coastal characteristics as at Lekki and (2) for the simulation of nourishment sites in the future may increase the model accuracies for these conditions.
- Although the calibration simulation results are very accurately, it is sufficient for the comparison of the morphodynamic behaviour of different construction variants, since the focus is here on the relative differences and not on absolute values.

7.2. Assumptions construction variant assessment

- For the development of the construction alternatives and the generalisation of the Lekki project, which was necessary for the model assessment study, several assumptions had to be made. The assumptions regarding the production rates of the hoppers are based on ship logs data from the Lekki project only from the first month. The variation in a discharge cycle durations varies as well as the sand volumes in the hoppers. This was because of practical reasons, which means that the execution of a construction variant always will be different in practise and that the production rates may be different.
- The exact cost for sand reclamation works and especially regarding extra cost for sediment losses and cost savings due to naturally accreted sediment into the design profile are roughly estimated. Since the price deviate for each project and circumstance, there are no fixed numbers. The cost are determined by the help of benchmarks within Boskalis and CDR, and are aimed for a relatively comparison of the different variants.
- Construction stages are schematized and modelled for each week, however in reality the sand nourishment continue 24/7 during project execution. Especially at moment with strong morphological development the implementation of a week nourishment volume is quite a rough estimation to assess the losses/capturing in this period of time. Furthermore, it is assumed that all nourished sand is placed inside the design profile, however this will never be the case in practice.
- The morphodynamic simulations for the assessment of the variant is applied with the developed SWAN wave climate. The order of the wave conditions randomized which is a schematization of the actual wave climate.
- The sediment losses of the morphodynamic assessment for variant 0 is different than the actual observed losses for the Lekki project. Possible reasons for less losses obtained from the modelling study can be the rough way of schematizing the sand nourishments in the model. Another reason impacting the results is the difference in the start moment of execution: the generalized variant 0 started in November with calmer conditions during the critical construction phases in the project compared to the actual Lekki project which started in December.
- A last major discussion point is what the conditions at certain construction stages are at once completely different. In the morpho dynamic assessment of the variants always the same wave climate is used. However, noticed from the Lekki project, deviant wave conditions than averaged impact the morpho dynamics very much. To assess this impact, a static situation of the reclamation of the Sandbar is simulated with the rough wave conditions (August climate) and is compared to the simulation with calm conditions (January climate). The impact on the losses was determined to be almost 30%.
- An alternative to the rainbowing method is ‘POK’ing’. This is a similar discharge process only with less high discharge velocities. POK’ing is executed by pumping the material through a wide nozzle resulting in sand being placed close by the vessel. This method is not implemented in the construction variants to make the scenarios not too complex and time consuming to analyse. However, this method is used in practise. This may result in a bit lower production rate during the stages when sand is pumped overboard through a nozzle, but differences from the rainbow method are small.

8. Conclusions

The answer on the main research question is be presented through concluding on the five sub-questions.

8.1. Sub research question 1: What was the comparison between the construction practice of the Lekki Sandbar breakwater project compared to the planned execution method regarding the wave conditions, sand nourishments methods, sediment losses?

The following conclusions can be drawn regarding the analysis of the construction process of the Lekki Sandbar breakwater project:

- The nourishment for the construction of the Sandbar breakwater was completed in 16 weeks. The observed wave condition are significantly different from the wave climate which was developed based on the SWAN wave analysis of the last 10 years for the Lekki coast. In the construction period the average observed wave height (H_s) was significant lower than expected (20%), the wave period (T_p) was almost the same (2% higher) and the wave direction was 1.5% more coming from the west than expected. Most of the time the conditions were calmer than expected which resulted in less strong morphodynamics. Only at some moment strong swell conditions have been noticed enhancing the morphodynamic behaviour.
- The sediment losses during the Lekki project (250,000 m^3) are higher than expected (150,000 m^3). This can be largely attributed to the strong deviant conditions at certain moments during the construction execution.
- The first stages of the project (reclamation of the submerged bund and the Sandbar Road) the conditions were calmer than expected, resulting in relatively low sand losses to the east side of the design.
- The sand losses into the Inner Lake are significant large (more than 200,000 m^3) during the reclamation of the Sandbar. The most important causes seem to be the strengthening of transport of sand by (the overwash of) waves towards the shore. Another important deviant condition was the strong western wave direction (θ) at certain moments in the project (Figure 3.8). This impacted the morphodynamics by enhancing the longshore sediment transport rate resulting to a western movement of sand into the Inner Lake.
- The reclamation works of the Lekki project have commenced relatively late in the calm season. This resulted in more rough wave conditions during the reclamation of the Sand Engine in April.
- After completion of the reclamation of the Sandbar breakwater significant short-term morphological development is been observed: accretion at the west side at the Sandbar and erosion from the Sand Engine at the east side.

8.2. Sub research question 2: What is the performance of the XBeach application regarding modelling morphological changes for a typical swell dominated reflective beach for the assessment of the morphodynamical behaviour of the construction scenarios?

Based on the rapid morphodynamic development observed at the Sand Engine located at the east side of the Sandbar breakwater a XBeach model performance analysis was carried out. After various model adaptations and optimisations the following conclusions can be drawn on the XBeach model performance:

- None of the model simulations predict the morphodynamic development of the Sand Engine very accurately. The observed erosion at the Sand Engine (210,000 m^3) is after extensive model calibration still underestimated (65,000 m^3).
- The best performance was obtained by using the lower MorFac, alpha, gammax and wet slope parameter settings and higher facua and gamma parameter settings than the default settings. This resulted in small improvements of the model morphological prediction accuracy: the erosion rate from the Sand Engine improved by somewhat more than 10,000 m^3 as it is compared to the actual bathymetric survey data while the cross-shore development prediction of the model almost remains the same (Brier Skill Score=0.51, considered as good by van Rijn et al et al (2003)). After

an extensive calibration process, the results can be satisfactory since the morphodynamic assessment of the construction variants is aimed for the relative comparison of the sediment losses. Absolute erosion and sedimentation value may differ from reality, although this margin of error is present in all assessed variants.

The used model is developed for the simulation of storm events at a typical Dutch coastal system which has different characteristics than the Lekki coast. The slope of the beaches in the Netherlands are more gentle, the wave height peaks are higher and no swell conditions are presented (long wave periods). This study has shown that the (near) optimal morphodynamic predictability of the XBeach application is not possible for this reflective, swell dominated coastal system.

8.3. Sub research question 3: Which construction methods are recommended regarding the morphodynamic behaviour?

The most optimal construction method regarding the morphodynamic behaviour is the situation the sediment losses during the construction phase are minimised and that the sand naturally accreted into the design profile is maximised.

This criteria can be best met by a correct construction sequence as well as the implementation of (a) groyne(s) at the start of the construction process:

- A large difference in morphodynamic behaviour was noticed between nourishments at deep(er) locations and the nourishments above the sea level.
- The submerged bund below -5 m is not sensitive to morphodynamic changes which results in maximum sediment losses of 8,000 m^3/week. This can be attributed to the fact that these nourishment take place outside the active surf zone where strong (western) sand transport takes place due to wave action and the presence of a strong longshore sediment current.
- When the waves reclamations are executed up to or even above the water level, the model simulation proves that the nourished sand is very sensitive to be transported by natural processes. The sediment losses during the sand nourishments around the water level vary between 25,000 and 70,000 m^3 /week depending on the locations where the sand is being placed. Sand transport onshore and to the east is observed which can be attributed to the wave action and the existing longshore current.
- The quantity of sediment losses does significantly depend on the wave height (Hs) and direction (θ) , which is proven by the observed conditions during the Lekki project execution and the simulation for more western directed wave conditions (see 7.2. Discussion). The sediment losses during the period were 5 to 10 times larger per day than the average daily losses of the Lekki project. The losses for the model simulations with rough wave conditions (July) instead of calm conditions (January) increased by 30%.
- Sand nourishments at the 'inner side' of the Sandbar close to the Inner Lake are significant more sensitive to be transported into the Inner Lake than nourishment further offshore. This impact is assessed in construction variant 1, in which the Sandbar is reclaimed at the 'offshore seaside' of the design profile. The losses are lowered by 50,000 m^3 for the 'offshore' Sandbar reclamation compared to the 'onshore' Sandbar reclamation) which can be explained by the a larger distance so sand will less rapidly be eroded to the Inner Lake. Also the further distance from the active coastal surf zone may decreases the morphodynamic changes for this situation.
- The morphodynamic behaviour of offshore nourishments as was investigated in variant 3, show that this construction method is more sensitive for sediment losses to the east than other construction variants.

- The order of the reclamation of the Sandbar from the west side or from the east side seems to have no significant impact on the sediment losses.

From the morphodynamic point of view the following nourishment strategy is recommended: the construction of a submerged bund for all possible area with sufficient depth (below -5 m at Lekki). For these reclamation works not necessarily a large production rate has to be achieved (1 hopper is sufficient, see results *construction variant 1 stage 1*). For the reclamation up to +4.5 m larger production rates are desired to minimize losses and prevent a breakwater breakthrough during the construction process (minimum of 2 hoppers). After the construction of a submerged bund this construction sequence is advised: to prevent significant losses into the Inner Lake and the east side of the design profile the reclamation of the Sandbar Road is recommended to be reclaimed from the shore and the Sandbar along the 'offshore seaside' of the Sandbar. Furthermore, The Sandbar breakwater reclamation should not be applied over de full width of the design as horizontal progress is recommended to have early access to the Sandbar Groyne and contribute to a rapid closure of the Sandbar (the main land with the Sandbar Road).

8.4. Sub research question 4: Which construction methods are recommended regarding the project cost?

The most optimal construction method regarding the financial project cost is in case that the total cost for the construction of the Sandbar breakwater are minimised. The maximum cost difference between the construction variants is $ 2,800,000. This is most impacting factors for the differences between cost of the variants are: the nourishment method and the number of operating dredging vessels.

The nourishment method which has the lowest unit price per cubic meter is desired, which is bottom dumping (\$3/m^3) The rainbowing is a more expensive method (\$4/m^3) and the most financial unattractive method is pumping ashore (\$5/m^3) since the production rates are much lower and the execution of this method requires more materials and equipment. A certain construction strategy or sequence may impact the volume of sand which can be maximally nourished by a specific construction method. A significant difference in the construction scenarios appears whether the Sandbar is reclaimed from the inner 'shore side' or the 'offshore seaside'. By the 'offshore seaside' reclamation much more sand needs to be pumped ashore to the inner side slope after the closing of the offshore side of the Sandbar by rainbowing, which increase the total cost for the reclamation works. This increase of cost is much more than cost savings by the decrease of sediment losses.

The financial cost regarding the implementation of temporary groynes in the design can be stated as follows: the cost for the Western Groyne are a bit larger than the cost savings by the 'costless' natural accretion of sand into the design profile ($30,000). For the construction of the Eastern Groyne the cost and the savings are respectively and $290,000 and $90,000.

From the financial cost point of view the following nourishment strategy is recommended: the construction of a submerged bund for all possible area with sufficient depth (below -5 m at Lekki). The reclamation of the Sandbar along the inner shore side of the design profile is recommended. Although the cost for the sediment losses increases, the total cost for the reclamation works are much cheaper due to less sand has to be pumped ashore. Furthermore, the construction of the temporary Groynes leads to a small increase of the project cost. This difference is small and due to the various assumptions made in the construction variants on the financial feasibility cannot be concluded with certainty.

8.5. Sub research question 5: Which construction methods are recommended regarding the practicability?

The most optimal construction method regarding the practicability of the project is when an efficient and straight-forward nourishment strategy can be used. An efficient and straight forward method is defined:

- Low nourishment cycle times resulting in large production rates;
- Accuracy of the placement of nourished sand;
- The number of other required dredging equipment apart from the dredging vessels;
- The duration of the reclamation works;

These criteria are best met when the volume of sand nourished by the bottom dumping method is maximised. This method provides a rapid (initial) build-up of a reclamation area for which no other dredging equipment is required apart from the hopper vessel. Furthermore, a maximum number of hoppers (TSHDs) is desired for this criteria in order to speed up the process and minimise the project risks as project time exceedance and to prevent a breakthrough of the breakwater.

From the practicability point of view this means concretely for the Sandbar breakwater: a submerged bund for all possible area with sufficient depth (below -5 m at Lekki) should be constructed. A fast (maximal) construction progress can be accomplished by 3 or 4 TSHD. Less hoppers will reduce the production rates much, while more hoppers will result that the vessels are in each other's way.

8.6 Answering the main research question: Which construction strategies for the Sandbar breakwater concept are optimal regarding the morphological behaviour, project practicability and cost?

In this section the answers on the sub research questions are combined to one overall recommended strategy for the construction of a Sandbar breakwater. This is discussed on the basis of the optimal construction sequence, method, start moment, the (number) of operational dredging vessels, the impact of the hydrodynamic conditions on the construction phase and the whether the implementation of temporary groynes is desired.

- *Regarding the moment of execution of the reclamation work:* From the Lekki project analysis appears that the start of the reclamation works was relatively late in the calm season. The start of the construction of the submerged bund is advised in October/November. This consequently mean that the critical sand nourishments at the Mean Sea Level (such as the expansion perpendicular to the coast of the Sandbar Road and the Sandbar reclamation) can be executed during the calmest moths of the year. This will result in less sediment losses and minimises the possible risk as project delay or a breakthrough of the Sandbar during the construction phase.
- *Regarding the dredging vessels for the reclamation work:* To further ensure a smooth and durable construction process the use of two hopper dredgers (TSHDs) and one cutter dredger (CSD) is recommended. This number of vessels is the optimum between a safe and quick construction and the financial cost. The chance that is sand nourishments have to be executed during rough wave conditions is minimal and the production rates of about 400,000 m^3 per week to ensure enough progress to exclude a Sandbar breakwater breakthrough during the construction process.
- *Regarding the sequence of the reclamation works:* the construction of a submerged bund for all possible area with sufficient depth (below -5 m) is recommended since all the results for all criteria as cost, morphodynamic behaviour and practicality state that this is the most optimal start of the reclamation of the Sandbar breakwater. The construction of the submerged bund the bottom doors provides a rapid (initial) build-up of the reclamation area.

The Sandbar breakwater reclamation above the water level should not be applied over de full width of the design as horizontal progress is recommended to have early access to the Sandbar Groyne and contribute to a rapid closure of the Sandbar (the main land with the Sandbar Road).

The next recommended step after the submerged bund is to reclaim the Sandbar Road from the (east side of the) coast. This is the most direct way and rapid way to the Sandbar Groyne tip and enables an early start of the construction of this groyne in order to prevent sand from eroding to the east.

The next stage in the construction phase two main assessed criteria are in conflict: the morphodynamics and the financial cost. The reclamation of the Sandbar along the inner shore side of the design profile (Variant 0/1) is significant cheaper than the offshore sea side expansion of the Sandbar (Variant 2 and 3). Although the sediment losses are larger for variant 0 and 1, the total cost for the reclamation works (mainly rainbowing) is still significant lower due to less sand which has to be pumped ashore.

- *Regarding the actual conditions during the reclamation works:* As critical reclamation are planned to be executed, it is recommended to let the best sequence and execution method depend on the expected wave conditions on forehand. In case strong swell from a deviant wave direction is predicted it is not advisable to start with the reclamation of the inner slope of the Sandbar (Road).
- *Regarding the implementation of the (temporary) groynes in the Sandbar design:* from the financial assessment the temporary groynes proved not to be financial feasible. However, the cost depend highly on the specific situation. In case the cost for production or transportation appear to be lower and due to the fact that is a promising Building with Nature concept than the construction of one or two temporary groynes is certainly recommended.

8.7. Recommendations

During this research multiple factors have been pointed out which are key when moving forward with subsequent research to this opportunity. This section suggests recommendations to remove uncertainties and increase the affirmation of the construction method of a Sandbar Breakwater. Only the key recommendations are presented below:

- *Regarding the modelling study:* More detailed calibration analysis of the XBeach model in these type of coastal systems will gain more insight in the model limitations for the model application during different coastal characteristics such as steep, reflective beaches and a hydrodynamic conditions which is dominated by swell conditions. Furthermore, it would be useful whether other morphological modelling packages as Delft3D and FINEL are able to predict the morphodynamic behaviour of a typical Lekki coastal system. This will contribute to an always ongoing process of improving the model performance for different types of coastal areas.
- *Regarding the implementation of the (temporary) groynes in the Sandbar design:* to even further optimise the objective of the (temporary) groynes it is recommended to build the groynes a while before the reclamation works commence (most preferable during the rough season June-September). In the construction variants, the time that sand accumulate into the design profile takes only place for several weeks. This resulted in the fact the temporary groynes are not financial feasiable. However, an earlier construction of groynes will result that this concept is financial more attractive. Further research on what the maximum volume of sand which can accrete behind a groyne after a longer period should be investigated. This can be done in the same way as it is done in this research only the simulation time should be increased.

Bibliography

Allersma, E. T. (1993). Coastal conditions in West Africa-A Review. *Ocean and coastal Management 19*, 199-240.

Austin, T. (2007). *Tidal Currents in a Microtidal Estuary.*

van der Spek, B. J. T. (2017). *Comparison between XBeach and FINEL morpho-dynamic moddelling of a Sandbar breakwater.* Amersfoort: CDR-International.

Bart, L. (2017). *Long-term modelling with XBeach: combinning stationary and surfbeat mode in an integrated approach.* Delft: TU Delft.

Boateng, I. B. (2011). Estimating the fluvial sediment input to the coastal sediment budget: A case study of Ghana. *Geomorphology*, 100-110.

Bosboom, J. S. (2012). *Coastal Dynamics I: Lectures Notes CIE4305.* VSSD.

Boskalis. (2017). *Works Method Statement for Dredging and Rock Works.*

Guiavarc'h, A. M. C. (2009). *Deep currents in the Gulf of Guinea: along slope propagation of.* Ocean Science.

CDR-International. (2017). *Detailed design report Sandbar breakwater for RoRo Jetty at Lekki at 9.8 km, Lekki Free Trade Zone.* Amersfoort: CDR-International.

Copline Engineering Services. (2016). *Laboratory Sand Testing and Reporting - B1609-05-Dangote-Lekki KM 9.8 Jetty Sampling Campaign.* Lekki, Lagos.

De Vries, S. S. (2012). Dune behaviour and aeolion transport on decadal timescales. *Coastal engineering 67*, 41-53.

Deltares, C. R. (2013). *Appendix C: Hydrodynamic, Wave, and Sediment Transport Modeling. Mississippi Barrier Island Restoration.* Delft: Deltares.

DHI-GROUP. (2017a). *Litoral Procces FM User Guide.*

Drake, T. C. (2001). Discrete particle model for sheet flow sediment transpot in the nearshore. *Journal of Geohysical Research, 106*, pp. 19,859-19,868.

Lesser, J. R. (2004). Development and validation of a threedimensional. *Coastal Engineering, 51(8-9)*, 883-915.

Holthuijsen, L. (2007). *Waves in Oceanic and Coastal Waters.* Cambridge: Cambridge University Press.

Horn, D. (2002). Beach groundwater dynamics. *Geomorphology 48 (1-3)*, 121-146.

J. Bosboom, M. S. (2012). *Coastal Dynamics I: Lecture Notes CIE4305.* Delft: VSSD.

Chapas, A. R. (1964). Evaporation and evapotranspiration in southern Nigeria. *Quarerly Journal of the Royal Meteorological Soceity Vol. 90, 385*, 313-319.

Mariño-Tapia, I. R. (2007). Cross-shore sediment transport on natural beach and its relation to sandbar migration pattern: 1. Field observations and derivation aof a transport parameterization. *Journal of Geophysical Research: Oceans, 112 (3)*, pp. 1-15.

Munk, W. (1950). *Origin and Generation of Waves. Technical Report 531.* Institute of Geophysics and Scripps Institution of Oceanography.

Nishi, R. (1997). *Geomorphological aspects of beach and dune profile evolution due to waves.* Kagoshima University.

Orupabo, D. (2008). *Coastline migration in Nigeria.* Hydro International.

Oyegun, C. (1990). The Management of Coastal Zone Erosion in Nigeria. *Ocean & Shoreline Management 14*, 215-228.

Peters, J. (2018). *The determation of the feasiability of a "Sandbar breakwater" on the Nigerian coastline at Badagry.* Delft: TU Delft.

Pi, D. R. (2015). *XBeach Model Description.*

Prinos, P. (2016). *Coastal Wiki*. From Coastal Wiki: http://www.coastalwiki.org/wiki/Modelling_coastal_hydrodynamics#Physical.2C_Numerical_and_Composite_Modelling

Ranasinghe, C. S. (n.d.). Morphodynamic upscaling with the MORFAC approach: dependencies and sensitivities. . *Coastal Engineering 58(8)*, 806–811.

Roelvink, D. R. (2009). Modelling storm impacts on beaches, dunes, and barrier islands. *Coastal Engineering*, 1133-1152.

Roelvink, D. v. (2015). *XBeach Technical Reference: Kingsday Release pages 1-141.*

Roelvink, J. (2006). Coastal morphodynamic evolution techniques. *Coastal morphodynamic evolution techniques. Coastal Engineering, 53(2-3)*, 277–287.

Roelvink, J. S. (1989, April 15). Bar-generating cross-shore flow mechanisms on a beach. *Journal of Geophysical Research, 94 (C4)*, p. 4785.

Roos, P. C. (2017). *Marine Dynamics Short Waves lecture notes 195400800.* University of Twente, Enschede.

Royal. HaskoningDHV. (2016). *Dangote Permanent Jetty at KM9.8 -Tender Documents.*

Schwartz, L. (2005). Africa, coastal ecology. In L. Schwartz, *Encyclopedia of Coastal Science.* Dordrecht: Springer.

Sexton, J. M. (1994). The morphology and sediment character of the coastline of Nigeria- the Niger Delta. *Journal of Coastal Research 10-4*, 959-977.

Short, A. D. (2012). *Coastal processes and beaches*. From Nature: https://www.nature.com/scitable/knowledge/library/coastal-processes-and-beaches-26276621

Svasek. (2017). *Morphological Design Study.* Rotterdam: SVASEK Hydraulics.

Svasek. (2015). *FINEL*. From FINEL2D: http://www.finel2d.com/

The Open University. (1999). *Waves, tides and shallow-water processes.* Oxford: Butterworth-Heinemann.

Thomas, R. C. (2013). *Shoreline change modeling using one- line models: General model comparison and literature review. Coastal and Hydraulics Engineering Technical Note CHETN-II-55.*

Turner, I. M. (1998). Swash infiltration-exfiltration and sediment transport call flow rates of net. *Journal of Geophysical Research 103 (C13)*, 30,813-30,824.

van Bentum, K. (2012). *The Lagos coast; investigation of the long-term morphological impact of the EKo Atlantic City project.* TU Delft.

Verhagen, H. J. (2009). *Breakwaters and closure dams.* VVSD.

VLIZ. (2018, 04 03). *Littoral drift*. From Coastal Wiki: http://www.coastalwiki.org/wiki/Littoral_drift

Appendix A: Lekki project

In this appendix more explanation is provided on different aspects of the construction process of the Lekki Sandbar breakwater. First a detailed explanation on the acquisition of the data before and during the construction is given (A.1), followed by an overview of the (bathymetric) situation of the area of interest before and during the construction phase (A.2).

In order to be able to execute the assessment of the construction variants, the Lekki construction variant (Variant 0) had be schematized (Chapter 4.3). This is comparable to the stage elaborated in Chapter 3 however there are some adaptation and optimizations made. This is described section A.3 of this appendix.

A.1. Acquisition of data

Wave climate data SWAN

The wave conditions at the Lekki coast are obtained from the modelling study for the development of the final design of the Sandbar breakwater (CDR International, 2017). The wave climate is based on a large scale SWAN model which is calibrated against the local measurements. The SWAN data provides wave data for 10 years over the period 2005-2015. By using this nested SWAN model a monthly nearshore wave climate was set up by CDR. This wave climate is in this research to compare the actual observed wave data during the Lekki project with the SWAN data (Chapter 3) and is later on used for the morphodynamic modelling study of the construction variants.

Wave Rider

For the measurement of the wave conditions during the construction of the Lekki project a Directional Wave Rider (Figure A.1.) is used. This buoy is the world's standard in measuring wave height and direction. The wave direction can be determined with an error between 0.4 and 2 degrees, with a typical error of around 0.5 degrees and a resolution of 1.4 degrees. The wave height can be measures with a resolution of 0.01 meters and can measure waves within a range of -20 to +20 m. The accuracy of the wave height measurements is less than 0.5% of the measured value after calibration (Datawell, Directional Waverider MkIII). The wave buoy was located south west of the Sandbar breaker during the project and gives each half hour output data.

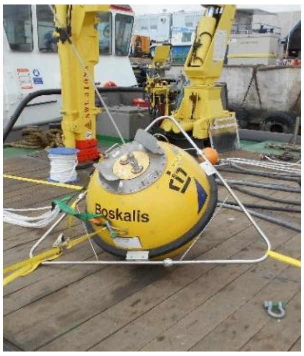

Figure A.1: An impression of the Wave Rider used during the Lekki project

Bathymetric survey data

Two methods were used to acquire the surveys used in this report. The submerged parts of the project were measured by a multibeam. For the parts of the project that were above water, a drone with photogrammetry was used.

A multibeam echo sounder (MBES) system (Figure A.2.) is an extension of a single beam echo sounder. The MBES transmits several sound beams to the sea bed, covering a much larger area than the single beam can. The transmitted beam reflects back to the ship. The time it takes for the beam to arrive back at the ship can be used to calculate the distance between the ship and the sea floor (Theberge and Cherkis, 2013).

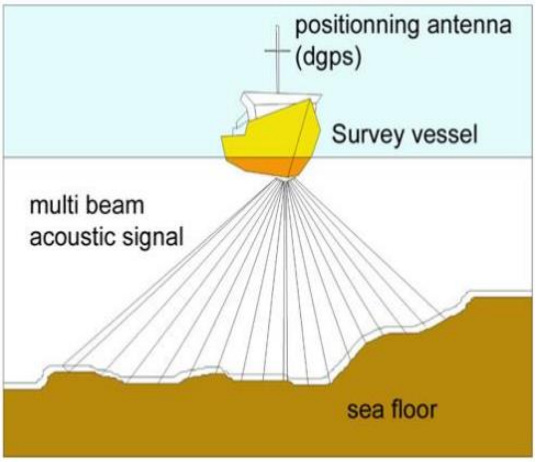

Figure A.2 A multibeam echo sounder (www.idscope.mc/Geophy03_EN, retrieved: July 14th

The drone uses a concept called photogrammetry. Photogrammetry is a three-dimensional coordinate measuring technique that used photographs to measure the bed level. The fundamental principle used in this method is aerial triangulation. Several photographs are taken of the same spot, but from at least two different angles. 'Lines of sight' are developed from these photographs and are mathematically intersected to extract the three-dimensional coordinates of that spot (Pillai, 2015).

These two datasets are later combined into one survey, containing the data above water level and below water level. There is a small area that both methods cannot reach. The ship containing the MBES cannot reach the shallow surf zone, and the drone can only measure the bed level above water. To combine these two datasets into a complete survey, the missing area is linearly interpolated.

Bathymetric data before the construction phase

The bathymetric data of the study area where the Lekki Sandbar breakwater is constructed was obtained from CDR International project data. This survey was obtained from the situation in May, 2016, which is 1.5 years before the actual construction of the Sandbar. By that time two groynes were present at the coastline (see Figure A.4). The area which was surveyed has a length of about 4000 m alongshore and a width of about 1000 m in cross-shore direction.

Bathymetric data during the construction phase

Each week a bathymetric week survey was acquired explained in the way above to supervise the progress of the project. These bathymetric surveys are used for the Lekki project analysis and the calibration of the XBeach model (Sand Engine).

Dredger vessel data and ship logs

The data from the operating hoppers for the Lekki project is used for the project analysis (Chapter 3) and later on for the development of construction variants in Chapter 4. The operational time of the different vessels is obtained from AIS data from the Boskalis World website where all available information of the Boskalis fleet is available.

The details of the trip duration, nourishment activities, dump location of the different operating vessels was obtained from the ship logs obtained from the Lekki construction site. This was used as a framework for assumptions regarding production rates, trip duration and (un)loading time of the vessels which is implemented in the different construction alternatives.

A.2. Situation before and during the construction of the Sandbar breakwater

In this section the situation of study area before the construction phase of the Sandbar breakwater is presented as well as during the construction execution (by bathymetric week surveys). The Sandbar and Sand Engine were constructed from December 2017 until April 2018.

Before start construction- January 2015

In Figure A.3 the situation of the coastline in January 2015 is shown. What can be seen from this image is the straight shoreline and the absence of long roller waves. Furthermore, a community is located in northwest from the Sandbar breakwater design.

Figure A.3: Top view of the Lekki coast in January 2015 (Svasek, 2017)

Between 2015 and 2016 two groynes have been built in the area of interest. Two short groynes are present perpendicular at the coastline shown in Figure A.4. The morphological impact of these groynes is also clearly visible: erosion east of the groynes and sedimentation west of the groynes. The situation in Figure A.4. after the removal of the groynes is considered as the situation before the start of the construction of the Sandbar Breakwater.

Figure A..4: Top-view of the Lekki coast in May 2016 (Svasek, 2017)

Bathymetric week surveys January Sandbar

In Figure A.5. the progress of the nourishments during the month January is visualized by four bathymetric week surveys: the reclamation of the submerged bund and the Sandbar Road from the coast.

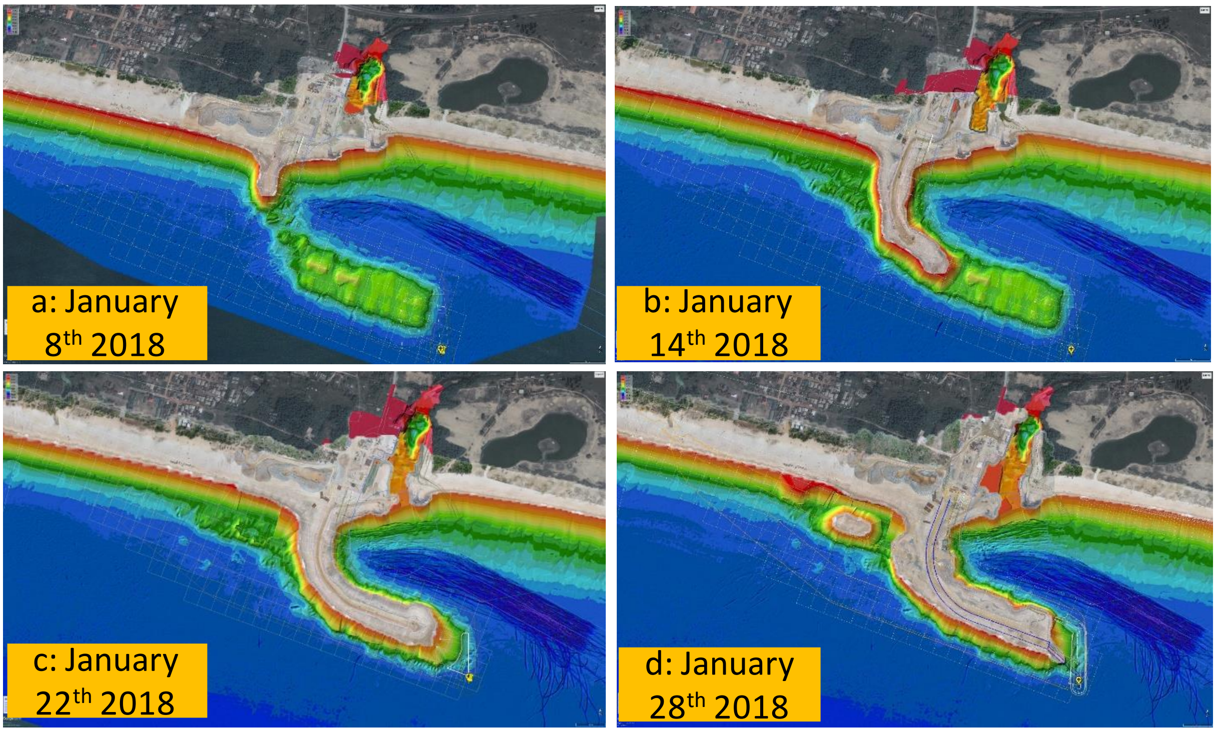

Figure A.5: Bathymetric week surveys January Sandbar: (a): Survey of 8th January (b): Survey of 14th January (c): Survey of 22th January (d): Survey of 28th January (Boskalis, 2018).

Bathymetric week survey February Sandbar

In Figure A.6. the progress of the nourishments during the month January is visualized by four bathymetric week surveys: the reclamation of the Sandbar.

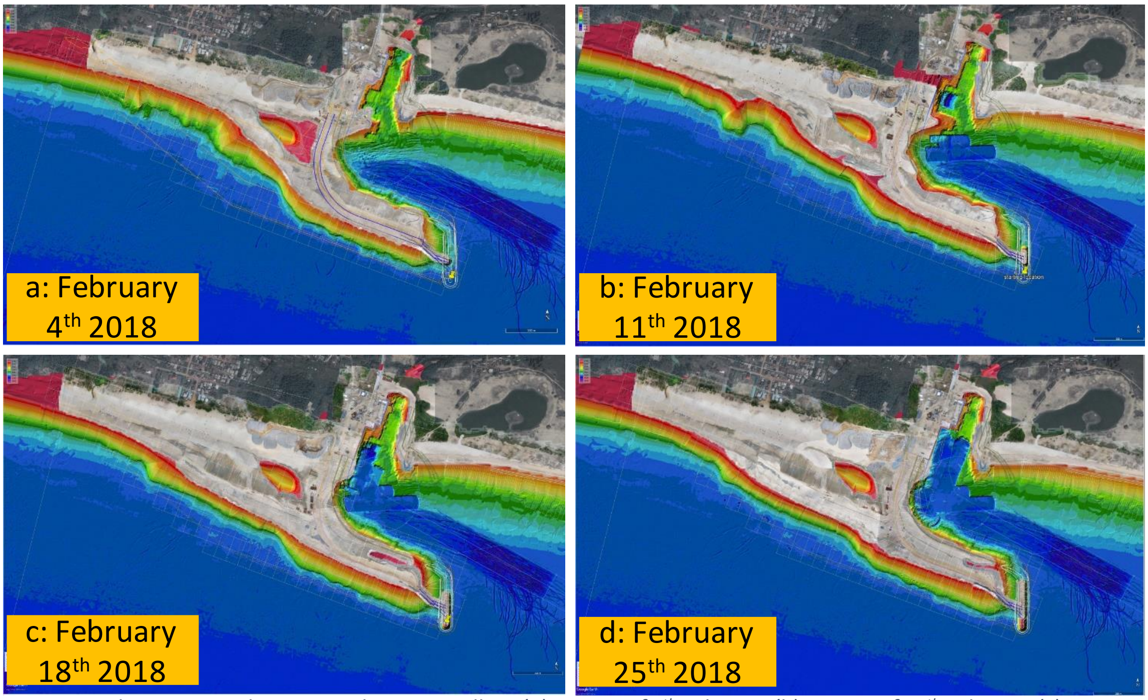

Figure A.6: Bathymetric week surveys February Sandbar: (a): Survey of 4th February (b): Survey of 11th February (c): Survey of 18th February (d): Survey of 25th February (Boskalis, 2018).

Bathymetric week survey March Sandbar

In Figure A.7. the progress of the nourishments during the month January is visualized by four bathymetric week surveys.

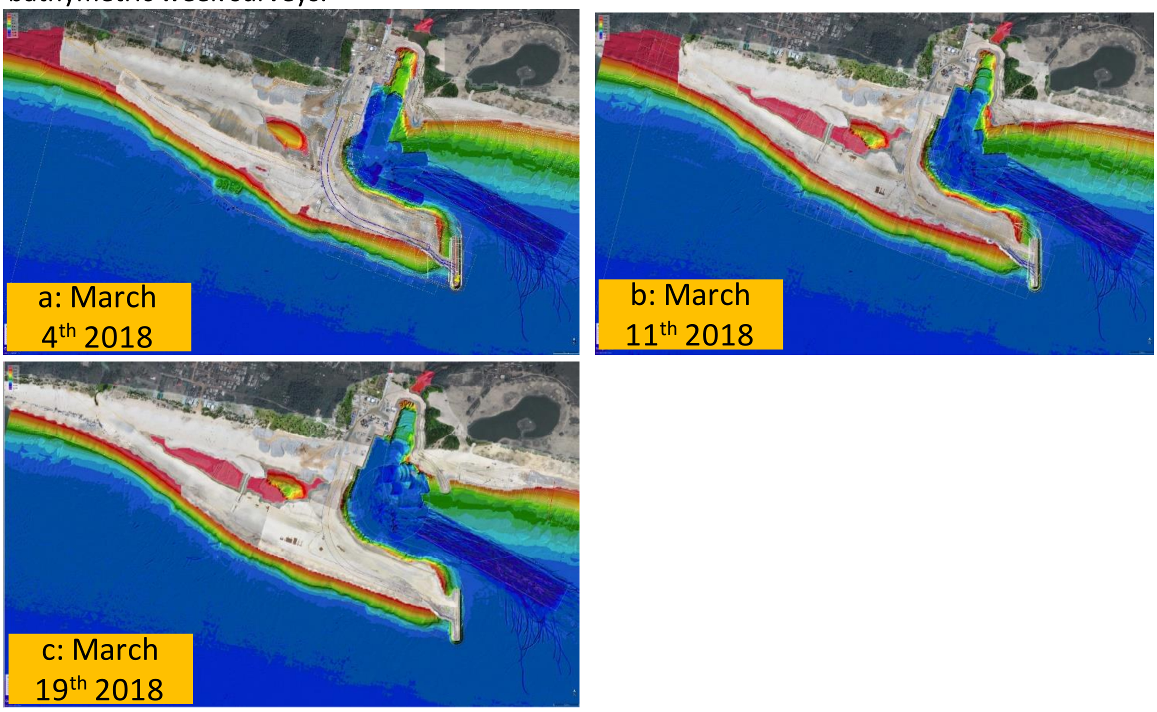

Figure A.7: Bathymetric week surveys March Sandbar: (a): Survey of 4th March (b): Survey of 11th March(c): Survey of 19th March (Boskalis, 2018).

Bathymetric week survey Sand Engine March & April

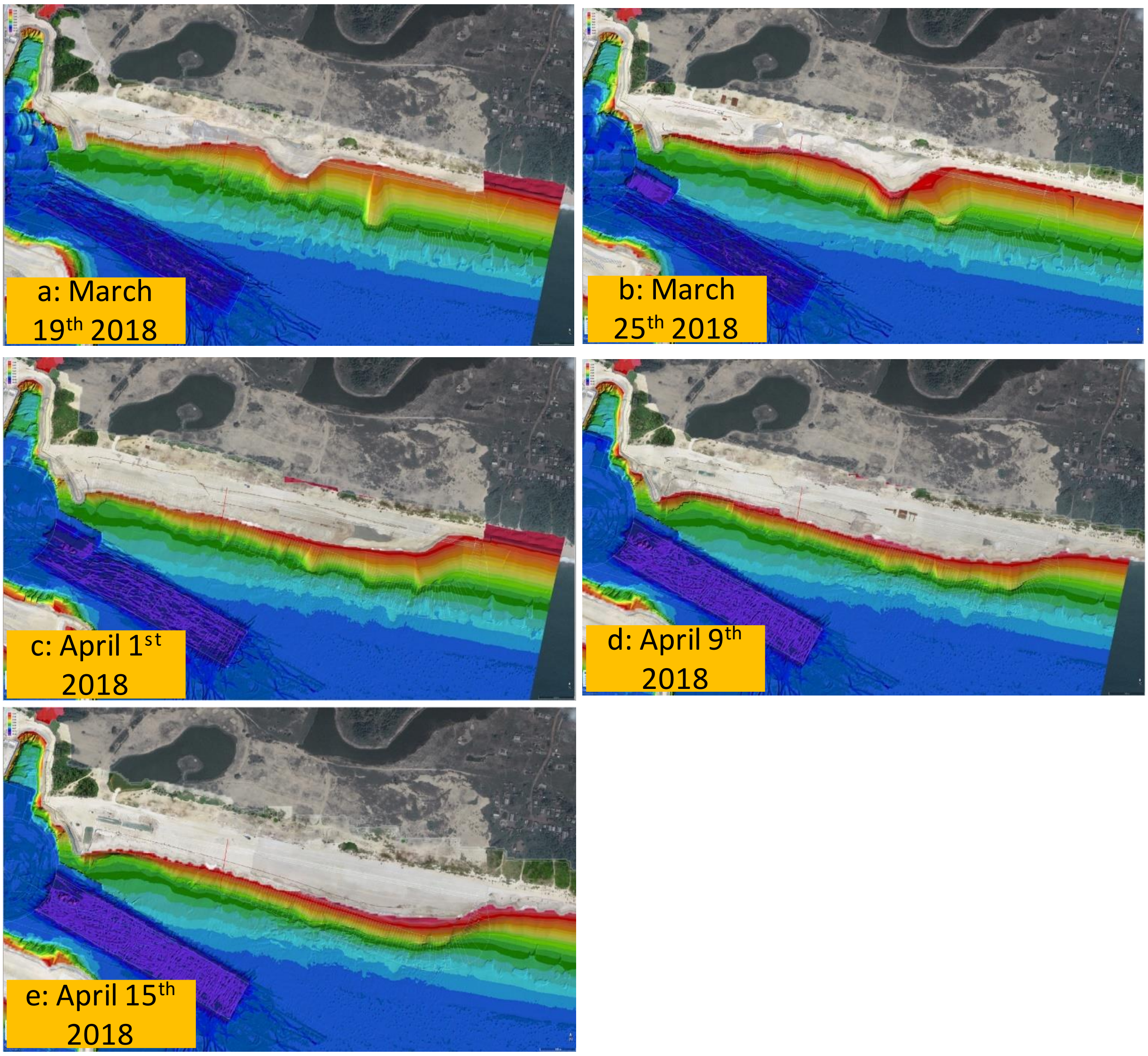

Figure A.8: Bathymetric week surveys Sand Engine: (a): Survey of 19th March (b): Survey of 25th March (c): Survey of 1st April (d): Survey of 9th April (e): Survey of 15th April (Boskalis, 2018).

Final bathymetric survey Sandbar and Sand Engine 25 July

The bathymetry of the Sandbar breakwater several months after completion

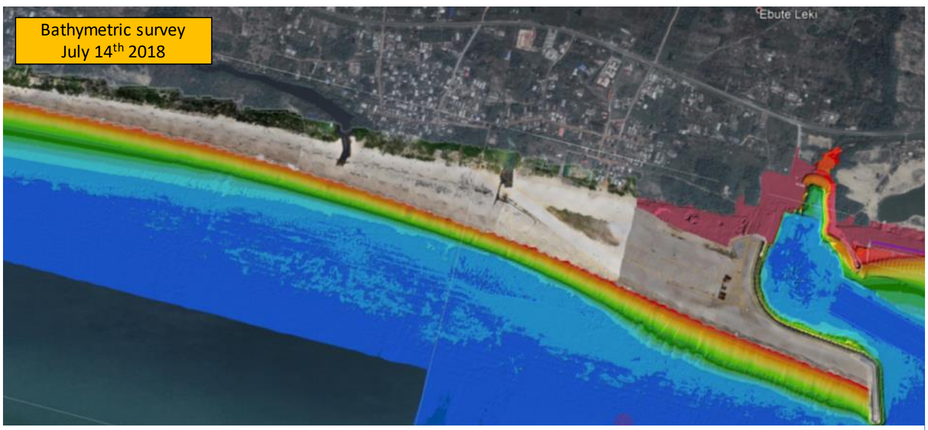

Figure A.9: Final bathymetry of the Sandbar breakwater (July, 2018) (Boskalis, 2018)

A.3. Generalized construction method Lekki project [Variant 0]

Construction variant 0 represents the executed construction method for the Lekki Sandbar breakwater which is a reference case [Variant 0] for the different construction alternatives.
In this section the construction method will be briefly summarized and generalized which is used for the model simulations regarding sediment losses. In principle the construction process for this scenario can be summarized by six main stages:

1. Nourishment offshore submerged bund
2. Reclamation of Sandbar Road
3. Construction of Sandbar Groyne
4. Reclamation of Sandbar to the west from Sandbar Road
5. Further widening and heightening up to design requirements
6. Reclamation Sand Engine and construction of lee side revetment Sandbar breakwater

1. Nourishment offshore submerged bund by bottom dumping

In the first stage of the project a hopper vessel (TSHD) will commence with the nourishment of an offshore submerged bund up to -5 m by discharging the load via opening the bottom doors. The location of the submerged bund is presented in the design in Figure A.10-1 which is based on the surveys after the first construction weeks from the beginning of January 2018. The dimensions of the bund are approximately 400 x 100 m with a volume of 525,000 m^3. At certain moments there was more than one THSD operating on the nourishments of the offshore submerged bund, however it is assumed that on average this construction stage is executed by one TSHD. When taking into account these losses the duration of this stage of the project is estimated to be almost 4 weeks with one TSHD operating on the site nourishing a total volume of 525,000 m^3 of sand.

2. Reclamation of Sandbar Road by rainbowing/ 3. Construction of Sandbar Groyne

As one hopper (TSHD) is still working on nourishing the offshore submerged bund, a second TSHD is started at reclaiming the Sandbar Road expanding from the coast at the east side of the Sandbar breakwater design (Figure A.10-2). This TSHD will expand a bund in offshore direction by applying a combination of the discharge methods bottom dumping and rainbowing depending on the water depth. The bund up is heighten up to approximately +1 m.

This process will continue to the south eastern tip of the Sandbar Road. The bund expansion is not applied over the full width of the Sandbar design profile as horizontal progress is preferred to access the Sandbar Groyne. The two operating TSHDs in this stage of the project have a production rate of 350,000 m^3 per week. The volume of sand which is needed to nourish a small bund from land up to the Sandbar Road tip is 900,000 m^3 which takes 2.4 weeks (17 days). When taking into account these losses the duration of this stage of the project is estimated to be 4 weeks with one TSHD operating on the site nourishing a total volume of *900,000* m^3 of sand. The further widening of the Sandbar will be done by pumping sand ashore from the Turning Basin in a later stage of the construction project. As soon as the Sandbar Groyne is been accessed from land an access road will be created in order to start the construction of the Sandbar Groyne. By the time the tip of the Sandbar Road is reached from land (Figure A.10-3) the construction of the so-called 'Sandbar Groyne' has been commenced in order to prevent sediment from eroding/bypassing from the Sandbar breakwater profile. The dimensions and specification of the Sandbar Groyne are stated in the Table A.1. below.

Table A.1: Specifications of the Sandbar Groyne constructed at the south-eastern tip of the Sandbar Road

Specification	Quantity
Length	225 m
Crest width	Minimum 8 m wide at +4 m on top of (temporary) Quarry Run for construction
Crest height	+5 m at finished level (QR core at +4m during construction)
Slope	1:1.5 for concrete elements and rock material and a 1:3 slope on backside protection
Rock material	QR (1-500/1000kg), backside protection (10-60 kg + 60-300kg), Underlayer (300-1000 kg or 500-1500 kg), 1-3 t Rock and 2 m^3 Concrete Elements (Accropode 1)

4. Reclamation of Sandbar to the west from Sandbar Road, further construction of Sandbar Groyne

The next stage in the Lekki Sandbar breakwater project was the expansion of the Sandbar from the Sandbar Road at the onshore side of the design profile (Figure A.10-4). This means that two hoppers (TSHDs) are rainbowing the onshore Sandbar bund to the East up to +1 m. Furthermore, the construction of the Sandbar Groyne will continue and be completed.

The will be done up to the most western location of the Sandbar design profile closing the inner lake by connecting the Sandbar with the initial coastline which is visible in Figure A.10-5. This stage will be reached after 2.5 weeks after the start of the construction.

5. Further widening and heightening up to design requirements

Once the Sandbar is connected with the initial coastline at the western tip of the design profile, further widening of the Sandbar will be will be executed. The further widening of the Sandbar will be executed up to + 1m by discharging the load via rainbowing. When taking into account these losses the duration of this stage of raising the bed up to +1 m for the entire design profile of the project is estimated to be 4 weeks with two TSHDs operating on the site nourishing a total volume of *875,000* m^3 of sand. Simultaneously, a cutter (CSD) will start with the dredging of the Turning Basin and the Access Channel in order to further heighten the Sandbar breakwater up to the design requirements. The maximum crest level of the Sandbar breakwater is 4.5 m. The cutter starts heightening the Sandbar from the landside of the Sandbar Road (Figure A.10-6). For pumping sand ashore extra equipment is needed, such as pipelines, bulldozers to spread the sand and the extra time and man hours. This is further specified in the Chapter 6 'Financial cost'.

The widening and heightening continues in order to meet Sandbar breakwater design requirements (Figure A.10-7). The total volume which is been dredged by the CSD and pumped ashore is 700,000 m^3. The remaining volume of sand which is needed to heighten the Sandbar up to +4.5 m is done by the operating TSHDs by pumping sand ashore. The total volume of Sand which is been discharged by pumping ashore by TSHDs is 300,000 m^3 with a duration of 3.4 weeks (33 days).

6. Construction of the Northern Groyne, reclamation of the Sand Engine and construction of lee side revetment Sandbar breakwater

The last phase of the project is to reclaim the Sand Engine and to construct the leeside revetment at the inner slope of the Sandbar Road and the construction of the North Groyne, which is illustrated in Figure A.1.8. At the Sand Engine a volume of 850,000 m_3 of sand should be nourished. For the construction of the North Groyne and the Sandbar Groyne a total mass of 270,000 t is required. For the installation of the geotextile 18,000 m^2 is needed. After the completion of this stage the construction of the Sandbar breakwater is fully completed which is illustrated in Figure A.10-8.

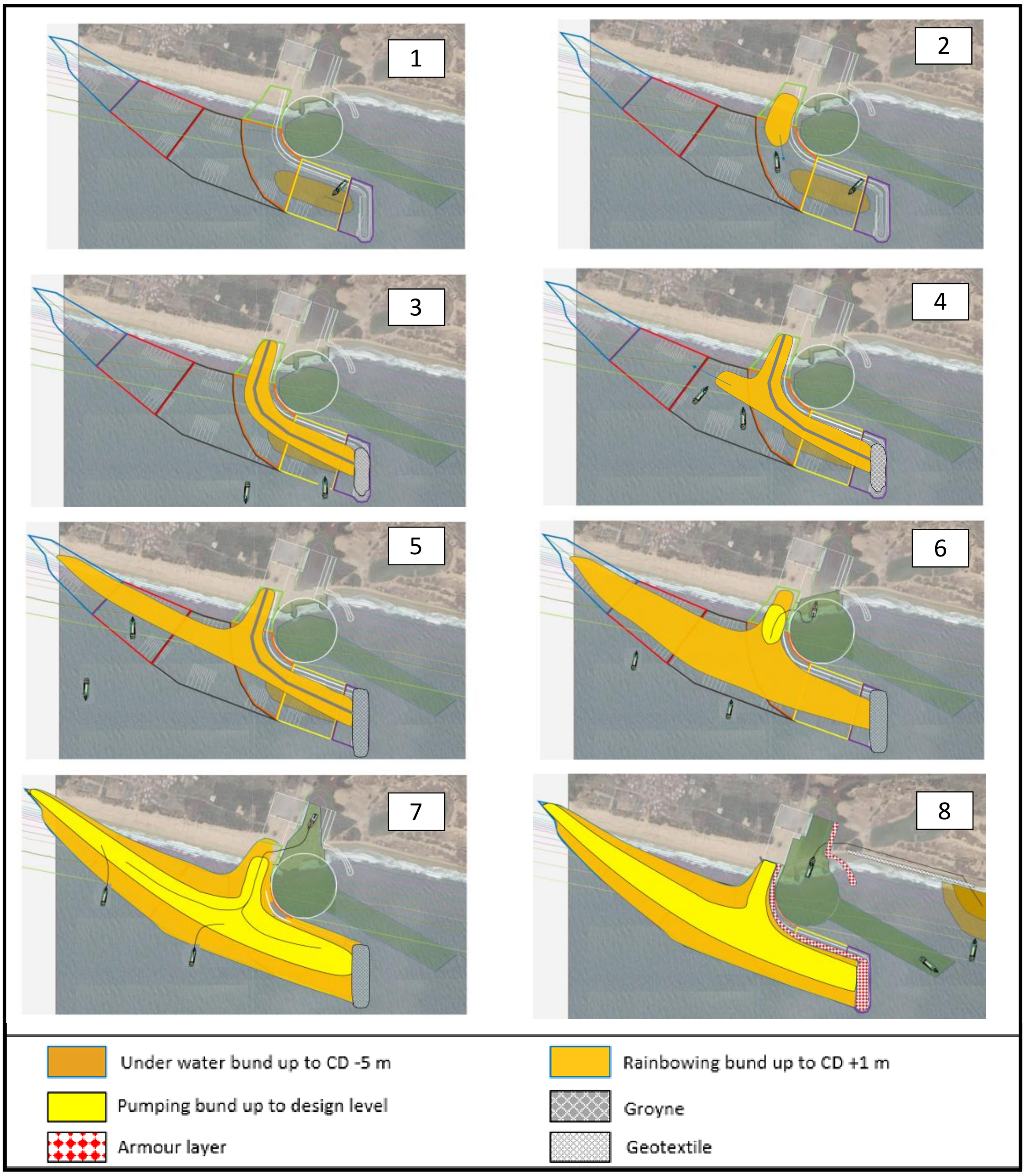

Figure A.10: An overview of the 8 stages for the generalized construction method of the Lekki project [Variant 0], starting with the nourishment of an offshore submerged bund (1) followed by the reclamation of the Sandbar Road (2). Next to that the Sandbar is reclaimed by two TSHDs (3,4,5) and subsequently the profile is further brought up to design requirements by pumping ashore (6,7,8).

Time planning of reference scenario [Variant 0]

The time planning of construction scenario 0, which started in at the beginning of November and is finished at the end of February to ensure nourishment execution during the calm season.

Months	November				December				January				February				March
Weeks in month	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1
Cummulative weeks	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Stages																	
Stage 1: Submerged bund																	
Stage 2: Sandbar Road																	
Stage 3: Sandbar Groyne																	
Stage 4: Sandbar																	
Stage 5: Widening and heightening Sandbar																	
Stage 6: Sand Engine, Lee Side Revetment																	
Operational time dredging vessels																	
TSHD-1 (active full period, in actual project 4 TSHD partly in operation)																	
TSHD-2 (active full period, in actual project 4 TSHD partly in operation)																	
CSD-1																	

Nourishment method volumes

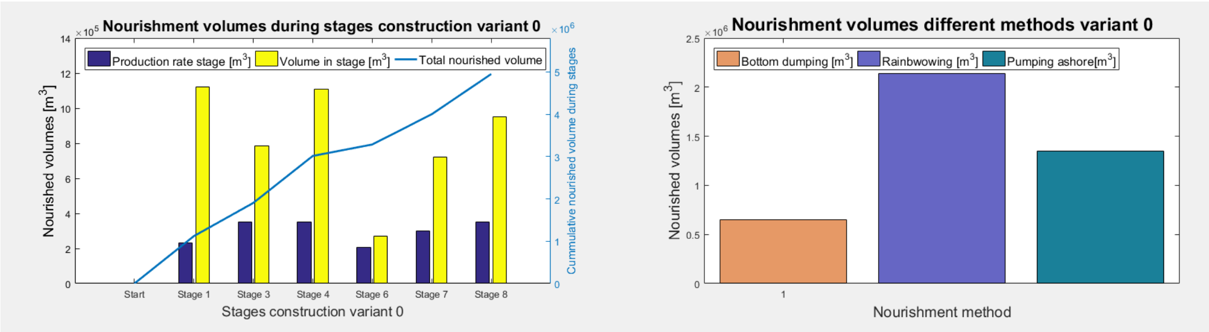

Figure A.11: Construction variant 0 details: (a): Time planning of different stages in scenario (b): Nourishment volumes during different stages (c): Nourishment volumes of applied nourishment methods in scenario.

Appendix B: Volume and cost determination sand nourishments work

In this this Appendix a detailed description is given on the different applied nourishment methods and the corresponding production rates which is required for the development of the construction variants. Next in this Appendix, various cost assumptions and calculations are stated which are required for the financial assessment of the construction variants.

B.1. Dredging equipment and nourishment methods

First a general description is elaborated on the used dredging equipment for the execution of the reclamation works. Also the different applied nourishment methods (bottom dumping, rainbowing and pumping ashore) is generally explained which is useful for the estimations and calculations regarding the development of the construction scenarios (B.2.).

B.1.1. Reclamation work equipment

The main reclamation work equipment used for the construction of a Sandbar Breakwater are a hopper vessel (TSHD) and a cutter dredger (CSD).

Trailing suction hopper dredgers

A Trailing suction hopper dredger (TSHD) is classified as a hydraulic dredger. This type of dredger is used for a broad variety of maritime construction and maintenance projects.
An example of projects where a TSHD is good applicable are the maintenance dredging of ports and access channels to remove sand to bring these areas to necessary depths. Other kind of project which could be executed by a TSHD may be a giant land reclamation projects that require millions of cubic metres of sand (IADC, Facts about Trailing Suction Hopper Dredger, 2014). The construction of the Sandbar breakwater suits very well in this kind of project descriptions. The performance efficiency of a TSHD has a direct influence on the cost of a project (see section B.2.).

Hopper (TSHD) used in construction variants

For the scenarios it is assumed that a Trailing Suction Hopper Dredger (TSHD) type 'Shoalway' is used for carrying out the sand nourishments. The THSD 'Shoalway' is chosen since it is a middle large hopper which is highly manoeuvrable and is equipped with a powerful engine. More specifications of the TSHD 'Shoalway' is given in Table B1. and an images of this hopper is shown in Figure B.1: The TSHD 'Shoalway', obtained from Boskalis Equipment SheetFigure B.1.

Table B.1: Technical specifications of Trailing Suction Hopper Dredger (TSHD) type 'Shoalway'.

Trailing Suction Hopper Dredger (TSHD)	
Dimensions	Length: 90 m; width: 19 m
Maximum hopper capacity TSHD type 'Shoalway'	4,500 m3
TSHD capacity in practise	3125 m3
Draft of TSHD when fully loaded	5.82
Rainbow distance	30-80 m
Sailing speed TSHD 'Shoalway'	11 kts (5.7 m/s)

Figure B.1: The TSHD 'Shoalway', obtained from Boskalis Equipment Sheet

Cutter suction dredgers

A Cutter suction dredger (CSD) can also be classified as a hydraulic dredger. This type of dredger is generally the most common ships used in the hydraulic category (IADC, Facts about Cutter Suction Dredgers, 2014). All CSDs are equipped with a rotating cutter head, which is applicable for cutting a wide range of materials like hard soil, gravel, sand, silts, etc. and rocks into particles. The soil which is sucked by the dredge pumps of the CSD is pumped by the use of pumps, floating pipelines or loaded in a split hopper which is moored alongside. A CSD is generally used for land reclamation, deepening of harbours and for the construction and expansion of ports and navigational channels or for pipeline trenching in the seabed. When the dredged material is being used for land reclamation, the distance between the dredging and disposal areas is usually shorter than the distances covered by Trailing Suction Hopper Dredgers.

A CSD is sensitive to rough seas and is not easily moved during project execution. They are however characterised by high production rates with continuous rates and are suitable to work in shallow waters. In the Sandbar breakwater project the CSD is non-propelled and is not able to be propulsive by it selves. It was used for the deepening of the entrance channel and the turning basin. Factors influencing the production rate, besides the type of soil being dredged, include the minimum and maximum width of the cut. This will influence the installed cutter head side winch power, the strength of the ladder, the spuds and the pontoon (IADC, Facts about Cutter Suction Dredgers, 2014).

Cutter (CSD) used in construction variants

For the cutter dredging activities in the different construction variants, it is assumed that a CSD type ‘350’ is used. The CSD type ‘350’ is chosen as it a middle large, often used cutter dredger which is well suited for dredging the Turning Basin and Access Channel. More specifications of the CSD ‘350’ is given in Table B.2. and an images of this cutter is shown in Figure B.2.

Table B.2: Technical specifications of Cutter Suction Dredger (CSD) type ‘350’.

Cutter Suction Dredger (CSD) type ‘350’	
Dimensions	Length: 30 m; width: 18 m
Dredging depth	9 m
Draft of CSD	2.82 m

Figure B.2: The CSD ‘350’, obtained from Boskalis Equipment Sheet

Other machinery

Apart from the dredgers used for the breakwater construction several other types of machinery is been used like bulldozers, excavators and wheel loaders, which is especially used for the pumping ashore method (see B.1.2). The way this equipment is used for the project of the Lekki Sandbar breakwater is described in the Literature Review developed before this study (Wilbrink, 2018).

B.1.2. Sand nourishment methods

In this section the applied nourishment method for the construction variant have been shortly explained which forms a basis for the determination of the production rates for the dredging equipment and different nourishment methods.

Bottom dumping

The bottom dumping method can be described by discharging the load through the bottom doors once the captain is sure the vessel is in the correct location (see Figure B.3.).

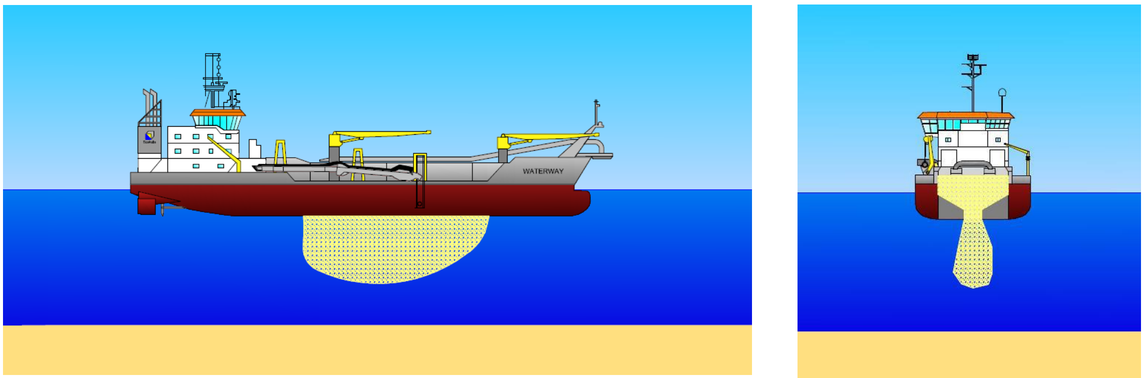

Figure B.3: TSHD discharging at reclamation area, via bottom doors (Boskalis, 2017).

Unloading sand by bottom dumping provides a rapid (initial) build-up of a reclamation area. On the Lekki project the water depth is limited, however the TSHDs have for the deeper areas the possibility to discharge their load by opening the bottom doors.

Rainbowing

The rainbowing method can be used for areas where the dredger can approach the shoreline closely, and at areas where material has previously been discharged via the bottom doors that have become too shallow for additional dumping. The dredged material in the hopper will be mixed with water and pumped overboard through a jet nozzle at the bow of the TSHD, which is illustrated in Figure B.4.. The rainbowing technique is often the best method for shallow areas from economic perspective since it is a fast, straight-forward method and does not require floating or submerged pipelines, boosters or landlines, it is often the most economical method.

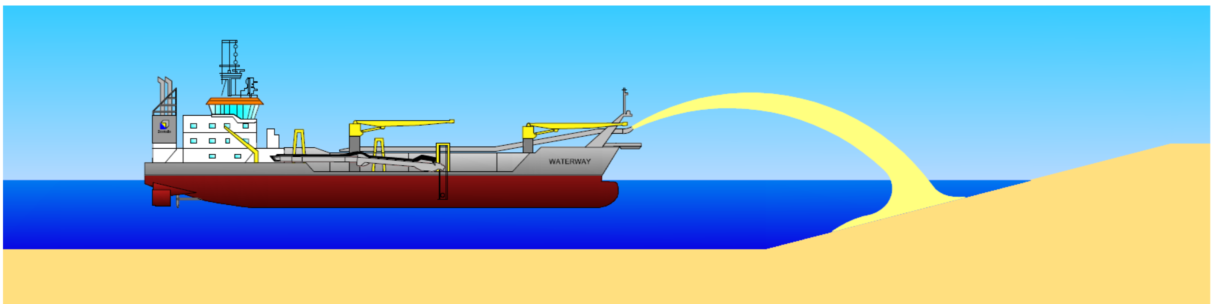

Figure B.4: TSHD discharging via rainbow installation (Boskalis, 2017).

Pumping ashore (PASH)

Furthermore, another method of nourishing sand is discharging through a pipeline (PASH). It can placed or pumped on site through floating or submerged pipelines when other methods are not possible (area too remote, etc.). This method will be used when the dredger cannot reach the shore because of depth restrictions, or other obstacles. During regular reclamation works, the shore line will be extended as the reclamation area is being filled with materials. On the Lekki project a combination of floating pipeline and shoreline is applied. An illustration of the pumping ashore discharge method is schematised in Figure B.5.

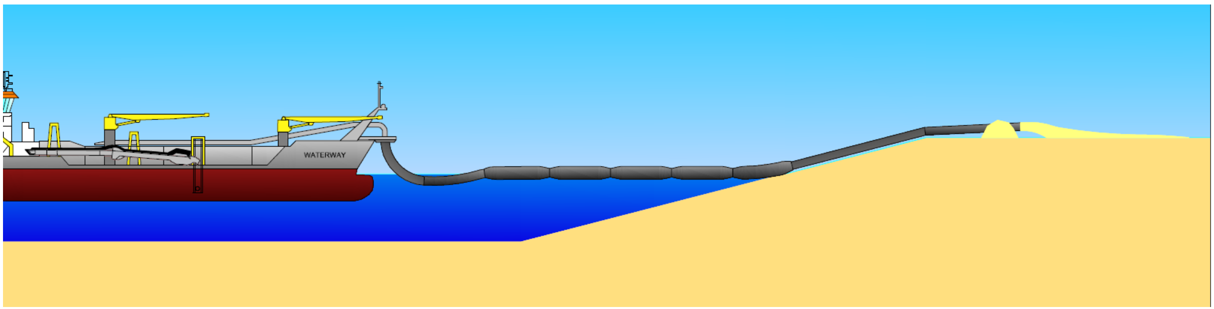

Figure B..5: TSHD discharging via floating pipeline to a reclamation area (Boskalis, 2017).

Several practicability aspects have to be taken into account during the nourishment method:

- Pipelines need to be moved/extended from time to time In order to progress the reclamation further onward. To not interrupt the discharging process, a pipe with a quick coupling system will be connected while discharging continues. A short and direct route is desired to minimizes the internal friction between the sand-water mixture and the pipeline and is therefore more efficient.
- Excavators and bulldozers need to be deployed in order to manage the flow of the sand water mixture when the reclaimed area is above the water level. This equipment is used to drive in front of the discharge pipe by creating channels in the sand just below the water surface to direct the mixture to the desired location or to directly deflect the sand water mixture.

Sand nourishment methods in construction variants

Based on the technical specifications of the implemented dredging equipment in the construction variants, literature research and expert appraisal, the depth levels to which a certain nourishment method can be executed are determined. These depth are presented in Table B.3. Based on these level, the volumes of sand which can be nourished by a certain method are determined. These volumes of sand in the Sandbar breakwater design profile are also specified in Table B.3.

Table B.3: Nourishment method specifications: level to which a specific nourishment method is applicable and the maximum volume of sand which can be nourished by a certain nourishment method into Sandbar breakwater design (Bak, 2017) .

Nourishment method specifications	
Level to which bottom dumping method is applicable	-5 m
Level to which the rainbowing method is applicable	+ 1 m
Level to which the pumping ashore method is applicable	+4.5 m (design requirements)
Volume in the Sandbar breakwater design profile below -5 m (where bottom dumping method is applicable)	1,090,000 m^3
Volume in the Sandbar breakwater design profile between -5 and +1 m rainbowing into Sandbar breakwater design	1,890,000 m^3
Maximum volume of sand which can be nourished by pumping ashore into Sandbar breakwater design	1,020,000 m^3

B2. Sand nourishment production rates

The major work for the construction of a Sandbar breakwater is the nourishment of sand in the design profile. Different nourishment methods and equipment are used. It is assumed that the dredging works will be conducted during 24 hours per day and 7 days a week during the nourishments phase which was also at the Lekki project. The production rates per week for the TSHD and the CSD for the different nourishment methods are determined based on literature and data from the Lekki project (ship logs).

B.2.1. Production rate Trailing Suction Hopper Dredger

In order to obtain realistic estimations of the production rates for the Trailing Suction Hopper Dredger (TSHD), the loading and unloading time and the sailing time to the borrow area are quantified in Table B.4.

Table B.4: Time durations different activity during sand nourishment execution of a hopper vessel (TSHD).

Activity of hopper during project	Time
Sailing time borrow area to construction site	1 hour
Loading duration of TSHD at borrow area	1 hour
Discharge duration of TSHD at construction site 'bottom dumping'	15 minutes
Discharge duration of TSHD at construction site 'rainbowing'	1 hour
Discharge duration of TSHD at construction site 'pumping ashore'	1 hour and 30 minutes

Based on the analysed data and estimations, the weekly production rates can be obtained for the different discharging methods which is presented in Table B.5 below.

Table B.5: Production rates different discharge methods of a hopper vessel 'Shoalway' (TSHD).

Sand nourishment method	Cycle time	Production per hour in practice	Cycles per week
Bottom dumping	2 hours and 15 minutes	1400 m^3	75
Rainbowing	3 hours	1050 m^3	56
Pumping ashore	3 hours and 30 minutes	900 m^3	48

B.2.2. Production rate Cutter Suction Dredger

Also for the Cutter Suction Dredger (CSD) an estimation of the weekly production rate is been made. The maximum production rate per hour is 2,000 m^3. However what appears from the Lekki project in practice this rate is much lower, since the CSD has to move from time to time to dredge the entire borrow area up to the desired bed levels. Also the installation, the movement and the maintenance of the pumping pipes lowers the production rates. Therefore an actual averaged hopper capacity of 1100 m^3 per hour is determined. An overview of the production rates is presented in Table B.6. below.

Table B.6: Production rate of cutter suction dredger '350' (CSD).

Discharge method pumping ashore CSD		
Maximum production per hour	Effective production per hour in practice	Dumping production per week
2000 m^3	1100 m^3	205,000 m^3

B.3. Financial cost estimations

In this section the financial cost for the different construction variants are determined. First various bulk- and unit prices are estimated for the required materials, the (de)mobilization of the dredging equipment and the execution of the different nourishment methods. Next, the total cost for each construction variant can determined as well as the cost for the sand reclamations and the construction of the hard structures being part of the conceptual designs of the different construction variants. This is presented in a cost table for each variant in section B.3.3. In order to assess the financial cost of the different variants, the cost are compared to the Lekki project (Variant 0) as well as to each other.

B.3.1. Cost component determination

Nourishment cost

In order to quantify the cost for the sand nourishment, first the cost price per m^3 for the different nourishment methods are determined. Based on experiences from the Lekki project, literature (Bak (2017), Hauer (1998)) and benchmarks within CDR and Boskalis the cost price of all applied nourishment methods, (de)mobilization of the dredging vessels and the captured-and lost sediment during the construction phase quantified during the modelling study. The unit cost are presented in Table B.7 and briefly explained below.

Table B.7: Cost unit prices for sand reclamation works.

Cost component	Unit price
Mobilization cost	
Mobilization Hopper (TSHD)	*$1,000,000*
Mobilization Cutter (CSD)	*$ 950,000*
Reclamation cost	
Bottom dumping reclamation works	*$ 3/m^3*
Rainbowing reclamation works	*$ 4/m^3*
Pumping ashore (PASH) reclamation works	*$ 5/m^3*
Financial losses/gains morpho dynamics	
Sand naturally accreted into design profile	*$ 3.5/m^3*
Sand losses	$ 5/m^3

The mobilization cost for a middle large hopper (TSHD) included all the preparations, travel time to site, equipment and labour made in advance, etc. which is for a cutter ($ 950,000) a bit lower than for a middle large hopper ($ 1,000,000).

The nourishment method cost vary between 3 and 5 $/m^3. The dumping method is financial most attractive due to high production rates and little extra required dredging equipment. Pumping ashore is a lot more expensive ($5/m^3) due to complex discharge execution, lower production rates and extra required equipment such as pipelines.

The cost for the sediment volumes which are considered as a loss or captured from natural processes 'naturally' into the design profile are also estimated. Since sediment losses during the construction process increases the complexity and at the same time decreases the project execution these unit cost prices is estimated to be 7 $/m^3. Since the most captured sediment is trapped into design profile at bed levels where normally the bottom dumping- or rainbow discharge method is applied the cost saving per captured cubic meter is estimated as *$3.5/m^3.*

B.3.2. Cost hard structures

General

Before the financial cost calculations for the different construction scenarios, different cost components in the Sandbar Breakwater design scenarios are determined. Since this research is on the sandbar only the construction cost for the Sand Engine (sand nourishments, installation of Geo Tubes) have been left out of consideration. In this section the cost components of the Sandbar Groyne, the temporary groynes (Western Groyne and Eastern Groyne), the North Groyne and the Leeside

Revetment are specified. Therefore, first estimations and calculations regarding the production, the transport and the placement of the hard materials have been made.

The main material which is been used for the construction of the hard structures in the design is Quarry Run (QR 1-500 kg & QR 10-500 kg). Furthermore in the Sandbar Groyne, the Leeside Revetment and the North Groyne also other construction materials as Backside Protection, Underlayer, Rock and concrete elements (Accropode 1) have been used.

Production

In this section estimations on the placement of hard materials have been drawn. From a study to conventional rubble mound breakwaters (M. Hauer, 1998) multiple unit prices have been found. Benchmarks within Boskalis have confirmed these numbers. The characteristics of the main used material are briefly discussed in this section. The other materials used for the groynes and leeside revetment are summarized in Table X. Regarding the main used material Quarry Run (1-500/1000 kg) the production cost depend on the opening of a quarry, equipment, blasting, sorting, loading and overhead cost. The total average production cost are approximated at *US $ 7,5* per ton irrespective of the number and size of the different rock classes (QR, Rock). The production cost for other/heavier materials are significant larger, however these materials are only used in the Sandbar- and North Groyne and not for the temporary groynes. In Table B.8 an overview of the unit prices is presented.

Transport

The transportation cost for the hard materials rocks and accropodes are based on the weight and distance. In case of the lighter class of rocks (lighter than 700 kilograms) the transport cost were estimated at $0.125 per ton per kilometre. For this estimation, fuel, equipment, and unloading at the project site is taken into account. For rock sizes heavier than 700 kilogram the transport cost were estimated at $0.20 per ton per kilometre. Since the temporary groynes materials are an combination of lighter and heavier stones the cost are estimated at $0.15 per ton per kilometre. The distance from the quarry to the construction site is set to be 75 kilometres.

Placement

Placement unit cost are found to be in the range $3 per ton for the placement of core material to $10 per ton for the placement of stones over five tons. Placement cost are subjected to the method of the placement itself. This is especially of impact when regarding larger stone sizes. Whether the stones are placed, through rolling or floating equipment and submerged or emerged impacts the unit price. To be on the conservative side the unit price of floating submerged placement is taken into account. Very large rocks and concrete elements are designed to implement. These rocks and concrete elements require accurate placements and therefore are extra vulnerable to a harsh wave climate. Three times the normal placement cost for core material (M. Hauer, 1998) is consequently used in this cost determination.

Table B.8: Material cost for hard structures in the Sandbar Breakwater variants.

Cost component				
Material component	**Placement [$/ton]**	**Production [$/ton]**	**Transportation [$/ton]**	**Total**
Quarry Run and coarse grading (1-500/1000 kg)	9.00	7.50	11.00	**27.50 [$/ton]**
Heavy grading	30.00	7.50	18.00	**55.50 [$/ton]**
Concrete elements	250.00	200	45.00	**495 [$/m^3]**
Granular filter	22.50	7.50	18,00	**48 [$/m^3]**

Temporary Groynes cost

In the construction variant 1 and 3 one or two temporary groynes are implemented: the Western Groyne and Eastern Groyne. As described in the final design of the construction variants the required weights of Quarry Run for the construction of the temporary Groynes the Western and Eastern Groyne are respectively 8,000 and 13,000 ton. As the cost per ton are known the total cost for the temporary groynes can determined which is presented in Table B.9.

Table B.9: Cost of the temporary groynes implemented in the construction variants 1 and 3.

Cost component			
Groyne component	**Weight of Quarry Run [ton]**	**Cost per ton [$/ton]**	**Total [$]**
Western Groyne	8,000	27.50	$230,000
Eastern Groyne	13,000	27.50	$400,000

Lekki project hard structures components cost

The cost for the components of the different variants which were also part of the Lekki Sandbar Breakwater design were obtained from involved construction site experts. These components are present in all construction variants. For these obtained numbers the production and transportation cost are not included. These extra cost are determined and added to these cost components which is presented in Table B.10.

Table B.10: Cost of several hard structural design components part of the Lekki Sandbar Breakwater design.

Design component	Construction cost	Material production cost	Transportation cost	Total cost
Sandbar Groyne	$4,000,000	$ 1,600,000	$ 3,500,000	**$ 9,100,000**
North Groyne	$300,000	$ 520,000	$ 670,000	**$ 1,490,000**
Leeside revetment	$1,000,000	$ 810,000	$ 1,050,000	**$ 2,860,000**

B.3.3. Cost table overview Variant 1

In this section an overview cost table is presented for the calculation of the total cost of a construction variant. In Table B.11 the total cost for construction variant 1 is presented. The cost for the other variants are calculated in the same way and are briefly presented in Chapter 6.2.

Table B.11: Cost table for construction variant 1.

Construction Variant 1					
Dredging and reclamation work costs				**Hard structures costs**	
Mobilization costs	Unit price [USS$]		**Total cost [USS$]**	**Hard structural component**	**Total cost [USS$]**
Mobilization 2 TSHDs	1,000,000		2,000,000	*Construction Western Groyne*	*225,000*
Mobilization 1 CSD	950,000		950,000	Construction Sandbar Groyne	9,100,000
Total mobilization costs	*USD*		*2,950,000*	Construction North Groyne	1,490,000
Nourishment costs	Unit price [USS$/m3]	Volume [m3]	**Total [USS$]**	Construction Leesite Revetment	2,860,000
Bottom dumping reclamation works	3	1,190,000	2,975,000		
Rainbowing reclamation works	4	1,845,000	6,457,500		
Pumping ashore (PASH) reclamation works	5	965,000	4,342,500		
Financial losses/gains morphodynamics	Unit price [USS$]	Volume [m3]	**Total [USS$]**		
Sand naturally accreted into design profile	-3.5	55,000	-192,500		
Sand losses	5	200,000	1,000,000		
Total dredging/reclamation costs	*USD*		*17,532,500*	*Total costs hard structures*	*USD 13,675,000*
Total costs variant 1	***USD***				***31,207,500***

Appendix C: XBeach model analysis

In this Appendix more explanation is provided on the XBeach model, the executed model performance analysis, the calibration processes and the modelling approach for the assessment of the construction variants.

C.1. Model set-up and analysis

For the morphological analysis of the different construction scenarios, a XBeach model has been used. With this model first several general analyses and a sensitivity and calibration analysis is been carried out. In this appendix the general model set-up and characteristics are explained. Also the different applied boundary conditions, evaluation area and period for the model analysis have been distinguished.

C.1.1. General

The XBeach model for the Sandbar breakwater study area which is used for the assessment of the morphological behaviour of the construction scenarios in this research was set-up by CDR International colleague B.J.T. van der Spek. This was done in order to assess the morphological development of the Sandbar breakwater after completion. With the FINEL2-SWAN model also a morphological study was executed (Svasek, 2017) and the objective was to set-up another model (the XBeach model) to compare the different model results to each other.

There exists several XBeach versions, however for these study all runs were performed using the Kingsday release 1.22 revision 4867 in stationary mode. The model has a variable rectangular grid (dx=2-20 m, dy = 10-50 m, total of 228 x 307 grid cells), with smaller grid cells in the zone of interest. The hard part of the breakwater, the Sandbar Groyne is included in the model as hard structures (non-erodible layers). In order to carry out a proper sensitivity and calibration process all settings were set back to their default values.

C.1.2. Performed model analysis

XBeach is developed for 1-D modelling of beach erosion during storm conditions. The defaults settings are based on a typical Dutch coast and may differ for area with other characteristics and dynamics, they do not necessarily result in the best performance of the model at Lekki, Nigeria. For this research the performance of XBeach is investigated for the coastal system at Lekki, Nigeria. Therefore first several general model analysis are performed for non-calibration followed by a sensitivity- and calibration analysis. In the next section the methodology of the different model analysis is discussed.

C.2. Evaluation area and -period model simulations

In order to execute the sensitivity and calibration process an adequate modelling period and study area is determined. This was done for the Sand Engine over a time period of 20 day (13 April - 3 May), see chapter 5.1.

For the model analysis the morphological development for the cross-shore component and the volume changes (erosion and accretion) in the profile were evaluated by comparing these aspects with the real data obtained from the bathymetric surveys for the Sand Engine (

-a,b). The methodology of these evaluation criteria are detailed threated in section C.4. Evaluation criteria.

C.3. Boundary conditions model simulations

The (boundary) conditions determine the morphological development during the model simulations. There are different options to set the lateral boundaries for the wave model. For this study cyclic boundaries (keyword: cyclic) have been used which means that conditions on the lateral boundaries are copied to each other.

For the model performance runs (sensitivity/calibration) and the model simulations of the construction stages different wave input is determined. For the model performance analysis real observed data is used and for the model simulations construction stages variants the SWAN monthly wave climate is been used which is descripted in Appendix C.8.).

C.3.1. General description model boundary conditions

The way in which the hydro dynamic conditions are implemented in the XBeach model is briefly described below.

Wave boundary conditions

XBeach has several options for specifying the wave input. In this study the *jons_table* option is used in which a series of JONSWAP spectrums is defined. In each spectra different wave parameters are specified which is presented in Table C.1.

Table C.1: Parameters which need to be specified as boundary conditions for the XBeach simulations.

Parameter	Description
Hm_0 [m]	Spectral significant wave height
T_p [s]	Peak period
mainang [°]	Wave direction
gammajsp [-]	Peak enhancement factor for JONSWAP spectrum
s [-]	Wave spreading
duration [s]	Duration of each specified condition

Wave directional grid

The wave directional grid specifies the number of directional wave bins in the XBeach model. The wave direction (the direction where the waves originate from) are specified in Nautical coordinates (with an angle relative to the North (0°) and in clockwise direction (East = 90°). Due to the uniform wave climate the wave direction range is small and is specified between 180° and 230° (range of 50°). The *dtheta* is the defining parameter for the number of directional bins in the model. The number of directional bins should not impact the model results since it is not a calibration parameter. The *dtheta* was set to 5 degrees, dividing the wave directional grid into 10 directional bins since *dtheta* with a larger *dtheta* value gave different results.

Tidal boundary conditions

To account for a shifting breaker line the tidal water level variation has been incorporated in the model. From the system processes analysis it was stated that a small longshore tidal variations with a weak current is present in the study area. This means that the water levels are not exactly equal at the west and east boundary of model. This is implemented in the model by the option tideloc=2 within XBeach, which means that the water levels at both lateral boundaries can be specified.

C.3.2. Hydro dynamic boundaries for model performance analysis

Here the boundary conditions used for the model performance analysis are explained.

The wave boundary conditions for the model performance analysis are obtained from the wave buoy data, which gives wave height, period and direction for each half hour (see Appendix A.1). Therefore for every half hour a wave condition is inserted in the model which gives 960 conditions for 20 days for the model performance simulations except the spin-up time (see for more explanation of spin-up time: section C.5.3. Forcing and spin-up time). The tidal signal data during the 20 days of the model performance study is implemented in the model.

C.4. Evaluation criteria model simulations

The model simulations are evaluated by several different criteria. In this section the evaluation criteria of the model performance analyses are explained.

Different readers of this thesis, for example: researchers, engineers and contractors might all use different criteria to evaluate the accuracy of the model. Therefore the models will be evaluated mainly based on the following criteria, so this needs to be kept in mind when reading the results:

1. The coastal retreat at MSL [m] as a first indicator
2. The volume changes (erosion and accretion) in the profile [m^3]
3. The agreement of the bed level changes using the Brier Skill Score method [-] (Bosboom et al. (2014a):

The first indication is only used to check whether the results are reliable at the first sight. This is done by visualizing the bathymetric bed level output to check whether no instabilities or unrealistic phenomena have occurred. The second and third assessment criteria are quantitatively determined and further explained below.

C.4.1. Volume balance (2)

In order to investigate in which extent the model is able to simulate the morpho dynamic behaviour of the Sand Engine a polygon is drawn around this area and the volume balance between the start and the end of the study evaluation period is determined. This is done for the obtained data (start and end bathymetric survey) and the model simulations (start and end simulation bathymetry).

The various types of volume changes are determined as follows:

- Total volume change =$\int [z_b - z_{b,i}] dx$
  This value is expected to be negative, because of the blockage of net alongshore transport by the Sandbar more sand is eroded than accreted at the Sand Engine.
- Total erosion volume: =$\int^{-} [z_b - z_{b,i}] dx$

All negative volume changes in the cells are added up to determine the total erosion volume (denoted with $\int^{-}$.

- Total accretion volume: $=\int^{+}[z_b - z_{b,i}]dx$
All positive volume changes in the cells are added up to determine the total erosion volume (denoted with $\int^{+}$.

In which: z_b= Bed level
$z_{b,i}$= Initial bed level.

C.4.2. Brier Skill Score (3)

In order to compare whether the sensitivity analysis and calibration simulations are resulting in more efficient or accurate models, the models were compared with a reference case. A common method for evaluating the model performance is a skill score. The definition of a skill is (according to the glossary of meteorology (2016)) is “A statistical evaluation of the accuracy of forecasts or the effectiveness of detection techniques". The skill score that is most commonly used in comparing bed level changes in coastal engineering studies is the Brier Skill Score (BSS). This skill score could also be called a Mean-Squared Error Skill Score (MSESS) according to Bosboom et al. (2014a):

$$BSS = 1 - \frac{MSE(z_{b,c}, z_{b,m})}{MSE(z_{b,i}, z_{b,m})}$$

Where $z_{b,c}$ is the modelled bottom at the end of the simulation
$z_{b,m}$ is the measured bottom
$z_{b,i}$ is the initial bottom (variables taken at each cross-shore coordinate i).

The Brier Skill Score (BSS) represents how well the model predicts the bathymetry compared with the initial bathymetry Perfect agreement gives a skill score of 1 and when the modelling results is exactly the initial bathymetry the BSS gives 0. If the model prediction at the last timestep is further away from the final measured condition than the initial bathymetry at the start of the simulation, the skill score is negative. The following classification was given for the BSS by Van Rijn et al. (2003) (Table C.2.).

Table C.2: Classification of the Brier Skill Scores (BSS) by Van Rijn et al. (2003).

	BSS
Excellent	1.0–0.5
Good	0.5–0.2
Reasonable/fair	0.2–0.1
Poor	0.1–0.0
Bad	<0.0

The BSS is only determined for parts of the bathymetry for which real bathymetric data was available. Bathymetry onshore above +1 m MSL is not included in the BSS analysis since XBeach model is not able to simulate the development of these locations.

Constrains model evaluation criteria

(Bosboom, 2014a) pointed out that skill scores do not always represent the researcher's perception of model performance well. The same can be stated for the volume balance method. A nearly perfect volume flux does not always consequently mean a better model performance. For instance, when the total erosion flux is almost equal to the actual observed data, however this occurs at other locations or the model cross-shore development is significant different than the surveys show.

C.5. Results general model performance analysis

C.5.1. General model analysis set-up

Now the model set-up is described and the model evaluation area (Sand Engine) and criteria are known, the next step in the general model analysis is to bring the existing XBeach model parameter settings back to default settings in order to have a proper starting point for the modelling study. In the default settings the roller model is included while this process is almost absent at the Nigerian coast.

Therefore there is first investigated whether all occurring physical processes are present in the model (impact roller model) which settings best can be selected regarding several non-calibration parameters in order to increase the model speed and accuracy. The investigation of the non-calibration parameters is carried out before the sensitivity and the calibration analysis are executed. For the following parameters, the best model settings determined: grainsize, roller model, MorFac and spin-up time. An overview of the general model analysis parameters is presented in Table C.3 and further described below.

Table C.3: Overview of analysed non-calibration parameters before the start of the sensitivity and calibration study.

Description parameter	Keyword in model	Analysis aim	Tool
Grainsize of sand nourishments	D_{50} & D_{90}	To check for correct grainsizes in the model	- Sieve analysis
Roller model	Roller	Impact of roller model on model simulations compared to surveys	-Volume balance -Brier Skill Score
Morphological Acceleration Factor	MorFac	Speeding up simulation time without significant inaccuracies	-Volume balance -Brier Skill Score
Spin-up time	Morstart	Speeding up simulation time without significant inaccuracies	-Volume balance -Brier Skill Score

C.5.2. Physical parameters representation in the model

Grainsize

The majority of the volume required for reclaiming the Sandbar and Sand Engine will come from an offshore borrow area. Based on the sieve analysis taken from the nourished sand at the Lekki beach the grain sizes were determined. The sieve analysis was executed to assess the quality and characteristics of the nourished sand. Based on this analysis, it can be concluded that the average grain size (D_{50}) was about $6 * 10^{-4}\ m$ which is equal to $600\ \mu m$. The D_{90} is estimated to be $1.1 * 10^{-3}\ m$ which is equal to $1100\ \mu m$. These values are implemented in the model. There are also model simulation executed during the general model analysis phase with different grainsize values (D_{50}=400 & D_{50}=800). The erosion rates with a larger grain size decreases and vice versa, which is in accordance to the theory. However, the difference were not really significant (10 % more erosion for D_{50} of $400\ \mu m$) indicating that the model is not very sensitive for grain size which is confirmed by Bart (2017).

Roller equation

In the default settings of the XBeach application a wave roller equation is implemented to account for the onshore wave energy which is moved towards the coast by a wave surface roller. The model cannot solve that because this are complex sub-grid processes. However, to take this effect into account, the roller equation is developed in the XBeach application. The roller energy balance is represented by:

$$\frac{\delta E_r}{\delta t} + \frac{\delta E_r * \mathrm{c} * \cos(\theta)}{\delta x} + \frac{\delta E_r * c * sin(\theta)}{dy} = D_w - D_r$$

In which

- D_w is the loss of organized wave motion due to breaking or in other words Dispersion due to wave breaking. This term is a source term for the roller energy balance.
- D_r is the dissipation due to the roller ($D_r = \frac{2g\beta_r * E_r}{c}$) (Roelvink et al, 2015).

The roller equation typically causes a delay of the moment that wave refractive energy is released in the model.

As mentioned in Chapter 2 the process of wave rolling is almost completely absent at the Nigerian coast. However in the default settings of the XBeach model the roller equation is enabled since in most coastal areas this process of wave energy transport towards the coast is taking place. To improve the model as it better represent the physical processes in the coastal system, the impact of the wave roller equation is investigated by the developed evaluation criteria: the erosion rates and cross-shore development of the Sand Engine during the 20 assessed days.

The results are presented in Table C.4.

Table C.4: Results of evaluation criteria 'volume balance (net erosion from Sand Engine)' and the Brier Skill scores for the Sand Engine polygon for simulations with the roller model on (=1, default setting) or switched off (=0). Green colours indicate the setting which is chosen in the next step of the model analysis.

Volume balances Sand Engine			
Simulation run	Net volume flux (net erosion)	Deviation from survey data (observed volume flux)	
		m^3	Percentage (%)
Reference run (roller=1)	325,000 m^3	-115,000 m^3	-54 %
roller off (roller=0)	140,000 m^3	71,000 m^3	36 %
Brier Skill Score Sand Engine			
	BSS Sand Engine	Deviation BSS from survey cross-section	Deviation from BSS ref. run [%]
Reference run (roller=1)	0.34	0.66	-66%
Roller off (roller=0)	0.54	0.46	46%

For this analysis results (Table C.4) it can be concluded that for the simulation with the roller energy balance model on (=1) the erosion rates simulation are significant larger than obtained from the bathymetric surveys (325,000 m^3 vs 210,000 m^3). The simulation with the roller model switched off (=0) resulted in an erosion rate of 140,000 m^3 which is much less than the surveys show.

Furthermore, when the overall bed levels and cross-sections of the simulation with the roller equation on is analysed a bumpy instable pattern is noticed. A top-view of the bed level after the simulation of a run with (a) and without (b) the roller model enabled is shown in Figure C.3.

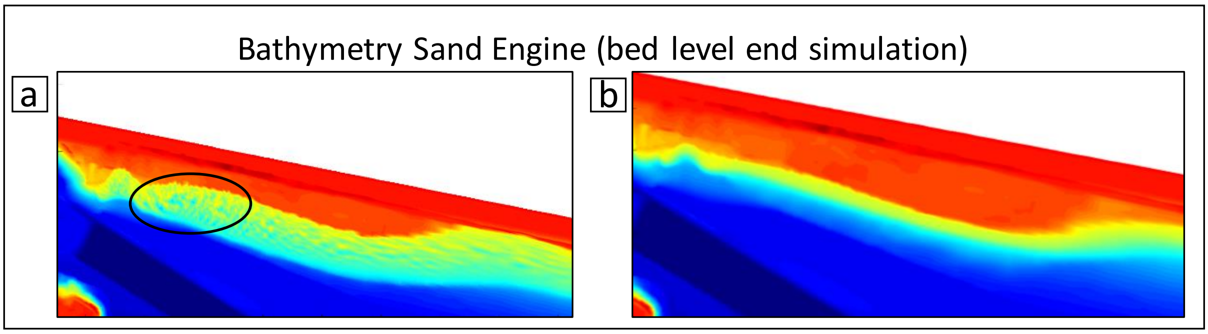

Figure C.1: Bed level of end of simulation for the Sand Engine with (a): the default run without the roller equation switched off (roller=1) where many instabilities in the bed profile are noticed (black circle) (b): the simulation run with the roller equation switch off (roller=0).

Thus it can be concluded that the impact of the roller energy balance model for the morphological development of the Sand Engine is very large. The difference between the roller switched on or off is almost 200,000 m^3 and the difference between the Brier Skill score is 0.2 resulting in a 20 % lower score for the simulation with the roller on (Table C.4), which is caused by the large fluctuations in the bed level onshore (black circle Figure C.1.-a).

Based on these result and the knowledge of the coastal system that the wave roller is almost absent at the Lekki coast, it is decided to switch the roller equation off for the further model simulations, which from now on is considered as the reference run.

C.5.3. Forcing and spin-up time

Spin-up

The spin-up time can be considered as the time that is needed before initial conditions don't affect the model results anymore. Until now the model simulations were performed with a very large spin-up time (80 days) in order to minimize this impact on the model results. However this increases the model simulation time a lot, so therefore it was decided to assess the impact for lowering the spin-up time.

As it was seen from the model output the spin-up time was not really visible after several days. Therefore the sensitivity regarding the spin-up time setting was evaluated and simulations with a *Spin-up time* of 10, 3 and 1.5 days were performed and compared to the model simulation with a spin-up time of 80 days which was used up to this moment.
The results are presented in Table C.5. at the next page:

Table C.5.: Results of evaluation criteria 'volume balance (net erosion from Sand Engine)' and the Brier Skill scores of the impact for simulations with different spin-up times (10, 3 and 1.5 days) compared to the reference run with a spin-up time of 80 days. The simulation with a spin-up=3 days is selected for further simulations. Green colours indicate the setting which is chosen in the next step of the model analysis.

Simulation run	Deviation volume flux from spin-up time 80 days		**BSS difference from spin-up time 80 days [-]**
	[m3]	%	
Reference run (spin-up=80 days)	**0**	**0**	**0**
Spin-up=10 days	**1980**	**1.5 %**	**0.01**
Spin-up=3 days	**2575**	**1.9 %**	**0.01**
Spin-up=1.5 days	**3760**	**2.8 %**	**0.03**

It can be concluded that the impact of the spin-up time is small on the simulation results. The differences in bathymetry model output is almost not visible and the volume balance and the Brier Skill scores do not deviate strongly for the different simulations. However, the computational time decreases for lower spin-up time. Lowering the spin-up times further than 3 days resulted in a bit stronger deviation.

From this analysis, it is decided that a spin-up time of 3 days will be used and is implemented as the reference run from now on.

MorFac

In order to accelerate the morphological change of the model, which saves simulation time the morphological acceleration factor (MorFac) can be used. However, large MorFac may lead to unrealistic morphological change of the model (Lesser, 2009). In order to avoid this, the sensitivity and stability of the model to increasingly large MorFac values was investigated. Since the model is going to be used for very short-term simulations (7 days up to 20 days), the bed level difference and the cross-sectional development are assessed with different MorFac values after 20 days of simulation for the Sand Engine. The best results are obtained when the model is run with no morphological acceleration (MorFac=1) but this leads to a high computation time.

The MorFac of the used model was *40* however this model was used for simulations to assess the morphological development of the Sandbar for 2 years. Therefore the sensitivity regarding the MorFac setting is evaluated and simulations with a MorFac of 10, 5 and 1 were performed and compared to the MorFac=40-simulation. The results are presented in Table C.6.

Table C.6: Results of evaluation criteria 'volume balance (net erosion from Sand Engine)' and the Brier Skill scores of the impact for simulations with different MorFac values (10, 5 and 1) compared to the reference run with a MorFac of 40. The simulation with a MorFac=10 is selected for further simulations. Green colours indicate the setting which is chosen in the next step of the model analysis.

Simulation run	Deviation volume flux from MorFac=40		**BSS difference from spin—up time 80 days [-]**
	[m^3]	%	
Reference run (MorFac=40)	**0**	**0**	**0**
MorFac=10	**2570**	**1.9 %**	**0.01**
MorFac=5	**3240**	**2.4 %**	**0.02**
MorFac=1	**5540**	**4.1 %**	**0.04**

It can be concluded that the impact of the MorFac is small on the final results. The differences in bathymetry model output as is almost not visible and the volume balance and the Brier Skill scores do not deviate strongly for the different simulations in Table C.6. However, the interpretation of in Table should be done correctly: the values for the volume flux for the reference run are 0 and 5540 m^3 for MorFac=1 simulation. Since the MorFac=1 gives the most realistic results, the MorFac=40 simulation has an Error Margin of 4.1 % relative to a MorFac of 1.

However, the computational time decreases for higher MorFac. Increasing the MorFac further than 10 the fluctuations become significantly larger. Therefore it is decided that in this study a MorFac of 10 is applied, since there are no significant differences in the results compared to simulations with lower values. Furthermore, it results in a computational time of 3.5 hours, which is acceptable.

C.5.4. Conclusion general model analysis

An overview of the settings determined in the general model performance analysis which will be used for further model analysis is given in Table C.7. below.

Table C.7: The parameters settings which will be used in the model analysis resulting from the general model performance study.

Parameter description	Parameter in model	Value in model	Unit
Roller energy balance model	roller	0	[-]
Median grain size	D_{50}	600	[μm]
Particle diameter representing the 90% cumulative percentile value	D_{90}	1,100	[μm]
Spin-up time	Morstart	259,200	[s]
Morphological acceleration factor	MorFac	10	[-]

After the implementation of the measured grainsize on site and turning off the roller energy model, the spin-up time and MorFac settings have been decreased. This leads to a decrease of erosion from the Sand Engine and a small change in the Brier Skill score compared to the reference simulation with no morphological acceleration factor and a very high spin-up time. The net volume flux and Brier Skill Score for the Sand Engine after the general model analysis compared to bathymetric survey data are presented in Table C.8.

Table C.8: Results for the erosion and the Brier Skill Score for the Sand Engine from the bathymetric survey data after the general model analysis.

	Erosion from Sand Engine [m^3]	**BSS [-]**
Survey data	210,000 m^3	1
Simulation before decrease of MorFac and spin-up	140,000 m^3	0.54
Simulation after determination of MorFac and spin-up	135,000 m^3	0.52

C.6. Sensitivity and calibration analysis calibration parameters

XBeach contains about 250 model settings. Approximately 150 of these settings describe physical and numerical behaviour. The other 100 are case specific parameters. Several non-calibration parameters (as MorFac and D_{50}) are already investigated. In this section the aim is to assess the XBeach model of XBeach in how sensitive/important several calibration parameters are for this type of coastal area. several calibration parameters are assessed. Due to limited time it was not possible to do a sensitivity analysis for all settings. According to Van Geer et al. (2015) and other calibration researches (Vousdoukas, 2014) seven specific XBeach parameters are important calibration parameters for the model results.

C.6.1. Assessed calibration parameters

The parameters used for the sensitivity analysis, their default setting and the simulated test settings are presented in Table C.9. In Table C.10 a brief description of the sensitivity/calibration parameters which are assessed is given.

Table C.9: Investigated parameters for the sensitivity analysis

Keyword	Default setting	Tested settings	Relative to default setting	Deviation from default (%)
facuA	0.1	**0.05**	0.05	50.0
		0.15		
wetslp	0.3	**0.25**	0.05	16.7
		0.35		
lws	1	**lws= 0**	-	-
wci	0	**wci=1**	-	-
alpha	1	**0.8**	0.2	20.0
		1.2		
gamma	0.55	**0.4**	0.15	27.3
		0.9		
gammax	2	**1.7**	0.3	15.0
		2.3		

Table C.10.: Description of the assessed sensitivity/calibration parameters

Model parameter	Parameter description (from XBeach manual)
facua	Calibration factor time averaged flows due to wave skewness and asymmetry
facAs	Calibration factor time averaged flows due to wave asymmetry
wetslp	Defines the critical avalanching slope above and below water (Critical avalanching slope under water (dz/dx and dz/dy))
lws	wave stirring; lws=1 enables long wave stirring
wci	Wave-current interaction is the interaction between waves and the mean flow. The interaction implies an exchange of energy, so after the start of the interaction both the waves and the mean flow are affected by each other. This feature is especially of importance in gullies and rip-currents (Reniers et al., 2007). Wci=1 turns on wave-current interaction
alpha	Wave dissipation coefficient in Roelvink formulation
gamma	breaker index *γ also described as b*reaker parameter in Baldock or Roelvink formulation
gammax	Maximum ratio wave height to water depth, Reducing *gammax* will reduce wave heights in very shallow water, the value 2 is a reasonable value.

C.6.2. Results sensitivity analysis

In this section the results of the sensitivity analysis is given in terms of volume fluxes (erosion from the Sand Engine) and the Brier Skill Score.

All simulations output have been assessed regarding bed level, flow, sedimentation and erosion patterns. Next to that model simulations have been assessed by the established evaluation criteria by using MatLab. The results for the volume flux and the Brier Skill Score and presented in Table C.11. To visualize the impact of the different calibration parameters, the cross-section through the centre of the Sand Engine is given in Figure C.4. The interpretation of the results is summarised at the end of Chapter 5.

Table C.11: Results of assessed calibration parameters for sensitivity analysis, + values for volume flux indicate a better model representation (closer to the survey data) (green) and – values indicating a larger deviation of the erosion rates from the Sand

Engine (red). Positive values for the Brier Skill Score indicate a better cross shore prediction by the model (green values) and negative values vice versa (red values).

Simulation run	Deviation volume flux to reference run		Brier Skill scores deviation [%]
	[m^3]	%	
facuA			
Decreased	+17,000	+12.6 %	-32.7 %
Increased	-3,000	-2.2 %	- 8.6 %
wetslp			
Decreased	+16,000	+11.3 %	-8.7 %
Increased	-14,000	-10.4 %	5.8 %
lws			
Off	+9,000	+6.7 %	6.1 %
wci			
Off	+8,000	+5.9 %	-5.3 %
Alpha			
Decreased	+20,000	+14.8 %	-21.2 %
Increased	-12,000	-8.9 %	13.5 %
Gamma			
Decreased	-24,000	-17.8 %	2.3 %
Increased	+37,000	+29.8 %	-12.6 %
Gammax			
Decreased	-4,000	-3.0 %	+3.8 %
Increased	+2,000	+1.5 %	-13.4 %

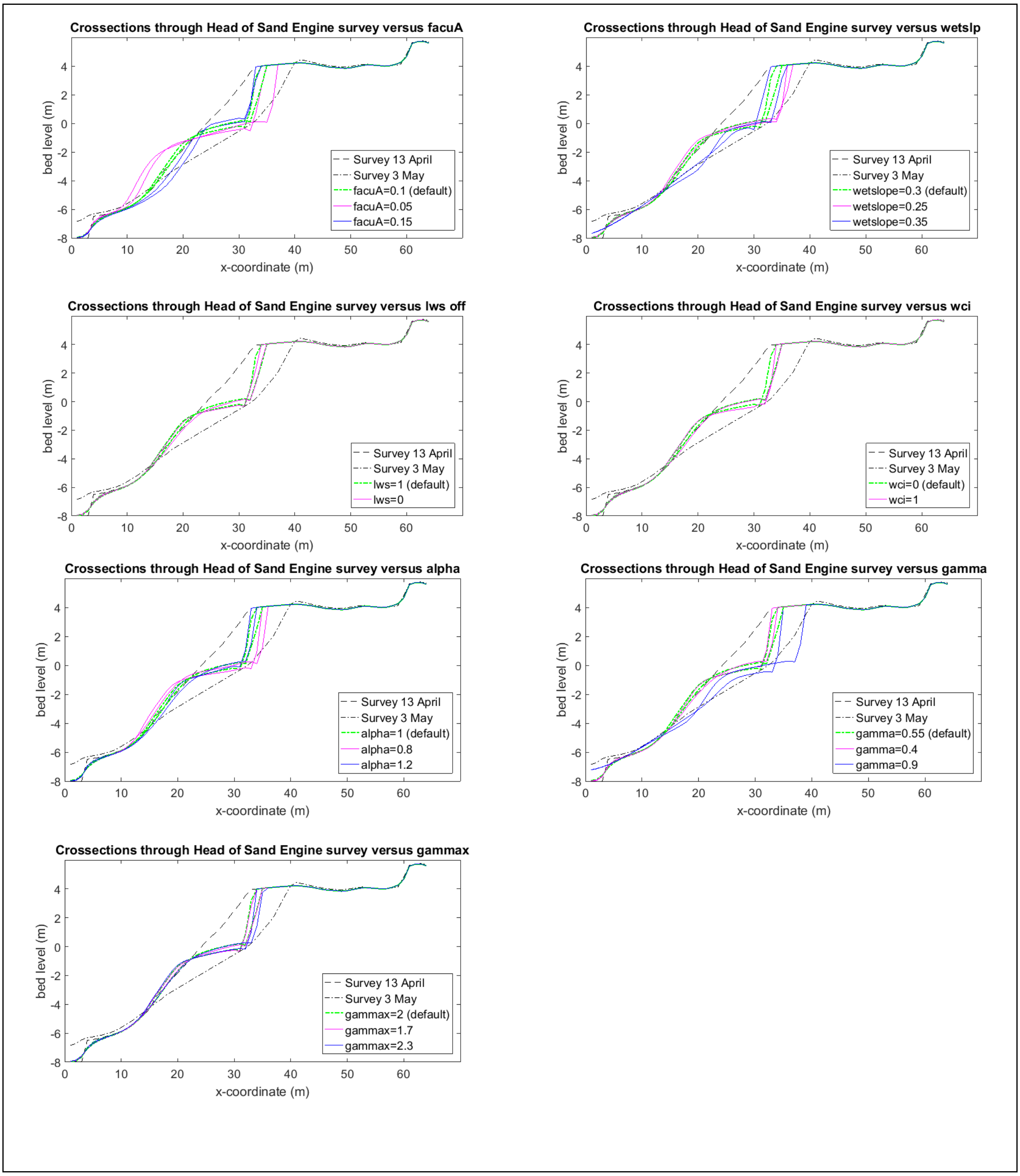

Figure C.2: Results of the sensitivity analysis for cross-sections trough the Head of the Sand Engine (N=68) for the 7 investigated XBeach calibration parameters facuA, wetslp, lws, wci, alpha, gamma, gammax.

C.7. Calibration analysis

The final step in the model performance analysis is the execution of a calibration process in order to optimize the XBeach model for the area of interest. This forms the basis for the further analysis for the morphological development of different construction scenarios of the Sandbar breakwater at Lekki.

For the calibration process various model simulations have been performed based on the information obtained from the sensitivity analysis. In the calibration process appeared that none of the reference or optimised models gave a (near) perfect prediction; where the one model scored better on the prediction of the beach profile, the other scored better on the prediction of the erosion volumes. After various calibration simulations and the assessment of these runs on the evaluation criteria, the model simulation which scored the best regarding both criteria is selected.

The net volume flux (erosion) and Brier Skill Score for the Sand Engine resulting from the calibration analysis are presented in Table C.12. and compared to bathymetric survey data of the Sand Engine.

Table C.12: Results for the erosion and the Brier Skill Score for the Sand Engine from the bathymetric survey data after the general model analysis.

	Erosion from Sand Engine [m^3]	**BSS [-]**
Model simulation	**145,000 m^3**	**0.51**
Survey data	210,000 m^3	1
Difference between surveys and model simulation	65,000 m^3	0.49

From the calibration analysis it can be concluded that none of the model simulations predict the morphodynamical development of the Sand Engine very accurately. For the best run which is selected to assess the morphodynamical behaviour of the construction scenarios it is still an underestimation of the erosion rate from the Sand Engine of about *65,000 m^3*. The Brier Skill comes down to *0.51* which can be considered as a 'good' value (see section C.4.2).

Table C.13: Overview of important model parameters as a result of the calibration analysis

Important model parameters	Setting
D_{50}	600
D_{90}	1000
Bed friction	Manning
Morfac	10
CFL	0.8
Wetslp	0.24
Form	Soulsby_vanRijn
Alpha	0.95
Gamma	0.59
Gammax	1.64
facuA	0.09
dtheta	5
Cyclic	1
roller	0

This means that after the calibration, the prediction of the erosion flux from the Sand Engine by the optimized model is 10,000 m^3 (135,000 m^3 for reference run vs 145,000 m^3 after calibration. The settings for the most important parameters for the final simulation run is presented in 3. The morpho dynamic behaviour resulting from the final simulation run for the bathymetry (both top-view as well the cross-shore component) is presented in Chapter 5.

C.8. Modelling approach construction scenarios

C.8.1. General

For the assessment of the morphological development a modelling study for four cases is executed: three construction alternatives (Variants 1-3) and the reference scenario (Variant 0). Until this phase the modelling calibration analysis was executed over a period of 20 days. In this modelling study the stages in the scenarios are simulated for each week. This means that the new nourished sand is added once per week to the model. In practice the sand nourishment will be executed continuously 24 hours per day, 7 days per week. However, the sediment losses for each stage are compared relatively to each other therefore this modelling of the construction phases of the different Sandbar breakwater strategies enables us to draw conclusions on what strategy would be an optimal form regarding reducing sediment losses. The different executed steps for this modelling study are briefly summed in the next section. For the simulations of the different construction stages, the model settings of the best runs obtained from the calibration analysis is used (section C.7.). The boundary conditions which have been applied are further explained in the sections C.8.3.

C.8.3. Steps in construction phase modelling

In the methodology there was already stated that in order to assess the morphological behavior of the construction scenarios each construction stage is been simulated. The different steps were summarized in a scheme in Chapter 6 (Figure 6.1) which is further explained in this section.

i. **Start:**
Each scenario starts with the bathymetry before the construction stage of the Sandbar breakwater. Depending on the specifications such as production rate, location of the nourishment, sequence of construction the bathymetry before construction phase is updated for the situation after a week of sand suppletion.

ii. **Bottom updating:**
The raising of specific areas with the correct volumes in the Sandbar breakwater design is done by determining polygons and volume calculations using MatLab. The slope during the construction phase was measured to be 1/8. This is implemented along the edges of the raised area in order to have a realistic sand nourishment in the model bathymetry.

iii. **Simulation of updated bottom for week:**
The next step is the simulation of the new situation after one construction week for 7 days with the corresponding (hydrodynamic) boundary conditions which occur at the start of the project.

iv. **Processing bathymetric output:**
After simulation the XBeach model output can be obtained; the bathymetric output file will be processed into MatLab.

v. **Quantification of losses & captured sediment:**
After the simulation of the first week, the sand which is moved outside the design profile by natural processes to locations where it is not contributing to the stability of the Sandbar i.e. the sediment losses as well as the captured sand into the design profile are quantified for the first stage. This is done based on volume balances between the start and the end of the simulation. The concept of the volume balances is already explained in section C.4.1. Volume balance However, in this analysis it became clear that there was a need to split the natural sediment losses from a nourishment to the 'loss' areas (Inner Lake and West side) and the natural movement of sand at from other locations in these 'loss' areas.

The **sediment losses quantification** can be explained by the following steps:

- *Volume flux from nourished bund:* around the updated bottom a polygon is drawn and the volume flux between the start and the end of the simulation is determined. Usually the flux has a negative value indicating a net erosion from the nourished bund. By knowing this flux, there is known how much sediment is moved by natural processes to other locations. However not all this sand is moved to areas where it is considered as a loss.
- *Volume flux at designated 'losses' polygon areas:* now there is known how much sand it moved, the volume of sand which is considered as a loss needs to be quantified. The change in volume flux between the start and the end of the simulation in the 'losses' polygons is considered as the volume of nourished sand which is lost. However, for the

reclamation of the Sandbar Road one extra remark needs to be made. As the Sandbar Road from the coast is reclaimed sand will starts accumulated at the east side in the Inner Lake polygon which cannot be counted as a sediment loss. The processes of sediment capturing from LST and movement of sand from the nourished sand bund to the Inner Lake will be split up. This is done by calculating the difference between the volume flux from the Sandbar Road bund (erosion) and the volumes flux at the east and westside of the Sandbar Road. The amount of sand which has accumulated more at the east side than was eroded from the bund is considered as sediment trapping from LST.

The **capturing of sediment quantification** can be determined as follows:

- *The volume flux of bathymetry within the design profile:* For the construction variants where temporary groynes are implemented into the design which have the objective to capture free sediment into the Sandbar breakwater design profile, the volumes at the westside of the groyne are calculated. This 'captured' volume depends on when the construction of the groyne is finished, the location and dimensions of the groyne (see construction variants description, Variant 1& Variant 3The quantity of trapped sediment for the stages when the capturing takes place is determined by drawing a design profile polygon at the east side of the groyne and applying a volume flux between the start and the end of a construction week. This volume difference indicates the volume of accumulated sand behind the temporary groynes.

vi. **Repetition of steps for all stages:**
The steps for the first stage will be repeated for all construction weeks apart from the construction stages where only further widening and heightening of the Sandbar is executed. This is done since in this stage no significant morpho dynamic development will occur anymore and since it is time consuming to schematize and develop bathymetries for this stage.

vii. **Determination of total captured sand/losses volume:**
After the full simulation of the construction scenarios the total sediment losses will be determined and analysed (location, rate of losses) and compared to the actual construction method (scenario 0) and the other alternatives.

Input data/Boundary conditions

The wave boundary conditions for the assessment of the sediment losses is derived from the existing wave climate for the area of interest. This wave climate with nearshore representative wave conditions was developed based on a large scale SWAN model and calibrated against local measurements, resulting in a limited set of wave conditions for each month. Since the scenario simulations take place on weekly basis the durations of these conditions are scaled from monthly to weekly durations.
For construction scenario simulations tide data from the existing tide input file is used after adaptation of the tide lengths.