MSc thesis

Uncertainty analysis of the mud infill prediction of the Olokola LNG approach channel

Final report



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Preface

In your hands you have the report of my master thesis with the title 'Uncertainty analysis of the mud infill prediction of the Olokola LNG approach channel'. This report is the conclusion of my master phase of the Civil Engineering study at Delft University of Technology. This thesis regards the section of Environmental Fluid Mechanics in the field of Hydraulic Engineering.

When I started this thesis, I was planning on 'just' performing a risk analysis to the mud infill of the above mentioned approach channel. When I dug into the available data, I found out quite soon that I had to find a way to extract parameter characteristics necessary for the mud infill prediction from data that did not directly tell me what I wanted to know and even pointed into a direction that raised some eyebrows.

In the end I had to combine knowledge of metocean data, soil mechanics, cohesive sediment in the water column, (simple) modelling and probabilistic analysis to come to the report in front of you. The variety of subjects I had to master to a certain extent made this research interesting and instructive.

To reach the result in front of you, many people around me gave support, advice, input, and well-founded comments. First I'd like to thank David Veale, who encouraged me to dig deep into the data but also made sure I kept the big picture in mind. Although based in the UK and working on the Olokola LNG project there, he would come to the Netherlands for committee meetings regularly. I really appreciate his close involvement with my work.

The other members of my graduation committee were also keen to help me with my research. Han Winterwerp made the muddy waters clear so to speak; his expertise was crucial in interpreting the sediment data and making the sediment dynamics understandable. Wim Uijttewaal was very supportive and helped me figure out how I could define a trapping criterion. Bas Jonkman increased my probability of success considerably with his probabilistic background.

If I had any questions about previous studies, applied methods or to discuss any of my findings, Mark Klein at Svasek Hydraulics was very enthusiastic and supportive. He was always willing to critically look at my findings and gave clever comments on my work.

Jan de Waal helped me to look at any difficulties from a different angle in order to obtain more clarity on my next step. Bert van der Valk was so kind to critically review and discuss the geological part of the system description. All my geotechnical questions were patiently answered by Willem Bierman and Mark Cunningham.

Lastly I would like to thank Bram Bliek for answering my questions on the modelling done before, Arie Dijksman for helping to find reference data at Forcados, Pieter van Gelder for his expertise on probabilistic analyses, Sytze van Heteren for answering my questions regarding the origin of the sediment along the Niger Delta, Walther van Kesteren, Anastacia Oranugo, Lodewijk Werre and my colleagues at the Civil Engineering department of Shell Global Solutions.

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Abstract

Olokola LNG (OKLNG) is a proposed liquefied natural gas (LNG) export facility located approximately 100 km east of Lagos in Nigeria, Africa and the western limits of the Niger Delta. The development includes an approximately 10 km long and 17 m deep approach channel designed to allow tankers to reach the marine export terminal located at the shoreline. Mud is expected to be deposited in the channel because of the persistent swell climate which mobilises cohesive sediment. In order to assess operational costs and dredging requirements predictions of the infill rates are required which realistically include possible uncertainties.

This thesis aims to define a conceptual model of the day-to-day sedimentation processes that will cause infill of the proposed dredged approach channel, make estimates of the channel infill rates and assess the uncertainties to finally propose a strategy to reduce uncertainties.

An analysis of the offshore environment at the project location shows that the area is dominated by persistent fairly unidirectional and high-energy swell waves. The average wave height is 1.4 m and the average wave period is 14 s in the wet season. Geostrophic ESE and WNW currents have a magnitude of roughly 5-10 cm/s near the bottom. Tidal currents are negligible. The coastline to the east of the project area is dominated by the Niger Delta; it is formed by sediment transported by the Niger and Benue River to the coast. Two opposing longshore currents meet at the project site and the coastline has been advancing for millennia.

An extensive study on the sediment characteristics in the OKLNG area is conducted. The top soil layer of the area consists of a thick and very soft layer of fine mud. This mud shows viscous behaviour and the settling rate is low. The slope of the seabed is very gentle.

Next the behaviour of the sediment in the water column is looked at. The settling velocity of the material has a large influence on the sedimentation and is largely determined by the flocculation behaviour of the sediment. Cohesive sediment in the marine environment is typically flocculated. However during the analysis of the soil, indications are found that the sediment in the water column at OKLNG is unflocculated or poorly flocculated. If confirmed, this is very unusual and in fact unknown to the best knowledge of the consulted experts for this thesis and in the studied literature.

In terms of identifying and reducing uncertainties, the sediment state in the water column is found to be the most important uncertainty for the prediction of the mud infill. Because of this large uncertainty, and in the absence of definitive data, it is decided to investigate the implications of both unflocculated (scenario 1) and flocculated (scenario 2) sediment.

A simple model is formulated to investigate the channel infill rate for each scenario. The models are based on the current velocity near the bottom, the amount of sediment in the water column integrated over the water depth, the channel length and the percentage of the sediment that is trapped in the channel. The input parameters are the current velocities measured 1.5 m above the bottom, the measured concentrations over the water depth fitted to an analytical probability distribution, the channel length and a trapping efficiency.

The used models are not validated and if a more precise infill prediction based on hydrodynamic parameters is required, a more sophisticated hydrodynamic model is recommended. However, these models do demonstrate which parameters influence the infill rate most and cause the largest uncertainties, which is the goal of this thesis.

An uncertainty analysis is executed as well. This includes a sensitivity analysis whereby the input parameters are varied within their possible range and the influence on the outcome is analyzed. Probability distributions of the infill rate and mean yearly infill quantity are subsequently generated using the models and a program called Crystal Ball.

If the sediment is found to be unflocculated, the infill rate is a factor 10 higher than when it is flocculated. The lack of knowledge on the sediment concentrations near the bottom introduces

the second largest uncertainty in the infill prediction. All uncertainties in the other parameters are of minor importance in comparison to the mentioned two.

The result of the modelling and uncertainty analysis is that in case of scenario 1 the order of magnitude of the infill is such that the channel is filled up with very low density mud within weeks. If the sediment is found to be not to poorly flocculated, it may therefore be more practically useful to examine the implications of keeping the channel navigable with rapid infill of low density material. It is therefore recommended to investigate the settling and consolidation behaviour and define the maximum density of mud vessels can still sail through.

In scenario 2, a simplified model of mud infill was used to predict the mud infill in this thesis. The model does not represent all relevant physical processes properly, but it does provide insight into the uncertainties. Also, information on the sediment concentration near the bottom is not available. Concentrations above 8 kg/m³ could not be measured with the instruments used during the conducted measuring campaign.

The probability distribution of the sediment concentration – especially the tail of the distribution – thus had to be estimated, which introduces a large uncertainty. The concentrations near the bottom and the layer height in case a mud layer is generated during a storm event need to be measured to reliably predict the infill rate. Considering the large infill, it is also recommended to examine the settling and consolidation behaviour in case of this scenario.

Besides recommendations for additional data collection to enable a more complete and accurate infill estimate including a probabilistic assessment to quantify uncertainties, it is also advised to organize a brainstorm to identify all possible channel infill mechanisms (besides day-to-day infill) and to validate and improve the models.

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1 Introduction

A new liquefied natural gas (LNG) export facility is planned along the Nigerian coast for which an approach channel is planned for tankers to reach the terminal. This thesis will elaborate on the sediment infill of the approach channel for this inland terminal and the uncertainties surrounding the infill.

1.1 Project description

The Olokola LNG (OKLNG) project is an initiative of the Nigerian National Petroleum Company (NNPC), Chevron Nigeria Limited, Shell Gas & Power Development BV and BG International Limited (BG) to jointly develop a Liquefied Natural Gas Production and Export Plant. The project site is located on an undeveloped area within the Olokola Free Trade Zone close to the borders of Ogun and Ondo state, approximately 100 km east of Lagos as shown in Figure 1-1. This is along the muddy open coastline west of the Niger Delta.



Figure 1-1: Location of the OKLNG project in West-Africa [After Google, 2007]

The proposed OKLNG project consists of an onshore LNG plant that includes gas receiving and processing facilities, refrigeration equipment, electrical generators and utilities, product storage tanks and loading facilities and support buildings. The project's marine facilities will consist of an inland marine terminal for liquefied natural gas (LNG) and liquefied petroleum gas (LPG) export, and an offshore condensate tanker loading facility at a single point mooring offshore. The current layout is presented in Figure 1-2.



Figure 1-2: Layout of the OKLNG project¹ [After OKLNG, 2008a]

In the proposed design the LNG and LPG carriers will access the new marine export terminal through an approximately 10 km long approach channel. The approach channel is this long because the foreshore is gentle and will have a declared navigation depth of -15.5 m CD. Chart Datum is defined as Lowest Astronomical Tide² [Svasek Hydraulics and Royal Haskoning, 2008b].

1.2 Problem definition

1.2.1 Uncertainty in mud infill prediction

The OKLNG area is subject to persistent swell waves, so a large infill in the approach channel is expected due to mobilization of sediment during periods of high swell activity and due to continuous sediment transport [Svasek Hydraulics and Royal Haskoning, 2008b]. Unfortunately the prediction of siltation in approach channels is inherently uncertain.

Extensive metocean and soil data has been collected for the OKLNG project. Svasek Hydraulics and Royal Haskoning [2008b] have conducted a sedimentation study including a limited assessment of uncertainties. In order to obtain more information on the cohesive sediment infill under normal day-to-day circumstances OKLNG is considering to acquire more and reliable data on the sediment at the OKLNG site and to dredge a large-scale trial trench to monitor the actual infill. This thesis should provide a more profound basis on whether or not to pursue this course of

¹ SPM stands for single point mooring

² Lowest Astronomical Tide is the minimum predicted level of low water in the period 2000-2018 by Svasek Hydraulics and Royal Haskoning based on measured data from May 2006 until May 2007.

action. Therefore the sediment dynamics around OKLNG have to be determined and an objective and more complete uncertainty analysis is required.

The nature of the uncertainties can be the result of a limited understanding of the physical processes – especially for cohesive sediments – and subsequent uncertainties in the prediction method, the input parameters, the limited availability of data, and other underlying uncertainties. These uncertainties have not been fully identified nor have they been rationally and objectively quantified, but they can have a large influence on the capital and operating costs. It is therefore important to quantify the potential for impact on the project when considering the business case and economics of the project. When the impacts are understood, a decision can be made on how resources can be applied most efficiently in managing risks and reducing uncertainty. The problem, which this thesis addresses, is therefore the reliability of the infill prediction.

1.2.2 Broader background

Morphological risks are frequently a key feature of major marine developments and predictions of their impact are typically very uncertain, so OKLNG is not unique in that respect. Often, morphological predictions are expressed deterministically with perhaps indicative "upper and lower bound" values to indicate uncertainty. However, frequently, such upper and lower values may not be supported by any rational analysis of uncertainty. It has not always been evident if there is any opportunity to improve the confidence in the prediction.

Hence Shell was very interested to support research that would lead to a more considered, rational and above all quantitative assessment of uncertainty in respect of morphology and sedimentation for application into risk-based project management and business decision making. Such an approach may, for example, enable investment on surveys, data collection and trials to be better targeted and provide an early opportunity to select marine concepts which minimize morphological risks and life-cycle costs.

1.3 Objectives

The goal of this thesis is threefold with regard to the previous section:

- 1. Define a conceptual model of day-to-day sedimentation processes that will cause infill of the proposed dredged approach channel.
- 2. Make estimates of the channel infill including a quantitative uncertainty analysis
- 3. Present strategies to manage risks and reduce uncertainty

1.4 Limitations

In order to focus on the objectives of the thesis, some starting points and restrictions are formulated for which a motivation is given.

1.4.1 Starting points

- The current location of the OKLNG project is given: this is the result of extensive discussions and the final decision is based on technical, environmental, commercial and political considerations.
- Only the current terminal concept is considered: in a previous design stage an offshore terminal with a jetty was also investigated. However the inland terminal now proposed has significant advantages in terms of cost and construction aspects and no significant disadvantage in terms of coastal morphology and sedimentation compared to the jetty option.
- The current layout and dimensions of the approach channel are given; the goal of this thesis is not to optimize the layout or dimensions of the channel, but to focus on the infill process, infill quantity and uncertainties.

 Svasek Hydraulics and Royal Haskoning [2008b] expect that after dredging the side slopes will slowly adjust to the new situation. Infill due to slope flattening is a temporary process; the infill calculation in this thesis will assume an equilibrium situation with final slopes as estimated by the consultants.

1.4.2 Restrictions posed on the extent of the research

- Only infill of cohesive sediment is taken into account, not additional sand infill.
- Only infill of the approach channel will be investigated. Infill of the port basin is not taken into account.
- The behaviour of the sediment while settling in the channel, the consolidation behaviour, will not be investigated in this thesis.
- The maintenance and dredging strategy is not analyzed in-depth in this report.

1.5 Contents of the report

To reach the objectives stated in section 1.3 the OKLNG environment is analyzed first. The next chapter therefore provides a system description. As a result the geology, hydrodynamics and bathymetry of the area are known. Characteristic bathymetric, wave, current and seawater conditions are identified and quantified. Next the top soil layer in the OKLNG approach channel area is analyzed in chapter 3.

The processes and parameters from chapters 2 and 3 serve as input for the infill modelling in chapter 4. A simple analytical model is chosen to calculate the infill of the approach channel to later obtain proper insight in which parameters, processes and uncertainties influence the infill most. This model addresses objective 1.

Based on an analysis of the calculated deterministic infill quantity the model is extended to a probabilistic model in chapter 5 to reach objective 2. Parameters, which influence the outcome most, will be identified using a sensitivity analysis. Attention is paid to the integration over the channel length and over time. Dependencies between parameters will be quantified as well. Deterministic values and distributions of the relevant parameters from chapter 2, 3 and 4 are then used to perform a Monte Carlo analysis and generate a probability distribution for the infill rate of the OKLNG approach channel. An expected yearly infill quantity is presented as well.

The infill prediction of chapter 5 will be discussed in chapter 6. This chapter presents a reflection on the methodology applied in this thesis and the results. It also addresses objective 3. A set up for a risk analysis for the mud infill is made, it is discussed if any risks deserve attention in a next project phase, risk mitigation measures are proposed and general learnings are listed.

Lastly chapter 7 with the conclusions and recommendations will finish the thesis.

This thesis also includes 7 appendices of which the last 2 are confidential.

2 System description of OKLNG

This chapter provides a description of the geology, hydrodynamics and bathymetry of the coastal system around the OKLNG site. Based on this analysis the coastal processes dominating the sediment transport can be assessed. This chapter therefore concludes with a summary of the important coastal processes at the project site and an overview of characteristic system parameters, which is needed to model the infill and reach objective 1 of this thesis. The soil conditions are analysed in a next chapter.

2.1 Site location

2.1.1 Nigerian coastal regions

The Nigerian coast can be divided into four regions. This division is based on differences in morphology, vegetation and beach type [Ajoa *et al.*, 1996; Dublin-Green and Awobamise, 1997]. The regions are depicted in Figure 2-1. Their characteristics are described next.



Figure 2-1: Four main coastal regions of Nigeria - barrier-lagoon coast (1), Mahin mud coast (2), Niger Delta (3) and strand coast (4) [After Figure 2, Ajoa *et al.*, 1996]

2.1.1.1 Barrier-lagoon coast

The first region starting from the west and indicated as number 1 in Figure 2-1 is the barrierlagoon coast. The coasts of Togo, Benin and western Nigeria consist of lagoon systems with mangrove swamps and muddy marshes. Badagry Creek, Lekki Lagoon and Lagos Lagoon (not indicated in Figure 2-1) contain complicated coastal-barrier lagoon systems, which are connected through intertidal channels with Lake Nokoué in Benin. Only Lagos Lagoon is connected to the Ocean; a sand barrier of 2 to 21 km wide separates the lagoons from the ocean. The connection between Lagos Lagoon and the Atlantic is protected by the Lagos Harbour Moles. The coastal barrier is mainly built and maintained by waves. Most beaches consist of fairly coarse sand, for example $D_{50,Lagos} \approx 400 \ \mu\text{m}$. This is due to the strong wave climate. However the foreshore and landward sides of the lagoons are muddy. The lagoons are shallow with depths of 1.5 to 3 m. This system extends to the western margin of the Niger Delta [Allen, 1965b; Ajoa *et al.*, 1996; Flemming, 2002; Healy *et al.*, 2002; Ihenyen, 2003].

2.1.1.2 Mahin mud coast

At the western margin of the Niger Delta a 75 km long, low-lying mud beach is found along the open coast: the Mahin mud coast. It is referred to as number 2 in Figure 2-1, the transgressive mud coast. This mud beach ends at the mouth of Benin River. Little sand is found along this stretch. Freshwater swamps back the mud beach. The coastal stretch from Lagos to Mahin is about 160 km long [Allen, 1965b; Ajoa *et al.*, 1996; Flemming, 2002; Healy *et al.*, 2002; Ihenyen, 2003].

2.1.1.3 Niger Delta

The Niger Delta dominates 500 of the 850 km long Nigerian coastline. The Niger River drains much of West-Africa south of the Sahara. Most of the year the discharge is 2,000 m³/s, with peaks during part of the wet season from August till November. The discharge in October can be as much as 19,500 m³/s [Allersma and Tilmans, 1993]. This tenfold increase is also measured in the Benue River branch at Yola, close to the Nigerian-Cameroon border in the east [Rider, 2004]. Annually the Niger River discharge is about $1.9 \cdot 10^{11}$ m³ water and roughly 11 million m³ of sediment, of which about 80% is clay and silt. The Benue is more important than the Niger in the sediment supply. The vast majority of the sediment is carried in suspension [Allen, 1964; Allen, 1965b; Oomkens, 1968; Anonymous, 2002].

The delta is wave-dominated and almost perfect in symmetry. The western flank of the Delta is mainly fed by sediment from Forcados River [Allen, 1965b]. Muddy intertidal mangrove swamps occupy the entire Delta region; Nigeria has the largest area occupied by mangrove forests in Africa [Ajoa *et al.*, 1996]. This pioneer vegetation suggests a young and developing coast.

Despite the huge amount of sediment transported by the Niger River, retrogradation has been observed. Debate is ongoing on the influence of the different causes: human interference in the longshore sediment transport, subsidence due to normal settlement and/or oil and gas extraction, the existence of dams in the major river branches or a modest sea level rise. The construction of dams in the major river branches from the 1970s onwards has additionally reduced the sediment load of some smaller branches by 50%. On the other hand mangroves are still found to expand within the delta plain. Research from the 1980s onwards has found a net coastline retreat. Only at the western flank marginal accretion was still observed [Ibe, 1988; Allersma and Tilmans, 1993; Abam, 1999; Flemming, 2002; Fugro, 2005b].

2.1.1.4 Strand coast

The last 85 km of the coastline towards the Cameroon border consists of many estuaries, so active mixing of river and oceanic waters occur. Tidal ranges here are the largest along the Nigerian coastline. Mangrove swamps similar to those in the Delta back this system.

2.1.2 Description of the location

The OKLNG project is located about 100 kilometres east of Lagos, Nigeria, as indicated in Figure 1-1. Figure 2-2 shows that the site is located on the open coastline along the Atlantic Ocean at the far northwest border of the Niger Delta. Approximately 40 km west the submarine Avon canyon is located with its heads close to the shoreline.



Figure 2-2: Large-scale overview of the coastline around OKLNG with a barrierlagoon coast to the west, submarine canyon to the southwest and the Niger Delta with its many rivers to the southeast [After Google, 2007]

The OKLNG project will be realized just east of the Lagos lagoon system and just west of the Mahin mud coast, which is indicated in Figure 2-3. Offshoots of the Lagos lagoon system even border the project site. Omu Creek north of OKLNG is directly connected to Lekki Lagoon [Flemming, 2002; Healy *et al.*, 2002; Ihenyen, 2003]. The onshore plant area is roughly 4 by 5 km². The coastline at the project site currently advances seawards as will also be discussed in section 2.2.2.



Figure 2-3: Small-scale coastline around OKLNG with the Lagos barrier-lagoon coast to the west and the Mahin mud coast to the southeast; the transition from a sandy to a muddy coastline is visible [After Google, 2007]

The coastline around OKLNG is closed. At the location of the inland terminal two small creeks of roughly a kilometre long discharge into the Atlantic, but these creeks only serve as dewatering channels for the area. They are only open for a short period during the wet season. The closest coastline interruption in the west is 110 km away: the channel that provides access to Lagos port and Lagos Lagoon. The first Niger Delta river branch near the project site is Benin River 100 km to the southeast. Further along the coastline Forcados and Escravos River discharge into the Atlantic at roughly 120 and 145 km from OKLNG.

2.2 Geology

2.2.1 Geological history

The West-African coast started to develop about 135 million years ago in the Cretaceous period when South-America drifted apart from Africa. The most important geological feature along the Nigerian and perhaps even West-African coast is the Niger Delta. Rivers deposited sediments in the relatively narrow and long Benue trough³ on the oceanic crust, forming this Delta. The passive continental margin is therefore of depositional and not of tectonic origin [NEDECO, 1959; Allen, 1964; Cratchley and Jones, 1965].



Figure 2-4: Geological history of the West-African coast showing the development of the Niger Delta, which is its most important feature [Figure 2, Allersma and Tilmans, 1993]

The evolution of the Niger Delta can be divided in three phases: downcutting by rivers as the sea level decreased resulting in gullies and shelf edge canyons, transgressive deposition during sea level rise and regressive deposition when a balance between sea level rise, sediment supply and subsidence was reached. This results in a soil stratigraphy with interbedded layers of sand, silt and clay.

For the current Nigerian coastline the late Quaternary Delta is most important. Two important formations can be discerned which will be described in further detail and which are related to the last two phases in coastline development: the Older Sands and the Younger Suite. These formations now form a lens-shaped body with a thickness of about 45 m near the delta axis and decreasing towards the flanks and continental shelf edge according to Allen [1965b]. The Older Sands and Younger Suite lie upon the sandy Benin formation, which is up to 2000 m thick.

2.2.1.1 Older Sands

The Older Sands layer dates from the Late Pleistocene to Early Holocene period when the sea transgressed [Allen, 1964; Allen, 1965b]. The sea level during this period some 16,000 years ago was at least 100 m below its present stand [Ihenyen, 2003]. Sand from the river mouths spread across the shelf to form beaches and offshore bars. The bottom rose in terraced stages due to the combined tectonic and compactional subsidence of the continental margin. The Older Sands consist of well-rounded and sorted quartzose sands with shell debris and glauconite [Allen, 1964].

³ The Benue trough is about 300 km wide and 1000 km long.

2.2.1.2 Younger Suite

The Younger Suite was deposited during the most recent post-glacial sea level rise [Allen, 1964; Allen, 1965b]. These Holocene sediments are thus less than 10,000 years old. The Younger Suite sediment entails sands, silts and clays in the modern delta and estuary and barrier-lagoon systems [Allen, 1964]. Transgression was converted into regression due to a new balance between subsidence, sediment supply and sea level change. The delta prograded seawards when sediment supply was so abundant that subsidence and sea level rise could not keep up. These sediments were subsequently deposited on the Older Sands. The last 5,000 to 6,000 year, sea level rose at an almost constant rate with the exception of the 20th century.

Sediments mainly came from rivers and coastal erosion. Losses were offshore transport and relative sea level rise effects. Figure 2-5 shows a typical cross-section of the Niger Delta.



Figure 2-5: Geological cross-section of the soil in the Niger Delta with Holocene deposits on top of a Pleistocene base [After Figure 14, Allersma and Tilmans, 1993]

Due to the large sediment supply by the rivers the Niger Delta advanced. The beach ridge barriers inland are evidence of this advance. Each beach ridge marks a former position of the coastline. On a satellite image from December 1995 close to the OKLNG site the coastal advance and beach ridges can be properly discerned [Allersma and Tilmans, 1993; Abam, 1999]. This image is portrayed in Figure 2-6. The dotted line shows the edge of the delta formation and the Pleistocene coastline of the area [Burke, 1972; Olabode and Adekoya, 2008].



Figure 2-6: Satellite image depicting the coastal advance around the project site due to Younger Suite deposition; each beach ridge marks a former coastline position

Since the layers were compacted slowly and sediment supply was abundant, submarine landslides often occurred. These landslides can be identified at places with a rapid accumulation of sediment and a significantly inclined seafloor [Hampton and Lee, 1996]. This leads to high tangential shear stress and slope failure. These so-called growth faults are numerous in the Niger

Delta area and are always directed northwest-southeast, parallel to the direction in which the Delta advanced. The planes of the successive collapses are indicated in Figure 2-7.



Figure 2-7: Overview of growth faults in the Niger Delta region; growth faults are parallel to the direction of rapid coastline advance [After Figure 15, Mascle, 1976]

The closest growth fault to OKLNG is approximately 75 km to the southeast [Merki, 1972; Mascle, 1976]. Figure 2-7 dates from 1976; a more recent paper by Corredor *et al.* [2005] shows growth faults considerably closer to the project site: one 20 km to the east and one 35 km to the south. Over all, the region is tectonically stable and has low seismic activity [Fugro, 2005b]. Growth faults should be kept in mind, but have not played a role in the OKLNG area up until now since literature, geological maps, satellite images or site visits did not present evidence of these faults.

2.2.2 Recent coastline evolution analysis

2.2.2.1 Coastline evolution analysis based on literature

The West-African coastline is dominated by the Niger Delta. Its large rivers transport sediment to the sea. Coarse material forms the beach and finer material settles in less turbulent waters. Through beach ridge accretion the coast advances. Littoral transport due to the persistent swell is the main form of longshore transport; the rate of transport depends on the angle of incidence of the waves with the coastline. The longshore littoral drift is schematically presented in Figure 2-8.

As can also be seen in Figure 2-8 sand moves from the main mouth of the Niger River along the two flanks of the Delta. At either side of the Niger Delta accumulation occurs [NEDECO, 1954; Allen, 1965a]. One of these accumulating areas is where the OKLNG terminal will be located.



Figure 2-8: Longshore transport direction along the Nigerian coastline based on the predominant wave direction in the area [After Google, 2007]

Zooming in on the OKLNG area and taking the wave angle of incidence of the predominant wave types at OKLNG into account the same conclusion can be drawn. These wave types and their angles of incidence will be further explained in section 2.4.4 on waves. It is evident from Figure 2-9 that two opposing longshore currents meet at the project site. Fugro [2005b] also noted a convergence of opposing longshore currents near the OKLNG site and subsequently came to the same conclusion. Note however that the given directions are predominant directions. On average the longshore current pattern as drawn below is correct, but in time it can change. For the swell waves a reasonable range for the angle of incidence is 185-200° and for sea waves 205-225° [Svasek Hydraulics and Royal Haskoning, 2007a]. What can be concluded is that considering the coastline orientation the westwards longshore current is stronger than the eastwards current.



Figure 2-9: Direction of the longshore transport based on the direction of the incoming sea and swell waves at the OKLNG project site. The directional spread of the wave types is indicated as well [After Google, 2007]

East of the site rapid seaward advance of the coastline during the past few centuries has occurred. Reports from local inhabitants suggest that about 1.5 km of land now existing between the village of Araromi and the present coastline is the landmass gained during the 300 years the community has now existed. This would yield a progression of about 5 m/yr [Fugro, 2005a]. Ihenyen [2003] and Dublin-Green and Awobamise [1997] on the other hand have reported serious erosion the past decades around Mahin, 50 km to the southeast. West of the site the coast is eroding rapidly according to a local guide. He reported several strips of coconut plantation lost since the 1960s [Fugro, 2005b]. Due to lack of further information, conclusions cannot be drawn here.

2.2.2.2 Coastline evolution analysis based on satellite images

Geoserve [Wouters, 2006] has undertaken an analysis of the coastline evolution using satellite images. Satellite images from December 1986, December 1994, February 2000 and January 2005 were obtained, covering a period of over 18 years. The images were chosen based on their negligible difference in coastline definition. The most interesting plot is the one on which the 1986, 1994 and 2005 coastlines are superimposed. This plot is portrayed as Figure 2-10.

OKLNG is located between x = 215 km and x = 217.5 km. The colours in the right corner indicate in what years that specific part of the coastline was present. The Atlantic Ocean is portrayed in black. The 15-20 km coastline with the project site more or less in the middle steadily progressed further southwards over the years. The average rate of coastline advance at the site is 3-7 m/yr [Svasek Hydraulics and Royal Haskoning, 2008a; Svasek Hydraulics and Royal Haskoning, 2008b]. Westwards of this zone hardly any change is observed and east some variation is visible, but no structural changes can be discerned. Note that the image resolution was only 30 m, so the advance rate is only an indication.



Figure 2-10: Coastline advance at the OKLNG site made visible by overlying satellite images from 1986, 1994 and 2005 [After Figure 2.2, Svasek Hydraulics and Royal Haskoning, 2008a]

2.2.2.3 Coastline evolution analysis using models

The net annual longshore sediment flux in the present situation has also been modelled using a schematized wave climate, bathymetric data, the SWAN model and the CERC-formula [Svasek Hydraulics and Royal Haskoning, 2008a; Svasek Hydraulics and Royal Haskoning, 2008b]. Coastline changes can subsequently be deduced by determining the longshore gradients in the sediment flux.

According to the model the annual net longshore sediment flux changes direction 2 km east of the project site. In the west the net annual longshore sediment transport is eastwards directed

and east of the transition point westwards, which is caused by a change in coastline orientation relative to the angle of wave incidence. Sediment from both sides is therefore deposited in front of the coastline of the OKLNG project. The model predicts sedimentation along a 12 km stretch in front of the OKLNG site.

2.2.2.4 Summary of the coastline evolution findings

The most important conclusion to be drawn from the coastline analysis is that due to a coastline orientation change with regard to the main wave angle of incidence sedimentation occurs in front of the OKLNG site. Sediment is trapped in front of the site. Generally sand is transported longshore from the Lagos area to the west and not further than the project site and mud is transported from the Delta region to the east as indicated in Figure 2-8. Literature studies by Allersma and Tilmans [1993] and Allen [1965a; 1965b], a coastline analysis based on incoming wave directions as presented in Figure 2-9, satellite images and sediment transport models all support this conclusion. The westward directed longshore current is stronger than the eastwards directed current when taking the coastline orientation into account.

The coast at the OKLNG site currently advances with roughly 3-7 m/yr. The Fugro [2005a] site visit, the Geoserve satellite images [Wouters, 2006] and Svasek and Royal Haskoning [2008b] model results all show remarkable consensus on this advance rate. The length of the zone is less evident, but also highly influenced by sediment availability.

West of the OKLNG site the coast is stable according to both the modelling and satellite images exercise. Fugro has not come to a clear conclusion on this part of the coast. Field visits suggest a retreat. It is therefore not possible to predict how this part of the coastline will behave in the future, and monitoring is required.

The sediment model expects the coastline east of the project site to retreat [Svasek Hydraulics and Royal Haskoning, 2008a; Svasek Hydraulics and Royal Haskoning, 2008b]. However this coast is muddy and the model was only valid for sandy coasts. The model result is therefore much less reliable than other methods used to analyse the coastline development. The satellite pictures show a slight coastline advance and Fugro also reports a coastline advance, although more significant. Since the coastline has been advancing for the past centuries, this process is likely to continue for the years to come.

Note that research from the 1980s and onwards has found a net coastline retreat of the Niger Delta as previously explained in section 2.1.1.3 on the Niger Delta [Ibe, 1988; Abam, 1999] and reported by Ihenyen [2003] and Dublin-Green and Awobamise [1997]. Eventually this will have its effect on the OKLNG area as well, but this may very well not be during the lifetime of the OKLNG project.

2.2.3 Sediment distribution

2.2.3.1 General composition of the Nigerian shelf bottom soil layer

The bottom geology in the Bight of Benin is shown in Figure 2-11. This figure is based on the Admiralty Chart, and also confirmed by research from Allen [1964] and supported by a sand search campaign conducted by others in 1999.

The bottom of the Bight of Benin is predominantly muddy. No rock is found offshore Nigeria. Allen [1964] describes the bottom down to a depth of about 900 m as "pale greenish grey silty clay". Only the nearshore area between the entrance to Lagos Lagoon and OKLNG has a sandy seabed as is evident from Figure 2-11. No mud layer has formed in this area. However it is likely that fine sediments do reach this area, due to the strong longshore currents as shown in Figure 2-8. The sandy area surrounds Avon canyon, which lies close to the shore. Thus it is likely that the fine sediment transported eastwards by the longshore current is channelled towards deeper water every now and then via the canyon [Van der Valk, 2009].



Figure 2-11: Seabed soil type around OKLNG [Based on Admiralty Chart, 1998]

The large sandy seabed area is part of the Older Sands layer according to Allen [1964] as can be seen in Figure 2-12. Other patches of sand can locally be found on the seabed as well, which can be part of the Older Sands as well as this layer underlies the entire deltaic area. More recent sandy areas can be identified close to river mouths.



Figure 2-12: Location of outcrops of Older Sands deposits near the OKLNG site [After Figure 2C, Allen, 1964]

In any case the existence of the Older Sands outcrop east of OKLNG is due to large-scale processes, which have not been studied in detail. Relevant for this thesis is that despite the strong eastward longshore current the outcrop will not extend further to the east. This is due to the converging longshore currents at the project site. At the OKLNG project area a change in seabed composition from sand to mud is apparent.

2.2.3.2 General sedimentary environment at OKLNG

The subsoil at OKLNG is mainly composed of clay and sand layers. The change in seabed composition as deduced from the Admiralty Chart is confirmed by conducted soil investigations for OKLNG [GEMS, 2008a; GEMS, 2008b; GEMS, 2008c; GEMS, 2008d] and a study by Allen [1965b]. Figure 2-13 shows the grain-size distribution around OKLNG. West of the location of the future OKLNG approach channel the Older Sands surface and no Younger Suite mud layer has formed on top.



Figure 2-13: Grain size distribution of the seabed material around OKLNG showing sand towards the west surrounded by fine sediments [After Figure 3 and 9, Allen, 1965b]

2.2.3.3 Shoreline sand layer

At the shoreline of the project site sand is overlying earlier Holocene marine clay. Sand samples taken from the beach at different heights during the cross-shore profiling campaign mentioned in section 2.3.2 show a D_{50} of 0.4 to 0.6 mm, which is very coarse sand. Dublin-Green and Awobamise [1997] also report medium to coarse sand. Almost only sand was found in the samples. Unfortunately the exact locations where the sand samples were taken have not been recorded.

Sand found at the OKLNG site does not only come from the Niger Delta. It is likely that river sediments are transported longshore from the west as well. A strong littoral drift transports sediment from the Volta, Mono and Ouemé Rivers in Ghana and Benin eastwards.

The eastwards sand transport is clearly visible at the Lagos harbour moles. Sand has accumulated at Lighthouse Beach in the west for over a century now. At the eastern side Bar Beach has eroded considerably over the last 100 years. Between 1924 and 1972 Lighthouse Beach has prograded about 1,200 m [Fugro, 2005b]. Figure 2-14 shows the evolution over the years.



Figure 2-14: The evolution of the Lagos coastline after construction of the Harbour Moles shows that the longshore transported is directed eastwards [Ibe, 1988]

Most of the sand will be trapped in the coastal-barrier system, but a small part will escape eastwards and be transported further. Locally the outcrops of the Older Sands are also sources of sands due to current reworking. The sandy coastline east of Lagos consists of river sediment and sand from outcrops drifted by the west-east longshore current [Allen, 1965b].

About 8-10 kilometres east of OKLNG the Mahin mud beach starts. Sand coming from the Delta apparently cannot reach this coastal stretch. Only 20% of the sediment transported to the Niger River mouth is sand and this coarse sediment is deposited near the river mouths. Sand from the

west cannot reach the area either as can be seen in Figure 2-8. Along the Mahin mud beach the longshore current is directed to the northwest; sand from Lagos simply cannot reach this stretch.

2.2.3.4 Offshore stratigraphy

Over the whole site generally a top layer of varying thickness of very soft greenish grey clay is present. The clay layers are very soft at the sea bed [GEMS, 2008b]. The bulk density generally increases with depth. The top mud layer thickness increases from 0 m southwest of the site to 8 m in the northeast and near the shoreline.

Underneath the mud layers of dense sand are present, at depths from 2 m to more than 35 m [GEMS, 2008e]. Especially on the extreme flanks of the Delta layered sediments are found. The Older Sands layer can locally be only a few decimetres thick, but on the whole Allen [Allen, 1965b] suggests a thickness of 5-10 m. This estimation seems likely when comparing this layer to transgressive sand layers the same age in other parts of the world. Soil data of undertaken field campaigns will be analysed extensively in a next chapter.

2.3 Bathymetry

2.3.1 General bathymetry in the Bight of Benin

The continental shelf in front of the Nigerian coastline is narrow; 20-25 km in front of Lagos until 50-65 km in front of the Niger Delta. The Western Nigerian continental slope is steep, but the shelf itself is flat and thus effectively reduces wave energy. The continental slope towards the delta is much gentler as can be seen in Figure 2-15.



Figure 2-15: Bathymetry offshore Nigeria showing the continental shelf break and several submarine canyons [After Figure 3, Mascle, 1976]

The shelf usually breaks at the 100-120 m depth contour. Bathymetric lines run parallel to the coastline, except where submarine canyons incise the continental shelf. One of these canyons, Avon canyon, is close to the OKLNG site. Mahin canyon lies further offshore and to the south. This canyon is located past the continental shelf break and does therefore not influence the nearshore bathymetry [Allen, 1964; Allen, 1965b; Allersma and Tilmans, 1993; Ajoa *et al.*, 1996; Ihenyen, 2003].

2.3.2 Beach topography

Beach ridges with an elevation of 3 to 6 m above MSL form the border between land and water at the OKLNG site [Fugro, 2005b]. The beach is relatively narrow due to the small tidal range. The horizontal distance between the tidal marks is roughly 50 to 150 m [NEDECO, 1954].

At the beach in the OKLNG area a cross-shore profiling campaign was undertaken between May 2007 and September 2008. The general cross-shore profile is a sandy shoreline where the waves break quickly on a relatively steep beach with a slope of about 1:7.5. The cross-shore profiles show a beach slope of 1:5 to 1:10 above the water line. Although this is steep, this range is confirmed in research by Allen [1965b] and Dublin-Green and Awobamise [1997]. Below the water line, the slope is 1:50 to 1:100 [NEDECO, 1954]. The beach slope measurements are presented in Figure 2-16.



Figure 2-16: Measured beach slopes at OKLNG

After the steep beach quickly falls to -5 m CD, it abruptly shifts to a gentle slope [Allen, 1965b; Royal Haskoning, 2007]. This seabed bathymetry is consistent with a swell climate [Karsten, 2004].

2.3.3 Offshore OKLNG bathymetry

2.3.3.1 Continental shelf break

The Admiralty Chart 4 of the area around OKLNG [Admiralty Chart, 1998] is depicted in Figure 2-17.



Figure 2-17: Bathymetry of the OKLNG area showing the gentle slope near the coast, the sudden continental shelf break and Avon canyon [After Admiralty Chart, 1998]

⁴ The earliest surveys date from the early 19th century.

From the western flank of the Delta the shelf break is about 50 km offshore measured perpendicular to the shoreline. The water depth quickly increases to a couple of hundred meters after the sudden shelf break. Then the ocean floor steadily drops to 4 to 5 km below sea level. This can also be concluded from Figure 2-15.

2.3.3.2 Avon canyon

Besides the continental shelf break the Admiralty Chart clearly shows the previously mentioned Avon canyon at approximately 6°15′N and 3°53′E. This canyon is located about 40 km to the west of the project site and has a southeast direction. The canyon is about 13 km wide, 600 m deep and has a V-shape [Ihenyen, 2003; Olabode and Adekoya, 2008]. On both sides of the head small gullies feed the main canyon [Olabode and Adekoya, 2008]. The canyon head reaches until 3 to 5 km of the beach in a water depth of less than 15 m [Dublin-Green and Awobamise, 1997; Olabode and Adekoya, 2008].



Figure 2-18: 3D-impression of Avon canyon, its gullies and from which direction sediment is likely to flow into the channel [After Figures 10a and b, Olabode and Adekoya, 2008]

Olabode and Adekoya [2008] suggest that Avon canyon was formed earlier than the Miocene when the sea level was much lower than at present. Several rivers emptied into Avon canyon during the Pleistocene and subsequently cut further into the Benin formation [Burke, 1972]. When the sea level rose during the Holocene, other channels in the Delta quickly filled up, except for the Avon, Mahin and Calabar canyons. Both Burke [1972] and Petters [1984] argue that the converging longshore drifts at both sides of the Niger Delta resulted in gravity-driven sediment flows down slope, which kept the canyon from filling up.

Olabode and Adekoya [2008] found the Avon canyon to be still active. The canyon's orientation shows that most sediment channelled offshore comes from the west. This induces a density current which can lead to the erosive activity of the south eastern walls observed by Olabode and Adekoya [2008]. However the orientation of the channel and the absence of gullies directed towards the project site direction do not indicate that large amounts of sediments are carried away from the OKLNG area via the canyon towards deeper water.

2.3.3.3 Depth contours

At the OKLNG site, the shoreline changes direction from southeast-northwest to east-west. The bottom contours are influenced by the western Niger Delta flank and Avon canyon and are therefore not parallel to the shoreline. Southeast of the site towards Benin and Forcados River, the depth contours do run parallel to the shoreline.

For the OKLNG project a bathymetric survey was conducted as well. EGS surveyed the area for HR Wallingford [2005] the last two weeks of March 2005. This bathymetric map is portrayed in Figure 2-19. Since Avon canyon incises the continental shelf only 40 km west of the project location, it influences the bottom depth contours nearby. The contours curve around the canyon, so south and southeast of OKLNG they are not parallel to the shoreline. More to the southeast the canyon is sufficiently far away, so the contours are directed southeast-northwest and parallel to the shoreline.



Figure 2-19: Bathymetric map of the OKLNG area showing depth contour lines with regard to CD changing from running parallel along the shoreline in the east to being distorted by Avon canyon in the west [Based on Admiralty Chart, 1998; HR Wallingford, 2005]

2.3.3.4 Bottom slopes

The bottom slopes at the project site appear to be influenced by the nearby convex Older Sands layer as depicted in Figure 2-12. Nearshore the slope is very gentle at approximately 1:1100. At -8 m CD a slope discontinuity can be discerned; the bottom contours start to lie closer together. From a slope of 1:800 at -8 m CD, the slope gradually increases to 1:350 at -30 m CD. An impression of the seabed slopes perpendicular to the coastline at the project site is given in Figure 2-20.



Figure 2-20: Impression of the seabed slope offshore OKLNG perpendicular to the coastline; the slope is convex upwards with gentle slopes normal for outbuilding deltas and the distance from the shelf break to the beach is approximately 50 km

A 1:350 slope is found along the entire western Niger Delta flank between the -11 m and continental shelf break contour. Literature [Allen, 1965b], the Admiralty Chart [1998] and recent bathymetric surveys of the site all give this 1:350 slope. The bottom slopes from the -30 m depth contour towards shallower water at OKLNG do not match the apparent equilibrium slopes found closer to the Delta, but the convex older sand layer slopes.

It is noted that it is typical for an outbuilding delta that close to the shore the bottom slope is so gentle. Allen [1965b] mentions a slope of 1:200 to 1:4000. Apparently sediment at OKLNG accumulates faster than the equilibrium slope is reached. The prograding coastline and formation of the Niger Delta support this assumption.

This might also indicate a possible instability of the seabed soil layers although the nearby Older Sands layer has the same slope pattern. Considering the large amount of growth faults in the Niger Delta as discussed in section 2.2.1.2, the stratigraphy of the OKLNG area should be investigated in more detail.

2.4 Metocean data

2.4.1 Data sources

A number of investigations have been conducted since 2005 to provide input parameters for the design of the OKLNG terminal. These input parameters include measurements and models of the wind, wave, current and tidal conditions, and a collection of meteorological data. Measuring sequences of up to a year are recorded. Where needed, additional regional data sources and models were used to obtain a proper metocean overview for the project.

2.4.1.1 OKLNG field campaign

For the OKLNG field campaign GEMS conducted measurements at three offshore locations at different depths: at -9 m CD, -12 m CD and -15 m CD. Note that Chart Datum is defined as Lowest Astronomical Tide. These three offshore and one additional onshore location are indicated in Figure 2-21. Every 5 weeks the instruments were read and placed back in the water.

The three locations in Figure 2-21 are located outside the surf zone. The breaker line would lie at the -3 m CD depth contour for a wave height of 2 m. The breakwater extends to -6 m CD, so it is safe to say that the measurements concern non-breaking waves.



Figure 2-21: Locations of measuring devices for the OKLNG data collection campaign by GEMS. Location 1 is at the -9 m depth contour, location 2 at -12 m and location 3 at -15 m

A Nortek AWAC device was placed at the three offshore locations, which obtained the 3D velocity vector every 0.5 m starting approximately 1.5 m above the seabed. Current velocity time series and wave height, period and direction time series can be deduced from these data. On the Norton AWC device an Acoustic Surface Tracker or AST measured water level time series.

Additionally Sontek downward looking Acoustic Doppler Profiler or ADP measured current velocities every 1.9 cm at location 1 and 2.

On a high frame at each of the offshore locations YSI turbidity sensors at 0.1, 0.4 and 0.6 m above the seabed collected data on the turbidity, temperature, salinity and water pressure. The instrument was subject to significant biofouling. The turbidity measurements will not be discussed in this chapter, but in the next chapter on the OKLNG soil characteristics.

An onshore weather station at 10 m elevation was also deployed, collecting wind, air temperature, relative humidity, atmospheric pressure and rainfall data. Meteorological data are not of importance for this study and are therefore not paid attention to in this chapter.

2.4.1.2 Additional data sources

Besides field campaigns at the OKLNG site itself, additional data was also used. Many wind data sources were available for OKLNG. The NOAA (National Oceanographic and Atmospheric Administration) wind models provides hourly-averaged wind speeds on a relatively large grid from 1997 and onwards. Also Bonga and Escravos wind data are available, the locations of which are indicated in Figure 2-2. NOAA and WANE also generate wave and current data. In 14 m deep water off Benin River, approximately 90 km southeast of the OKLNG site, current velocities have been measured for almost a year. Finally some older research is used to compare current data.

2.4.2 Water levels

2.4.2.1 Tidal range

Tides along the Nigerian coastline are semi-diurnal with a range of 1.0 m around Lagos increasing to 3.0 m in the Cross River estuary at the eastern side of the Niger Delta according to Allersma and Tilmans [1993]. At Forcados the tidal range is 1.3 m [Allen, 1965b]. Analysed measurements from May 2006 to May 2007 give tidal components at the OKLNG site as presented in Table 2-1.

Table 2-1: Tidal components with the largest amplitudes measured at the OKLNG site[Svasek Hydraulics and Royal Haskoning, 2007a]

Tidal	Amplitude
component	(cm)
M2	51.1
S2	18.0
K1	13.2
N2	10.7

Admiralty Tide Tables and Allersma and Tilmans [1993] show negligible seasonal variations in MSL. MSL is +1.0 m CD, with Chart Datum defined as Lowest Astronomical Tide. The tide is semi-diurnal and has a mean tidal range of 1 m. During spring tide the water level difference between high and low water can increase to 1.7 m and during neap tide the tidal range is only 0.45 m. The daily inequality is small.

2.4.2.2 Storm surge, wave set-up and tsunami waves

For infill under average conditions, storm surge, wave set-up and tsunami wave levels are irrelevant and therefore not treated here. Moreover, 1:100 years extreme water levels are limited to \pm 0.5 m [Svasek Hydraulics and Royal Haskoning, 2007a].

2.4.3 Wind

West Africa has a mild wind climate offshore. Wind at OKLNG is fairly unidirectional and primarily comes from the southwest. Given the location close to the equator and thus a fairly constant and high temperature year round, this is as expected. The speed is low, only rarely exceeding 12 m/s at 10 m height. Wind data are not important for this specific sedimentation study, but a short summary is provided to be complete.

2.4.4 Waves

2.4.4.1 Time series

A unique wave dataset is available for OKLNG. Simultaneous data of 6 months to one year at -9 m CD, -12 m CD and -15 m CD have been recorded. Every hour a wave spectrum is composed per measuring location, based on a sample duration of 1,024 s. NOAA hindcasts from covering the ten years from 1997 until 2007 have also been used for the analysis.

2.4.4.2 Wave characteristics

At OKLNG, mainly swell and sea waves occur. During storm events also low-frequency waves are present, which height is strongly correlated to the swell wave height. The time series show fairly unidirectional long swell waves with a peak period of 14 s and sea waves with a peak period of 6 s coming from the south-southwest. Swell waves with periods of 15 to 18 s arrive first at the site after which the peak period slowly decreases over a period of a few days [GEMS, 2009]. The average significant wave height roughly varies between 1 and 1.7 m. The wave height depicts seasonality. In July and August the wave height is higher than on average. Between the three measurement stations at the –9, –12 and –15 m depth contours the wave height barely differs. The mean wave direction generally varies between 180° and 230° as can also be concluded from Figure 2-9. NOAA data show a range between 180° and 210°. The difference between NOAA and OKLNG data is also visible in the wave roses of Figure 2-22. The offshore NOAA data show a smaller directional spreading and smaller wave heights. The locations in Figure 2-22 refer to Figure 2-21.

Although waves generally come from the south-southwest, in the wave roses of Figure 2-22 two directional segments can be discerned. The predominant offshore wind direction at OKLNG, which generates the sea waves, is $\theta_{wind} = 225^{\circ}$. Since the wind direction and sea wave direction are strongly correlated, the corresponding segment thus represents mainly sea waves. They do not correspond exactly, due to amongst others the influence of bottom topography nearshore. The segment around $\theta_{wave} = 195^{\circ}$ represents mainly swell waves. The swell originates from a direction slightly different from the wind direction. This is also confirmed by values found in literature [e.g. Allen, 1965b] and online metocean databases [Argoss, 2009].



Figure 2-22: Measured (top) and NOAA (bottom) wave roses at OKLNG showing wave height and direction [Figure 5.13, Svasek Hydraulics and Royal Haskoning, 2007a]

2.4.4.3 Wave types at OKLNG

Three wave types can be discerned at OKLNG: sea, swell and low-frequency waves. This is evident from Figure F-1 in Appendix F. A distinction between sea waves with T < 8 s, swell waves with 8 < T < 22 s and low-frequency waves of T > 22 s can be made.

Swell waves have a high-energy content due to their length and dominate the spectrum. Swell waves are 0.9 m high on average and the sea waves are 0.7 m high on average. The majority of the waves are 1.1 to 1.5 m high and peaks in significant wave height are primarily caused by swell waves.

The low frequency waves have been investigated as well using the OKLNG dataset. The low frequency wave height increases strongly with the swell wave height. 90% of the time the low-frequency wave height is smaller than 0.2 m. During storm periods higher waves are observed with a maximum of 0.6 m. These waves shoal considerably, so the wave energy increases towards the shoreline [Svasek Hydraulics and Royal Haskoning, 2007a].

Wave heights at decreasing depth correlate well; differences in significant wave height between the locations are less than 5%.

2.4.4.4 Monthly averaged wave statistics

The wave height is season-related. The highest waves are found in July and August and the lowest in December and January. This difference in wave height between the wet and dry months is significant: a significant wave height of 0.8 m in December and January and 1.4 m in July and August.

2.4.4.5 Annual wave statistics

For sea waves 75% of the time the wave height is smaller than 0.8 m. According to Svasek and Royal Haskoning [2007a] the distribution of the sea waves resembles a Gaussian distribution. The swell wave distribution has a heavier tail towards the larger wave heights. Since the swell and low-frequency waves are correlated, it seems likely that their distributions are alike. The spectrum of the swell is best described using a lognormal distribution [Ewans, 2005]. Swell waves are lower than 1.4 m 90% of the time.

2.4.5 Currents

2.4.5.1 Time series

Measurements at the OKLNG site and offshore of the Benin River were used to analyse the currents. The Benin River data also cover a year, but a different one than the OKLNG data. At Benin River, velocities were measured at a mean water depth of 14 m, so comparable to location 3 at OKLNG. This location is portrayed in Figure 2-23.



Figure 2-23: Location where velocity measurements comparable with OKLNG were done [Figure 1, Rider, 2004]

2.4.5.2 Current characteristics

The currents at OKLNG are bi-directional: a WNW ($\theta \approx 290^{\circ}$) directed current and an ESE ($\theta \approx 110^{\circ}$) directed current. This bi-directional current distribution is apparent in shallow water – location 1 in Figure 2-21 at a water depth of –9 m CD – and the upper part of the water column in deeper water – locations 2 and 3 in the same figure at a water depth of –12 and –15 m CD.

Both currents have an equal contribution to the current statistics. In the lower water column in deeper water the current velocity has a peak around 290°, so an undercurrent is dominant there. This sometimes causes vertical stratification in the water column.

Current reversals occur irregularly and are not related to the tide. GEMS [2009] and Svasek and Royal Haskoning [2007a] cannot find a predictable pattern. The largest rate of change in the current velocity is 0.6 m/s in 9 hours. Generally a change in current direction from ESE to WNW can take 1 to 8 days. Although the direction itself is not well predictable, current directions perpendicular to the shoreline are reasonably similar in the same period.

Near surface velocities did not exceed 1 m/s in the monitored year. Note again that this concerns current velocities outside the breaker zone. Velocities near the surface are generally larger than at the bottom. Velocities not in one of the main two directions are small as can be seen in Figure 2-24 and Figure 2-25. The currents are thus generally parallel to the depth contours. For the locations the reader is referred to Figure 2-21.



Figure 2-24: Current roses for location 1 at a depth of –9 m CD showing the strong bidirectional current pattern at OKLNG [Figure 7.12, Svasek Hydraulics and Royal Haskoning, 2007a]



Figure 2-25: Current roses for location 3 at a depth of –15 m CD showing the strong bi-directional current pattern at OKLNG [Figure 7.13, Svasek Hydraulics and Royal Haskoning, 2007a]

The magnitude of the velocities near the bed, at mid-depth and near the surface does not differ much per location. The near bed current velocity rarely exceeds 0.4 m/s. The near-bed velocities in deeper water are restricted to about 0.2 m/s, except in the ESE direction where it can amount up to about 0.4 m/s. In July and August current velocities are highest.

2.4.5.3 Current origin

Several current types are present offshore the OKLNG project site; large geostrophic currents and currents generated by waves or tides.

The tidal current along the Nigerian coast is relatively weak. As can be noted in Figure 2-26, tidal currents are indeed very small close to OKLNG. Allen [1965b] states a maximum current of 0.05 to 0.10 m/s.



Figure 2-26: Wave and tidal currents near the OKLNG site [Figure 6, Allen, 1965b]

The maximum velocities generated by waves at the project site are much larger as can be seen in both Figure 2-26 and Figure $2-27^5$. The average wave height in July and August of 1.4 m already generates a maximum orbital velocity strong enough to erode clay or silt deposited during calmer periods. Wave driven currents are only important close to the shore until a water depth of maximum –5 m CD, so within the surf zone.

This indicates that on a larger scale, the currents at the OKLNG site have to be geostrophic currents. The two main current directions at OKLNG have the same direction as the Guinea current and the Ivorian undercurrent. The Guinea current is directed ESE and the Ivorian undercurrent is directed WNW. Both currents follow the depth contours.

The Guinea current flows east at approximately 3°N and originates from both the North Equatorial Counter current and the Canary Current. The Guinea Current is a relatively shallow flow, extending from the surface to about 15 m water depth near the coast and 25 m offshore [Ajoa *et al.*, 1996; Gyory *et al.*, 2005]. At depths shallower than 40 m it is in contact with the sea bed [Allen, 1965b]. It extends 400 to 480 km offshore [Encyclopædia Britannica, 2009].

⁵ The velocities were calculated using Airy wave theory. The shallow water assumption is found to be valid for the used waves.


Figure 2-27: Maximum near bottom orbital velocities at OKLNG depending on water depth, wave height and wave period (Water depth with regard to MSL = +1.0 m CD)

The Guinea Current is strongly influenced by the North Equatorial Counter current, which has a seasonal variation. In summer from May through September, when this current is at its strongest, the Guinea current is also at its strongest. In the Bight of Benin at 5°N it can reach velocities up to 1 m/s in summer; the OKLNG location is located at 5°22″N. A minimum occurs from November through February; the current velocity is around 0.5 m/s in winter [Gyory *et al.*, 2005].

The Guinea Current is geostrophically balanced. Isotherms slope upwards near the northern coast. Intensification of the current causes a steeper slope and a thermocline closer to the surface. Coastal upwelling and intensification in summer are thus related. The current in the Gulf of Guinea flows towards the equator and finally joins the South Equatorial Current. The current is warm and has a relatively low salinity [Gyory *et al.*, 2005].



Figure 2-28: Guinea Current in January-March and June-August. Plots are made using the Mariano Global Surface Velocity Analysis [Gyory *et al.*, 2005]

The Ivorian undercurrent runs underneath the Guinea current. Since the water of the Ivorian undercurrent has been identified as South Atlantic Central Water, it is believed that this undercurrent is a westward flowing extension of the northern branch of the South Equatorial Undercurrent (SEUC). The SEUC flows between 1°N and about 4°S and is deflected counter clockwise by the continent. Sometimes the Ivorian Undercurrent can be observed at the surface [Ajoa *et al.*, 1996; Norris, 1998; Bonhoure *et al.*, 2004; Gyory *et al.*, 2005]. Near the coast the average speed is around 30 to 40 cm/s, about half the speed of the Guinea Current. Considering the current roses at OKLNG it can be observed that the WNW current is about half as strong as the ESE current. In the lower half of the water column in deeper water (location 3) the current direction near the bed is more uniform as can be seen in the current rose of Figure 2-25. A peak is visible in the direction of the Ivorian undercurrent. Near the coast (water depth of -9 m CD) and in the top half of the water column the current direction alternates between the two.

Geostrophic currents are thus dominant for the current velocities at the OKLNG site, not the tidal currents. This is supported by a fairly unidirectional current in January and February, whereas local wind speeds are small. Larger scale wind patterns thus have to dominate the currents. Also the time scale over which this directional change takes place is larger than the tidal period. No diurnal or semi-diurnal variation in current velocity is observed. Wave-driven currents are important on a local scale only, especially near the bottom.

2.4.5.4 Monthly averaged current statistics

Near the bottom currents are highest in July and August. Near the surface an extra peak is visible in January. On average, the velocity in the water column at 1.5 m above the bottom is about 0.15 m/s [GEMS, 2009]. At mid-depth it is about 0.18 m/s and near the surface 0.20 m/s. In July and August the velocity is generally 0.05 m/s higher. Currents in shallower water are slightly stronger.

2.4.5.5 Annual current statistics

The Benin River current dataset has similar trends as the OKLNG measurements at location 3. The current at Benin River is also bi-directional and follows the depth contours. The trend in velocity magnitude over the year is similar to OKLNG. For 2000-2001 data in the Benin River were analysed. The results are presented in Table 2-2.

Table 2-2: Benin current data for	2000-2001, which are	similar to OKLNG current
data [After Table 4, Rider, 2004]		

Current	Average value	Standard deviation	Maximum speed
Surface	0.19	0.13	0.81
Bottom	0.13	0.08	0.40

This corresponds well to the OKLNG dataset, so it is likely that it is also representative for the longer term and can be used as annual current statistics for OKLNG.

2.4.6 Sea water characteristics

An important seawater characteristic is the density. In order to determine this value, salinity and temperature measurements have been conducted. From literature it is known that the waters on the Nigerian shelf are stratified; warm fresh tropical water (25-29°C, 33-34 ppt) overlies cooler subtropical water (19-28°C, 35-36.5 ppt) [Ajoa *et al.*, 1996].

Nigeria experiences two seasons: a wet season from March to November and a dry season in winter. These seasons influence the salinity and temperature of the ocean water.

2.4.6.1 Salinity

Biofouling made the salinity measurements hard to interpret, but Svasek and Royal Haskoning [2007a] estimate the near bed salinity to vary between 30 and 35 ppt. According to Dublin-Green and Awobamise [1997] the salinity of the coastal waters surrounding the Niger Delta is 27-30 ppt. Relatively low sea surface salinities occur near the Nigerian coastline due to large river runoffs and high precipitation near [Encyclopædia Britannica, 2009]. For example, in 2006-2007 OKLNG received 3,000 mm of rainfall. In July and September, the wettest months, around 800 mm fell. In January and December no rain fell at all. This is comparable to rainfall data of Benin and Warri [Dublin-Green and Awobamise, 1997]. In the ocean water a shallow thermocline is visible at around 30 m depth where the warmer and lighter water is separated from colder, more saline and denser water [Encyclopædia Britannica, 2009]. This thermocline is located much lower in the water column than the depth until which the approach channel will be dredged.

Rider [2004] performed measurements at five transects along the Nigerian coastline from Lagos to the east end of the Niger Delta for one year. After interpolating values from the two transects surrounding the OKLNG site, she found surface salinities at -15 m CD varying from 23 ppt in October to 30 ppt the rest of the year. Note that in October the Niger River has its peak discharge, which is tenfold of its normal discharge. Bottom salinities vary from 30 ppt in October to 34 ppt in July. Near major river outflow salinity can even be as low as 17 to 25 ppt [Ajoa *et al.*, 1996].

2.4.6.2 Temperature

The water temperature varies from 31°C in April to 26°C in August [GEMS, 2009]. The large-scale variation is similar to the large-scale variation in air temperature.

2.4.6.3 Density

Based on Table 8.1 in Svasek Hydraulics and Royal Haskoning [2007a], the density at the OKLNG site varies between 1,017 and 1,023 kg/m³. The highest density will occur at low temperatures and high salinity. The storm season with the highest waves and current velocities occurs in July and August when the water temperature is low and runoff is high.

2.4.6.4 Viscosity

The dynamic viscosity of water depends on the temperature. For water of 25°C the dynamic viscosity is 8.9·10⁻⁴ Pa·s and for water of 30°C it is 8.0·10⁻⁴ Pa·s [Battjes, 2002; Messe, 2003]. Subsequently the kinematic viscosity can be computed by dividing the dynamic viscosity by the seawater density, $\nu = \mu / \rho_w$.

2.5 Overview of the coastal processes

The Niger Delta with the future OKLNG site at the outer end of its north-western flank is a highly dynamic area in terms of coastal processes. Figure 2-29 depicts the Nigerian coastline with a focus on the project site. Important bathymetric features, the sediment distribution on the seabed and the hydrodynamic processes are indicated and will all be summarized in this section.



Figure 2-29: Overview of the governing hydrodynamic processes in front of the Nigerian coast with a focus on OKLNG [After Google, 2007]

At the OKLNG project site a narrow, steep and sandy beach forms the division between land and sea. Slopes range between 1:5 and 1:10. The sand is quite coarse with a D_{50} ranging between 0.4 and 0.6 mm.

At a depth of -5 m CD the steep beach slope abruptly shifts to a gentle slope. The bottom slope is convex with a 1:1100 slope near the coast increasing to the 1:350 slope at -30 m CD. This convex slope is consistent with the slope of a prograding delta like the Niger Delta. Sediment is deposited quicker than it is transported offshore or than relative sea level rise due to subsidence or global warming.

In front of the site a narrow but gently sloping continental shelf is present. This shelf breaks around the 100-120 m depth contour line, which is about 50 km offshore of OKLNG. Bathymetric contour lines run parallel to the shore at the east of the site, but are distorted by a submarine canyon 40 km west of the project site which incises the continental shelf. This also leads to a steeper slope at that side.

The bathymetry is also consistent with the wave climate in the area. At the site sea waves, swell and low-frequency waves can be discerned, of which swell waves are dominant. Long swell waves contain much energy. They have a relatively low wave height, so they break close to the shore. Therefore fine sediments will not be found at the shoreline. Coarser sediment results in steeper beach slopes. Outside the breaker zone swell waves generate a relatively strong and regular orbital motion, effectively flattening the bottom. Finer particles can settle here as well. As a consequence, the bottom slope is gentle.

The swell waves originate from the southern hemisphere. Their predominant direction is 195°. The low-frequency waves are strongly correlated with the swell. The predominant direction of the sea waves is influenced by the local wind climate and is 215°. Concluding, a fairly unidirectional wave spectrum is observed at OKLNG.

The wave climate determines the longshore sediment transport along the Nigerian coastline. The coastline changes direction around the designated project area. The western flank of the Niger Delta is oriented southeast-northwest, because of the prograding wave-dominated Delta. The coast from Lagos to the site is oriented east-west. The fairly unidirectional incoming waves result in two opposing longshore currents meeting at the OKLNG shoreline. The eastward longshore current is stronger than the westward directed one. Sand is transported eastwards from the

Lagos coastal barrier–lagoon system. From the east mud is transported along the western Delta flank and past the Mahin mud beach to the site.

The seabed in the area is muddy, except west of the project site until a depth of roughly -30 m CD. There the Late Pleistocene-Early Holocene Older Sands layer surfaces at the seabed. Swell waves induce large orbital velocities near the sea bottom, which prevent fine sediments from settling. In suspension the geostrophic currents can easily transport these light particles. Therefore a wide band of muddy water surrounding the Niger Delta can be seen on satellite images.

In the west the Older Sands layer lies at the surface; this layer is not further studied. It is likely that Avon canyon has channelled a lot of sediment towards deeper water. In the east a Younger Suite mud layer of several meters thick has developed on top of the Older Suite. These clay and silt sediments are not older than 12,000 years. The Younger Suite consists of sediment transported by the Niger and Benue Rivers. The western flank of the Delta is mostly fed by Forcados River, 120 km to the southeast of the future inland terminal. Considering the persistent swell waves in this area, it is possible that wave driven transport of liquid mud occurs from the Delta river mouths along the flanks and towards OKLNG.

OKLNG is located at the utmost north-western point of the Niger Delta, where the Lagos sand coast meets the Mahin mud coast. For the past centuries, the shoreline has advanced outwards to the southwest. How the coastline will behave in the future is uncertain. The sandy coastline west of the site seems stable at the moment. The Niger Delta is currently eroding due to human interference in the area and erosion of the Mahin mud beach has been reported. Eventually this will have its effects on the OKLNG area, although for the past millennia the coast has advanced.

The governing currents at the site are geostrophic currents. The Guinea Current follows the depth contours and is directed ESE. From time to time the Ivorian Undercurrent suppresses the Guinea Current on the continental shelf and an opposing WNW-current can be observed. These two currents are a constant factor and have an equal contribution to the current statistics. Generally a change in current direction takes several days.

The geostrophic currents are sufficient to generate a constant flow of water from the shoreline extending hundreds of kilometres offshore, but are not powerful enough to stir up sediment near the seabed. Tidal currents are very small along the open coastline due to the small tidal range, but wave-induced orbital velocities are high and sufficient to erode sediment from the bed. Wave-induced longshore currents are only of importance within the surf zone.

To conclude this chapter the characteristic metocean parameters are summarised in Table 2-3 on the next page. For the infill modelling the current data are most important. The water levels and seawater characteristics are required to model the infill as well. The wave climate influences the sediment state in the water column as will be discussed in the next chapter.

Metocean parameter	Value	Comments
Water levels: • Mean Sea Level MSL • Tidal range	+1.00 m LAT 1.07 m	Tidal range is 0.45 m at neap tide and 1.7 m at spring tide
 Wind: Predominant offshore direction (NOAA) Predominant onshore direction (OKLNG) Mean wind speed u₁₀ 	225 ° 250 ° 5 m/s	$210 < \theta_{offshore} < 240^{\circ}$ $240 < \theta_{onshore} < 270^{\circ}$
 Sea waves: Predominant sea wave direction Average sea wave height H_{s,sea} Average wave period T_{p,sea} 	215 ° 0.7 m 6 s	$205 < \theta_{sea} < 225^{\circ}$ $H_{s,wet}$ = 0.9 m, $H_{s,dry}$ = 0.4 m
 Swell waves: Predominant swell wave direction Average swell wave height H_{s,swell} Average wave period T_{p,swell} 	195 ° 0.9 m 14 s	$185 < \theta_{swell} < 200^{\circ}$ $H_{s,wet}$ = 1.0 m, $H_{s,dry}$ = 0.7 m
 Waves in general: Average wave height in DecJan. H_{av,dry} Average wave height in July-Aug. H_{av,wet} Yearly significant wave height H_{s,1 year} Measured max. wave height H_{max,1yr} 	0.8 m 1.4 m 1.7 m 3.0 m	
Governing currents: • Direction of the Guinea Current • Direction of the Ivorian Undercurrent	110 ° 290 °	ESE WNW
 Other currents: Maximum wave-induced orbital velocities near the bottom Maximum tidal velocities Wave-driven currents (longshore current) 	> 1 m/s 0.5 m/s 0.08 m/s - m/s	Measured at -9 and -15 m CD In depths < -5.5 m CD Around -15.5 m CD $0.05 < u_{max,tidal} < 0.1$ m/s Only important close to shore
Current magnitude over the water depth: • Max. near bed current velocity $u_{max,bed}$ • Average near bed current velocity $u_{av,bed}$ • Av. mid-depth current velocity $u_{av,mid}$ • Average surface current velocity $u_{av,surf}$.	0.40 m/s 0.15 m/s 0.18 m/s 0.20 m/s	Measured at 1.5 m above the bottom
Sea water characteristics:Sea water densityDynamic viscosity	1,020 kg/m ³ 0.85 mPa·s	1,017 < ρ_{sea} < 1,023 kg/m ³ 8.0·10 ⁻⁴ < μ < 8.9·10 ⁻⁴ Pa·s for 25 < T < 30°C

Table 2-3: Summary of characteristic OKLNG metocean parameters

3 Analysis of the OKLNG mud

Most of the seabed of the nearshore project area is covered with a layer of mud as can be concluded from sections 2.2 and 2.3. This chapter will therefore first briefly describe what mud is, after which the top mud layer at the project site will be analysed. Since data that unambiguously characterizes the mud is not available, many different data sources are used resulting in the many figures in this chapter. The measurements of the sediment in the water column are discussed as well. The findings lead to a discussion on how the sediment behaves in the water column. To reach objective 1, so to model the infill, conclusions are drawn on the OKLNG sediment characteristics and on how the uncertainties surrounding the sediment behaviour will be incorporated in the model.

3.1 General description of mud

3.1.1 Composition

The Coastal Engineering Manual [2002] describes mud as "watery mixtures of clay and silt, typically in approximately equal proportions, often with minor amounts of sand and organic material." Sedimentologists define mud based on particle size, i.e. deposits composed primarily of particles smaller than 62.5 μ m [Wang and Healy, 2002]. This includes silt and clay particles according to two widely used classification systems in civil engineering, the Wentworth [Krumbein and Sloss, 1963] and ASTM [1994] classification.

Clay minerals contain silicates, oxygen, aluminium and other elements [Lambe and Whitman, 1969]. In combination with water this causes cohesive behaviour and clay particles form flocs. Clay particles are small sheet-like plates, so their surface is large compared to their volume. This and the composition of clay lead to a chemically active and plastic bulk form. The water content typically lies between 70 and 98% [Winterwerp, 2008]. Mud may also contain organic matter and additional mineral matter such as fine sands, and its composition may vary in space and time. The density of clay particles is about 2,650 kg/m³ [Coussot, 1997].

3.1.2 Definition

A definition of mud, which entails all the above points and will be used in this report is "a sediment-water mixture composed of grains that are predominantly less than 63 μ m, exhibiting rheological behaviour that is visco-elastic when the mixture is particle-supported and is highly viscous and non-Newtonian when it is in a fluid-like state" [Metha *et al.*, 1994]. The state of the mud depends on its thixotropy, its time-dependent properties [Winterwerp and Van Kesteren, 2004].

3.2 Data sources

Several field campaigns to obtain soil data nearshore the OKLNG site have been undertaken the past years. The area that is covered is indicated in Figure 3-1. The OKLNG plant site and the approach channel are also depicted.



Figure 3-1: Surveyed area around OKLNG with the borehole, turbidity measurement and soil sampling locations indicated

3.2.1 Soil campaigns

Geophysical surveys with a pinger to obtain shallow sub-bottom profiling were conducted in 2005 [GEMS, 2006] and January 2007 [GEMS, 2008f]. The investigated area is depicted in grey in Figure 3-1 and stretches from 15 km west to 25 km east of the site. The water depth ranges from -5 m CD to -11 m CD.

The boreholes, CPTs and vibrocores are indicated with blue dots and are concentrated west of the approach channel. The soil investigations are summarised in Table 3-1 and extends over an area 8 km along the coast and 18 km offshore [GEMS, 2008e]. Fugro [2006] also analysed 5 samples of the mud from existing borehole locations taken from the seabed and Van Oord [2007] performed a settling test.

Phase	Execution period	Number of locations	Type of investigation	Reference
Phase A	FebMarch and Nov. 2006	9	4 boreholes and 5 CPTs	[GEMS, 2008a]
Phase B ⁶	August and October 2006	68	50 vibrocores and 18	[GEMS, 2008b]
			dropcores	
Phase 1	February-April 2007	10	9 boreholes and 1 CPT	[GEMS, 2008c]
Phase 2	April-June 2007	14	14 boreholes	[GEMS, 2008d]

Table 3-1: Executed soil campaigns by GEMS

⁶ GEMS did not give this campaign a name, in this report it will be referred to as phase B.

3.2.2 Turbidity measurements

The locations where turbidity measurements were conducted are indicated with yellow dots in Figure 3-1. Data were collected between 13 April 2006 and 15 May 2007 [Svasek Hydraulics and Royal Haskoning, 2008b]. At these locations measurements were taken at a height of 0.1, 0.4 and 0.6 m above the seabed. The measuring periods are given in Table 3-2.

Location	Height	Start date	End date of	Num-	Comments
	above	of measu-	measu-	ber of	
	bottom	rements	rements	days	
Location 1	0.10 m	13 April '06	18 May `07	400	Covers an entire year plus one
					extra month in the calm season
Location 1	0.40 m	13 April '06	18 May `07	400	Not measured during calm months
Location 1	0.60 m	20 Sept. '06	18 May `07	240	Measured part of stormy season
Location 2	0.10 m	13 April '06	10 Oct. '06	180	Not measured during NovMarch
Location 2	0.40 m	13 April '06	29 Nov. `06	230	Not measured during calm months
Location 2	0.60 m	13 April '06	29 Nov. '06	230	Not measured during calm months
Location 3	0.10 m	23 May `06	10 Oct. '06	140	Not measured during calm months
Location 3	0.40 m	23 May `06	10 Oct. '06	140	Not measured during calm months
Location 3	0.60 m	11 Aug. `06	10 Oct. '06	60	Only measured in stormy season

Table 3-2: Period of turbidity measurements

Most measurements were not continued in the calm season from November to April when wave heights are much smaller (see Table 2-3). July and August are the roughest months as explained in section 2.4.4. This should be kept in mind when computing infill rates.

Turbidity measurements were conducted using optical backscatter instruments (OBS). Heavy fouling negatively influenced the measurements. Downing [2006] even states that fouling nearly always results in inaccurate OBS data and regular cleaning of the instruments is required to obtain reliable data. Instruments were read off every five weeks and redeployed. On average 10% of the measurements were recorded as 'not a number', which can be due to maintenance, reading off the instrument, fouling or failure of the instrument [Klein, 2009]. At location 1 the percentage of 'not a number' entries was much higher than average. Also, this percentage increased with decreasing height above the bottom.

Note however that although the metocean report [Svasek Hydraulics and Royal Haskoning, 2007a] states that the measurements were conducted at 0.1, 0.4 and 0.6 m above the sea bed, the bed was not clearly defined and instruments sank into the mud regularly. These height values should thus not be taken very strict [Bliek, 2009].

3.3 Spatial distribution of the mud layer

3.3.1 Shallow geology

Over the whole site generally a top layer of very soft silty clay is present. This clay layer has a thickness between 0 m to the southwest of the approach channel and 8 m in the northeast near the shoreline. In Figure 3-3 the mud layers thickness on site is presented.

The clay layers are very soft at the mud line⁷ [GEMS, 2008b]. The relative density generally increases with depth. At this extreme flank of the Niger Delta layered sediments are found, so below the mud several meters of fine to coarse sand can be found. A sequence of interbedded sands, silts and clays to a depth of some 30-50 meters is observed in the western part of the site. In the east more firm to stiff sandy clay is found.

⁷ According to GEMS the mud line is the interface between the sediment comprising the seabed and the water column. Where there is no clearly defined transition an estimate is made judging the point where the composition changes from being more sediment than water to being more water than sediment.

In the southwest the Older Sands layer can locally be only a few decimetres thick, but on the whole Allen [1965b] suggests a thickness of 5-10 m. This estimation seems reasonable when comparing this layer to transgressive sand layers the same age in other parts of the world as also argued in section 2.2.3.4. The sandy Benin formation is found at 45 to 75 m depth [GEMS, 2008f].

The bed is essentially flat with an average gradient of less than 1° and featureless. No debris lies on the bed. In all areas local fishermen are active, so occasional trawl marks were observed on the seabed [HR Wallingford, 2005; i.e. GEMS, 2006; 2008e; 2008f].

3.3.2 Mud layer thickness

Allen [1965b] investigated the thickness of the bottom sediment layer in the Niger Delta area. His conclusion is shown in Figure 3-2.



Figure 3-2: Younger Suite layer thickness around OKLNG [After Figure 9, Allen, 1965b]

Borehole logs and a geophysical survey provided information on the mud layer thickness at the project site. This information presented in Figure 3-3 corresponds well to Allen's [1965b] findings.



Figure 3-3: Bottom mud layer thickness at OKLNG

3.4 Classification of the OKLNG mud

72 samples of the top mud layer taken from 48 of the locations indicated with blue dots in Figure 3-1 were analysed. Samples were taken from the seabed until a depth of 3.20 m.

3.4.1 Granular classification

3.4.1.1 Soil classification diagram

The soil classification diagram for the top mud layer is presented in Figure 3-4. This diagram is based on the 72 analysed soil samples mentioned above. According to NEN5104 [1989] the soil can be classified as highly silty clay and according to Shepard and Folk's [After Flemming, 2000] heuristic classification as clayey silt. The samples taken from the seabed all belong to the clayey silt domain.



Figure 3-4: Soil classification diagram for the top mud layer at the project site

The clay to silt ratio generally lies between 1:2 and 2:1, so the material can be classified as mud. A minority of the samples is better described as sandy mud. Especially the samples deeper below the surface match the mud classification perfectly.

3.4.1.2 Particle size distribution

The particle size distribution shows that the average clay content is 35%. Clay is defined as particles smaller than 2 μ m and sand as particles larger than 63 μ m, so the ASTM [1994] classification is applied. About 80% of the samples have a clay content between 25% and 50%. The average silt percentage amounts up to 49%. More than two thirds of the samples have a silt percentage between 35 and 70%.

The average D_{50} of all mud samples is 30 µm, but 72% of the samples has a D_{50} between 2 and 20 µm. This means that the material is very fine. The average D_{50} of the 22 samples taken at 0 m depth from the seabed is 18 µm, so based on these values the material is silty.

60% of the samples has less than 10% sand by weight. Some quite sandy samples will thus result in a too high average sand percentage. If samples with a sand content over 25% are discarded, the average sand percentage of the mud is 7%.

The 21 samples taken from the seabed the mud consists of 37% clay, 57% silt and 6% sand. These values will be taken as characteristic for the bottom soil material and is indicated with a red dot in Figure 3-1. Apparently the samples with a high sand content have primarily influenced the silt percentage. The clay percentage of all samples has lower spreading.

3.4.1.3 Organic content

The average organic content of the mud at the project site is 8.3% based on tests by GEMS [2008c; 2008d], which is slightly to medium organic according to BS14688-2 [2004]. Almost 75% of the samples of which the organic content was determined has an organic content between 6 and 12%. This means that the mineral solids dominate the soil behaviour [NEN, 1989].



Figure 3-5: Distribution of the organic content percentage in the mud

3.4.2 Geotechnical classification

As explained in section 3.1.1, cohesive soils show plastic behaviour at certain water contents. The Atterberg limits, the liquid and plastic limit,⁸ provide a measure for the water content and states whether the soil behaves non-plastic, plastic or viscous. They are empirically defined boundaries between states of soil consistency. Because of their general application the Atterberg limits are very useful, even though they are highly empirical [Winterwerp and Van Kesteren, 2004].

3.4.2.1 Water content

The average water content of the OKLNG samples is 76%, which lies within the range mentioned in section 3.1.1. The distribution is presented in Figure 3-6. Note that the water content is defined as the weight of the water divided by the weight of the soil particles, thus a water content of more than 100% is possible.

⁸ The plastic limit is defined as the water content at which a thread of soil with a 3 mm diameter starts to crumble. The liquid limit is defined as the water content at which a certain number of blows are required to close a specific groove width for a specific length in a certain prescribed apparatus [see e.g. Verruijt, 2004].



Figure 3-6: Distribution of the water content percentage in the mud

When the water content of a soil is much higher than the liquid limit, a soil is expected to behave as a viscous fluid [Dias and Alves, 2008]. At 37 locations both the water content and Atterberg limits of a mud sample recovered from the same depth are known and can therefore be compared. The data points are plotted in Figure 3-7. At some of the locations in the project area the soil indeed behaves viscous; of approximately ¹/₄ of the samples the water content is higher or close to the liquid limit.



Figure 3-7: Classification of the soil so far in relation to the liquid limit

3.4.2.2 Atterberg limits

The plasticity of the OKLNG material is assessed using a plasticity plot, which is depicted in Figure 3-8. The plasticity index is defined as the difference between the liquid and plastic limit. The mud has a very high to extremely high plasticity. The large spread in plasticity does not depend on the sand content, as is also noted by Van Oord [2007]. All data are situated between the so-called A- and B-lines. Soils above the A-line are classified as clay and soils below this line as silt. The B-line envelops sediments found in the natural environment.



Figure 3-8: Plasticity chart of the OKLNG mud

From this activity plot, no relation is found between the plasticity index and clay content; the parameters are not correlated. Also the organic matter percentage and clay content are not proportional, which generally is the case for mud. A constant clay/silt ratio cannot be found either. Even though the mud in the area does not originate from one source only, this still does not explain the findings. Cohesive sediment samples found in different marine environments from all over the world have a more or less constant silt/clay ratio [e.g. Flemming, 2000], so even the two strong opposing longshore currents which meet at the site and carry sediment from the rivers draining the eastern Niger Delta region, the Lagos area and the Volta basin, should not result in the large spread in clay/silt ratios found.

The plasticity chart also shows a rather large spread, which would normally be explained by the varying sand content. Summarizing, the OKLNG observations are not typical for mud behaviour generally found elsewhere in the world.

3.4.2.3 Mineral composition

The mineral composition of the OKLNG mud has not been identified through tests. The measured particle densities, the comparison between the liquid limit and water content, the high plasticity of the material and the humid tropical environment point towards kaolinite and montmorillonite clay minerals. Kaolinite is a coarse clay with particle sizes between 1 and 5 μ m, while montmorillonite is a fine clay with particles smaller than 0.1 μ m [Chien and Zhaohui, 1999]. Porrenga [1966] identified that recent Niger Delta sediments consist mainly of these two minerals and some illite.

At both the sides of the Niger Delta the montmorillonite content of the clay fraction is higher than along the rest of the Delta coast. Porrenga [1966] found that this mineral flocculates slowly and forms smaller flocs than for example kaolinite. Therefore it also has a very low settling of 0.015 mm/s in ocean water of 26°C and 18‰ chlorinity [Whitehouse *et al.*, 1958]. The settling velocity of kaolinite is an order of magnitude higher, namely 0.14 mm/s [Whitehouse *et al.*, 1958]. The higher the montmorillonite content of clay, the lower the settling velocity.

Due to the large geostrophic currents and differential flocculation, montmorillonite is transported further from the river mouths and subsequently accumulates near the project site. 30-40% of the clay fraction offshore OKLNG consists of this mineral [Porrenga, 1966]. The liquid limit of kaolinite is around 50%, while for montmorillonite it can be as much as 600% [Winterwerp, 2008].

3.4.3 Density

3.4.3.1 Bulk density

The average bulk density based on the analysis of soil samples is 1,370 kg/m³. OKLNG [2008a] uses an in situ bulk density of 1,350 kg/m³. This value is fairly uniform throughout the site, with more than 74% of the samples having a bulk density between 1,300 and 1,400 kg/m³ as can also be deduced from Figure 3-9. This bulk density has a corresponding average porosity of 0.68. Based on PIANC [2008] it can be concluded that the mud layer at the project site is generally not well consolidated.



Figure 3-9: Distribution of the bulk density of the mud

The relation between the depth and the measured bulk density is very weak, so below the seabed the bulk density is also low. Only few samples from a depth greater than 2 m are available, but these findings do suggest poor consolidation of the upper layer.

3.4.3.2 Particle density

Based on the particle density determined by GEMS [2008b; 2008c; 2008d] and Fugro [Klabbers, 2007] it can be concluded that the density of the mud particles is $2.6 \cdot 10^3$ kg/m³. Almost 90% of the samples has a particle density between 2,500 and 2,700 kg/m³.

3.4.3.3 Solid content

The average water content of 76% corresponds to a solid content of 625 kg/m³ and a bulk density of 1,400 kg/m³ assuming a particle density of 2,600 kg/m³ and a seawater density of 1,020 kg/m³. This corresponds well to the average bulk density of the tested samples.

3.4.4 Settling velocity

The settling velocity of the mud in the project area has not been measured recently. The only currently available measurement originates from the Lekki area, about 20 km west of the OKLNG site. The performed test resulted in a settling velocity of 0.004 mm/s [HR Wallingford, 1981]. Published data show that the settling velocity of fine-grained sediment is in the order of 0.01-1 mm/s [e.g. Berlamont *et al.*, 1993; Voulgaris and Meyers, 2004; Winterwerp and Van Kesteren, 2004; Xia *et al.*, 2004]. In section 3.8.1 0this will be discussed.

3.5 Mud rheology

Normally sediment properties are classified using three properties: sediment composition, particle size and bulk properties such as particle density and water content. Because of its cohesive properties mud should also be described by its rheology, i.e. its flow and deformation properties [Berlamont *et al.*, 1993]. Under deformation, mud shows interesting characteristics differing from Newtonian fluids like water. Often mud doesn't flow before a certain yield stress is exceeded. The yield stress is the principal indicator of cohesive behaviour.

Secondly, the viscosity is not constant. The viscosity of mud depends on the material, temperature, stress history, nature of the deformation, deformation magnitude and time [Merckelbach, 1996]. The time dependence of the viscosity is called thixotropic behaviour. The viscosity for mud decreases with increasing duration of shear and sometimes only partially recovers when the stress is removed. The shear thinning or pseudo plastic behaviour of mud is also related to the viscosity, since it decreases with increasing shear rate.

3.5.1 Flow curve

The relation between stress and deformation rate is known as the flow curve. Figure 3-10 shows the flow curves of the 5 OKLNG samples analysed by Fugro [2006]. For the locations the reader is referred to Figure 3-1.



Figure 3-10: Flow curves of seabed samples taken from the OKLNG site with 123 < water content < 162% and 1189 < ρ_{bulk} < 1209 kg/m³

For purely viscous non-Newtonian fluids, the deformation rate depends solely on the shear stress. Berlamont *et al.* [1993] states that for sedimentological purposes only shear rates smaller than 100 s⁻¹ should be studied.

Figure 3-11 depicts the most common models used to describe visco-plastic mud flow curves. The OKLNG flow curves from Figure 3-10 resemble the Bingham model [1920] or the Herschel-Bulkley model [1926] most.



Figure 3-11: Common rheological models to describe a flow curve

3.5.2 Yield stress

Using Figure 3-10 and either the Bingham [1920] or Herschel-Bulkley [1926] model it can be deduced that the OKLNG mud samples have a low yield stress of 40 to 75 Pa. This is probably because of the low density of approximately $1,200 \text{ kg/m}^3$.

3.5.3 Thixotropy

Surprisingly, the Fugro [2006] measurements only show thixotropic behaviour at high shear rates of $\gamma > 600 \text{ s}^{-1}$. For all other shear rates hardly any thixotropic behaviour is visible, so the mud strength does not depend on previous stress stages. Chien [1999] states that when the clay particles are arranged in a certain way the destruction of flocs is compensated by the restoration of flocs, so no thixotropic behaviour is observed. At OKLNG it is more likely that the wave climate induces such high stresses, that (extensive) networks of flocs, which are required for thixotropic behaviour, cannot be built up.

3.6 Soil strength

3.6.1 Strength observations and measurements

GEMS [2008a; 2008b; 2008c; 2008d] states that the mud at the seabed is very soft. This means that the soil exudes between your fingers [BS14688, 2004]. Van Oord [2007] comments that the seabed material consists of freshly deposited, very soft material. They even report that "the strength is so low that it is practically not feasible to take an undisturbed sample or to measure the strength accurately in situ".

Measurements conducted with a torque vane in situ by GEMS [2008b; 2008d] show an undrained shear stress of 2 to 8 kPa with densities of 1,290 until 1,480 kg/m³, which is barely measurable. The undrained shear strength is the strength of the soil measured without allowing any dissipation of pore pressures [Verruijt, 2004]. It is usually measured in triaxial compression. UU-triaxial tests show a similar undrained shear strength of 2.8 until 11 kPa [GEMS, 2008d]. Bulk densities ranged from 1,310 until 1,870 kg/m³ and the samples were taken at 1.3 to 6.0 m depth. Based on BS14688 [2004] the OKLNG mud can be classified as having a very low strength. Often at these densities a mud bed is well-consolidated [PIANC, 2008] and the mud

shear strength will be much higher [Winterwerp and Van Kesteren, 2004], but at OKLNG this is clearly not the case.

3.6.2 Relation between undrained shear strength and bulk density

If the Fugro [2006] data is analysed further, a clear exponential relation between the bulk density and the strength is found. The strength increases with shear rate. The correlation per set with the same shear rate is good: $0.93 < R^2 < 0.98$. The test samples however do have a much lower bulk density than the average of 1,370 kg/m³ found in situ.

Fortunately GEMS has also performed strength tests using a torque vane. In Figure 3-12 these results [GEMS, 2008b; GEMS, 2008d] are plotted together with the Fugro [2006] measurements. This figure clearly shows that the undrained shear strength at the site can be determined using the density at least until a density of 1,400 kg/m³.



Figure 3-12: Relation between the shear strength of the OKLNG mud and its density

3.6.3 Settling behaviour

Van Oord [2007] performed settling tests on 5 OKLNG mud samples, which revealed a very low settling rate. Starting with a solid content of 100 to 140 kg/m³ this content increased to 175 to 225 kg/m³ after 6 days. This solid content corresponds to a density of 1,127 to 1,157 kg/m³. The strength thus remained low as can be deduced from Figure 3-12 and the soil builds up strength very slowly.

3.7 Concentration in the water column

3.7.1 OKLNG turbidity measurements

The deployed OBS had a scale between 0 and 3,800 NTU. At the level closest to the bed the turbidity was regularly above 3,800 NTU. At the measurement points higher in the water column

this happened less frequently. The turbidity levels decrease with increasing water depth, so turbidity levels were highest in location 1.

Svasek and Royal Haskoning [2007a] related sediment concentrations to wave heights. They have plotted the turbidity values up to 3,000 NTU versus the local wave height. First a large scatter is visible. At 0.10 and 0.40 m the turbidity generally increases with wave height. Turbidity levels at 0.60 m above the bottom hardly depend on wave height and are relatively low.

GEMS [2009] also concluded that turbidity results respond well to wave climate results. Turbidity peaks lower in the water column often follow periods of high waves. However it is interesting to note that at location 1 at 0.60 m height high turbidity values of around 1,000 NTU were recorded mostly at low wave heights of approximately 0.8 m [Figure 8.6, Svasek Hydraulics and Royal Haskoning, 2007a].

3.7.2 OKLNG concentration series

3.7.2.1 Time series

GEMS has converted the recorded turbidity time series to concentration time series using calibration curves. Sediment calibrations are frequently required to convert NTU to suspended sediment concentration [Downing, 2006], so it is not surprising that these curves show a large spreading per location and elevation. The accuracy of the calibrations is not known.

The concentration time series are depicted in Figure 3-13. The time step between two consecutive measurements is 7.5 minutes.



Figure 3-13: Sediment concentration time series at three locations with different water depths and at 0.1, 0.4 and 0.6 m above the sea bottom at OKLNG from May to December 2006

Maximum concentrations are unknown; the maximum range of the OBS was reached regularly. The maximum value for all locations in Figure 3-13 is set at 4,000 mg/l to enable a proper comparison of the data. At location 1 concentrations up until 8,000 mg/l could be measured and at location 2 up until 5,100 mg/l. Higher values were cut off at these thresholds.

3.7.2.2 Concentration characteristics

The concentration varies quickly and with large steps in time. Peaks in different locations do not always correlate. A small time frame as presented in Figure 3-14 also shows this quick variation in concentration with many peaks. The amount of sediment in the water column responds quickly to the wave climate [Svasek Hydraulics and Royal Haskoning, 2007a]. This indicates that sediment moves up and down in response to wave forcing. From the time series in Figure 3-14 the response to wave forcing cannot be decisively deduced, since the measuring interval is much larger than the characteristic wave period at the site.⁹ It is however clear that the tide does not have a pronounced influence on the sediment concentration in the water column.



Figure 3-14: Concentration time series in location 1 at 8 November 2006 showing rapid changes in concentration between two measuring intervals, primarily at 10 cm height (time step is 7.5 minutes)

The probability distributions of the measured concentration at the different heights above the bottom are presented in Figure 3-15 until Figure 3-17. The average sediment concentration over the height for the three locations is 260 mg/l for 0.40 m and 150 mg/l for 0.60 m. Concentrations in the order of a gram per litre at these heights do not occur frequently: 4% of the time at 0.40 m height and 2% of the time at 0.60 m height. The concentration at these heights significantly increases with decreasing water depth as is also apparent from Figure 3-15 until Figure 3-17. For z = 0.10 m the average concentration cannot be computed as easily, since more than one third of the observations are in the long tail of the distribution.

⁹ 32 swell waves of 14 s fit into one measuring interval of 7.5 minutes.



Figure 3-15: Distribution of the measured sediment concentration at z = 0.10 m above the bottom at three locations



Figure 3-16: Distribution of the measured sediment concentration at z = 0.40 m above the bottom at three locations



Figure 3-17: Distribution of the measured sediment concentration at z = 0.60 m above the bottom at three locations



The cumulative distribution of the sediment in the water column is presented in Figure 3-18. This figure clearly shows that the OBS range influences the results for z = 0.10 m.

Figure 3-18: Cumulative distribution curve of the measured sediment in the water column

3.7.2.3 Annual concentration statistics

It is acknowledged that only one data series covers a year and most concentration series did not measure during the calm season. This can also be concluded from Table 3-2. For this research it is found more important to use the entire available data series and one of the goals of this thesis is to gain insight in the yearly infill quantity, so therefore all data are used to obtain annual concentration statistics. The likely result is that the concentrations will be overestimated, since waves will stir up more sediment during the stormy season than during calmer periods.

Next the data are fitted to different probability distributions, e.g. the lognormal, Weibull, beta and gamma distribution. To test the goodness of fit of the found distribution with the data series the χ -square, Kolmogorov-Smirnov and Anderson-Darling were used. All three tests showed the lognormal distribution to be the best fit for all concentration data series.

The probability density function of the lognormal distribution is given by the following equation:

$$f_{c}(c;x,y) = \frac{1}{cy\sqrt{2\pi}} \exp\left(-\frac{(\ln c - x)^{2}}{2y^{2}}\right)$$
(3.1)

With the sediment concentration c > 0. The distribution is characterized by a mean μ and standard deviation σ . These parameters follow from x and y as used in equation (3.1) according to $\mu = \exp\left(x + \frac{1}{2}y^2\right)$ and $\sigma = \exp\left(x + \frac{1}{2}y^2\right)\sqrt{\exp\left(x^2\right) - 1}$.

For the data series taken at 10 cm height above the bottom not all data were used to find a distribution. For locations 2 and 3 concentrations up to 5,000 mg/l were used, so almost all data below the cut-off value of 5,100 mg/l were taken into account. For location 1 the concentrations above 7,000 mg/l were taken out, since the cumulative distribution shows a discontinuity and these measurements are likely to be influenced by the maximum reach of the OBS.

Using the least-squares method a lognormal distribution was fitted to the remaining data.¹⁰ Since the complete 40 and 60 cm series and the 10 cm series up until the OBS maximum matched the lognormal distribution best it is assumed that the tail of the 10 cm concentration distribution can also be modelled with the lognormal distribution. The result is shown in Figure 3-19. Based on these distributions there is a 3.5% probability of exceeding a concentration of 20 g/l at 10 cm height and a 1% chance of exceeding 50 g/l.



Figure 3-19: Fitting of the cumulative concentration series measured at z = 0.10 m above the bottom to a lognormal distribution based on the least-squares method

Table 3-3 summarizes the characteristics of the lognormal distributions used to model the yearly concentration statistics at 10, 40 and 60 cm height above the bottom at the three locations.

Location	Height at	Mean value µ	Mean value µ	Standard
	which was	of data series	of best fit	deviation σ of
	measured		lognormal	lognormal
			distribution	distribution
Location 1	10 cm	-	3,794 mg/l	7,343 mg/l
	40 cm	300 mg/l	289 mg/l	399 mg/l
	60 cm	230 mg/l	223 mg/l	324 mg/l
Location 2	10 cm	-	4,126 mg/l	104,865 mg/l
	40 cm	270 mg/l	239 mg/l	312 mg/l
	60 cm	120 mg/l	118 mg/l	111 mg/l
Location 3	10 cm	-	3,527 mg/l	53,646 mg/l
	40 cm	190 mg/l	190 mg/l	211 mg/l
	60 cm	85 mg/l	85 mg/l	59 mg/l

 Table 3-3: Characteristic values of the fitted lognormal distribution for the concentrations in the water column at the three locations

¹⁰ The cumulative distribution of each sediment data series is compared with a cumulative lognormal distribution. The difference between the cumulative percentages is squared. With an iteration the sum of the squared differences is minimized, leading to the mean and standard deviation of the lognormal distribution that gives the best fit.

Note however that the method of fitting a distribution greatly influences the outcome. A different method leads to different values of the mean μ and standard deviation σ than given in Table 3-3. This uncertainty should be kept in mind when using the distributions in Figure 3-19 for the approach channel infill calculation.

3.8 Discussion on the sediment state of the OKLNG mud

In order to assess the infill of the OKLNG approach channel, it is essential to know how the sediment in the water column behaves. If mud has a settling velocity in the order of 0.01-1 mm/s as mentioned in section 3.4.4, waves stir up the sediment after which it settles again. This means that there is a direct relation between the amount of sediment in the water column and the wave height.

However, while analyzing the sediment at OKLNG, we have come across some indications that the sediment in the water column at OKLNG is unflocculated to poorly flocculated and subsequently has a very low settling velocity. Such unflocculated conditions in the marine environment have not been found in literature and experts consulted for this thesis have not encountered these conditions before. However no definite information or data on the sediments at OKLNG was found.

To conclude this chapter first the indications that point towards an unflocculated system will be treated. Then the sediment regime at OKLNG is discussed. Finally a conclusion will be drawn on how the OKLNG mud behaves and how the relating uncertainties will be incorporated in the model.

3.8.1 Indications of unflocculated sediment in the water column

The circumstantial evidence for unflocculated conditions is explained below:

1. Measured concentrations versus saturation concentration:

A maximum amount of sediment can be carried in suspension in the water column before the turbulent flow field collapses and a lutocline develops; a sharp gradient in the concentration profile. This relation is described by Winterwerp [2001].

If this relation is applied to the OKLNG site, the concentration, which can be kept in the water column, is relatively low due to the low current velocities. Although waves cause high orbital velocities at the site, this only causes sediment stirring near the bottom. Mixing and transportation is due to the velocity profile induced by the currents. The tide does not induce large velocities in this area, so the low velocity large-scale geostrophic currents are the main agent carrying the sediment.

However, concentrations of several 100 mg/l to several 1,000 mg/l are encountered in the water column, also at 0.4 and 0.6 m above the bottom [Svasek Hydraulics and Royal Haskoning, 2007a]. From Figure 3-20 it can be deduced that low settling velocities are required to explain these concentration at the project site.

The found low settling velocity at Lekki mentioned in section 3.4.4 leads to the same conclusion: the large concentrations in the water column can only be explained if the settling velocity is around 0.004 mm/s, as was measured as well.



Figure 3-20: Maximum concentrations in the water column depending on current velocity and settling velocity show that the measured concentrations at OKLNG can only be possible if the sediment has a low settling velocity, based on the relation found by Winterwerp [2001]

2. Settling velocity measurement at Lekki:

The result of one settling velocity measurement in the vicinity of OKLNG is known: a settling velocity of 0.004 mm/s at Lekki in 1980. This settling velocity corresponds to sediment particles having the size of primary clay or silt particles, but not to large flocs. However it is unknown how this test was performed: what kind of water was used, what were the test circumstances, etc. Considering the author of the Lekki report, it is highly likely that the measuring device was an Owen tube. Eisma [1997] found that settling velocities measured with an Owen tube are an order of magnitude lower than when using other instruments. Berlamont *et al.* [1993] confirmed this. Fettweis [2008] found that the relative standard deviation for settling velocity measurements is 100%. The reliability of this value can thus rightfully be questioned, but still this value is two orders of magnitude lower than the settling velocities normally encountered in the marine environment.

3. Plasticity chart and silt/clay ratio:

The plasticity chart presented as Figure 3-8 shows a large range in plasticity. Normally this would be explained by the varying sand content of the samples, but at OKLNG there is no relation between the plasticity and sand content.

Cohesive sediment samples from different marine environments all over the world have a more or less constant silt/clay ratio [e.g. Flemming, 2000]. It is hypothesized that silt is captured in clay flocs, leading to a constant silt/clay ratio. At OKLNG a constant ratio is not found, which can be explained by sorting, i.e. sediment not being flocculated. Since silt particles will then not be captured within clay flocs, there is no reason for the clay/silt ratio to be constant.

4. Strength of the mud layer:

The strength of the mud layer is very low as can be seen in Figure 3-12. Generally clay is consolidated when having a density of 1,300 to 1,400 kg/m³, while the OKLNG mud has a maximum strength of only 8 kPa in this density range. This points towards small particles, which have not built up mud strength by creating bonds.

5. Suspended sediment concentration versus current velocity variation:

Measured temporal variations of suspended sediment concentration at Lekki [HR Wallingford, 1981] do not correlate with variations in current velocity. This indicates a large memory effect of the water column, meaning that the sediment remains in the water column for a long time after being brought into suspension since they are too fine to settle considerably around slack water conditions.

At OKLNG it is evident that the sediment concentration is not related to the tidal cycle, but other conclusions regarding the memory effect cannot be drawn based on the available data.

6. *Measured settling behaviour:*

Van Oord [2007] performed settling tests on 5 OKLNG mud samples, which revealed a very low settling rate. Starting with a solid content about 120 kg/m³, the solid content increased to approximately 200 kg/m³ after 6 days. This solid content corresponds to a density of only 1,137 kg/m³. From Figure 3-12 it can be deduced that the strength thus remained low. A low settling rate also indicates small particles.

7. Relation between turbidity and concentration:

A first estimate correlating turbidity to suspended sediment concentration yields that 1 mg/l corresponds to 2 NTU [Winterwerp, 2009]. The calibration curves relating turbidity to suspended sediment concentration given by GEMS show a different relation, ranging from 1 mg/l \triangleq 1.7 NTU at a water depth of –9 m CD to 1 mg/l \triangleq 1.0 NTU at a water depth of –15 m CD. Small particles absorb more light in the water column, leading to a higher turbidity at the same concentration than with larger particles.

8. Composition of the Niger Delta mud:

The Niger Delta clay has a high montmorillonite content. This mineral flocculates slowly, forms small flocs and has a low settling velocity. Additionally Torfs [1997] found that montmorillonite has a critical shear stress for erosion about half of that of other mud mixtures. This is consistent with sediment that flocculates poorly and does not build up mud strength.

No direct measurements of the particle size over the water depth, i.e. settling velocity distribution, at the OKLNG site are currently available. However, the arguments above suggest that the sediment is poorly to not flocculated, yielding very low settling velocities. Although the reliability of each of these arguments can be questioned, there is sufficient circumstantial evidence that the sediment at OKLNG is not to poorly flocculated.

No literature on such low to non-flocculated fine sediments in the marine environment has been found and experts consulted for this thesis have not encountered these conditions before. Direct in-situ measurements are therefore strongly recommended.

The only mechanism explaining these low settling velocities, which are two orders of magnitude smaller than commonly encountered (i.e. ~ 0.5 mm/s), is the large stresses induced by the continuous, highly dynamic ocean waves beating the OKLNG coastal waters. The mineralogy is likely to amplify this mechanism. The clay minerals at OKLNG are probably smaller than at other locations due to the high montmorillonite content, so when wave-induced stresses break up flocs, smaller particles remain in the water column.

3.8.2 Sediment regime in the water column

The amount of sediment in the water column influences the behaviour of the sediment-water mixture. According to Winterwerp [1999] three stable regimes of cohesive sediment in the vertical are discerned:

- 1. *Low-concentrated mud suspensions (LCMS)*: suspensions of cohesive sediment with a concentration of several 10 to a few 100 mg/l, with Newtonian behaviour and not significantly affecting the turbulent flow field.
- 2. *High-concentrated mud suspensions (HCMS)*: suspensions of cohesive sediment with a concentration of a few 100 to a few 1,000 mg/l, with Newtonian behaviour and transported and interacting with the main turbulent flow field.
- 3. *Fluid mud*: suspension of cohesive sediment at a concentration beyond the point at which floc networks are formed, so the concentration can be several 10 to 100 g/l. The effective stress is negligible compared to the excess pore pressure; sediment particles are mainly supported by pore water. Fluid mud shows non-Newtonian behaviour and can be stationary or moving. If the fluid mud is flowing, it is fairly independent from the flow in the water column above. The water content is high.

The maximum concentration in the water column at 0.10 m will be in the order of 100 g/l as can be deduced from Figure 3-19. This means that the density of the layer near the bottom will then be 1,080 kg/m³. Concentrations in the order of several tens g/l of sediment in the water column have a probability in the order of 1% providing the concentration modelling is reliable.

If a high-concentrated mud layer is present on the bottom either continuously or for short periods of time wave damping is usually observed. However no significant wave damping has been observed [Bliek, 2009] and wave measurements do not indicate it either, since the significant wave height hardly differs between the measurement stations at the -9, -12 and -15 m depth contour [Svasek Hydraulics and Royal Haskoning, 2007a]. A damping calculation based on Gade's [1958] wave damping coefficient can be found in Appendix A. This shows that wave damping is limited at the OKLNG site. Additionally the wave height hardly changes when approaching the shoreline if shoaling is taken into account. Based on these observations it is thus impossible to say whether or not a high concentrated mud layer is present near the bottom continuously or only in exceptional cases.

Due to the uncertainty regarding the sediment state it cannot be concluded what the general sediment regime at OKLNG is. Drawing a conclusion based on wave damping is not possible either.

In case of poorly flocculated sediment a high concentrated mud layer will continuously be present near the bottom due to the low settling velocity. Waves only slightly influence this layer. The layer thickness and concentration will vary in time due to wave forcing; internal waves on the mud layer may explain the measured variation in concentration at 10 cm above the seabed. Little sediment is present higher in the water column, but wave forcing directly influences the sediment concentration in this part of the water column. To this scenario, scenario 1, sediment regime 3 applies.

It should however be mentioned that section 3.5 shows that the OKLNG mud displays fairly Newtonian behaviour. Thixotropic behaviour indicating networks of flocs is not found. These findings point towards a higher settling velocity of the OKLNG sediment. In that case the amount of sediment in the water column is directly influenced by the wave climate. Only under extreme waves a mud layer near the bottom is formed, so the sediment regime would generally be a low concentrated mud suspension and only after excessive wave forcing the concentrations profile collapses and a sharp gradient in the concentration profile develops. The two different scenarios are schematically indicated in Figure 3-21.



Figure 3-21: Difference in sediment behaviour in case of a very low (\sim 0.004 mm/s) and a commonly found settling velocity in the marine environment (\sim 0.5 mm/s)

3.8.3 Conclusion on the OKLNG mud behaviour

A thick layer of several meters of very plastic and viscous mud is found around the planned OKLNG approach channel. This layer is present over an area of 10 by 10 km with the channel in the middle. This is based on boreholes as can be seen in Figure 3-3. Based on literature [e.g. Allen, 1964; Allen, 1965b; Admiralty Chart, 1998] this mud layer covers the entire coastal area except for a sandy area towards the southeast, see also the previous chapter. This sand layer at the surface will not be of significant influence on the expected channel infill, since its closest point is located 1.5-2 km from the channel tip. Currents are mainly directed perpendicular to the channel and will thus generally not flow over the sandy part before passing the channel. Additionally the thick mud layer in the entire OKLNG area will result in more than enough sediment being available to fill the channel.¹¹

The top mud layer can be classified as silty clay or clayey silt. It consists of 37% clay, 57% silt and 6% sand. The organic content is low. The water content is 76% on average, which is quite high. Approximately 1/4 of the samples from which both the water content and liquid limit is known has a water content higher or close to the liquid limit, hence the viscous behaviour of the soil. The plasticity chart also shows a high plasticity. Not surprisingly with a high water content is that the average bulk density is only 1,370 kg/m³. The particle density is 2.6 \cdot 10³ kg/m³, which is normal for soils.

From the flow curves, UU-triaxial tests, strength observations and torque vane measurements can be concluded that the OKLNG top mud layer has a very low strength. In fact, it would exude through your fingers when picking it up. Also, no thixotropic behaviour was observed, indicating that (extensive) floc networks have not been built up.

A clear exponential relation can be observed between the mud density and undrained shear strength. More important however is that at a density of 1,300-1,400 kg/m³ the soil still has a low strength. Additionally settling tests show a very low settling rate.

 $^{^{11}}$ The approach channel has a volume of 39 \cdot 10⁶ m³. Even when assuming that the channel will be filled with mud that has the same density as the surrounding top mud layer, a layer of 39 cm over the 10 by 10 km area is scraped off to fill the channel. In reality, the infill will have a much lower density than the average bulk density of 1,370 kg/m³, so much less sediment is required to fill the channel. This calculation also excludes the continuous sediment transport towards the project site due to the converging longshore currents.

At several decimetres above the bottom the average concentration is around 200 mg/l. At 0.10 m above the bottom a concentration of several g/l is reached often. It should be kept in mind that the concentration at 0.4 and 0.6 m above the bottom increases significantly with decreasing water depth. Unfortunately the relation between wave height and concentration cannot be investigated using the time series, because the concentration measuring interval is at least an order of magnitude larger than the characteristic wave period.

Finally, the most important issue that arose in this chapter is the uncertainty in the mud behaviour: is the sediment poorly to not flocculated and does it subsequently have a very low settling velocity? Several indications point towards this sediment state at OKLNG, although such unflocculated conditions have not been reported in the marine environment before as far as the experts consulted for this thesis know. Arguments include:

- The measured concentrations exceed the saturation concentration in case of a normally encountered settling velocity in the marine environment
- A very low settling velocity measured 20 km west of the site
- A very low soil strength
- Low settling rate of OKLNG sediment samples
- The absence of a constant clay/silt ratio
- High montmorillonite content of the clay; this mineral flocculates poorly and forms smaller flocs than other clay minerals

The question of whether or not the sediment is flocculated introduces an important uncertainty into the upcoming infill calculation. In the framework of this thesis, to apply a risk-based approach to the channel infill, this uncertainty has to be dealt with.

To reduce uncertainty it is strongly recommended to measure the sediment characteristics at OKLNG to obtain certainty on the behaviour of the sediment. These measurements are listed in section 6.3.3.1. If the sediment is unflocculated this is most likely due to the persistent swell waves generating too high stresses for flocs to form.

3.8.4 Modelling approach

The most important uncertainty of the mud behaviour lies in whether or not the sediment is poorly flocculated and subsequently has a low settling velocity. This greatly influences its behaviour in the water column as explained in section 3.8.2. Svasek and Royal Haskoning [2008b] have investigated scenario 2, the scenario with the \sim 0.01-1 mm/s settling velocity, since in the initial phase of the project it was assumed that the sediment would be normally flocculated. The sediment in the water column is then directly related to the wave climate. However this research shows that scenario 1 with the low settling velocity seems the more likely scenario for Olokola LNG.

Because of the large uncertainty surrounding this conclusion, both scenarios should be investigated. Since scenario 2 has already been investigated, the infill calculation in the next chapter will focus on scenario 1. In a later chapter a reflection on the likelihood of each scenario and the implications for the infill prediction will be made.

4 Approach channel infill modelling

This chapter describes the channel infill modelling and addresses objective 1 as stated in section 1.3 now that the system and soil characteristics are properly analyzed. First the relevant infill scenarios will be addressed. Then a simple model is formulated to calculate the yearly infill quantities.

The model is kept simple on purpose; the goal of this thesis is to provide an overview of the uncertainties when calculating a channel infill. By choosing a simple model, it is more straightforward to find out which parameters, processes and uncertainties influence the infill most. A sophisticated model such as DELFT 3D, MIKE 21 and FINEL 2D takes a long time to run. These models cannot be run a large numbers of times, each time with different possible input parameters, to do an extensive uncertainty analysis. However the drawback of using a simple model is that the infill process is so strongly simplified that not all physical processes can be included. This will be further discussed in chapter 6.

Next the channel and hydrodynamic parameters have to be modelled. The chapter concludes with an overview of the parameters necessary to calculate the channel infill.

4.1 Schematization of infill scenarios

4.1.1 Infill mechanisms

Several mechanisms can result in sedimentation of the OKLNG approach channel. This study focuses on sedimentation outside the breaker zone. Figure 4-1 shows four infill mechanisms.



Figure 4-1: Channel infill mechanisms

Each infill mechanism depicted in Figure 4-1 is explained below:

1. *Concentrated mud layer infill:* depending on the sediment characteristics a mobile mud layer is permanently present on the seabed or can be formed during storm conditions. In case the density and thickness of the layer are large enough – which is always the case if a mud layer is present as will be demonstrated in this chapter –, the current is unable to transport the sediment up the opposing slope and all sediment will remain in the channel.

- 2. Suspended sediment infilk when passing the approach channel, part of the suspended sediment will settle in the channel depending on channel parameters such as depth, width and slope, on sediment characteristics as settling velocity and on the current velocity. This mechanism distinguishes itself from the previous one based on the amount of sediment that is trapped in the channel. Now only little sediment will settle, since most of the sediment stays in suspension.
- 3. *Side slope instability*: due to several events like an earthquake, side slopes being dredged too deep, a ship touching the side slope and a compacting and sliding soil layer, the side slope can become unstable and slide into the channel.
- 4. *Infill from the surf zone*: in case the longshore current is diverted around the planned breakwater tips, the breakwaters do not extend far enough through the surf zone or sediment accumulation has reached the breakwater tip, case sediment from the surf zone can be deposited in the approach channel.

Mechanisms 1 and 2 are the ones that will be addressed in this thesis, since these take place under day-to-day circumstances and the goal of this thesis is to gain insight into the average yearly sediment infill as explained in sections 1.2 and 1.3.

Extreme infill events such as mechanism 3 are not taken into account, since the channel design should be such that the side slopes are stable. The equilibrium slopes are expected to be very gentle (1:20 to 1:60), making channel slope instability unlikely. Also, initially additional dredging will arise due to adjustment of the side slopes, but this thesis looks at the long-term equilibrium slope. Moreover, earthquakes are rare in the area due to low seismic activity and it is unlikely that a ship crashes into such gentle side slopes and causes a large sudden mud infill.

Regarding mechanism 4, no infill is expected from the surf zone. The breakwaters should properly function and no sediment-laden currents from the surf zone into the channel are expected to occur in the first decades. Nonetheless 3D-modeling is required to verify this assumption; this thesis will not address this infill mechanism any further. When conducting a complete risk analysis of the channel infill, mechanisms 3 and 4 should be evaluated.

4.1.2 Infill scenarios to be investigated

This thesis will focus on infill under day-to-day conditions, since there are large uncertainties in the volumes to be dredged and a regular maintenance dredging strategy has to be designed. As concluded in the previous chapter, the sediment state in the water column is highly uncertain. Therefore two scenarios will be investigated:

- Scenario 1: the sediment is fine and not to poorly flocculated, yielding very low settling velocities (i.e. ~0.004 mm/s). The sediment concentration in the water column is not directly related to the wave climate, but a mobile mud layer is present near the bottom, which concentration and thickness vary in time. A clear bottom cannot be defined. Sedimentation of the channel under day-to-day conditions is caused by transporting the mobile mud layer in the channel and being trapped there and by settling of suspended sediment that is present in the water column above the mud layer. Day-to-day infill for this scenario is thus due to mechanisms 1 and 2 as explained in the previous section.
- 2. *Scenario 2*: the sediment is flocculated and yields settling velocities in a range normally encountered in the marine environment (i.e. ~0.5 mm/s). The amount of sediment in the water column is directly related to the wave forcing. Continuous sediment infill is a result of suspended sediment settling in the approach channel. Only during storm events a mobile mud layer can be formed on the seabed, which is subsequently transported by the currents into the channel. Infill is thus again due to mechanisms 1 and 2.

Both scenarios will be discussed, although this thesis will focus on scenario 1. This is because Svasek and Royal Haskoning [2008b] have investigated scenario 2 already. The sediment characteristics found in chapter 3 indicate that scenario 1 can also be the case at OKLNG, so this scenario will therefore be investigated in this thesis as well.

4.2 Schematization of the infill

The amount of sediment in the channel M is the infill rate per meter channel length s in kg/m/s integrated over the channel length and over time:

$$M = \int_{0}^{t} Sdt = \int_{0}^{t} \int_{0}^{L} sdLdt$$
(4.1)

The time interval that will be considered is one year. Note that the amount of sediment in the channel M is sediment mass in megaton or kilogram accumulated in the channel in a certain time interval. It does not represent the volume of the sediment in the channel. S is the infill rate in kg/s.

Whether or not the channel should be dredged after a certain infill mass depends on the density of the material in the channel, which is time-dependent. Reliable and sufficient data to predict the settling and consolidation of the sediment lack and investigating this process lies outside the scope of this thesis as outlined in section 1.4.2. A suitable dredging strategy can be chosen using a reliable prediction of the sediment mass per time interval that will be trapped in the channel and further research into the settling and consolidation behaviour.

In literature the infill rate per meter channel length *s* of an approach channel is usually determined by subtracting the sedimentation from the erosion, which is included in this schematisation by a channel trapping efficiency. Then the channel sedimentation is a function of the specific sediment mass – the amount of sediment in the water column integrated over the depth –, the transport velocity and the channel trapping efficiency. This is schematically depicted in Figure 4-2.



Figure 4-2: Schematization of the infill rate per meter channel length based on a the amount of sediment integrated over the water column, transporting currents and a trapping efficiency depending on the channel configuration and sediment characteristics

This results in *s* being defined as follows:

$$s = u(L) \cdot c(z, L) \cdot z \cdot p(u, c, L)$$
(4.2)

With the infill velocity u in m/s depending on the channel section, the concentration c in the water column varying over the depth and the location along the channel axis in kg/m³, the height over which the concentration needs to be integrated z in m and the trapping efficiency p depending on all parameters. The infill rates per meter channel length for both scenarios will be looked at in more detail in the next sections.

4.2.1 Infill modelling of scenario 1

In case a mud layer is permanently present and flows into a channel, it is expected that due to gravity all mud will be trapped and the layer will not be transported up the opposite slope out of the channel again. To check this assumption the following force balance for the two-layer system of water and mud is drawn up:

$$F_{p.u.w.} = \underbrace{\tau_d \cdot \Delta x}_{\text{water-mud shear stress}} - \underbrace{\tau_b \cdot \Delta x}_{\text{mud-bottom shear stress}} - \underbrace{\tau_{F_z} \cdot \Delta x}_{\text{gravity component}}$$
(4.3)

Where p.u.w. stands for per unit width. The force balance is also sketched in Figure 4-3.



Figure 4-3: Force balance of a mud layer on a channel slope under water

Dividing by Δx and assuming equilibrium results in equation (4.4), which has to be solved:

$$F_{p.u.w.} / \Delta x = \tau_d - \tau_b - \tau_{F_z} = 0$$
(4.4)

Subsequently for $\tau_d > \tau_b + \tau_{F_c}$ the mud layer will be transported out of the channel by the flow.

The drag of the water on the mud layer that might cause the mud to flow up the opposite slope can be calculated using:

$$\tau_d = \frac{1}{2} k_d \rho_w \left(\overline{u} - u_m \right)^2 \tag{4.5}$$

With drag coefficient k_d , seawater density ρ_w , depth-averaged velocity \bar{u} and velocity of the mud layer u_m . The mud layer velocity is much smaller than the measured depth-averaged velocity.

The shear stress between the mud layer and the bottom, which provides additional resistance for the current, is initially neglected, so $\tau_b = 0$.

Lastly, the gravity component on the mud layer is an extra force that tries to keep the sediment in the channel:

$$\tau_{F_{a}} = \delta \Delta \rho g i_{b} \tag{4.6}$$

With mud layer height δ , density difference between the seawater and the mud layer $\Delta \rho$, gravitational constant g and channel slope i_b .

The density difference $\Delta \rho$ will be expressed as a function of the measured concentration c:

$$\Delta \rho = \rho_m - \rho_w = (1 - c/\rho_s) \cdot \rho_w + c - \rho_w = c(1 - \rho_w/\rho_s)$$
(4.7)

With concentration c, seawater density ρ_w and sediment density ρ_s .

Neglecting the shear stress between the mud layer and the bottom and using equations (4.5), (4.6) and (4.7) a criterion for which the mud layer stays in the channel can be formulated:

$$\tau_{d} = \frac{1}{2} k_{d} \rho_{w} \left(\overline{u} - u_{m} \right)^{2} < \delta c \left(1 - \rho_{w} / \rho_{s} \right) g \sin \left(1 / \alpha \right) = \delta \Delta \rho g i_{b}$$
(4.8)

This criterion is finally formulated as a function of the specific mass of the mud layer δc in kg/m²:

$$\delta c > \frac{\frac{1}{2}k_d \rho_w \left(\overline{u} - u_m\right)^2}{\left(1 - \rho_w / \rho_s\right)g\sin\left(1/\alpha\right)}$$
(4.9)

Note that this is a trapping criterion. Equation (4.9) gives a maximum value of the specific mass of the mud layer on the seabed for which the sediment is still transported out of the channel. If it is larger, it is trapped.

Table 4-1 presents the parameters values needed to calculate this critical specific mass of the mud the layer. The possible variation of these values is also given. The mean value of the mud layer velocity is assumed to be the same as the average velocity of the current near the bottom, which is approximately 0.055 m/s. If the concentration of the mud layer is not too high, this is a reasonable assumption.

Variation of the seawater and sediment density within their possible range leads to a difference in specific mud layer mass of \pm 2%. The channel slope, drag coefficient and velocities have much more influence. If the mean values are used, the critical specific mud layer mass is 0.014 kg/m². If the mud layer has a greater specific mass, the layer will be trapped in the channel.

 Table 4-1: Parameters required to calculate if the mud layer is trapped in the approach channel

Parameter	Value	Comments/reference
 Velocities: Depth-averaged velocity u Mud layer velocity um 	0.0-0.50 m/s 0.0-0.25 m/s	Section 2.4.5.4, mean is 0.20 m/s Assumed to be maximum $0.5 \cdot \overline{u}$, mean assumed to be 0.055 m/s
Material densities: • Sea water density ρ_w • Sediment density ρ_s	1,010-1,030 kg/m ³ 2,500-2,700 kg/m ³	Section 2.4.6.3, mean is 1,020 kg/m ³ Section 3.4.3.2, mean is 2,600 kg/m ³
Channel characteristic:Channel slope α	8-60	Section 4.3.3, generally 20
Constants: • Drag coefficient k_d • Gravitational constant g	0.0001-0.0015 9.81 m/s ²	Delft Hydraulics [1974] states 4·10 ⁻⁴

To gain insight in the value of the critical mud layer mass, Figure 4-4 shows its dependency on the different parameters. The figure is based on equation (4.9) and the values from Table 4-1.



Figure 4-4: Critical specific mud layer mass dependent on the current velocity and while varying the channel slope, drag coefficient and mud layer velocity; the value of the critical mass when using mean values for all parameters is indicated with a red dot

A small mud layer of 5 cm height with a concentration of 20 kg/m³ already results in a specific mass of 1 kg/m². The critical specific mud layer mass does not even come close to this value when varying the relevant parameters. (Note that the scale of Figure 4-4 does not go beyond a specific mass of 0.2 kg/m².) Also friction between the mud layer and sea bottom is not included in this calculation; this would keep a mud layer with an even lower concentration trapped in the
channel. It is thus fair to say that in case of scenario 1 all sediment in the layer near the bottom is trapped in the channel, thus p = 1.

For now additional suspended sediment infill due to settling of sediment in the water column above the mud layer is neglected and only infill mechanism 1 is taken into account. In a next chapter it will be discussed whether or not this simplification is justified. The infill quantity in case of scenario 1 can now be modelled as equations (4.10) and (4.11):

$$M_{\text{scenario 1}} = \int_{0}^{t} \int_{0}^{L} s_{ML} dL dt$$
(4.10)

With

$$s_{ML} = u(L) \cdot (\delta c) \tag{4.11}$$

4.2.2 Infill modelling of scenario 2

In scenario 2 most of the time infill due to settling of suspended sediment takes place. Only during storm events a mud layer will be developed. Therefore a criterion has to be developed to determine which infill mechanism takes place under which conditions. Svasek Hydraulics and Royal Haskoning [2008b] used the correlation between wave height and concentration to set a criterion. Above a wave height of 1.7 m they computed the chance a mud layer would be formed. For the simple approach adopted in this thesis this criterion cannot be applied. Instead of the wave height, it is proposed to use the concentration of the formed mud layer near the bottom directly, analogue to the criterion applied to scenario 1 in the previous section. A concentration integrated over the layer height will thus serve as a threshold for the generation of a mud layer. The trapping efficiency in case of a mud layer is 100%.

This means that for scenario 2 the next infill model will be used:

For
$$d_1c_1 < (d_1c_1)_{threshold} \Rightarrow M_{scenario 2} = \int_0^t \int_0^L \int_0^{z=h} s_{SS} dz dL dt$$
 (4.12)

For
$$d_1c_1 \ge (d_1c_1)_{threshold} \Longrightarrow M_{scenario 2} = \int_0^t \int_0^L s_{ML,scenario 2} dLdt$$
 (4.13)

$$s_{ss} = u(L) \cdot c(z,L) \cdot z \cdot p(u,c,L)$$
(4.14)

and

With

$$s_{ML,\text{scenario 2}} = u(L) \cdot (d_1 c_1) \tag{4.15}$$

Infill mechanism 2, the infill due to settling of suspended sediment, is modelled with equation (4.12) and (4.14). Infill mechanism 1, the mud layer infill, is calculated using equation (4.13) and (4.15).

The specific mud layer mass threshold is given as equation (4.16):

$$\left(d_{1}c_{1}\right)_{threshold} = \frac{\frac{1}{2}k_{d}\rho_{w}\overline{u}^{2}}{\left(1-\rho_{w}/\rho_{s}\right)g\sin\left(1/\alpha\right)}$$
(4.16)

With a depth-averaged velocity \bar{u} of 0.2 m/s as given in section 2.4.5.4.

The model for scenario 2 is a very crude representation of the physical processes taking place. Two sediment regimes and corresponding infill mechanisms have to be modelled: the low concentrated mud suspension resulting in suspended sediment infill and the fluid mud regime resulting in mud layer infill. In reality the formation of a fluid mud layer depends on hydrodynamic parameters such as the wave height and wave period and is influenced by the strength of the seabed and the current velocity. For example the amount of sediment that can be transported is proportional to u^3 [Winterwerp, 2001]. A high current velocity thus prevents a collapse of the sediment concentration.

A division between the two infill mechanisms is made based on the concentration distributions in Figure 3-19 and an assumed layer thickness (see section 4.4.2.2 and Figure 4-10) and not on for example the wave conditions or the current velocity. The product of a concentration at 10 cm height and a layer height is compared to the outcome of equation (4.16). Based on the specific mass is then decided if a mud layer is present or if suspended sediment infill takes place. The physical processes are thus not modelled, which makes the applicability of this method doubtful. Instead the measured sediment concentration, which is the result of the physical processes, and a criterion to decide which sediment regime is applicable are used.

Additionally this criterion, equation (4.16), cannot not be validated with any measured data. So it is not known if this criterion is suitable to differentiate between the two sediment regimes and will result in a reliable infill prediction. Note that for scenario 1 only one infill mechanism needs to be modelled, since the fluid mud sediment regime is present all year round. Less simplifications thus had to be made. The issue if a simple model is suitable to predict the infill for both scenarios will be further discussed in chapter 6, section 6.1.2.

4.3 Schematization of the approach channel

The infill will be calculated along the approach channel axis, so schematization of the 10.55 km long channel is necessary. The schematization is described in this section. The layout of the OKLNG approach channel is depicted in Figure 4-5. This figure is based on drawing 9R6897-W2-DR-50010 [Figure 16, Royal Haskoning, 2008a]. The channel is divided in 3 sections named A, B and C. For each part a typical cross-section is sketched in Figure 4-5 as well.



Figure 4-5: Layout of the OKLNG approach channel showing channel sections, length, orientation, width, side slopes and channel depth and cross-sections

4.3.1 Channel depth

The navigable depth of the channel is set at -15.5 m CD and an overdepth of 0.5 m is anticipated for dredging operations [OKLNG, 2008a]. For the infill calculation a channel depth of -16 m CD is adopted along the entire channel axis. Note that the water depth in the channel is taken with regard to MSL, so it is 17 m.

4.3.1.1 Nautical bottom concept

It should be mentioned that for ports in muddy waters, the bottom or depth of the approach channels and port basins cannot be clearly defined. The nautical bottom concept is therefore often used. PIANC [1997] defines a nautical bottom as "the level where the physical characteristics of the bottom reach a critical limit beyond which contact with a ship's keel causes either damage or unacceptable effects on controllability and manoeuvrability". This level is where the navigable mud ends and the non-navigable sea bottom begins, it depends on the density and the mud's rheological properties.

Since rheological properties are hard to measure, the navigable depth is usually set at a certain critical density of the mud, which can be measured relatively easy. This density is a compromise between economics (i.e. dredging costs) and safety. The critical density is determined per location; so rheological parameters are also taken into account to some extent. German harbours are an exception and use a dynamic viscosity level as a criterion. Viscosity creates a 1,150 to 1,240 kg/m³ density range for the nautical depth [PIANC, 2008]. The critical density set for the OKLNG approach channel is 1,100 kg/m³ [OKLNG, 2008b].

4.3.2 Channel width, length and orientation

The channel can be divided into three sections with a characteristic width and orientation as shown in Figure 4-5. The section closest to the shore, section A, has an orientation of 165° and a width of 300 m. The western breakwater extends to about -5.8 m CD. This breakwater shelters a large part of section A. Infill of subsection A₁ is therefore only possible with a western directed current. Subsection A₁ has a length of 658 m from the western breakwater tip at -5.8 m CD to the eastern breakwater tip at -5.4 m CD. The remainder of section A has a length of 1000 m, after which the channel bends.

The bend, section B, has a radius of 2500 m and turns over 60°. Its representative orientation is 195°. The width increases to 300 m, but the course of widening is not clear from the current drawings. It is therefore assumed that the whole of section B has a width of 300 m. The last section of the channel has an orientation of 225°. The width of part C is 300 m [Royal Haskoning, 2008a].

The total channel length is subsequently 10.55 km. Note that in the sedimentation study of Svasek Hydraulics and Royal Haskoning [Tables 4.5 to 4-7, 2008b], the representative length is 10.4 km, so 150 m or 1.4% shorter. This length is measured from a water depth of –6 m CD until –16 m CD. For this thesis the channel length is calculated based on the precise coordinates of the channel centre line at the end and start of each section shown in drawing 9R6897-W2-DR-50010 [Figure 16, Royal Haskoning, 2008a], so the length of 10.55 km as described above is adopted.

4.3.3 Side slopes

The initially dredged slopes of the channel will be around 1:8, which is about 7°. These slopes are expected to evolve in time, depending on the soil characteristics. Svasek Hydraulics and Royal Haskoning [2008b] estimate that the slopes consisting of sandy material will obtain a slope of 1:5 or approximately 11°. According to Table 11 in BS6349-5 [1991] a typical underwater slope for sand in active water is 10°, which is similar.

Svasek Hydraulics and Royal Haskoning [2008b] expect that the slopes will range between 1:20 at -9 m CD and 1:60 at -6 m CD or 3° to 1° in due time. The British Standard [BS6349-5, 1991] indicates that a slope of 5° or less should be expected for soft mud bottoms in active water. For the infill modelling in this report the slopes given in Figure 4-5 and estimated by Royal

Haskoning. These slopes originate from drawing 9R6897-W2-DR-52020 [Royal Haskoning, 2008b].

It is assumed that the slope in a cross-section has a constant gradient. In case of intermittent sand layers, it is likely that a steeper slope than 1:60 to 1:20 will be formed. In this schematisation the soil composition will not be taken into account. In a next project phase it should be investigated what the most likely equilibrium slope along the channel axis is and what the upper and lower limits are.

4.3.4 Breakwaters

The western breakwater has a length of approximately 1700 m and extends to about -5.8 m CD into the sea. This is well beyond the surf zone, considering the moderate wave heights. The purpose of the breakwater is also to prevent channel infill due to surf zone sediment transport. The lee breakwater is around 700 m long and reaches until a depth of approximately -5.4 m CD. It is assumed that from the shoreline until a depth of -5.4 m CD the breakwaters retain all sediment. From -5.4 m until -5.8 m CD only western directed currents cause infill of the channel. Due to the sheltering western breakwater it is also assumed that all sediment transported by these currents between -5.4 and -5.8 m CD is trapped in the approach channel.

4.4 Schematization of the hydrodynamic parameters

The parameters needed to calculate the infill besides the channel parameters are the current velocity, the sediment concentration integrated over the water depth, the trapping efficiency for the suspended sediment infill of scenario 2 and the specific mud layer mass threshold, which will indicate the formation of a mud layer in scenario 2. The difference between the two scenarios mainly lies in the distribution of the sediment over the water depth as is also apparent from Figure 3-21 in the previous chapter. The schematization of the current velocity is the same for both scenarios.

4.4.1 Velocity

The near bottom current velocities measured at OKLNG provide the current magnitude and direction approximately 1.5 m above the bottom as already stated in section 2.4.1. However most of the sediment in the water column is found within decimetres of the bottom, so for the infill calculation the velocity at 10 or 20 cm height is required.

Sontek downward looking ADP devices that measured the velocity much closer to the bottom and mentioned in section 2.4.1.1 show a near bottom velocity of 5 to 10 cm/s [Klein, 2009]. This series is however less extensive than the AWAC-series and not properly analyzed yet. It is therefore decided to approximate the near bottom currents by adjusting the yearly 1.5 m above the bottom AWAC data series. The distribution of the current direction will not be changed; it is expected that they are similar. The AWAC velocities however are too high. When dividing the mean current magnitudes by 2, the resulting velocities are in the 5-10 cm/s range.

Concluding, by dividing the current magnitudes of the AWAC data series by 2 and by copying the directional distribution the near bottom current velocities are modelled. If refinement of the infill calculation is required, it is recommended to analyze the actual near bottom current data series of the ADP and use these for the infill modelling.

The current velocity is assumed to be constant over the sediment concentration profile, thus from the bottom until z = 0.8 m as will be defined in section 4.4.2. This is a reasonable assumption, since the current increases from 5-10 cm/s near the bottom to about 20 cm/s near the surface over a water depth of 6 to 17 m, so the increase in velocity will be limited in the first 0.80 m. More importantly, by far the most infill is due to the sediment that is present close to the bottom, say the first 10 cm above the bottom, as will be demonstrated in section 5.3.2. The variation of the current magnitude over this 10 cm is probably negligible.

Next, the currents will be modelled perpendicular to the channel, since the current velocity perpendicular to the channel equals the infill velocity. This current schematization is fairly easy.¹² The advantage of this method is that the channel parameters do not have to be schematized. For each channel section the current will be modelled. The directional spectrum is divided in 30° bins and the original AWAC current magnitudes in 0.1 m/s bins. When dividing by 2, these bins become 0.05 m/s wide. The yearly projected current magnitude for the infill calculation is presented in Figure 4-6.



Figure 4-6: Yearly near bottom current magnitude statistics perpendicular to the different approach channel sections

As indicated in equation (4.2) the velocity depends on the location of the cross-section along the channel axis. For sections A_1 , A_2 and B current statistics from location 1 are used, since the water depth in these sections is less than -9 m CD and location 1 is the closest location. For section C the average current statistics from location 1 and 3 are used, since this section has a water depth ranging from -8.3 until -16 m CD. From location 2 no long current measurement series was available at the time of writing of this thesis. The monthly variation of the current velocity is not taken into account.

Note that the probability of a current velocity of 0 m/s is significant, because currents directed along the channel axis do not cause any sediment flowing over the channel. For section A_1 , the western breakwater shelters the channel from currents directed to 0-150°, so more than half the time no infill takes place. The average infill velocity for the entire channel is in the order of 0.055 m/s.¹³

Uncertainty analysis of the mud infill prediction of the Olokola LNG approach channel

¹² First, the projected velocity is calculated using $u_{projected,bin} = u_{av,bin} \cdot |sin(\theta_{section} - \theta_{av,bin})|$. The corresponding original probability of that velocity is also the probability for the projected velocity, thus $p_{projected,bin} = p_{bin,original}$. Then a new probability distribution is constructed based on the projected current velocities.

 $^{^{13}}$ The average infill velocity for the different sections is 0.029 m/s for section A₁, 0.054 m/s for section A₂ and 0.064 m/s for section B. These values are based on data from location 1. The average projected current velocity on section B is 0.062 m/s based on data from location 1 and 0.049 m/s based on data from location 3. Figure 4-6 shows the average current statistics of the two locations and these will be used for section C.

4.4.2 Sediment concentration over the vertical

4.4.2.1 Sediment concentration for scenario 1

The schematization of the sediment concentration over the depth of scenario 1 is sketched in Figure 4-7.



Figure 4-7: Schematization of the sediment concentration profile over the water depth for scenario 1

In case of scenario 1 a mud layer with layer thickness δ and concentration c will be permanently present near the bottom. The sediment concentration in the water column above the mud layer can be schematized using the measurements conducted at 40 and 60 cm above the bottom. Therefore the concentration profile will be schematized using three layers with a constant sediment concentration and layer height; one mud layer with thickness δ on the seabed and two sediment layers above with much smaller sediment concentrations.

Naturally the lower boundary is the seabed and 0.8 m is taken as the upper layer above which the amount of sediment in the water column is negligible with regard to the amount of sediment lower in the water column. This means $h_0 = 0.0$ m and $h_3 = 0.8$ m. For the definition of the parameters one is referred to Figure 4-7. The boundary between the two upper layers lies in the middle of the two heights at which the turbidity was measured, so this leads to $d_A = 0.3$ m. The boundary between the middle layer and the mud layer depends on the mud layer height δ , which varies in time and about which little is known. Therefore measuring point m_1 is chosen as a boundary, so $d_B = 0.4$ m. This is a simplification, which will have little influence on the total infill, since d_B will vary only a few centimetres around its now fixed value. The concentrations c_1 and c_2 will be selected from the annual concentration statistics at 40 and 60 cm above the bottom.

This leaves the schematization of the mud layer near the bottom to be discussed. Of both parameters, the layer thickness δ and concentration c, little is known. It is also likely that the two parameters depend on each other to a certain extent as will be evident from Figure 4-8 and Figure 4-9 later in this section. It is therefore proposed to make an estimate of the probability distribution of the specific mud layer mass δc .

The concentration in the layer needs to be estimated, since concentrations over 8 g/l could not be measured as explained in section 3.7.2.1. Concentrations have been measured near Lekki, about 20 km west of the OKLNG site, by HR Wallingford [1981] from May to December 1980. On several occasions and especially in May and August, concentrations up to 110 g/l have been measured 10 cm above the bottom. Concentrations up to 10 g/l were measured 25 cm above the bottom. At OKLNG the concentration may very well vary from 5 to 150 g/l.

For all three locations 14.5% of the time the concentration was larger than 5.1 g/l at 10 cm height. The average layer thickness is therefore smaller than 10 cm; otherwise the OBS would have reached its maximum scale more often. To get a better idea of the possible mud layer height Vinzon and Mehta's [1998] equation for the height of a mud layer near the bottom is used. For the equation and calculation the reader is referred to Appendix B.

The hydraulic roughness height is calculated based on Soulsby and Clark's [2005] roughness coefficient for hydraulically smooth and freshly-deposited mud beds in turbulent flows. This is explained in Appendix C and Appendix D. All the above leads to the mud layer heights as depicted in Figure 4-8 and Figure 4-9. The used parameters are also given in these figures.



Figure 4-8: Mud layer thickness depending on sediment concentration and settling velocity using Vinzon and Mehta's [1998] mud layer height equation; the roughness height is based on the combined influence of waves and currents and the waves cause the roughness height to be relatively large despite the smooth bottom



Figure 4-9: Mud layer thickness depending on sediment concentration and settling velocity using Vinzon and Mehta's [1998] mud layer height equation; the roughness height is based on the influence of the currents only and very low due to the smooth bottom

Depending on whether or not the influence of the waves on the roughness height is taken into account the layer height is in the order of decimetres or in the order of centimetres. As also explained in the mentioned appendices the wave climate has by far the most influence on the roughness height. In any case the figures show that with very low settling velocities it is possible that a permanent mud layer in the order of 10 cm exists near the bottom. Note also that the layer thickness decreases as the sediment concentration in the layer increases, showing that the two parameters are indeed correlated.

Since little is known about the specific mass of the mud layer, the expected lower limit, upper limit and most likely value are estimated. The triangular distribution is used to model the parameter. Keeping in mind that the average mud layer height has to be smaller than 10 cm and based on Figure 4-8 and Figure 4-9, a most likely specific mass of 0.08 m \cdot 50 kg/m³ = 4 kg/m² is adopted. The lower limit is estimated to be half of that value, so 2 kg/m², and the upper limit twice that value at 8 kg/m². The distribution is purposely positively skewed. Since the fitted lognormal distributions of the sediment concentrations are positively skewed it seems likely that the distribution for the specific mass of the mud layer is positively skewed as well. The weighted average specific mass using this probability distribution is 4.67 kg/m².

Notwithstanding it is stressed that these values are not much more than an educated guess and highly uncertain. Validation of these values is not possible with the currently available data. This large uncertainty regarding the specific mud layer mass should be considered in the probabilistic infill modelling.

4.4.2.2 Sediment concentration for scenario 2

In case of scenario 2 most of the time a concentration profile as sketched in Figure 4-10 will be present. Only under storm conditions the concentration profile will collapse and a mud layer will develop near the bottom, resulting in the more L-shaped profile of scenario 1.





As also was done for scenario 1, the water column is divided into three layers. For the values of h_0 and h_3 , one is referred to the previous section. Height h_2 lies in the middle of m_2 and m_3 where the turbidity was measured. Height h_1 does not have a fixed value, since the layer near the bottom should be negatively correlated with the concentration measured at 10 cm height to include the mechanism of the concentration profile collapse when a mud layer is formed. This means that the layer height is expected to vary between 0.25 m and 0.05 m based on Figure 4-8. It is assumed that the probability of the 0.25 m layer is the highest and linearly decreases to a 0% probability of a layer height of 0.05 m. Layer thickness d_2 subsequently depends on d_1 according to the following relation: $d_2 = 0.5 \text{ m} - d_1$.

Statistics of measured concentrations at three heights above the bottom have been deduced in section 3.7.2.3. The statistics of concentrations at 10 cm height show probabilities of concentrations of several tens of grams per litre in the order of 1%, which represents the mud layer that is formed under extreme wave conditions. Using the annual statistics will thus automatically include the mud layer events as well. Concentration data of the nearest location will be used for each section.

4.4.3 Trapping efficiency in case of suspended sediment infill

Unfortunately there is no simple equation to calculate the suspended sediment trapping efficiency of a channel. While flowing over the channel the sediment particles settle under their own weight. Turbulent mixing causes flocculation and floc break-up, influencing the settling velocity. The settling velocity also decreases closer to the bottom due to the higher sediment concentration and sediment particles hindering each other [see e.g. Kinch, 1952; Winterwerp, 2002; Dankers, 2006]. These processes determine the deposition.

Applying a simple formula and only taking unhindered sediment settling into account result in an unrealistic 100% trapping efficiency. The combination of a low current velocity of 0.055 m/s, a constant settling velocity of 0.5 mm/s and a channel width of 400 m, results in an unrealistic settling distance of several meters.¹⁴

Additionally erosion is not taken into account, which is not a justifiable simplification in a persistent swell wave climate as is the case in the OKLNG area. Waves constantly erode sediment from the seabed, so assuming quiet settling and no resuspension is unrealistic. The amount of sediment being eroded depends on the state of the bed [see e.g. Mehta *et al.*, 1989; Teisson *et al.*, 1993; Winterwerp and Van Kesteren, 2004].

Alternatively a well-known and relatively simple formula for erosion is from Partheniades, which is later adjusted by Mehta and Partheniades [1979]. A similar formula by Krone [1962] exists for deposition. Unfortunately these formulas require detailed information of the shear stresses and strength of the bottom soil layer, which is not available for OKLNG. More importantly, these processes are still not well understood and the formulas always require validation with field measurements. Therefore numerical models such as DELFT 3D, MIKE 21 and FINEL 2D are almost always used to compute the trapping efficiency.

Nowadays no simple equation exists that properly takes all relevant processes into account and gives a reliable prediction of the trapping efficiency of a sediment-laden flow passing a channel.

It is therefore proposed to use the trapping efficiencies calculated by Svasek Hydraulics and Royal Haskoning using the FINEL 2D model. The depth-averaged shallow-water equations are the basis of this model. The trapping efficiency is computed based on the difference in flux before the flow enters the channel and while in the channel. The flux decreases and depends on the current velocity¹⁵ and bottom shear stress. A settling velocity corresponding to a fine grain diameter, so ~0.01-1 mm/s, is used as an input parameter as well [Klein, 2009].

The trapping efficiencies of the consultants come down to an average trapping efficiency of 55% for section A_2 and B and 12% for section C [based on Table 4.4, Svasek Hydraulics and Royal Haskoning, 2008b]. For the probabilistic approach a triangular distribution is assumed with the average values as most likely values and the range as determined by the consultants as minimum and maximum values. This means a range of 35 to 100% for section A_2 and B and a range of 0 to 19% for section C. The trapping efficiency of section A_1 is always 100%, since a breakwater prevents sediment from flowing out of the channel at the western side as also discussed in section 4.3.4.

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 $^{^{14}\}Delta z = w_s \cdot W_{channel}/u = 5.10^{-4} \text{ m/s} \cdot 400 \text{ m} / 0.055 \text{ m/s} \approx 3.6 \text{ m}$

¹⁵ Continuity states that $uh = u_{ch}h_{ch}$. Since the water depth in the channel is larger than the surrounding area or $h_{ch} > h$, it follows that $u_{ch} < u$. The current velocity decreases when entering the channel and hence also the flux decreases.

4.4.4 Specific mud layer mass threshold for scenario 2

Based on equation (4.9) and neglecting the friction between the mud layer and the sea bottom, assuming a stationary mud layer ($u_m = 0 \text{ m/s}$) and using the mean values stated in column 3 of Table 4-1, the threshold value varies from 0.08 kg/m² for a 1:60 slope to 0.03 kg/m² for a 1:20 slope. The gentler the slope is, the smaller the gravity component is as well, so for gentler slopes mud layers with a larger specific mass can be transported up the opposite slope again. Critical combinations of sediment concentration and mud layer thickness are graphically depicted in Figure 4-4. Note that the mud density corresponding to the sediment concentration is given on the right of the graph.



Figure 4-11: Combinations of sediment concentration and mud layer thickness to fulfil the specific mass criterion; the mud density corresponding to the sediment concentration indicated

The threshold depends on the channel section via the variation in slope. The average specific mud layer mass threshold for the entire channel would be $(d_1c_1)_{threshold} \ge 0.05 \text{ kg/m}^2$. If the threshold is exceeded, it is assumed that a mud layer is formed which will be trapped in the cross-sectional direction of the channel after transportation by the currents. Note that this is an assumption that cannot be validated.

4.5 Overview of the parameters needed for the infill calculation

To conclude, an overview of all parameters necessary to calculate the yearly infill quantity of the OKLNG approach channel is given in Table 4-2. Their possible bandwidth is included as well. The final column shows in which section this parameter was discussed.

Parameter Value Bandwidth *Comments/reference*¹⁶ Channel: 658 m Deterministic Section 4.3.2 and Figure 4-5 • Length section $A_1 L_{A1}$ 1,000 m Deterministic Section 4.3.2 and Figure 4-5 • Length section $A_2 L_{A2}$ 2,618 m Deterministic • Length section B L_B Section 4.3.2 and Figure 4-5 6,274 m Deterministic Section 4.3.2 and Figure 4-5 • Length section C L_C 10,550 m Deterministic Section 4.3.2 and Figure 4-5 Total length L • Slope $\alpha_{>-6mCD}$ 60 8-60, assumption Section 4.3.3, RH [2008b] Linear 8-60, assumption Section 4.3.3, RH [2008b] • Slope $\alpha_{-6/-9mCD}$ 20 8-40, assumption Section 4.3.3, RH [2008b] • Slope $\alpha_{<-9mCD}$ Water column: $1,020 \text{ kg/m}^3$ 1,010-1,030 kg/m³ Table 8.1, Sv/RH [2007a], • Sea water density ρ_w section 2.4.6.3 • Current velocity near Varies m/s 0-0.30 m/s Section 4.4.1 and Figure 4-6, the bottom u depends on channel section Sediment over the depth:¹⁷ $2,600 \text{ kg/m}^3$ 2,500-2,700 kg/m³ • Sediment density ρ_s Section 3.4.3.2 Varies kg/m² • Specific mud mass δc Unknown Section 4.4.2.1 • Sediment concentration Varies kg/m³ Lognormal Table 3-3 in section 3.7.2.3 distributions $C_{1,2,3}$ 0.10 m Deterministic • Layer thickness m_1 Section 4.4.2.1, Figure 4-7 0.30 m Deterministic Section 4.4.2.1, Figure 4-7 • Layer thickness d_A 0.40 m Deterministic Section 4.4.2.1, Figure 4-7 • Layer thickness d_B 0.25 m 0.05-0.25 m, Section 4.4.2.2, Figure 4-10 • Layer thickness d_1 depends on c_1 • Layer thickness d_2 0.25 m $d_2 = 0.5 \text{ m} - d_1$ Section 4.4.2.2, Figure 4-10 • Layer thickness d_3 0.30 m Deterministic Section 4.4.2.2, Figure 4-10 Varies kg/m² Unknown • Threshold $(d_1c_1)_{thr.}$ Section 4.4.4 Trapping efficiency: (Scenario 2 only) Trapping efficiency of 1.00 Deterministic Sheltering breakwater causes 100% trapping, 4.3.4/4.4.3 section A₁, p_{A1} 0.55 0.35-1.00 Sv/RH [2008b], section 4.4.3 • Trapping efficiency p_{A2} 0.55 0.35-1.00 Sv/RH [2008b], section 4.4.3 • Trapping efficiency p_B 0.12 0-0.19 Sv/RH [2008b], section 4.4.3 Trapping efficiency p_C (Scenario 2 only) Constants: 0.0004 0.0001-0.0015 Delft Hydraulics [1974], 4.2.1 Drag coefficient k_d 9.81 m/s^2 Deterministic Gravitational constant g

Table 4-2: Overview of the parameters necessary to calculate the infill rate S in kg/s of the OKLNG approach channel

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¹⁶ Sv is short for Svasek Hydraulics and RH is short for Royal Haskoning

¹⁷ Specific mud layer mass δc and layer thicknesses m_1 , d_A and d_B regard scenario 1. Sediment concentrations c_1 and c_2 concern both scenarios and the remaining parameters regard scenario 2.

5 Mud infill prediction and uncertainty

This chapter addresses objective 2 of the thesis; estimates of the mud infill of the OKLNG approach channel are made including a quantitative uncertainty analysis. First the set-up of how to make this estimate is presented. Next the infill prediction and uncertainty analyses are made. Theory on types of uncertainty is briefly discussed at the start of section 5.3 to be able to characterize the uncertainties and to assess later on if and how they can be mitigated. This chapter concludes with a prediction of the yearly infill and an identification of which parameters cause the largest uncertainty.

5.1 Set-up of the mud infill prediction

Figure 5-1 shows the sequence of analyses that will be made in this chapter to estimate the mud infill and give a quantitative uncertainty analysis.



Figure 5-1: Set-up of the mud infill prediction

To gain insight in the yearly infill quantity the approach channel infill is first determined deterministically in section 5.2. Mean values for the current velocity and sediment concentration over the depth are used to calculate a yearly channel infill.

Next a sensitivity analysis is conducted to identify which parameters have the largest influence on the infill quantity in section 5.3. The input parameters are varied within their expected range and the corresponding infill is calculated deterministically. This infill is compared to the infill quantity calculated based on mean values to show the possible range in infill quantity and importance of each parameter. To assess the type of uncertainty, this section starts with brief overview of the types of uncertainty that can be identified.

Besides offering insight into which parameters cause the largest uncertainty in the infill prediction the sensitivity analysis can be used as a starting point for a probabilistic analysis. Based on the influence a parameter has on the infill, it can be decided which parameters have to be modelled in a probabilistic manner and which can be modelled deterministically.

The goal of a probabilistic infill prediction is to gain insight in the uncertainties and spread around the mean, which is the average or expected value of all predicted values. The result of a probabilistic analysis is a probability distribution of the yearly infill quantity. A probabilistic approach is useful to apply to the OKLNG approach channel infill, because input parameters such as the currents and sediment concentrations in the water column are inherently uncertain and can be characterized with a probability distribution, and there are major uncertainties regarding the physical processes and the modelling of the infill. These uncertainties are not properly represented in a deterministic calculation [Housley, 2002]. Also the dependency of parameters can be included and investigated in a probabilistic approach.

In order to execute a probabilistic analysis, it is important to identify all important parameters, assign a probability distribution to every parameter based on available data, literature and expert opinions, and define correlation between parameters [Van Gelder, 2000]. Naturally a probabilistic analysis is only useful if a deterministic model is available that has reasonable predictive capacity. The model will be evaluated in section 6.1.2.

An attempt is made in this thesis to conduct a probabilistic analysis of the yearly mud infill of the OKLNG approach channel, since it would be very useful for project planning, determining possible maintenance strategies and assessing risks. Section 5.4 explains the set-up of the probabilistic approach and section 5.5 presents the results.

5.2 Deterministic infill calculation

Using the model and parameters from the previous chapter the yearly channel infill quantity for both scenarios is computed. For this first calculation the mean values of the current velocity, estimated specific mud layer mass and concentrations in the three schematised layers are used. The 10.55 km long channel is divided into 10 m long segments, so into 1,055 segments. Further decreasing the length of these segments leads to a negligible difference in infill quantity, especially compared to the other uncertainties. For each segment the channel cross-section is schematised and the infill rate per meter channel length calculated. Since the mean values are all based on yearly averages, the time integration does not pose any problems.

5.2.1 Deterministic infill quantity of scenario 1

For scenario 1 all sediment is trapped in the channel:

$$M_{\text{deterministic,scenario 1}} = \sum_{i=1}^{1055} u(L) \cdot (\delta c) \cdot \Delta x \cdot \Delta t$$
(5.1)

With the average infill velocity u depending on the channel section as stated in section 4.4.1 (i.e. ~0.055 m/s), the weighted average specific mass of the mud layer $\delta c = 4 \text{ kg/m}^2$ based on the assumed triangular distribution in section 4.4.2.1, $\Delta x = 10$ m and $\Delta t = 1$ year = 3.15 \cdot 10⁷ s.

Using these mean values leads to a deterministic infill for scenario 1 of 86 Mton/yr.¹⁸ Without consolidation of the mud, assuming that the mud contains 50 kg/m³ of sediment and no maintenance, the entire channel is filled up in 8.4 days. The depth of -15.5 m CD set for navigation is reached within 1 day. This clearly shows that the channel fills up fast.¹⁹ As will be evident from the sensitivity analysis in section 5.3, even if the parameters are varied within a very wide range the channel will always be full within weeks and the set depth for navigation will be reached within days.

 $^{^{18}}$ When using an average infill velocity over the entire channel length, the infill quantity becomes 0.055 m/s \cdot 4.67 kg/m² \cdot 10,550 m \cdot 3.15 \cdot 10⁷ s/yr = 85.4 Mton/yr, which is very close to the computed value of 85.9 Mton/yr for which the channel is divided into segments and the velocity is dependent on the channel section.

¹⁹ A quick calculation shows the same: assuming an average channel length of 600 m, an average depth with regard to the original sea bed of 6 m, an infill velocity of 0.055 m/s and a mud layer thickness of 0.08 m, the filling time would result in $(600.6)/(0.055.0.08) \approx 8.1 \cdot 10^5 \text{ s} \approx 9.5$ days.

5.2.2 Deterministic infill quantity of scenario 2

In the model for scenario 2 the threshold value is used to make a distinction between the times when a mud layer is present and when infill due to settling of suspended sediment takes place. For the deterministic calculation this poses an additional problem, since the distribution of the sediment at 10 cm height is used for both the suspended sediment and the mud layer. Additional assumptions thus have to be made to obtain a first indication of the infill quantity of scenario 2 on top of the schematizations already made to obtain this simple infill model. (Recall for example that the current magnitude influences the sediment state in the water column, but this relation is not included in the model.) All these assumptions, which cannot be validated, lead to the conclusion that this simple approach is not suitable to precisely calculate the infill quantity of scenario 2 deterministically. Note however that a precise computation of the infill is not the goal of this thesis, a simple model was adopted to obtain insight in the uncertainties. For this purpose the model is suitable.

To still provide a rough estimation of the deterministic infill quantity for scenario 2 and in the absence of a suitable calculation method, the following equation is used to approximate the infill:

$$M_{\text{det,scenario 2}} = \sum_{i=1}^{1055} \underbrace{u(L)(d_1c_1)_{ML} \Delta x \cdot p_{t,ML} \Delta t}_{\text{Infill due to mechanism 1:}} + \underbrace{u(L)((d_1c_1)_{SS} + d_2c_2 + d_3c_3) p(L) \Delta x (1 - p_{t,ML}) \Delta t}_{\text{Infill due to mechanism 2:}} + \underbrace{u(L)((d_1c_1)_{SS} + d_2c_2 + d_3c_3) p(L) \Delta x (1 - p_{t,ML}) \Delta t}_{\text{ucc} c alm metocean conditions}}$$
(5.2)

With the average infill velocity u depending on the channel section as stated in section 4.4.1, the average specific mud layer mass $(d_1c_1)_{ML}$, the percentage of the time the mud layer is present $p_{t,ML}$ based on the mud layer threshold as explained in section 4.4.4, the average concentration in the layer closest to the bottom when the mud layer is not present $(d_1c_1)_{SS}$, the average concentration in the other two layers d_2c_2 and d_3c_3 based on Table 3-3 and section 4.4.2, the trapping efficiency p(L) as discussed in section 4.4.3, $\Delta x = 10$ m and $\Delta t = 1$ year = $3.15 \cdot 10^7$ s. All parameters are weighted yearly averages, so multiplied by the amount of seconds in a year the outcome is a yearly infill quantity.

The specific mud layer mass threshold depends on the channels section. For this already rough estimation one threshold criterion for the entire channel is used. The average specific mud layer mass threshold for the occurrence of a mud layer near the bottom is $(d_1c_1)_{threshold} \ge 0.05$ kg/m² (see section 4.4.4). The average mud layer height is assumed to be 0.10 m based on Figure 4-8, the severe wave conditions and a settling velocity in the order of 0.5 mm/s corresponding to this scenario.

This specific mud layer mass criterion and layer height result in a mud layer concentration of 5 kg/m^3 . Above this concentration it is assumed that a mud layer is present for this deterministic approach. The probability that the concentration is higher than the set threshold concentration is used as the percentage of the time in a year this layer is present. The remaining percentage of the time suspended sediment infill takes place.

The probability distribution of the sediment concentration measured at 10 cm height is therefore artificially divided into a mud layer part with $c \ge 5$ kg/m³ and a suspended sediment part. This results in an average specific mud layer mass and an average concentration of the layer closest to the bottom in case of suspended sediment infill. These extra parameters for the deterministic infill calculation are listed in Table 5-1.

Table 5-1: Values for the concentrations of the mud layer $c_{1,ML}$ and suspended sediment layer $c_{1,SS}$ near the bottom and the percentage of the time a mud layer is present $p_{t,ML}$ to compute the deterministic infill quantity for scenario 2

Location	Height at	Mean value of	Mean value of	Percentage of
	which was	concentrations	concentrations	concentrations
	measured	<i>≥ 5 kg/m</i> ³	< 5 kg/m³	<i>≥ 5 kg/m</i> ³
Location 1	10 cm	19,000 mg/l	1,070 mg/l	15 %
Location 2	10 cm	24,000 mg/l	900 mg/l	14 %
Location 3	10 cm	21,600 mg/l	890 mg/l	13 %

This highly schematized infill calculation amounts to an infill quantity of 4.6 Mton/yr of which 1.9 Mton/yr is due to suspended sediment and 2.7 Mton/yr is due to mud layer infill. An infill of 4.6 Mton/yr means that the navigation depth is reached in 6 months based on a mud density of 1,370 kg/m³. This is the same density as the average in situ bulk density of the bottom layer (see section 3.4.3.1). Due to the low settling rates it is not expected that this density will be reached immediately. Using the nautical bottom of 1,100 kg/m³ (see section 4.3.1), the navigation depth is reached after 1.4 months. In any case this shows that after a few months the channel needs to be dredged.

In case of scenario 2 the infill rate is dependent on the channel cross-section. When the channel fills up, the overdepth decreases and so does the trapping efficiency. Because the infill rate decreases as the channel fills up, it cannot be estimated after how many years the channel is full. If the infill rate would not decrease and assuming a mud density of 1,370 kg/m³ the entire channel is full after 5 years, which demonstrates that also for this scenario the infill rate is quite high.

5.3 Sensitivity analysis of the deterministic infill calculation

The sensitivity analysis is part of the uncertainty analysis. Therefore this chapter starts with a brief overview of different types of uncertainties that can be identified. Then the sensitivity analysis will be discussed leading to a conclusion on how the parameters should be modelled in the probabilistic model and what the nature of the uncertainties is.

5.3.1 Types of uncertainties

As observed already in section 1.2 the mud infill process is inherently uncertain, i.e. subject to "randomness or variations in nature" [Van Gelder, 2000]. In general two types of uncertainty exist: inherent and epistemic or knowledge uncertainties. Inherent uncertainties cannot be reduced further after a certain number of measurements. Epistemic uncertainties however continue to decrease when knowledge increases. Data collection, literature research, expert judgment and comparisons between tests, measurements and model results can reduce epistemic uncertainties [Van Gelder, 2000; Burcharth, 2002].

With reference to Figure 5-2, 5 types of uncertainty are discussed. Statistical uncertainties originate from fitting a distribution to a limited or incomplete dataset. The main parameters, such as the mean and standard deviation, are then subject to uncertainty. It is also possible that the dataset fits several distribution types and the most suitable distribution is not known. Model uncertainty is due to schematization and not being able to describe the physical processes correctly. These three uncertainties are of epistemic nature.

Lastly there are inherent uncertainties in time and space. Metocean parameters like waves and currents are inherently uncertain in time. It is impossible to predict the exact wave height tomorrow at noon. Inherent uncertainties in space are due to a shortage in measurements, such





Figure 5-2: Types of uncertainty [After Figure 2.1, Van Gelder, 2000]

5.3.2 Influence of the parameters on the predicted infill quantity

The purpose of the sensitivity analysis is to investigate the influence of each input parameter on the infill quantity and to decide whether they should be treated as a deterministic or probabilistic parameter in the probabilistic infill model. All input parameters are varied within their possible range. If the variance of an input parameter has a significant influence on the predicted mud infill quantity, a distribution will be assigned.

The main parameters are the current velocity, the sediment concentration over the vertical and the channel length. The channel length is determined by the channel design and a deterministic parameter.

In the deterministic approach the average infill velocity is used, while metocean parameters are inherently uncertain in nature; their exact value at a certain time and date cannot be predicted. In the probabilistic approach the deduced distribution from section 4.1.1 will therefore be used. The sediment concentration is also an inherently uncertain parameter, thus the fitted distributions as given in Table 3-3 will be used for the probabilistic approach.

For both scenarios most of the sediment is present in the layer near the bottom. The bottom mud layer contains 97% of all sediment in the vertical in case of scenario 1. Neglecting possible suspended sediment infill of the two schematised layers above the mud layer thus results in only a small error. If the trapping efficiency of those two layers is 50%, the infill quantity will increase with 1.5%. This high trapping efficiency is however unlikely due to the low settling velocity of the sediment in this scenario, leading to a very small and maybe even negligible error.

Uncertainties in the concentrations c_2 and c_3 and variation in layer heights d_A and d_B thus have a limited effect on the final infill quantity. In case the used concentrations are a factor 2 too low, which is unlikely, and assuming a high trapping efficiency of 50%, the infill quantity would increase with only 3%. The simplification proposed in section 4.2.1 to not take infill mechanism 2 into account in scenario 1 is therefore justified.

For scenario 2 the bottom layer contains 90% of the sediment, the middle layer 6% and the top layer 4% assuming the distribution for concentration c_1 as fitted in section 3.7.2.3 corresponds well with reality. Then this means that the uncertainty in concentrations c_2 and c_3 and variation in layer heights d_2 and d_3 is again of much less importance than the uncertainties in layer height d_1 and concentration c_1 (of which also the tail is modelled resulting in additional uncertainty):

the uncertainty lies in the specific mass of the mud layer d_1c_1 . The tail of the distribution has an especially large influence on the total infill quantity, while little is known about this part of the concentration distribution.

The uncertainty in the specific mud layer mass δc in scenario 1 is also large. Of course these parameters are dependent on the wave climate, current velocity and soil characteristics, and hence inherently uncertain, but even the range between which these parameters can vary is simply not known. Based on the available data an estimate for a most likely specific mud layer mass cannot be made. The currently used triangular distribution and estimated most likely value of 4 kg/m² is a best guess.

The remaining parameters are only relevant for scenario 2. The seawater density and sediment particle density will be treated as deterministic parameters, since variation of these parameters within their possible range leads to a negligible difference in outcome of the threshold value. The drag coefficient, channel slope and gravitational constant thus determine the threshold value, which distinguishes between infill due to suspended sediment and due to a mud layer. The gravitational constant is a deterministic parameter and the channel slope is a given (see section 1.4.1) that depends on the channel section. In the deterministic analysis the influence of the threshold value on the infill quantity cannot be investigated, so this should be included in the uncertainty analysis of the probabilistic infill calculation. This can be done by varying the drag coefficient.

The last parameter is the trapping efficiency in case of suspended sediment infill. This parameter depends on the current velocity, sediment characteristics and channel parameters such as the depth, orientation, width and slope. It is partly an inherent and partly an epistemic uncertainty. The possible variation of this parameter cannot be properly assessed, since the relation between these parameters and the trapping efficiency is not incorporated in this simple model. The trapping efficiency does influence the suspended sediment infill substantially and therefore requires attention when performing the probabilistic analysis.

It is interesting to note that except for the channel length and the projection of the currents, the channel parameters do not have any influence on the infill in case of a very low settling velocity. The depth, slope and width only influence the channel volume and therefore the time it takes for the channel to fill up, but they do not influence the infill quantity.

5.3.3 Conclusion on how to model the parameters

Summing up, parameters that cause the largest uncertainty for scenario 1 are the current velocity u and the specific mud layer mass δc . The nature of the uncertainty of the current velocity is inherent in time and the specific mud layer mass uncertainty is epistemic. Once the distribution of the specific mud layer mass is known, this uncertainty will also be inherent. Only epistemic or knowledge uncertainties can be reduced, inherent uncertainties are random variations of nature and have to be dealt with.

For scenario 2 the specific mud layer mass d_1c_1 , the threshold value to distinguish between suspended sediment and mud layer infill $(d_1c_1)_{threshold}$ and the trapping efficiency p for all sections except section A₁ require further investigation. These parameters have to be modelled in a probabilistic manner and their uncertainties are of epistemic nature. As far as can be concluded at this point, the uncertainty in the sediment concentration near the bottom has the most influence on the infill quantity uncertainty for both scenarios.

Secondly, the seawater and sediment density will be treated as deterministic parameters, since they have no influence on the uncertainty of the infill quantity. The schematized layer heights d_2 , d_3 , d_A and d_B have almost no influence on the infill quantity and will thus also be treated as deterministic values. The probability distributions of concentrations c_2 and c_3 as deduced in section 3.7.2 and listed in Table 3-3 will be used in the probabilistic approach, but the

uncertainties regarding these parameters are negligible in comparison with the uncertainties regarding the concentration of the mud layer near the bottom for both scenarios.

5.4 From deterministic to probabilistic infill prediction

A probabilistic infill prediction has the advantage that the spread in the mud infill prediction becomes known and the uncertainties can be quantified. For project planning the P10 and P90 values are often just as important as the expected average infill quantity, they give an indication of the risks with regard to the investigated aspect of the project. The P10 and P90 values are the quantities that are exceeded respectively 90% and 10% of the time.

This section explains how the probabilistic model is set-up on the basis of the model, values and distributions of the parameters as discussed previously. With reference to Van Gelder [2000] on the steps required to execute a probabilistic analysis the parameters are identified in chapter 4, the assigned distributions will be reviewed briefly in this section (see Table 5-2) and the modelling of the correlations between parameters is explained next (see section 5.4.2). Pitfalls of a probabilistic analysis are not having identified all important parameters, not being able to select a proper probability distribution, which is especially difficult when few or incomplete data is available as is the case for this thesis, and not including all relevant correlations.

Based on the distributions of the parameters and their correlations equation (4.11) is used to compute an infill rate per meter channel length s in kg/m/s for scenario 1 and equations (4.14) and (4.15) for scenario 2. Additional aspects that remain to be addressed to progress from an infill rate per meter channel length s in kg/m/s via an infill rate S in kg/s to the amount of sediment in the channel M in megaton in one year (see also section 4.2) are the integration over the channel length and the integration over time. Lastly the choice of a probabilistic method is discussed.

5.4.1 Distributions of the parameters in the model

As discussed in 5.1 the mud infill is a stochastic process – it is subject to randomness –, and can be characterized with a probability distribution. The distribution of the infill rate per meter channel length s in kg/m/s is based on the distributions of the input parameters. An overview of the relevant parameters and the assigned distributions is given in Table 5-2.

Parameter	Distribution	Comments/reference				
Infill velocity:		(See Figure 4-6)				
 Current velocity near 	According to	Characteristics	of the	current	velocity	/
the bottom u	Figure 4-6 in	distribution f	or the c	lifferent	: sectior	ns are:
	section 4.4.1		A_1	A ₂	В	С
		$p_{0 m/s}$	0.57	0.12	0.09	0.11
		$p_{0-0.05 m/s}$	0.19	0.42	0.36	0.36
		$p_{0.05-0.1 m/s}$	0.15	0.32	0.33	0.33
		$p_{0.1-0.15 m/s}$	0.07	0.11	0.16	0.15
		$p_{0.15-0.2 m/s}$	0.02	0.03	0.05	0.05
		$p_{0.2-0.25 m/s}$	0.00	0.00	0.01	0.00
		$p_{0.25-0.3 m/s}$	0.00	0.00	0.00	0.00

Table 5-2: Overview of the assigned distributions to the parameters needed tocompute the mud infill of the OKLNG approach channel

Continuation of Table 5-2: Overview of the assigned distributions to the parameters needed to compute the mud infill of the OKLNG approach channel

Parameter	Distribution	Comments/reference		
Sediment over the depth:		(See Figure 4-7 and Figure 4-10)		
• Specific mud mass δc	Triangular	$\delta c_{most\ likely} = 4 \text{ kg/m}^2$		
		$\delta c_{lower limit} = 2 \text{kg/m}^2$		
		$\delta c_{upper\ limit} = 8\ kg/m^2$		
		$\delta c_{weighted average}$ = 4.67 kg/m ²		
 Sediment concentration 	Lognormal	Mean μ and standard deviation σ are		
<i>C</i> _{1,2,3}		presented in Table 3-3 of section 3.7.2.3		
• Layer thickness m_1	Deterministic	$m_1 = 0.10 \text{ m} \text{ (Scenario 1)}$		
• Layer thickness d_A	Deterministic	$d_A = 0.30$ m (Scenario 1)		
• Layer thickness d_B	Deterministic	$d_B = 0.40$ m (Scenario 1)		
• Layer thickness d_1	Depends	0.05-0.25 m, for correlation see		
	negatively on c_1	section 5.4.2.5 (Scenario 2)		
• Layer thickness d_2	Depends on d_1	$d_2 = 0.5 \text{ m} - d_1$ (Scenario 2)		
• Layer thickness d_3	Deterministic	$d_3 = 0.30 \text{ m}$ (Scenario 2)		
Channel length:		(See Figure 4-5)		
• Length section $A_1 L_{A1}$	Deterministic	$L_{A1} = 658 \text{ m}$		
• Length section $A_2 L_{A2}$	Deterministic	$L_{A2} = 1,000 \text{ m}$		
• Length section B L_B	Deterministic	$L_B = 2,618 \text{ m}$		
• Length section C L_C	Deterministic	$L_c = 6,274 \text{ m}$		
Trapping efficiency:		(Only for scenario 2)		
• Trapping efficiency p_{A1}	Deterministic	$p_{A1} = 1$		
Trapping efficiency of	Triangular	Characteristics of the trapping efficiency		
the remaining sections		distribution for the different sections are:		
p_{A2} , p_B and p_C		A ₂ B C		
		$p_{most\ likely}$ 0.55 0.55 0.12		
		<i>p_{lower limit}</i> 0.35 0.35 0.00		
		$p_{upper\ limit}$ 1.00 1.00 0.19		
Mud layer mass threshold: ²⁰		(Only for scenario 2)		
• Threshold section A ₁	Deterministic	$(d_1c_1)_{threshold,A1} = 0.08 \text{ kg/m}^2$		
• Threshold section A ₂	Deterministic	$(d_1c_1)_{threshold,A2} = 0.08 \text{ kg/m}^2$		
Threshold section B	Deterministic	$(d_1c_1)_{threshold,B} = 0.06 \text{ kg/m}^2$		
 Threshold section C 	Deterministic	$(d_1c_1)_{threshold,C} = 0.03 \text{ kg/m}^2$		

A probabilistic analysis is only successful if these distributions can be assigned with reasonable accuracy as mentioned before. Also the goal of this probabilistic analysis is to obtain a probability distribution of the yearly mud infill quantity. The distributions thus have to be based on data that are representative for a year and are reliable. The channel length is a design variable and a deterministic parameter and therefore not relevant in this discussion.

²⁰ The drag coefficient $k_d = 0.0004$, the depth-averaged velocity $\bar{u} = 0.20$ m/s, seawater density $\rho_w = 1,020$ kg/m³, sediment density $\rho_s = 2,600$ kg/m³ and the gravitational constant g = 9.81 m/s². Since the slopes differ per section, the specific mud layer mass threshold differs per sections. The slopes are 1:60 for sections A₁ and A₂, 1:43 on average for section B and 1:20 for section C.

The current velocity was measured for an entire year at the project site and compared to a data series of a different year at Benin River. The trend in velocity magnitude over the year and order of magnitude were the same, so it was concluded that the OKLNG current data are representative for an arbitrary year (see section 2.4.5.5). For the current velocity the probability distribution can thus be determined with reasonable accuracy and it is representative.

Because this research primarily concerns a prediction of the yearly mean it does not pose any problems that only data from one year is used. Only when one is interested in extreme values, data from multiple years is essential. The yearly mean will not vary much from year to year, but if one wants to increase the reliability of the estimate measurements should be conducted in different years.

At OKLNG the sediment concentrations and wave climate were measured in the same year as the current velocities. Comparison of the velocity data with another year shows that the year in which measurements were conducted at OKLNG is representative for an arbitrary year. If any other the parameters were measured during that same year, these data series can also be assumed to be representative for an arbitrary year. The reliability will be discussed next.

The concentration data series do not cover an entire year as can be seen in Table 3-2, so strictly speaking they cannot be used to predict a yearly infill. Estimating the distributions for the concentrations at 40 and 60 cm height is not a problem due to the large number of measurements (30,000 data points per data series on average). Moreover the specific mass in the two schematised upper layers contributes only little to the total infill as was concluded in section 5.3.2; the specific mass in the layer near the bottom has the largest effect on the mud infill of the three layers.

The problem of the concentrations measured near the bottom is that the deployed measuring devices could not record concentrations above 8 g/l as explained in section 3.7.2.1. The order of magnitude of the specific mud layer mass δc in scenario 1 is therefore simply unknown. The value chosen in section 4.4.2.1 is an educated guess, so measurements are required to make a sensible prediction of the specific mud layer mass.

The specific mass in the mud layer near the bottom d_1c_1 in scenario 2 is estimated based on fitting the available concentration data to a distribution as is done in Figure 3-19, but the reliability of this fitted distribution can be questioned. Also it is unknown if the tail can be modelled according to the lognormal distribution. This should be investigated before using the found distribution to model the infill probabilistically.

The trapping efficiency is calculated by Svasek Hydraulics and Royal Haskoning [2008b] with a 2D model based on the hydrodynamic parameters and expected sediment characteristics. It is therefore expected that the mean values are reasonably reliable. Nonetheless validation of these values is recommended. Also more research is required to gain insight in the value of the trapping efficiency along the channel axis and to justify the choice of a distribution.

The reliability of the mud layer threshold cannot be validated either. A sensitivity analysis can however demonstrate if the uncertainty surrounding this threshold is important, i.e. if variation of this parameter significantly affects the infill prediction.

Concluding, the current velocity and channel length are the only parameters of which the distribution can be estimated with reasonable accuracy. The largest problem is caused by the lack of knowledge of the order of magnitude of the specific mud layer mass δc in scenario 1 and the specific mass in the mud layer near the bottom d_1c_1 in scenario 2.

With the currently available data a full probabilistic approach that gives insight in the P10 and P90 values and the relative contribution of each parameter to the uncertainty is therefore not possible. First reliable data has to be available, and then this analysis can be executed and the uncertainties can be quantified. Notwithstanding, this analysis is executed with the distributions as given in Table 5-2 to demonstrate the steps that need to be taken and the possible results that can be obtained if proper data is collected in a next project phase.

5.4.2 Schematization of the correlations

Dependencies between parameters in time and in space need to be modelled; otherwise the uncertainties will be under- or overestimated. The influence of correlated parameters on the outcome is schematically depicted in Figure 5-3. The graphs in Figure 5-3 are schematized probability density functions. First a value is drawn from distribution X and depending on the correlation this influences the value drawn from distribution Y and subsequently the probability density function of variable Z.



Figure 5-3: The influence of correlated parameters on the predicted variable

If data is collected in a next project phase that justifies a probabilistic analysis it is recommended to make a table with all the relevant parameters and systematically check with which other parameters each individual parameter is correlated. For now only a limited amount of correlations will be discussed, which is sufficient to demonstrate what correlation entails. An attempt is made to identify the most important dependencies, but it is very well possible that certain important correlations have been overlooked.

In order to quantify the correlations between parameters, the correlation coefficient $\rho_{x,y}$ is used. It represents the linear relationship between two parameters and is defined as:

$$\rho_{x,y} = \frac{Cov(X,Y)}{\sigma_x \cdot \sigma_y}$$

$$(5.3)$$

$$(5.3)$$

Where $-1 \le \rho_{x,y} \le 1$ and $Cov(X,Y) = \frac{1}{n} \sum_{i=1}^{n} (x_i - \mu_x) (y_i - \mu_y)$. It should be noted that correlations below 0.7 have little influence on the overall outcome

It should be noted that correlations below 0.7 have little influence on the overall outcome [GUCENET, 2007]. Therefore strong correlations should be used between interdependent risks. A correlation of ± 1 means total dependence.

5.4.2.1 Correlation in currents at different locations

There is no clear correlation between the projected current magnitudes used for the different channel sections. The current magnitude at location 1 and used as input parameter for sections A_1 , A_2 and B is much smaller than at location 3, which is used together with location 1 for section C. Moreover, the current direction at location 1 is strongly bi-directional, which is not the case near the bottom at location 3 (see Figure 2-24 and Figure 2-25 in section 2.4.5).

More important is that even if the currents in the locations were correlated, due to the projection perpendicular to the channel section this correlation is lost as will become clear from Figure 5-4.



Figure 5-4: In case the same current direction and magnitude is projected on the entire section, the correlation will be lost due to the projection perpendicular to the channel sections which each have a different orientation

5.4.2.2 Correlation between the sediment concentration and projected current velocity

The amount of sediment in the water column most likely depends on the wave height, wave period and current velocity. As explained before, waves stir up the sediment and currents mix it over the vertical. It is therefore likely that in case of large current velocities more sediment can be found in the water column. On the other hand, if a mud layer is present near the bottom, the currents will not influence the concentration in this layer much. Additionally the currents are projected perpendicular to the channel axis, which seriously weakens a possible correlation. For now it is assumed that there is no correlation between the sediment concentration in the water column and the projected current velocity, but this will need further investigation in a next

project phase.

5.4.2.3 Correlation in sediment concentrations at different locations

A probability distribution is available for the sediment concentrations at 10, 40 and 60 cm above the bottom at three different water depths. The correlation in the concentration between the two locations can be investigated by plotting the concentration data in a certain time interval at one location versus the concentration data in that interval in another location. Time intervals of a month down to 6 hours have been investigated. Smaller time intervals are not considered, since the number of data points becomes too small.

Data plots show that the concentration in location 1 is sometimes higher, sometimes lower and sometimes of the same order of magnitude as in location 2 or 3. Hence it is concluded that there is no correlation between the concentrations at the three locations on a monthly, fortnightly, daily or 6 hourly basis. The found correlation coefficients confirm that there is no relation in concentration between the locations, since they are weak and range from -0.4 to +0.4.

From a physical point of view this can be explained. The three measuring points are too far apart – at least 2.5 km – and not located in a straight line. Different combinations of waves from several directions reach each location. The waves stirring up the sediment in each location are thus more or less uncorrelated, logically leading to no correlation between the concentrations found at each location.

5.4.2.4 Correlation in sediment concentrations over the vertical at one location

The same type of plots has been made to investigate the correlation between the concentrations at different heights at one location as were made to investigate the correlation between the concentrations at the three locations.

In case of scenario 1 near the bottom a permanent mobile mud layer is present. The concentration in the mud layer is not related to the concentrations in the two layers higher in the water column, which contain sediment in suspension, since the sediment regime in the mud layer is different from the sediment regime in the two top layers.

In case of scenario 2 this layer is not always present. In that circumstance a positive correlation between the concentration in layer 1 near the bottom and the two layers above is expected. However if a mud layer is formed during a storm, the concentration profile collapses and the concentration higher in the water column would decrease. So from a physical perspective a linear correlation is unlikely to exist. A correlation can therefore not be modelled easily. Correlation plots of concentrations measured at 10 cm with concentrations measured at 40 or 60 cm show an enormous scatter. The average correlation coefficient for data from 6 hour intervals is 0.11. Remember that correlations below 0.7 barely influence the model result.

Concluding, the correlation coefficient between the sediment layer near the bottom and the two upper layers is small and hence set at zero. If a correlation would exist, it would most likely be a non-linear correlation, which cannot be modelled using a correlation coefficient.

Next, it is expected that the concentrations measured at 40 and 60 cm are strongly and positively correlated. These points are higher up in the water column and influenced by the movements in the water column. Correlation plots give correlation coefficients of 0 to 0.5. The correlation is less strong than might be expected, which can be a result of not all measurements taken at exactly the same time, the time it takes for the sediment to reach the sensor and other measuring errors [Klein, 2009]. Averaging concentrations at 40 and 60 cm height over 6 hours and then plotting them in one graph gives a much stronger correlation and a correlation coefficient of around 0.8.



Figure 5-5: Correlation chart showing a correlation of 0.8 between the concentrations measured at 40 and 60 cm height at location 2

Consequently a correlation coefficient of 0.8 is adopted, which leads to a scatter plot as shown in Figure 5-5. Recall however that the concentrations at 40 and 60 cm height have a limited effect on the total infill quantity, so the adopted correlation coefficient will have a small impact on the probability distribution.

5.4.2.5 Correlation between the sediment concentration in the layer near the bottom and the layer height

From Figure 4-8 and Figure 4-9 and according to Vinzon and Mehta [1998] it is evident that in case a mud layer is present near the bottom the concentration is negatively correlated with the layer thickness. Unfortunately the relation between the concentration near the bottom c_1 and the mud layer height d_1 cannot be properly defined, since it also depends on for example the wave period, wave height and water depth [Vinzon and Mehta, 1998]. So instead a strong negative correlation coefficient of -0.95 is proposed. Applying a coefficient of -1 would result in model errors, since this implies that the parameters are directly related.

For scenario 1 this correlation does not have to be defined, since the mud layer concentration and height are modelled as one parameter, the specific mud layer mass δc .

5.4.2.6 Correlations between time steps

Parameters are strongly correlated in time if small time steps are used. For example, the current velocity does not change from 0.2 m/s to 0 m/s within an hour. The velocity varies in time according to the timescale of the governing processes. This correlation in time will be further explained in section 5.4.3.2.

For the infill computation a pragmatic time step of one week will be adopted. It is assumed that the values of the parameters in week 1 are independent from their values in week 2, so the input parameters are not correlated in time with themselves.

5.4.3 Set-up of the probabilistic model

5.4.3.1 Integration over the channel length

The infill rate per meter channel length s in kg/m/s based on the current velocity, concentration integrated over the vertical and trapping efficiency has to be integrated over the channel length to obtain the infill rate S in kg/s and as given in equation (4.1).

In the deterministic calculation the channel is divided into 1,055 channel segments of 10 m length and for each segment the infill rate per meter channel length s is calculated. It is impractical and too time-consuming to use this many segments for the probabilistic calculation. Consequently one characteristic cross-section per section is modelled and the infill is then calculated by multiplying the infill rate per meter channel length of each cross-section with the corresponding section length. The characteristic cross-section is located in the middle of a section. This schematisation results in a slightly different infill quantity, which has to be corrected. This can be seen in Figure 5-6.



Figure 5-6: Difference in infill rate per meter channel length caused by using less cross-sections to compute the total infill rate along the channel from the start of section A₁ at -5.4 m CD until the end of section C at -16 m CD in case of scenario 1

The difference in infill rate along the channel is caused either due to the use of different data sources for different segments or due to the changing cross-section along the channel axis. Since the channel parameters are not relevant in scenario 1 and not explicitly incorporated in the model in scenario 2 either, the difference in infill quantity between using characteristic 4 cross-sections to calculate the infill and using 1,055 segments is due to the use of different data sources.

For the deterministic approach, near bottom velocities and sediment concentrations of the nearest measuring location as indicated in Figure 2-21 or Figure 3-1 were used for each segment. The same method is now applied to the 4 characteristic channel cross-sections. The data sources used for the probabilistic calculation are given in Table 5-3. The last column states why the data from the specified location is used for the corresponding section.

Table 5-3: Data sources used per section to model the infill with reference to Figure 2-21 or Figure 3-1 for the locations and water depths where measurements were conducted

Channel	Water depth	Near bed current	Sediment	Comment
section	(m CD)	velocity	concentration	
Section A ₁	–5.4 to –5.8	Location 1 (-9 m CD)	Location 1 (-9 m CD)	Closest location
Section A ₂	–5.8 to –6.3	Location 1 (-9 m CD)	Location 1 (-9 m CD)	Closest location
Section B	-6.3 to -8.3	Location 1 (-9 m CD)	Location 1 (-9 m CD)	Closest location
Section C	–8.3 to –16	Average of location 1	Location 2 (-12 m CD)	Average water
		and 3 (-15 m CD)		depth of section

For sections A_1 , A_2 and B there is no difference in infill quantity when computing it with one cross-section per section or one per 10 m channel length. Therefore no model uncertainty has to be introduced for either scenario for these sections.

For section C different data sources are used, so the infill quantity does differ. In scenario 1 this is caused by using the average velocity from location 1 and 3, instead of using the data of location 1 for water depths closest to location 1 and data of location 3 for water depth closest to location 3. This results in a model uncertainty for this section that can be expressed using a model parameter γ . The model parameter can have two possible values; $\gamma = 1.1$ with a chance of occurrence of p = 0.48 and $\gamma = 0.88$ with p = 0.52.

In scenario 2 more different data sources are used for section C. Besides the use of current data from two sources sediment data from all three locations have been used. This means that the infill rate changes more gradually along the channel. Therefore a normal distribution is used for the model parameter with $\mu = 1.06$ and $\sigma = 0.24$ for the suspended sediment infill and $\mu = 0.90$ and $\sigma = 0.13$ for the mud layer infill.

Although it is a long section, only one characteristic cross-section is used to model the infill in section C. Using only one cross-section does not increase the uncertainty significantly, so it is not necessary to use multiple characteristic cross-sections to model this part of the channel. Only when the channel characteristics and especially the channel overdepth would be included in the model via for example the trapping efficiency, the model uncertainty due to the integration over the length may increase and using more cross-sections for section C becomes necessary.

5.4.3.2 Integration over time

After the integration of the infill rate per meter channel length s in kg/m/s over the channel length, the infill rate S in kg/s and as given in equation (4.1) is obtained. To estimate the distribution of the yearly infill integration over one year is required and the timescales of the relevant processes have to be considered.

The probability distribution of the input parameters, for example the concentration data, represents all possible concentrations from that year. However the concentration at a certain

point in time is not a random number, it is correlated the concentration earlier in time. The concentration varies according to the timescales of the processes causing the sediment to be in the water column and the interaction with the sediment. It is thus necessary to introduce the timescales of the governing processes if the yearly infill is investigated. The time step is chosen in such a way that the realizations from different steps can be assumed independent, and this is dependent on the characteristic timescale with which the infill processes and thus the input parameters vary in time.

To choose this appropriate time step the temporal variation in the physical processes needs to be considered. A representative time step results in the consecutive time steps being independent, i.e. the outcome of the first draw at $t = t_i$ does not influence the outcome of the next draw at $t = t_{i+1}$. In that respect a large time step should be chosen.

However, a too large time step causes overestimation of the variance and standard deviation of the yearly infill quantity. The mean infill value does not change if the number of time steps is increased, but the uncertainty decreases. The standard deviation of the yearly infill distribution decreases with a factor \sqrt{n} when the number of time steps *n* increases.

Mathematically this can be expressed as follows. Given a random variable X with an assigned distribution with a mean μ and standard deviation σ , the average \overline{X} of the sum of the sequence $\sum_{n=1}^{i=1} X_i$, so of a certain number of time steps, is given by:

$$\mu_{\bar{X}} = \mu_X \tag{5.4}$$

The standard deviation σ of the average \overline{X} is:

$$\sigma_{\bar{X}} = \frac{\sigma_{X}}{\sqrt{n}} \tag{5.5}$$

Appendix E shows the mathematical derivation of equations (5.4) and (5.5).

Ideally, the choice of the length of a representative time step should be based on an analysis of the correlation and the time scales of the relevant physical processes. Autocorrelation functions can be used to determine this time step. These functions analyse time series of variables and compare the values at time $t = t_i$ with the value at $t = t_{i+1}$. The time step is increased until the outcome at $t = t_i$ does not show any relation anymore with the value at $t = t_{i+1}$ [Van Gelder, 2000]. For this minimum time step the values in two consecutive time steps are independent, so this is a best guess for the characteristic timescale and consequently the best choice for a representative time step.

For this thesis a pragmatic time step of one week is adopted, its influence on the probability distribution will be discussed later in sections 5.5.1.4 and 5.5.2.4 respectively for each scenario. For now it is assumed that the input parameters vary on a weekly basis, so the number of time steps in one year is 52. This is a relatively large time step, since wave events last for a few days at most. Fluctuations in the currents at the project site however occur on a time scale that is significantly larger than the tidal time scale. Current reversals generally take a few days as discussed in section 2.4.5.2 [based on Figure 7.16, Svasek Hydraulics and Royal Haskoning, 2007a]. Decreasing the time step to every day or every 3 days might therefore be more realistic. On the other hand the uncertainty may become unrealistically small when increasing the number of time steps, so 52 time steps per year are adopted in the probabilistic calculation and can be seen as an upper limit for uncorrelated sampling.

A recommendation would be to analyse the time series of the current velocity, wave climate and sediment concentrations with an autocorrelation function to determine the characteristic

timescale of the infill process and to improve the choice of a representative time step. To show the influence of a certain timescale on the infill quantity distribution, a sensitivity analysis will be conducted. In addition to using a time step of one week, the model will be run with a time step of 1 month and with a time step of 3 days as well.

Note that this is not an issue for the deterministic calculation since this calculation does not provide insight in the uncertainties and spread around the mean. Adopting a time step only influences the spread around the mean and not the mean value itself. To obtain the amount of sediment in the channel M the deterministic infill rate S was simply multiplied by the number of seconds in one year.

5.4.3.3 Choice of probabilistic approach

A Monte Carlo simulation is chosen because it is easily applicable to the infill problem and it is a full probabilistic approach, which takes the parameter distributions into account as was the goal of this analysis. A value for each parameter is drawn from its assigned distribution and used to calculate the infill. This is repeated many times to obtain enough possible outcomes to generate a probability distribution.

5.4.3.4 Generation of the probability distributions of the infill rate and infill quantity

The model is set up in Excel. The Monte Carlo simulation is run with the software package Crystal Ball. The probability distribution of the infill rate and the probability distribution of the yearly infill (52 time steps) are generated.

To compute the probability distribution of the infill rate S in kg/s the model is run 1 million times (without integration over time). From the resulting 1 million different realizations of the channel infill rate the probability distribution is constructed. A distribution is fitted to the data to describe the found infill rate distribution analytically. This number of model runs is more than enough to minimize the model uncertainty due to the number of realizations and poses no problems for the used programs. Running the model and generating this probability distribution takes a couple of minutes.

The yearly infill quantity M in Mton is computed based on the infill rate S in kg/s times the number of seconds in one year and introducing the time step as explained in section 5.4.3.2. Therefore 52 realizations of the infill quantity are randomly generated by running the model 52 times. Each of these realizations is representative for one time step, which is a pragmatic choice of one week. So by averaging the 52 infill quantities, one realization for a yearly infill quantity M in Mton is obtained. This is repeated 10,000 times for each scenario. From these 10,000 realizations of the infill quantity a probability distribution is constructed and a distribution is fitted.

Using more than 10,000 realizations of the yearly infill distribution would result in a lower statistical uncertainty, but this is not feasible with regard to the programs used to process the results. The model can be run quickly, but the averaging of 52 realizations 10,000 times for 2 scenarios to construct the probability distribution costs a lot of extra time. However this number of realizations is already more than sufficient to fit a yearly infill distribution to as will be shown in sections 5.5.1.3 and 5.5.2.3. In any case the statistical uncertainty will not be of importance in comparison with the other uncertainties.

5.5 Probabilistic infill calculation

The probability distribution of the infill rate *S* in kg/s and of the yearly infill quantity *M* in Mton (with a time step of one week) are presented for each scenario. Due to the large uncertainty in the input parameters, and especially the lack of knowledge of the order of magnitude of the specific mud layer mass δc in scenario 1 and the specific mass of the layer near the bottom d_1c_1 in scenario 2, it is too soon to present P10 and P90 values and the relative contribution of each parameter to the uncertainty. This probabilistic analysis is executed to demonstrate how it can be

executed if proper data is collected in a next project phase, which was also explained in section 5.4.1. Then also a proper quantitative uncertainty analysis can be provided.

Important to keep in mind is that a yearly infill distribution does not provide insight in the infill quantities in for example a certain month or season. It is reasonable to assume that during the stormy season more mud flows into the channel than during the calm season as also concluded by Svasek Hydraulics and Royal Haskoning [2008b]. Current velocities and wave heights are after all highest in July and August. In order to investigate the seasonal or monthly infill quantities the data series will have to be split into seasonal or monthly sets. Note that the set-up of the model remains the same; only the parameters, their distributions and the number of time steps need to be adjusted. This study will be limited to the yearly infill distribution.

5.5.1 Probability distribution of the yearly infill rate in case of scenario 1

5.5.1.1 Computed probability distribution of the infill rate S

The probability distribution of the infill rate S in kg/s of scenario 1 is presented in Figure 5-7. In essence this calculation is partially probabilistic. A reliable distribution for the current velocity is used and the distribution and most likely value for the specific mud layer mass are estimated.



Figure 5-7: Computed probability distribution of the mud infill rate of the OKLNG approach channel for scenario 1

The average or mean and P50 of the infill rates are given in the first two columns of Table 5-4. By deterministically converting these infill rates to a yearly infill quantity, so by multiplying the infill rates by the number of seconds in one year, an estimate of the yearly infill quantity is obtained. The results are presented in the last two columns of Table 5-4.

The P50 of the probabilistically determined infill rate converted to a yearly infill quantity is 75 Mton/yr. The P50 is the value which is exceeded 50% of the time, which is not necessarily the same as the average or mean of all values. The mean yearly infill quantity based on the infill rate distribution shown in Figure 5-7 is much higher than 74 Mton. This large difference with the P50 is due to the heavy tail of the distribution.

Channel part	Mean	P50	Mean	Mean	P50
	infill μ	(kg/s)	infill µ	μ (Mton/	(Mton/
	(kg/s)		(kg/m/s)	year)	year)
Entire channel	2733	2389	0.26	86	75
Section A ₁	92	0	0.14	3	0
Section A ₂	253	201	0.25	8	7
Section B	778	647	0.30	25	20
Section C	1611	1275	0.26	51	40

Table 5-4: Characteristic infill values for scenario 1 based on the infill rate S

Figure 5-7 and Table 5-4 clearly show the value of a probabilistic calculation as opposed to a deterministic calculation. The chances of a 'low' infill rate are much higher than the chances of a 'high' infill rate; the probability distribution is not symmetrical. But although the chance of a 'high' infill rate – say larger than 6,000 kg/s – is relatively small the infill rate is so large that the tail of the distribution greatly influences the mean value. A deterministic calculation would not have given this insight.

The probability distribution of the infill rate as depicted in Figure 5-7 fits a lognormal distribution with a mean μ of 2,733 kg/s and a standard deviation σ of 1,830 kg/s. A gamma distribution results in a slightly better fit, but the probability distribution of the infill quantity fits a lognormal distribution best, so in order to be able to compare the distributions a lognormal fit is adopted for the infill rate as well.

The individual sections cannot be fitted properly to a distribution, since the chance of a zero infill in one time step is considerable for each section. As an example the probability distribution of the infill rate for section A_2 is shown below in Figure 5-8. The infill rate of each section is independent, so the probability distribution of the infill rate of the entire channel does not show this extreme peak. Recall that if the infill velocity for section A_2 is zero because the current is directed along the axis of this channel section, the infill velocity along section C is not zero because that section is oriented differently. This was also demonstrated in Figure 5-4 and explained in section 5.4.2.2.



Figure 5-8: Computed probability distribution of the mud infill rate of section A_2 the OKLNG approach channel for scenario 1

5.5.1.2 Infill rate per section

The average infill rate per meter channel has also been investigated. Except for section A_1 , which is partly sheltered by a breakwater, the average infill per meter channel length is around 0.26 kg/m/s. This value does not vary much along the channel, since the channel cross-section does not influence the infill. The other parameters, the current velocity and sediment concentration, do not vary much between a water depth of -5.4 and -16 m CD either. This means that the channel fills up with the almost same rate along the channel length.

In this scenario the sediment is poorly flocculated and it show viscous behaviour. It is therefore expected that the mud layer will distribute itself more or less evenly over the channel.

The channel cross-section does change along the channel axis seawards. This means that section C is filled up quicker than section A. As can be seen in Figure 5-9, once two-thirds of the channel volume is filled, the channel is filled up until a depth of about -8.3 m CD. Section C lies below that water depth, so instead of an infill rate of 2.7 ton/s, the infill rate decreases to 1.1 ton/s. This feedback mechanism is not included in the model, which means that the filling process thus takes more time than this model suggests.

However the set depth for navigation is -15.5 m CD. As soon as this depth is reached, about 10% of the channel volume is filled up. The infill rate will not have decreased significantly by then, so the computed rate does give a good impression of how quickly action needs to be taken to guarantee the accessibility of the channel and LNG terminal.



Figure 5-9: Volume of the channel above a certain water depth

5.5.1.3 Computed probability distribution of the yearly mud infill quantity

The computed probability distribution of the yearly infill quantity for scenario 1 is shown in Figure 5-10. A distribution is fitted based on the realizations generated by the model. A lognormal distribution with a mean μ of 86 Mton/yr and a standard deviation σ of 7.6 Mton/yr is the best fit. The goodness of fit of the distribution with the data series was tested with the χ -square, Kolmogorov-Smirnov and Anderson-Darling criteria. All three tests showed the lognormal distribution to be the best fit for the data series.

Note however that this yearly infill quantity is not realistic, since the channel would be full within days. The channel cannot accommodate more than 23 Mton of sediment when assuming a mud density of 1,370 kg/m³. Also the infill rate along the channel decreases as it fills up, overestimating these quantities as well as pointed out in section 5.5.1.2. It is therefore better to present the result as an infill rate per week. This infill rate – 1.66 Mton/week – gives a good



impression of how quickly maintenance is required to guarantee accessibility of the channel and LNG terminal.

Figure 5-10: Computed probability distribution of the yearly mud infill quantity of the OKLNG approach channel for scenario 1 while applying a time step of one week

5.5.1.4 Influence of the characteristic timescale on the yearly mud infill quantity probability distribution

As announced in section 5.4.3.2 a sensitivity analysis is conducted to demonstrate the influence of the characteristic timescale of the infill processes on the distribution of the yearly infill quantity. A probability distribution of the yearly infill quantity based on a time step of one month, one week and 3 days is generated for that purpose. The result is presented in Figure 5-11. A timescale of one month is physically not realistic, but this shows the influence of a larger characteristic timescale on the infill prediction. This figure²¹ clearly shows that the mean value does not change when the timescale is varied, but that the spread around the mean increases as the number of time steps decreases. This shows the importance of properly analyzing the timescales of the infill processes and subsequently choosing a representative time step as was argued in section 5.4.3.2.

²¹ The same method as explained in section 5.4.3.4 is applied, only one realization of the yearly infill quantity M is based on the average of a different number of time steps, i.e. 12, 52 or 122. The number of realizations of the yearly infill quantity generated is still 10,000 and based on those realizations the distribution as shown in Figure 5-11 is chosen.



Figure 5-11: Probability distributions of the the yearly infill quantity computed based on different characteristic timescales

Furthermore Figure 5-11 is in accordance with the theory on probability as explained in Appendix E and equations (5.4) and (5.5). The expected value of the average of a random variable is the same as the expected value of the random variable itself and the standard deviation decreases with the square root of the number of time steps, \sqrt{n} . This is demonstrated in Table 5-5.

Table 5-5: Comparison of the parameter	rs of the lognormal probability distribution
generated with different time steps	

Time step	n	Mean infill μ (Mton)	Standard deviation σ (Mton)	<i>Computed</i> <i>ratio of</i> σ (-)	<i>Theoretical</i> <i>ratio</i> (\sqrt{n}) <i>of</i> σ (-)	<i>Difference in ratio (%)</i>
One year	1	86.4	57.7	-	-	-
One month	12	85.8	15.7	3.7	3.5	5.7
One week	52	86.0	7.6	7.6	7.2	6.0
3 days	122	86.0	5.0	11.5	11.0	4.3

Additionally this table shows that the mean value of the distributions is not the same, although the differences are less than 1%.²² The reason for this difference and that the computed ratio of the standard deviation is not equal to the theoretically calculated ratio is due to a statistical uncertainty. This parameter uncertainty arises from fitting a lognormal distribution to a limited amount of data points; in this case 10,000 data points were used. This uncertainty can be decreased by increasing the number of model runs. If the number of model runs is infinite, the mean values would be the same and the theoretical ratio between the standard deviations would be reached.

5.5.1.5 Contribution of the parameters to the uncertainty

Based on the distribution of each parameter, it is investigated which parameter contributes most to the variance of the probability distribution of the infill rate in Figure 5-14. This analysis is performed with Crystal Ball.

Based on this analysis the current velocities are by far most influential. The uncertainty in the current magnitude is due to the natural variation and cannot be decreased. It is expected that the Sontek down looking data series will not result in a different distribution than the currently used AWAC data series. However it is recommended to check this assumption in a next project phase.

²² Largest percentual difference = $(86.4 - 85.8)/86.0 \cdot 100\% = 0.7\%$

The specific mud layer mass and the current velocity for section B each contribute around 15% to the total variance. The other parameters, the current velocity for section A_1 and A_2 and the model parameter for section C hardly contribute to the uncertainty. In case the assumed distributions were reliable, the current velocity is thus the most important parameter for the infill prediction.

The specific mass of the mud layer is however more uncertain than appears from its contribution to the variance. Based on the assigned distribution the contribution to the variance might be limited, but the problem with this parameter was that a distribution could not be properly assigned. As explained before the used value of 4 kg/m^2 is an educated guess and the applied distribution is an estimate. Measurements are required to reduce this uncertainty.

To show the influence of this parameter on the infill prediction, the Monte Carlo simulation for the infill rate S is repeated with different values for the specific mud layer mass. Each time the lower limit of the triangular distribution is half the most likely value and the upper limit twice the most likely value. The result is presented in Figure 5-12. It shows the cumulative distributions of the infill rates depending on the specific mud layer mass.



Figure 5-12: The value chosen as most likely specific mud layer mass influences the infill rate of the OKLNG approach channel linearly

This graph clearly shows that the infill rate and thus also the infill quantity strongly depends on the estimate for the specific mass of the mud layer. If it is as little as $0.1 \text{ m} \cdot 20 \text{ kg/m}^2 = 2 \text{ kg/m}^2$ as Svasek Hydraulics and Royal Haskoning [2008b] estimated, the mean infill rate is 1.4 ton/s or 0.8 Mton/week. If it is the 4 kg/m² as estimated in 4.4.2.1, the mean infill rate is 2.8 ton/s or 1.7 Mton/week and if it is $0.06 \text{ m} \cdot 100 \text{ kg/m}^2 = 6 \text{ kg/m}^2$ as might be concluded from the measured concentrations at Lekki, the mean infill rate is 4.2 ton/s or 2.6 Mton/week. The difference is very large. Every change in estimated specific mud layer mass with 1 kg/m² corresponds to a difference in infill rate of 0.86 Mton/week. This means that the largest uncertainty for the scenario with not to poorly flocculated sediment is the value of the average infill quantity. This is due to the lack of knowledge of the specific mass of the mud layer.

More importantly this analysis shows that even when wildly varying the estimate for the specific mud layer mass, the infill rate remains very high is comparison with the channel volume. That means that all discussed uncertainties do not influence the main conclusion that the channel fills up very fast and in case no measures are taken the entire channel is full with mud within months

under all circumstances. On the availability of the channel for vessels no conclusions can be drawn based on only the infill rate, since this also depends on the density and other characteristics of the material in the channel, as was also mentioned in sections 4.2 and 4.3.1. The order of magnitude of the infill is so large that obtaining more certainty on the exact infill quantity and its P10 and P90 value is not a first priority. In case of scenario 1 it is most important to know that the sediment is indeed not to poorly flocculated, which leads to low density mud being present in the channel.

5.5.2 Probability distribution of the yearly infill rate in case of scenario 2

5.5.2.1 Computed probability distribution of the infill rate S

The computed probability distribution of the mud infill rate per time step in case of scenario 2 is presented in Figure 5-13. This calculation is again partially probabilistic, but most of the input parameters are estimated. Only for the current velocity a reliable distribution is available. For the channel length also an accurate value is used.



Figure 5-13: Computed probability distribution of the mud infill rate of the OKLNG approach channel per time step for scenario 2

A similar table for this scenario as for scenario 1 is also presented with characteristic infill values based on the infill rate.

Table 5-6: Characteristic infill values	s for scenario 2 based on the infill rate S
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Channel part	Mean	P50	Mean	Mean	P50
	infill μ	(kg/s)	infill μ	μ (Mton/	(Mton/
	(kg/s)		(kg/m/s)	year)	year)
Entire channel	215	82	0.020	6.8	2.6
Section A ₁	9	0	0.014	0.3	0.0
Section A ₂	26	13	0.026	0.8	0.4
Section B	80	40	0.031	2.5	1.3
Section C	99	6	0.016	3.1	0.2

The average or mean infill rate for scenario 2 is 215 kg/s, which is 6.8 Mton if it is converted to a yearly infill rate. The deterministic infill quantity is lower, namely 4.6 Mton/yr. However the deterministic calculation is based on many additional and crude assumptions, so a proper comparison between the two predictions is difficult to make.

The average probabilistically computed infill quantity is just as with scenario 1 higher than the P50 value due to the heavy tail of the computed distribution. For this scenario the difference between the expected infill rate and P50 infill rate is very large. The P50 is the infill rate that has a 50% chance of being exceeded. This large difference is due to the amount of time each infill mechanism occurs and their relative contribution to the infill quantity. The strong asymmetry of the computed infill rate distribution shows that the majority of the time infill is due to suspended sediment infill, but that contributes relatively little to the total infill and hence the low P50 value. The mud layer infill does not occur that often, but when it occurs a very large amount of sediment is deposited in the channel. This causes the average or mean infill quantity to be much higher than the P50. This again shows the added value of a probabilistic approach, since a deterministic approach could not have lead to this insight.

That each infill mechanism results in an infill quantity of a different order of magnitude also becomes clear after fitting the realizations of the infill rate as depicted in Figure 5-13 to a distribution. A lognormal distribution seems to be the best fit, but the goodness-of-fit is limited. Especially the extreme values are not represented well by any distribution. The specific mud layer threshold divides the realizations in two categories: one due to mud layer infill and one due to suspended sediment infill. Representing all realizations by one distribution is then not allowed, since the computed data series is not homogeneous, i.e. the values do not originate from the same source or are not a result of the same physical process [Van Gelder, 2000]. For example wave statistics are always split into statistics of wind, swell and low-frequency waves for this reason. The infill due to the suspended sediment infill and due to the mud layer should also be fit to a distribution separately.

5.5.2.2 Infill rate per section

Section A_2 and B have the largest infill rates. These sections are not sheltered by a breakwater and have a high trapping efficiency as opposed to section C. Due to their location between certain water depths and their length, the volume of the sections is not the same either. The infill time per section will therefore be investigated. Table 5-7 gives the infill time per channel section in case the infill rate is constant in time. This is of course not the case, but this simplification makes it possible to compare the infill times of the different sections.

Section	Infill rate (kg/m/s)	Section length (m)	Volume (Mm ³)	Infill time ²³ (years)
Section A ₁	0.014	658	6.5	24.6
Section A ₂	0.026	1,000	8.7	11.6
Section B	0.031	2,618	15.5	6.8
Section C	0.016	6,2	8.6	3.0

Table 5-7	: Infill	time	per	channel	section
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Table 5-7 shows that section C, although having small infill rates, fills up the fastest due to its small volume in comparison with its length. This difference in infill rate along the channel axis should be looked into more closely in a next project stage.

²³ A mud density of 1,100 kg/m³ in the channel is assumed. The infill time is computed as follows: $t_{infill} = V_{section}/(s_{section} \cdot L_{section}/\rho_{mud})$
5.5.2.3 Computed probability distribution of the yearly mud infill quantity

Figure 5-14 depicts the probability distribution of the yearly infill rate for scenario 2. Note again that the infill quantities in Figure 5-14 are quite large. The mean yearly infill quantity based on this graph is 6.8 Mton and the P50 is 5.9 Mton.

Again a distribution is fitted to the 10,000 realizations of the yearly mud infill quantity. Based on the same goodness-of-fit criteria as for scenario 1 in section 5.5.1.3 a lognormal distribution is for this scenario also the best fit. However it is clear from Figure 5-14 that the fit is quite poor. The explanation as already given in section 5.5.2.1 is that the infill originates from two different infill mechanisms, so the data series is inhomogeneous and can therefore not be represented by one probability distribution.



Figure 5-14: Computed probability distribution of the yearly mud infill quantity of the OKLNG approach channel for scenario 2 while applying a time step of one week

5.5.2.4 Influence of the characteristic timescale on the yearly mud infill quantity probability distribution

Again the influence of the characteristic timescale on the predicted yearly mud infill quantity is investigated. Unfortunately the results for this scenario cannot be properly represented by an analytical distribution, so comparing the standard deviation is not possible. Instead the mean, P10, P50 and P90 of the generated realizations of the infill quantity is given in Table 5-8. Again the outcome based on a time step of one month, one week and 3 days is investigated. The mean value is independent of the number of time steps and the spread around the mean decreases if the time scale increases, just as expected.

Table 5-8: Comparison of the mean and characteristic percentiles of the computed
distribution generated with different time steps

Time step	п	Mean	P50	P10	P90
		μ (Mton)	(Mton)	(Mton)	(Mton)
One month	12	6.7	5.1	2.7	11.2
One week	52	6.8	5.9	3.9	10.2
3 days	122	6.7	6.2	4.5	9.4

5.5.2.5 Contribution of the parameters to the uncertainty

Since the values and distributions of the input parameters for scenario 2 are assumptions, proper data are required first before a reliable quantitative uncertainty analysis can be conducted. A sensitivity analysis of the probabilistic model will be executed instead.

The influence of the specific mud layer mass on the infill prediction is investigated by varying the drag coefficient. Its deterministic value is 0.0004 [Delft Hydraulics, 1974]. Figure 5-15 shows the influence of the drag coefficient on the mean and P50 of the yearly infill quantity calculated based on the infill rate *S* multiplied with the number of seconds in one year. Note that the threshold varies along the channel axis, since it depends on the channel slope. The specific mud layer mass corresponding to the drag coefficient is therefore an indication.



Figure 5-15: Influence of the drag coefficient on the yearly infill quantity

Decreasing the drag coefficient to as little as 0.0001 does not influence the infill quantity. The coefficient can increase a factor 2 before the infill rate is influenced. Doubling the drag coefficient leads to a specific mud layer mass of around 0.15 kg/m². Assuming a mud layer height of 0.10 m this mud layer mass corresponds to a concentration of 15 kg/m³. Svasek Hydraulics and Royal Haskoning [2008b] assume that a 0.10 m thick mud layer with a concentration of 20 kg/m³ will be trapped in the channel, which means that the criterion for the occurrence of a mud layer should not lie much higher than 0.15 kg/m².

If the drag coefficient is increased by a factor 10 the mean infill quantity decreases with 9%. When the drag coefficient is increased by a factor 100, the specific mud layer mass criterion is about 4 kg/m², which corresponds for example to a mud layer of 0.10 m with a concentration of

40 kg/m³ or a mud layer of 0.05 m with a concentration of 80 kg/m³. These layers will almost certainly be retained in the channel, especially considering the low current velocities in the area. The yearly infill quantity with this criterion becomes 5.9 Mton, so increasing the specific mud layer mass criterion with a factor 10^2 only decreases the predicted infill quantity with 13%. The infill of 5.9 Mton is also still a considerable infill quantity for this channel.

This all makes the mud layer criterion quite robust. Apparently most of the concentration data of the layer near the bottom is well below the threshold criterion and causes suspended sediment infill. The more extreme concentrations that cause large infill quantities are well above the criterion. This suggests that where the exact boundary between suspended sediment infill and mud layer infill is placed does not influence the infill quantity to a large extent.

The trapping efficiency p is studied next. The trapping efficiency is a model uncertainty. Including a proper method to compute trapping efficiencies can decrease this uncertainty. To study the effect of this parameter, one additional Monte Carlo analysis is performed with all trapping efficiencies increased with 5% and one with all trapping efficiencies decreased by 5%. Since this variation in trapping efficiency barely seems to have an effect on the infill quantity as can be seen in Table 5-9, the Monte Carlo analysis was done again, but now with a zero trapping efficiency and a 100% trapping efficiency. A zero trapping efficiency means that no infill due to suspended sediment takes place and a 100% trapping efficiency means that all sediment in suspension is trapped in the channel. The effect on the mean yearly infill quantity is presented in Table 5-9.

Table 5-9: Influence on the mean infill rate when changing the trapping efficiencies of all sections with \pm 5%

Channel part	Difference in mean infill	Difference inDifference inmean infillmean infill		Difference in mean infill for
	for p –5%	for p +5%	for p = 0%	p = 100%
Entire channel	-1%	0%	-2%	9%
Section A ₁	-1%	0%	0%	0%
Section A ₂	0%	0%	-3%	2%
Section B	0%	0%	-2%	1%
Section C	-3%	0%	-1%	19%

Based on Table 5-9 it can be concluded that the trapping efficiency generally does not influence the mud infill prediction much. Only when applying 100% trapping efficiency the infill quantity in section C is significantly influenced. This is quite a large section and the trapping efficiency of this section is much lower than that of the other sections (12% on average in comparison to 55% for sections A_2 and B). Surprisingly, this analysis shows that a reliable estimate of the trapping efficiency is not of great importance for a reliable mud infill estimate.

This also implies that suspended sediment infill is only a small part of the total infill. When running the model again with zero suspended sediment infill (essentially with p = 0), the average mud infill quantity is 6.7 Mton, which is only 2% less than if suspended sediment infill is taken into account. The suspended sediment infill calculated with the probabilistic model and the parameters as stated in Table 5-2 is only 0.12 Mton/yr. This model is thus set up in a way that almost all sediment infill is due to mud layer infill. The suspended sediment infill can almost be neglected, even when all suspended sediment is trapped; the average infill due to this infill mechanism is 0.70 Mton/yr. This makes the validity of the concentration statistics an important question. The infill is dictated by the tail of the probability distribution of the near bottom concentration. The validity of the model should also be investigated.

Finally the uncertainty in the specific mass of the layer near the bottom is investigated. Both parameters, the layer thickness d_1 and the concentration c_1 are highly uncertain. The nature of the uncertainty is epistemic.

The fitted distributions for the concentration at 10 cm height return concentrations in the range that was measured at Lekki. Furthermore there is no way of knowing whether the distribution is reliable. Also the frequency of occurrence of these high concentrations is unknown and may very well be totally different. Varying the distribution of the sediment concentration is quite cumbersome, so this will not be done for this sensitivity analysis.

To still get an impression of the influence of the specific mud layer concentration on the predicted yearly infill quantity, the minimum layer height d_1 will be varied. This parameter directly influences the specific mass of the mud layer d_1c_1 . The minimum layer height is now set at 0.05 m based on Figure 4-8. In case wave action is limited Figure 4-9 shows that this might also be 0.02 m. To show the influence on the outcome if the mud layer mass is underestimated, the model is also run once with a minimum layer height of 0.08 m.

The minimum layer height of 0.02 m leads to a yearly average infill of 5.3 Mton, so a decrease in infill of 23%. Increasing the minimum layer height to 0.08 m causes an increase in infill of 24% to 8.4 Mton/yr. This shows that the minimum layer height introduces a considerable uncertainty and that a probabilistic analysis is not useful when the value of an input parameter and its distribution cannot be estimated with reasonable accuracy.

5.5.2.6 Conclusion of the sensitivity analysis of the probabilistic model

This uncertainty analysis results in some unexpected conclusions. First the uncertainty in the value of the specific mud layer mass threshold and the trapping efficiency in case of suspended sediment infill does not appear to introduce significant uncertainties in the yearly infill quantity. In fact, this model is constructed in a way that almost all infill is due to mud layer infill, which means that the distribution of the specific mud layer mass dictates the infill prediction. This is a finding that needs to be checked if the model will be used. Therefore validation of the model is required. The predictive capacity of the model will also be discussed in section 6.2.2.2.

The uncertainty in the outcome is thus first and foremost due to the uncertainty in the specific mass of the mud layer d_1c_1 near the bottom. The relative importance of the trapping efficiency and thus the suspended sediment infill will only increase if the fitted probability distributions for the concentrations near the bottom are significantly overestimated or the specific mud layer threshold is significantly underestimated. If that is the case, the suspended sediment infill mechanism becomes of more importance in comparison with the mud layer infill.

5.6 Conclusion on the expected yearly infill quantity and uncertainties

5.6.1 Key uncertainties

The objective of the uncertainty analysis was to identify and characterise the main uncertainties in such a way that a mud infill prediction could be expressed in probabilistic terms, i.e. so the probability of exceedance of different infill quantities could be defined. Therefore a simplified model is used to predict the mud infill, which provides proper insight into the uncertainties of the prediction although it does not represent all relevant physical processes properly.

As stated in section 5.1 a probabilistic approach requires that a probability distribution can be accurately assigned to every parameter. This is not possible for every input parameter; the distribution of the sediment concentration near the bottom could not be reliably estimated due to lack of knowledge. The methodology of a probabilistic approach was explained in this chapter, but the uncertainties can only be quantified and a P10 and P90 value can only be sensibly predicted after more data on this parameter is collected.

In this chapter it was found that the sediment concentration near the bottom introduces the largest uncertainty for each infill scenario. Notwithstanding the most important uncertainty regarding the mud infill prediction in general is the sediment state in the water column, i.e. whether or not the sediment is flocculated. This was explained in section 3.8.2.

5.6.2 Conclusion of the infill modelling for scenario 1

Due to the lack of knowledge on the specific mud layer mass, it was decided to compute the infill quantities probabilistically for specific mud layer mass values of 2, 4 and 6 kg/m² and applying the estimated triangular distribution as described in section 5.5.1.5. Based on this approach the mean weekly mud infill for scenario 2 is estimated as presented in Table 5-10.

Table 5-10: Estimate of the mean weekly infill depending on the estimate for the specific mud layer mass (see section 5.5.1.5)

Specific mud layer mass (kg/m²)	Mean mud infill (Mton/week)
2	0.8
4	1.7
6	2.6

Note that the channel has a volume of $39 \cdot 10^6 \text{ m}^3$, which means that it can accommodate 5.2 Mton of sediment when the mud has a density of 1,100 kg/m³, which is the currently set nautical bottom for OKLNG. By adopting the average bulk density of the bottom of 1,370 kg/m³, the entire channel can accommodate 23 Mton of which 2.3 Mton is stored below the navigation depth of -15.5 m CD.

Although it has not been possible to complete the full probabilistic analysis of the infill, the uncertainty analysis demonstrates that in case of scenario 1 the channel will most likely be filled up with mud with a very low density in the order of weeks. This conclusion is not influenced by any of the uncertainties in the input parameters. The order of magnitude of the infill is so large for this scenario that it should be assumed that there is always mud with a low density in the channel. If the sediment is found to be not to poorly flocculated, it may therefore be more practically useful to focus on non-conventional dredging techniques and methods to keep the channel navigable. This will be further discussed in section 6.2.2.1.

5.6.3 Conclusion of the infill modelling for scenario 2

Based on the trapping efficiencies calculated with the FINEL 2D model by Svasek Hydraulics and Royal Haskoning [2008b], the fitted distributions for the concentration near the bottom from Figure 3-19 and the criterion as derived in section 4.2.1 and the probabilistic analysis, the applied schematization results in a mean yearly mud infill quantity of 6.8 Mton. This corresponds to an infill rate of 0.13 Mton/week.

Note that this number should not be used to base a maintenance strategy on; it provides an order of magnitude of the infill. First the quality of the sediment data has to be improved and the model needs to be validated. Then a probabilistic analysis as demonstrated in this chapter can be executed and a proper prediction of the mean infill can be made. Also sensible P10 and P90 values can then be given.

An infill in the order of several Mton/year means that the channel would require dredging every couple of months to keep it open for navigation. The characteristics of the mud after entering the channel such as the strength development in time together with dredging methods that are suitable for removing large quantities of mud from a channel should be investigated to decide how to deal best with these high infill rates

The uncertainty analysis also shows that the model presented in section 4.2.2 is formulated in a way that almost all infill is due to mud layer infill, so the distribution of the specific mud layer mass (the sediment concentration near the bottom times the thickness of the schematized layer) dictates the infill prediction. To check the reliability of the prediction, validation of the model is required. The uncertainty in the outcome is first and foremost due to the uncertainty in the specific mass of the mud layer near the bottom.

5.6.4 Conclusion on additional issues that came up during the modelling

Additional issues which came up in this chapter are the decrease in infill rate as the channel fills up, the difference in infill rate along the channel length and the applicability of a probabilistic analysis to the mud infill prediction of the OKLNG channel. These will be discussed briefly in the order just mentioned.

5.6.4.1 Consequence for the infill prediction of the decrease in infill rate as the channel fills up

To compute the yearly infill quantities it was assumed that the infill rate along the channel axis remained constant. Of course this is unrealistic, since the infill rate along the channel decreases as it fills up. Infill does not take place along parts of the channel which lie deeper than the level until which the channel is filled, as also explained in Figure 5-16, and the infill rate for suspended sediment infill decreases as the channel overdepth decreases.



Figure 5-16: Infill along the channel axis as the channel fills up

Note however that the set depth for navigation is -15.5 m CD. Only a mud layer of 0.5 m thick has to be in the channel before this depth is reached and maintenance measurements are required. The infill rate has not decreased significantly by then, so the computed rate does give a good impression of how quickly action needs to be taken to guarantee the accessibility of the channel and LNG terminal.

5.6.4.2 Difference in infill time per channel section

For scenario 2 the difference in infill rate along the channel length might lead to the situation that the set depth for navigation is reached sooner in one channel part than in another. This should be looked into more closely in a next project stage. For scenario 1 this is not expected to be a problem. Due to the viscous behaviour of the mud it is therefore expected that the mud layer will distribute itself more or less evenly over the channel.

5.6.4.3 Applicability of a probabilistic analysis to the mud infill prediction of the OKLNG channel

Due to the uncertainty in the data a full probabilistic analysis resulting in quantified uncertainties was not possible yet. However applying a probabilistic analysis in addition to the deterministic calculations and sensitivity analysis is valuable as is demonstrated in this chapter.

The probability distributions in Figure 5-7, Figure 5-13 and Figure 5-14 are strongly asymmetrical. The chance of a 'low' infill rate or quantity is relatively large, but this part of the distribution results in a relatively small contribution to the average infill rate or total yearly infill quantity. The chance of occurrence of a 'high' infill rate or quantity is much lower, but it greatly influences the average infill rate or total yearly infill quantity. The chance of occurrence of a 'high' infill quantity. The chance of eventually having a lower infill rate than the mean is thus quite large (more than 65% of the years in case of scenario 2, see Figure 5-14), but there is a small chance of having a much higher infill, which is important to know when deciding upon a maintenance strategy. Based on the calculation in this chapter an

infill of 10 Mton in one year would occur 10% of the years in case of scenario 2. A deterministic approach does not lead to this insight.

Lastly, determining the characteristic time scale should be paid attention to if a probabilistic analysis is applied in a next project phase. An autocorrelation function can be used to analyse the time series of the input parameters, so a proper estimate is made.

6 Discussion

The first two objectives of this thesis were to define a model of the infill processes and to use this model to estimate the infill and quantify the uncertainties. This chapter will discuss to what extent these objectives were met and address the final objective, which was presenting strategies to manage risks and reduce uncertainty.

First the applied methodology to model the infill processes is critically investigated. This involves discussing the data sources, the modelling of the infill processes and schematization of the infill and the applied uncertainty analysis. Next the results of this thesis are discussed. The analysis of the OKLNG mud, which was conducted in order to reach objective 1 and model the sedimentation process, led to an unexpected – but in hindsight the most important – result of this study. The results of the modelling of the mud infill and uncertainty analysis are analysed as well and the probabilistic analysis is evaluated.

Section 6.3 regards risk management. The mechanisms that can result in channel infill are discussed. However the focus of this section is on objective 3; reducing the uncertainties surrounding prediction of the day-to-day mud infill rate and yearly infill quantity. The key points of the discussion are summarized in section 6.4.1. This chapter concludes with general learnings based on the experiences while conducting this research.

6.1 Discussion on the methodology

6.1.1 Evaluation of the data sources

The reliability of a prediction depends heavily on the quality and quantity of the input data. Problems usually arise with scarcity of data, incompatibility and inhomogeneity [Van Gelder, 2000]. Two types of data that influence the day-to-day mud infill of the OKLNG channel are identified: metocean data as described in section 2.4 and soil data as described in chapter 3. The quality and quantity of these two data sources are discussed separately. By discussing the quantity the scarcity or availability is investigated. The quality is evaluated based on representation of the values found in reality, compatibility and homogeneity.

6.1.1.1 Metocean data

In section 5.4.1 the compatibility of the data – whether or not they are representative for an arbitrary year – is already discussed. It was concluded that the measured one year data series are compatible. In case more reliability is required, data should be obtained over multiple years. However, considering the uncertainty in the sediment data, this should not be a priority. The wave statistics are split into statistics of wind, swell and low-frequency waves to create separate homogeneous data sets, so inhomogeneity was also investigated. But there is more to say about the quality of the data.

Consequently the most important metocean parameter for the mud infill prediction, the current, will be looked at more closely. The AWAC current magnitude and direction data series measured 1.5 m above to bottom at location 1 and 3 as indicated in Figure 2-21 was transformed into a current magnitude close to the bottom and perpendicular to the relevant channel sections. Therefore the following two comments are made:

- 1. Measuring locations:
 - Location 1 measured the currents in a water depth of -9 m CD. The data were used to model the currents in sections A₁, A₂ and B, while these sections have a water depth of -5.4 to -8.3 m CD (see Table 5-3). The velocities measured at 1.5 m above the bottom at a location with a water depth of -9 m CD are higher than the velocities measured at location 3 with a water depth of -15 m CD. This trend may very well continue towards the coast, leading to underestimated velocities, but velocities (and other metocean data)

closer to the coast have not been measured. The length of the data series is sufficient as previously concluded, but the availability of data in space can be improved.

The current velocity has a large influence on the infill prediction, so it is important to investigate their magnitude closer to the shoreline. For OKLNG measuring important data, such as current velocities, at a water depth of -6 m CD as indicated in Figure 6-1 is recommended. This location is more representative for sections A₁, A₂ and B. For future projects it might be wise to choose the measuring locations evenly distributed over the project area.²⁴



Figure 6-1: Evaluation of the locations where data was collected based on the current channel design

For section C, which has a depth varying between -8.3 and -16 m CD, the average current statistics of location 1 and 3 is used. The average of these data is representative for section C. It is also possible to include data from location 2 if these are readily available.

2. Measuring height:

As explained in section 4.4.1, the AWAC current data series measured at 1.5 m above the bottom was used to compute the infill. The actual near bottom velocities were lower, so the current magnitudes were divided by 2 to obtain current velocities in the 5-10 cm/s range as measured close to the bottom by the Sontek downward looking ADP device. Statistics of this data series were however not yet available at the time of this research, so the converted AWAC data series was used instead.

Using the AWAC data instead of the Sontek data will most likely have no influence on the current direction. The distribution of the current magnitudes however might be different. It is therefore recommended to analyze the actual near bottom current data series of the ADP and compare them with the currently used distribution to assess the reliability of the used data series. Nonetheless, it is expected that these distributions will not differ significantly. Looking into the velocity distribution in smaller water depths has more priority.

 $^{^{24}}$ In a previous design phase an offshore terminal with a jetty was considered. The measuring locations at – 9, –12 and –15 m CD were chosen based on that design. Only after the measuring campaign started, the design was changed to an inland terminal.

Concluding, the metocean data are generally of good quality and quantity. It is however advised to consider measuring important metocean parameters such as the current velocity around a water depth of -6 m CD to obtain sufficient data along the entire channel length.

6.1.1.2 Sediment data

As already pointed out in the introduction of chapter 3, data that unambiguously characterizes the top mud layer of the soil and sediment in the water column is not available. Even though it was attempted to increase the reliability of the data in the reports of GEMS, Fugro and Van Oord by conducting a literature research [e.g. HR Wallingford, 1981] still the problem of lack of data – essentially data scarcity – remains. The settling velocity of the sediment in the OKLNG area, which is a very important sediment characteristic for a sedimentation study, is not measured. This is the reason two scenarios had to be adopted in chapter 4 and introduces a large uncertainty in the mud infill prediction.

Next the measured turbidities are discussed. These were measured at the same locations where the metocean data were collected. Turbidities were measured at 10, 40 and 60 cm above the bottom. These turbidities were converted to sediment concentrations and the concentrations are used to predict the mud infill in the channel. Enough data is collected; on average 30,000 data points were available per specific height and location. The following comments are relevant to assess the quality of the data:

1. Range of measured turbidity values:

As mentioned in section 3.7.1 the deployed OBS sensors could measure turbidities up to 3,800 NTU, which depending on the calibration curve corresponds to a maximum concentration of 8 g/l. At 10 cm height the OBS went out of scale approximately 15% of the time. Concentrations above 8 g/l mostly concern the concentrated mud layer infill mechanism, thus no information on the mud layer concentration is available. As shown in the sensitivity analysis this introduces a large uncertainty in the infill prediction.

Data from other sources were therefore examined. Concentration data measured near Lekki in 1980 show concentrations of up to 110 g/l at 10 cm height. This is however not at the project location. Next the OKLNG concentration data were fit to a distribution to get an impression of the possible concentration. The problem is that the sediment data represents two different sediment states: the lower concentrations represent a low concentrated mud suspension and the tail represents a fluid mud regime. The data series is therefore not homogeneous and cannot be represented by one distribution [Van Gelder, 2000]. The data series should be split.

The problem thus remains that there is no data available on the mud layer concentration. No proper estimate can be made without reliable data, so additional measurements are absolutely necessary.

2. *Measuring period:*

Turbidity measurements were mostly conducted during the storm season (see Table 3-2 in section 3.2.2). It is therefore likely that the percentage of the time in one year the OBS went out of scale is overestimated. At location 1 the measurements lasted for more than one year, but at location 2 and 3 no measurements were conducted during the calmer months. In the storm season not only the waves are higher (see section 2.4.4.4), but also the average current velocity is generally 0.05 m/s higher (see section 2.4.5.4). Since the amount of sediment that can be mixed over the vertical is proportional to u^3 [Winterwerp, 2001], much higher concentrations are expected to be measured during the storm season than during calmer months.

The percentage of all the analyzed measurements at 10 cm height for which the OBS went out of scale is 15% for location 1 while an entire year was measured and 14% for the other two for which measurements during calmer months were not conducted.

Following the reasoning that concentrations in the water column should be lower for a yearly average than for an average based on only data of the rough months, it is expected that the percentage in location 2 and 3 would be lower when data of an entire year is available.

The sediment concentration is however also influenced by location; closer to the shore wave forcing is more intense, leading to more sediment being stirred up, and the velocity measured at location 3 is generally lower than at location 1, leading to more sediment being mixed over the vertical. All in all, it is advisable to compare the data from the months when measurements were conducted at all three locations to investigate the influence of the measuring period on the sediment statistics. Note that it is expected that the averaged yearly sediment concentration in the water column at location 2 and 3 is overestimated, leading to a possible overestimation of the mud infill predicted for scenario 2. (For scenario 1 the turbidity data are not used as input parameters.)

3. Measuring locations:

For the sediment data a similar comment regarding the measuring locations can be made as was done for the metocean data. Data from location 1 had to be used to predict the sediment infill of channel sections A_1 , A_2 and B, since data from a location with a water depth, which might be more representative for these sections, were not available. It is subsequently also recommended to measure sediment data at a water depth of -6 m CD as indicated in Figure 6-1.

For section C, sediment statistics from location 2 are used. Since this section is represented by one characteristic cross-section in the middle of the section it is logical to use the data of location 2, which is located halfway this section, as representative for the entire section. If further refinement of the model is required, it is also possible to use data from location 1 and 3 for different parts of section C.

4. Measuring height:

Concentrations were measured at 10, 40 and 60 cm above the bottom. The measuring devices were deployed on a high frame, which was placed on the seabed. The seabed however is very soft as was concluded in section 3.6.1, so it is likely that the measuring devices sink slowly into the mud. The height at which they measure the velocity and sediment concentration then varies. It should be investigated if the distance over which the instrument sinks is significant and influences the mud infill prediction.

More comments on the reliability of the sediment concentration data can be made: the frequency of calibration of the measured turbidity versus the sediment concentrations found in the water column can be increased, the method of fitting the sediment data to a distribution curve greatly influences the magnitude of the sediment concentrations in the water column that are predicted, the mud layer thickness is now loosely estimated based on Vinzon and Mehta's [1998] equation on the lutocline height, but measurements are required to validate the assumed values, etc. However the quality of the sediment data in general is insufficient: the data do not represent the range of values found in the water column. The high sediment concentrations near the bottom were not measured, but do have the most influence on the mud infill prediction. The lack of knowledge about the extreme values of the sediment concentration near the bottom poses the largest threat to a reliable mud infill prediction using any model. All the other comments on the quality of the data are of much less importance. Knowledge on these high concentrations can be obtained by a proper measuring campaign during which concentrations in the order of 100 g/l can still be measured and preferably also the height of the mud layer is recorded. The alternative is to predict these concentrations with an appropriate model.

6.1.1.3 Concluding remarks on the quality of the data

The quality of the metocean and sediment data is quite different. The uncertainty introduced by the lack of knowledge on the settling velocity and the concentrations near the bottom is so large that the comments on the reliability and compatibility of the measuring locations with the channel sections are only of minor importance. Improving the quality of the metocean data would not improve the quality of the infill prediction, since the largest uncertainties are introduced by the sediment data. Consequently it is important to have data of similar quality, i.e. the uncertainties introduced by each data series have an impact of the same order of magnitude on the prediction. If a measuring campaign is set up, this should be kept in mind.

6.1.2 Infill model

The goal of this thesis was to gain insight in the uncertainties surrounding the mud infill. Therefore a simple model is chosen which does not represent all physical processes, but can be used to identify uncertainties and for a probabilistic analysis. Using a model as DELFT 3D, MIKE 21 or FINEL 2D more physical processes are modelled, but it is impossible to run this model say 10,000 times. The question is whether or not the used model represents the physical processes enough to still have predictive capacity.

The infill is schematized by two infill mechanisms: suspended sediment infill and mud layer infill. In case of scenario 1 only mud layer infill takes place²⁵ and in case of scenario 2 both mechanisms occur. This means that in case of scenario 2 a criterion has to be built in to decide when which mechanism takes place. The modelling of the two scenarios will be evaluated separately.

6.1.2.1 Modelling of scenario 1

The mud layer infill in case of scenario 1 is quite straightforward and includes the main drivers of the infill: a mobile mud layer is transported by the currents into a channel and stays there. This mud layer is always present, but its specific mass varies over time, most likely due to wave forcing and current magnitude. If reliable measurements are available of the mud layer concentration, the mud layer height and currents, the approach in this thesis seems justified. Note that validation of the model is still required.

The model can be improved by incorporating the correlation between the specific mud layer mass and current magnitude. This correlation can be investigated by analyzing the data series of these two parameters. The influence of the waves on the mud layer height and concentration is essentially already taken into account by using the sediment data directly.

A final remark regards the trapping efficiency. This model assumes that all mud that enters the channel is trapped. It is important to study when a mud layer will be trapped in a channel and when it is transported up the opposite slope and which parameters influence this mechanism by means of experiments or literature research.

6.1.2.2 Modelling of scenario 2

The modelling of scenario 2 is more difficult. The physical processes had to be highly schematized to formulate a simple mud infill prediction model which is suitable for a probabilistic analysis. Two input parameters could not be properly predicted: the specific mud layer mass threshold which was the criterion to decide when which infill mechanism takes place and the trapping efficiency for suspended sediment infill as explained in sections 4.4.3 and 4.4.4 respectively. However the uncertainty analysis in section 5.5.2.5 shows that for this specific project these two parameters have a limited influence on the prediction.

²⁵ Suspended sediment infill takes place as well, but as demonstrated in section 5.4.1 this infill mechanism contributes so little to the total infill that it can be neglected.

It thus also seems no problem that the channel cross-section – and especially the channel overdepth – and settling velocity of the sediment are not included in the model. These parameters largely determine the trapping efficiency of the suspended sediment.

The wave climate is not included either, although in this scenario the waves directly influence the amount of sediment in the water column. Using sediment data directly might make it not necessary to include the wave climate in the model.

The sensitivity analysis also demonstrates that the infill prediction in this particular case is dictated by the sediment concentration near the bottom. The predicted infill quantity consists almost entirely of infill due to a mud layer near the bottom. If this appears to be correct after validation of the model, the infill in case of scenario 2 can be computed according to equations (4.10) and (4.11) as well and using a more sophisticated model is not essential in that case.

But if this is not the case, the suspended sediment infill needs to be modelled as well. A more sophisticated model such as DELFT 3D, MIKE 21 or FINEL 2D is then recommended to predict the infill and compute the percentage of the time suspended sediment takes place, the trapping efficiencies and the amount of sediment in the water column based on the wave and current climate.

The next question is whether or not a simple model can be used at all to predict the infill in case two infill mechanisms take place alternately. The first problem is to decide when which infill mechanism occurs. This decision can also be made based purely on data. If enough data is available the percentage of the time each mechanism occurs can be used as a criterion instead of a physical one. Reliable and sufficient in situ measurements then have to be conducted. If data of multiple years is available the uncertainty in the percentage of the time each mechanism occurs can also be studied.

The mud layer infill as argued in the previous section is relatively straightforward if sufficient data is available, so the modelling of the suspended sediment infill should be evaluated next. Unfortunately there is no simple formula to calculate the trapping efficiency (see section 4.4.3). As long as such a formula is not found, using a simple model to predict suspended sediment infill is not possible. Studies aiming to find a reliable and simple expression for the trapping efficiency are very welcome in this respect.

Despite that a simple model may not be suitable to properly predict the infill in case two infill mechanisms take place alternately, it does provide proper insight into which parameters cause the largest uncertainty in the infill prediction and is thus quite valuable in that respect.

6.1.2.3 Validation

Since the used models highly schematize the physical processes, validation is important. This issue was raised in the two previous sections as well. Initially it was intended in this study to validate the model with data from reference projects. Several projects and neighbouring harbours were identified which seemed a promising project to validate the model formulated in this thesis.

Two projects indicated in Figure 6-2 are briefly discussed below:

- *NLNG*: Bonny channel in the eastern part of the Niger Delta is deepened to provide access to vessels to several jetties upstream. This channel is unsuitable as a reference project since the currents are much stronger in this area than at OKLNG due to the large tidal range and the river mouth which functions as a coastal inlet. Moreover the sediment that is dredged from the channel is mainly sand, which makes a comparison to OKLNG impossible.
- *Forcados*: At Forcados, approximately 120 km southeast of OKLNG, pipeline crossings exist. Unfortunately no sediment or dredging data was available.



Figure 6-2: Locations of studied projects in the Niger Delta which might be suitable for validation of the infill model

The locations of these projects are in the Niger Delta as is evident from Figure 6-2, since the chance of finding a compatible project in the same region is higher than finding it elsewhere in the world. Projects outside Nigeria in muddy areas such as Hazira in India were also considered, but proved not to be compatible with OKLNG.

Nevertheless, these models cannot be used to predict mud infill if they are not validated. Hence it is still valuable to find a project to validate them. An option is to dig a trial trench at the project site, monitor the infill and use that data to validate the models.

6.1.3 Uncertainty analysis

A quantified uncertainty analysis of the sedimentation of the OKLNG approach channel is useful for project planning, determining possible channel maintenance strategies and assessing risks, so this was part of the objectives of the thesis. The applied uncertainty analysis consists of a sensitivity analysis and a probabilistic analysis.

A probabilistic analysis is a strong method to obtain a quantitative uncertainty analysis as shown in this thesis. The relative contribution of each parameter to the variance can be computed based on its distribution. A probabilistic analysis does require a proper deterministic model and reliable information on the distributions of the input parameters. The probabilistic analysis in section 5.5 is therefore only executed to illustrate the methodology.

A sensitivity analysis is the next best option if the quality of the data is not sufficient for a full probabilistic analysis. The methodology is straightforward: the input parameters are varied within their possible range to investigate to what extent they influence the outcome of a deterministic calculation. No information on the distribution of the parameters is required. This method provides information on the possible range in outcomes of the model and can be quite powerful as well as is also demonstrated in section 5.3.2.

6.2 Discussion on the results

6.2.1 Sediment state in the water column

While analysing the sediment at OKLNG 8 independent indications were found that the sediment in the water column is not to poorly flocculated. Each indication separately can be disputed, but because 8 were found, they make a compelling case. Even though no literature on such low to non-flocculated conditions has been found and the experts consulted for this thesis have not encountered these conditions before, based on the found circumstantial evidence it seems more likely that the sediment is poorly flocculated. Whether or not the sediment is flocculated determines the sediment behaviour and the infill mechanisms that take place. This is sketched in Figure 6-3. This has a large impact on the infill rates, which can also be concluded from chapter 5. Fortunately this uncertainty can be resolved through measurements as will be explained in section 6.3.3.1.



Figure 6-3: Uncertainty regarding the sediment state in the water column results in two possible scenarios that have to be investigated to predict the mud infill

6.2.2 Mud infill prediction

One of the goals of this thesis was to identify uncertainties in order to quantify them. The mud analysis uncovered an unexpected but very important uncertainty. Since data that can provide certainty on the state of the sediment is lacking, the adopted strategy was to investigate both scenarios: unflocculated and flocculated sediment. The result of the mud infill prediction for both scenarios will therefore be discussed separately.

6.2.2.1 Mud infill prediction for scenario 1

As concluded from chapter 5, the infill rate in case of unflocculated sediment lies in the order of a few Mton per week, even when wildly varying the input parameters. As a consequence this scenario changes from a sedimentation problem into a consolidation problem. Since it should be assumed that there is always mud in the channel, focus should shift to non-conventional dredging techniques or to methods how to keep the channel navigable.

The density of the concentrated mud layer is estimated to be around 1,050 kg/m³. Considering the navigable bottom concept as discussed in section 4.3.1.1, keeping the mud navigable as long as possible might be an interesting maintenance strategy in case of a very low settling velocity. In for example the port of Paramaribo in Surinam vessels keep the channel open [Winterwerp, 2009]. With enough traffic in the channel, vessels stir up the mud regularly preventing it from consolidating too much. Water injection dredging was considered for OKLNG by Van Oord [2007] and might be an option as well. Determining the settling and consolidation behaviour of the material or choosing an optimum maintenance strategy in case of this scenario lies outside the scope of this thesis, but a strategy how to proceed from here will be presented in section 6.3.3.2.

6.2.2.2 Mud infill prediction for scenario 2

The yearly mud infill quantity for scenario 2 is calculated with a model that is not designed to precisely predict the mud infill for this scenario. The yearly infill rate of 6.8 Mton mentioned in section 5.5.2.3 should thus be treated with extreme care and not be used to base any maintenance strategy on. Data on the frequency of occurrence of the mud layer infill mechanism

and on the concentrations near the bottom is required, the problems with the prediction of the trapping efficiency have to be resolved and satisfactory validation of the model is necessary before a simple model as applied in this thesis can be used to accurately predict the mud infill if normally flocculated cohesive sediment is found in the water column.

Until then more sophisticated models are preferred. Svasek Hydraulics and Royal Haskoning [2008b] have investigated this scenario with the FINEL 2D model. They predicted a lower yearly infill, but the quantity is of the same order of magnitude. A comparison between the two models and the infill predictions is made in Appendix G.

Although a number cannot be stated, the yearly infill quantity is expected to be in the order of several Mton per year. The channel can accommodate 5.2 Mton in the entire channel assuming a mud density of 1,100 kg/m³ and 2.3 Mton below the navigation depth of -15.5 m CD assuming a mud density of 1,370 kg/m³ (see section 5.6.2). This clearly shows that an infill in the order of several Mton per year requires regular maintenance. For scenario 2 it would therefore also be useful to investigate the settling and consolidation behaviour of the sediment when in the channel. Also dredging techniques that are suitable for removing large quantities of mud from a channel should be studied.

Note that the infill rate alone does not determine the accessibility of the channel for vessels. The infill rate and the characteristics of the mud after entering the channel such as the strength development in time together with the maintenance methods determine the accessibility.

6.2.2.3 Value of the predicted infill rates and quantities

To obtain a mud infill prediction with the simple model as derived in section 4.2, the physical processes were highly schematized. In case of scenario 2 additional crude and unverifiable assumptions had to be made. Nonetheless, the model does indicate the order of magnitude of the infill. This is a very useful result, since it provides a clear direction for further research, namely to explore how to deal with large quantities of mud in the channel with a density in the order of 1,032-1,080 kg/m³ when entering the channel. These densities correspond to a mud layer concentration of 20-100 g/l.

6.2.3 Uncertainty analysis

6.2.3.1 Parameters of importance for the mud infill prediction

The investigation of the two scenarios clearly shows that the uncertainty with regard to the sediment state is the most important uncertainty for the mud infill prediction. The difference in computed infill rate is a factor 10 (see sections 5.6.2 and 5.6.3). Fortunately this uncertainty can be resolved through measurements. The possibilities for mitigation will be discussed in section 6.3.3.

In case of unflocculated sediment, the infill rate is so large that the exact infill quantity is not relevant. For scenario 2 on the other hand it is of importance. The next parameter of interest is therefore the concentrations near the bottom, or more specifically, data on the specific mass of the mud layer is required as also concluded in sections 5.5.1.5 and 5.5.2.6. No data are currently available on the high concentrations near the bottom and the mud layer height, so this needs to be obtained.

6.2.3.2 Quantification of uncertainties

One of the goals of this thesis was to quantify the uncertainties. A sensitivity analysis is not suitable to quantify uncertainties, but a probabilistic analysis is. As explained in section 5.1 this analysis can only be executed if a suitable model which takes the important physical processes and relevant parameters into account is available, the probability distribution of each parameter is known and correlations between the parameters are defined. For scenario 1 the uncertainty in the sediment data needs to be reduced before the application of a probabilistic analysis is useful.

In case of scenario 2 a suitable model needs to be developed first. Unfortunately this also means that it is too soon to reach the goal of quantifying uncertainties.

6.2.3.3 Added value of a probabilistic analysis

An uncertainty analysis identifies which parameters have the most influence on the predicted variable. This is very valuable in itself, since one can focus on these parameters during the design. For scenario 1 the sensitivity analysis even shows that when the specific mud layer mass is varied wildly, the infill rate is still very high and the channel fills up within weeks.

However by only applying a sensitivity analysis the influence of the distributions of the input parameters and correlations between them cannot be studied. This requires a probabilistic analysis. More importantly, if a good model and proper data are available a probabilistic analysis can also provide a prediction of the P10 and P90 values, which is important for project planning and risk identification, and quantified uncertainties. A deterministic calculation combined with a sensitivity analysis cannot provide this knowledge.

The strongly asymmetrical probability distributions in Figure 5-7, Figure 5-13 and Figure 5-14 show the added value of a probabilistic approach. They show that the tail of the distributions greatly influence the average infill rate and total yearly infill quantity. The chance of eventually having a lower infill rate than the mean is thus quite large, but there is also a chance of having a much higher infill, which is important to know when designing a maintenance strategy. A deterministic approach does not lead to this insight. The asymmetry in the probability distribution is a result of both the infill velocity and the sediment concentrations not being symmetrically distributed.

6.2.3.4 Uncertainties introduced by the probabilistic model

Schematizing the infill process introduces model uncertainties, which is the case for any sedimentation model. The model uncertainties introduced specifically by the probabilistic model have not been discussed before. The uncertainties regarding the integration over the length, the integration over time and the correlations are briefly described. The uncertainties regarding the schematization of the infill processes were discussed in section 6.1.2.

- Integration over the channel length:

The current schematization, which uses only 4 cross-sections instead of 1,055 channel segments, does not introduce any additional uncertainties. In case of scenario 1 the infill rate does not depend on the channel cross-section, also not during the infill process. The infill rate only depends on the channel orientation and length.

For scenario 2 the trapping efficiency does depend on the channel cross-section, so when more is known about the distribution of the trapping efficiency along the channel axis, this might introduce additional model uncertainties. In the current model this is not the case.

- Integration over time:

As demonstrated in sections 5.5.1.4 and 5.5.2.4, the integration over time introduces an uncertainty in the standard deviation of the computed distribution when the length of the representative time step n is not known precisely. This difference is considerable and scales with \sqrt{n} when the time steps are independent and the predicted parameter can be reliably represented by an analytical distribution.

This uncertainty can be reduced by analyzing the time series of the current velocity, wave climate and sediment concentrations with an autocorrelation function. This function returns the minimum time step for which the value of an input parameter at time $t = t_i$ does not have any influence on the value at $t = t_{i+1}$. This minimum time step represents the timescale of the governing physical processes and is the best choice for a representative time step.

- Correlations:

Only a few possible correlations were discussed in section 5.4.2. If any correlations were overlooked or not modelled properly, the uncertainties in the probability distribution of the investigated parameter – in this case the mud infill rate and quantity – can be underor overestimated. This was also schematically explained in Figure 5-3.

If a probabilistic analysis is desired, a systematic identification of all possible correlations and subsequent assessment of the correlation coefficient is recommended in a next project phase. For example, a matrix with all the relevant parameters can be used to systematically check for each individual parameter with which other parameters it is correlated. The correlation coefficients can be assessed by plotting the data series of one parameter versus the data series of another parameter.

Of the discussed correlations in section 5.4.2, the correlation between the sediment concentration and current magnitude deserves attention. In this research it is assumed that there is no correlation between these two parameters (see section 5.4.2.2). Since the amount of sediment that can be mixed over the vertical is proportional to u^3 [Winterwerp, 2001], the parameters are positively correlated in reality. The projection of the current velocity has probably weakened this correlation, but assuming no correlation may thus very well have resulted in an underestimation of the infill rate.

For scenario 1 the infill rate is already very high, so this does not influence the conclusion of the infill modelling. For scenario 2 this cannot be estimated. In a 2D model the relation between the current and the sediment concentration in the water column is explicitly defined.

Again a note has to be made that these uncertainties are of much less importance than the uncertainties identified in section 6.2.3.1. Also, reducing the uncertainties described above is not difficult; the methodology is explained above.

6.3 Risk management of the infill of the OKLNG approach channel

A risk is often defined as the probability of an event times its consequences. Events and consequences can be beneficial or threatening to success. Risk management aims to identify, assess and mitigate risks. Mitigation can be through reducing uncertainties. The risk management process is sketched in Figure 6-4.

This process is addressed briefly in the next sections to show its relevance for the project, however the focus of section 6.3 is on objective 3; reducing the uncertainties surrounding prediction of the day-to-day mud infill rate and yearly infill quantity. Figure 6-4 clearly shows the steps to be taken to reach objective 3. This thesis addresses only a small part of the risk analysis of the OKLNG channel infill. This section provides starting points and input for this analysis, but does not form a complete risk assessment. The last step, a mitigation strategy for all possible infill mechanisms, will therefore not be included. What will be included is the strategy to reduce the uncertainty regarding the prediction of the day-to-day mud infill as studied in this thesis.



Figure 6-4: Risk management process and the application to OKLNG [based on Figure 1, Hitchings and Wilson, 2002; Figure 5.2, GUCENET, 2007; and Figure 1.5, Jonkman, 2007]

6.3.1 Scope of the risk analysis

This thesis focuses on the prediction and uncertainties of the day-to-day mud infill of the OKLNG approach channel. The risk implicitly investigated in this thesis is thus the magnitude of the day-to-day infill rate and yearly infill quantity. This was the goal of this thesis; however, channel infill can be caused by more mechanisms than the ones investigated in this thesis. In a risk analysis a broader view on the infill prediction needs to be adopted.

6.3.2 Risk analysis

The magnitude of the day-to-day infill rate and yearly infill quantity are identified (chapter 1), assessed (chapters 2 to 5) and evaluated (this chapter). Two infill mechanisms that cause this infill have been identified: suspended sediment infill and mud layer infill.

As just explained other infill mechanisms that can also contribute significantly to the infill have not been evaluated yet. In section 4.1.1 two other mechanisms were identified but excluded from this thesis on grounds that only day-to-day infill would be investigated. The chance of the approach channel being inaccessible for a period of time is not looked into either, whereas this is an important risk to assess. Shortly said, while writing this thesis several risks and opportunities besides the day-to-day suspended sediment and mud layer infill were identified, although they were not investigated. A complete risk analysis of the OKLNG channel infill should be executed. This section provides starting points and input for this analysis.

6.3.2.1 Risk identification

In practice often risks are overlooked, so this step in the process is very important. The method of risk identification should be designed such that as many ideas as possible are generated and not written off too soon. Therefore it is strongly advised to organize a brainstorm with several stakeholders and experts on for example sedimentation, navigation, cohesive sediment, soil

mechanics and the geology of the Niger Delta area to identify as many mechanisms that contribute to the infill as possible, their likelihood of occurrence and impact.

Then it can be decided if other infill mechanisms need to be investigated as well. The brainstorm should result in as many relevant risks regarding the channel infill as possible and be part of the risk analysis of the entire project. This thesis and especially sections 6.2.1, 6.2.2 and 6.3.2 can be used as input for the risk analysis concerning the channel infill.

6.3.2.2 Risk assessment

A brainstorm as recommended in the previous section was not organized, since this thesis was focused on the day-to-day suspended sediment and mud layer infill. However the following infill mechanisms and opportunities also attracted attention in the course of this research:

1. Sand infill:

As explained in section 1.4.2 sand infill has not been investigated. Svasek Hydraulics and Royal Haskoning [2008b] added 5% to the mud infill they computed to include sand infill in their prediction. During the measuring campaign of HR Wallingford [1981] at Lekki both silt and sand concentrations were measured. In 70% of the samples the sand concentrations are 10% or less of the measured silt concentrations. Excluding the very sandy and therefore not representative samples, the sediment in the water column near Lekki and 20 km west of OKLNG consists on average of 94% silt and 6% sand. The estimate of Svasek Hydraulics and Royal Haskoning is thus a very reasonable first estimate. To properly predict the amount of sand taken along the sediment in the water column at OKLNG should be analyzed. Properly predicting the sand content is important, since the nautical bottom concept does not apply to sand. The material needs to be dredged.

2. Advancing coastline:

The advancing coastline results in an additional infill of approximately 20 ton/yr.²⁶ This is negligible compared to the computed infill rates in chapter 5. Also it would take at least 100 years for the coastline to reach the end of the lee breakwater.²⁷ The coastal advance is thus not a risk for the project when a lifetime of 50 years is adopted.

3. Mud outflow at channel end:

Svasek Hydraulics and Royal Haskoning [2008b] assume that 5% of the mud in case of mud layer infill will flow out of the channel at the seaward end. Considering the viscous behaviour of the mud, this is possible and should be investigated. If in the end the channel works as a drain, maintenance requirements might even be quite low.

4. Channel slopes:

The slopes of 1:60 to 1:20 are based on an educated guess by Royal Haskoning [2008b]. Also the soil composition in the vertical should be considered, since below the top mud layer intermittent sand and clay layers are present which may result in a steeper channel slope overall. Verification of these values is needed to estimate the additional infill due to slope flattening. Additionally in case of scenario 2 the slopes influence the infill rate via the trapping efficiency. The time scale of the slope flattening is also worth investigating.

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²⁶ The coastal advance is 3-7 m/year. Assuming an average sediment bulk density of 1,370 kg/m³, a sediment density of 2,600 kg/m³ and a seawater density of 1,020 kg/m³, every m³ contains 576 kg sediment. With a water depth of 17 m and an average channel width of 400 m, this results in 5 m \cdot 17 m \cdot 400 m \cdot 576 kg/m³ \approx 20 \cdot 10⁶ kg = 20 ton. The infill due to the coastal advance lies between 12 and 27 ton if the variation in coastal advance is taken into account.

²⁷ The lee breakwater is 700 m long. With a coastal advance of 3-7 m/yr, this would be reached after 100-235 year.

Possible risks besides a large day-to-day infill of the channel come across in this thesis are:

1. Channel inaccessibility due to a sudden large infill quantity.

For scenario 1 this risk is less relevant, considering that it is expected that there is always mud in the channel (see section 5.6.2). Maintenance strategies should therefore already include how to keep the channel navigable with mud in it.

Yet this is not the case for scenario 2. The infill rate is highest when mud layer infill takes place. Assuming the channel is empty at the start of a high swell event which generates a mud layer with a height of 5 cm and adopting the average current velocity of 0.0055 m/s, the navigation depth of -15.5 m CD would be reached after 39 hours.²⁸

Svasek Hydraulics and Royal Haskoning [2008b] predict that approximately 50% of the infill occurs in July and August and about 40% in May, June, July and September. This means that almost all the infill takes place during five months of the year. During these rough months it is very likely that a high swell event lasts for a few days, possibly leading to temporary channel inaccessibility due to a large sudden infill. Concluding, this risk should definitely be thoroughly investigated in case of scenario 2.

2. Channel destruction due to growth faults.

In section 2.2.1.2 growth faults were investigated. A fairly recent paper by Corredor *et al.* [2005] shows two growth faults within a range of 40 km of the OKLNG project site. It might be a good idea to consult an expert on the possibility of a submarine landslide taking place in the project area.



Figure 6-5: Growth fault

Keep in mind that the listed mechanisms and risks do not form a complete risk assessment. They can be used as input for the risk analysis of the OKLNG channel infill.

6.3.2.3 Risk evaluation

In addition to the day-to-day mud infill rate and quantity a risk that requires further investigation is the risk of the channel being inaccessible for vessels due to a large and sudden infill event. A criterion which expresses this risk should be formulated to quantify it. Examples of a criterion are the chance that a loaded LPG carrier cannot reach the harbour basin or the chance of an infill volume that fills up the channel until the set depth for navigation with a density higher than 1,100 kg/m³ within 3 days. The possibility of a growth faults at the project site is worth looking into more carefully. The outflow of mud at the channel end is an interesting mechanism, which should be further explored as well. The amount of sand infill should be estimated as well, since dredging is required to remove this material from the channel.

²⁸ Infill rate $S = u \cdot \delta \cdot L = 0.055$ m/s $\cdot 0.05$ m $\cdot 10,550$ m = 29 m³/s. The channel volume from the designed dredged depth until the navigation depth is 4.05 $\cdot 10^6$ m³, so this is reached after 4.05 $\cdot 10^6$ m³/ 29 m³/s = 39 hours.

6.3.3 Strategy to reduce uncertainties with regard to the mud infill prediction

Based on the findings on the sediment characteristics, the day-to-day mud infill modelling results and uncertainty analysis a strategy is devised to reduce the uncertainties that strongly influence the infill prediction. The presented strategy gives clear guidance on which measurements, tests and studies are relevant for the infill prediction and what their specific purpose is.

The most important uncertainty – the sediment state at OKLNG – needs to be resolved before anything else. The subsequent mitigation strategy depends on whether or not the sediment is flocculated and will be discussed separately. The measurements required to resolve the uncertainty on the sediment state are of course listed first.

6.3.3.1 Resolve the uncertainty on the sediment state in the water column

A proper measuring plan should be designed to collect data to determine the sediment state in the water column. Measurements that should be included are:

- Measure the settling velocity of the sediment at different heights in the water column and at locations with a varying water depth along the channel
- Investigate the flocculation behaviour²⁹
- Identify the mineralogy³⁰

6.3.3.2 Strategy for scenario 1 – the sediment is unflocculated

If the sediment is not too poorly flocculated, the following course of action should be followed, starting with the most important mitigation measure:

1. Investigate the settling and consolidation behaviour of the mud:

The necessity to dredge a channel not only depends on the infill quantity, but also on the characteristics of the mud in the channel. Since relatively large infill quantities are expected, it is important to know how quickly the mud settles and consolidates and when vessels cannot sail through the channel anymore. Questions that need to be answered are for example how quickly mud strength builds up, the influence of the wave climate on the mud strength, the flocculation behaviour and the sediment mineralogy.

Measuring the consolidation behaviour of material with a very low solid content and is still or almost a liquid is quite difficult. In a channel the sediment settles and consolidates under its own weight; no additional load is applied. Standard consolidation tests investigate the behaviour of the soil under loading. A possibility is to do a series of settling tests. The increase in solid content over time is then measured and gives an indication of the time it takes for the mud to reach a certain critical density which prevents vessels from using the channel.

2. *Revise the nautical bottom concept Investigate maintenance strategies suitable for high mud infill rates.*

The nautical bottom currently set for OKLNG is $1,200 \text{ kg/m}^3$ [OKLNG, 2008b]. A comparison is made with critical densities set for several other harbours in muddy areas in the world in Table 6-1.

The nautical bottom is mostly set around 1,200 kg/m³ [PIANC, 2008], so the critical density set for OKLNG is at the lower end. Increasing this criterion while, of course, also keeping in mind safety can result in significant reductions in dredging frequency.

²⁹ Take samples in the project area and investigate the floc size at different salinities and temperatures. See sections 2.4.6.1 and 2.4.6.2 for the variation in salinity and temperature respectively throughout the year in the area.

³⁰ Samples of the sediment should be taken and analyzed in a laboratory. Roentgen diffraction is a suitable method to identify the mineralogy of clay particles.

Harbour	Density level	Based on:
	(kg/m³)	
Bordeaux (France)	1,200	Full-scale navigation tests
Cayenne (French Guyana)	1,270	Nautical bottom 0.30 m above this level
Emden (Germany)	1,220-1,240	Undrained shear strength of 0.12 kN/m ²
Maracaibo (Venezuela)	1,200	Average rheological transition level
Nantes – StNazaire (France)	1,200	Full-scale navigation tests
Rotterdam (The Netherlands)	1,200	Full-scale navigation tests
Zeebrugge (Belgium)	1,200	Rheological evaluation of mud and full-
[Delefortrie et al., 2005]		scale tests (worst case, no sand)
OKLNG (Nigeria)	1,100	

Table 6-1: Nautical bottom criterion of several ports in the world with mud infill and basis of their criterion [After Table 6.1, PIANC, 1997]

- 3. Identify and investigate maintenance strategies suitable for large infill rates of mud with a density of 1,032 –1,080 kg/m³ when entering the channel:
 - a. Further investigate water injection dredging.

Already the suitability of water injection dredging has been investigated by Van Oord [2007]. Water injection dredging is a dredging strategy whereby water is injected in the mud that has settled in the approach channel. A gravity-driven density current is generated which flows towards deeper sections, in this case out of the channel towards the continental shelf break. This maintenance strategy is very effective in dredging soft sediments. Based on a detailed proposal for a water injection dredging strategy the financial and operational feasibility can be judged.

b. Study the possibility of calling vessels keeping the channel open.

The access channel to the harbour of Paramaribo in Surinam has fine mud infill from the Amazon. Enough vessels use the harbour to keep the channel open without dredging [Winterwerp, 2009]. The conditions for which this is possible can be investigated; this largely depends on the settling and consolidation behaviour, the wave climate and the frequency with which vessels use the channel. Maybe this is feasible for OKLNG.

c. Study how other ports with high mud infill rates deal with maintenance.

Many ports and waterways are located in muddy areas around the world; especially near large deltas such as the Amazon and Mississippi. The harbour of Paramaribo in Surinam, the approach channel of Tanjong Priok near Jakarta, Indonesia, Port Qasim in Pakistan, Hazira on the west coast of India, the Port of Itajai or Saõ Luis in Brazil and the ones listed in Table 6-1 might serve as an example for OKLNG.

This study can be started with a literature research to identify which ports are interesting to further investigate based on sediment characteristics, infill mechanisms and infill rates. Next a literature research on what maintenance strategies are used in practice can be conducted. The pros and cons of each strategy should be documented; the applicability range with regard to sediment characteristics, effectivity, costs, hindrance to the traffic in the channel, environmental impact, the operational requirements (percentage of downtime under different metocean conditions, especially under heavy swell), etc. If this information cannot be found in the public domain, experts who plan these strategies, port authorities responsible for channel maintenance or dredgers should be interviewed. Based on all gathered knowledge the feasibility of the found strategies can be assessed for OKLNG. Then promising maintenance strategies can be identified and further investigated.

- 4. Measure the mud layer concentration and height: If the OKLNG project team members and stakeholders wish to obtain more certainty on the mean infill rate, measurements of the specific mud layer mass need to be conducted. The correlation between the mud layer concentration and its thickness need to be investigated as well (see e.g. Figure 4-8).
- 5. *Validate the mud layer infill model* Either try to find suitable reference projects or dredge a trial trench in the project area and monitor the infill.

6.3.3.3 Strategy for scenario 2 – the sediment is flocculated

If the sediment is flocculated and scenario 2 represents the correct sediment state the following course of action should be followed, starting with the most important mitigation measure:

1. *Properly measure the concentrations near the bottom*:

The high sediment concentrations near the bottom have the most influence on the mud infill prediction, so measuring the sediment concentration near the bottom has the highest priority in case of scenario 2. A device should be used that has a very wide range and can properly measure sediment concentrations in the order of 100 g/l. A densitune which directly measures densities or acoustic measuring devices might be suitable.



Figure 6-6: A densitune can measure the density of a silt layer directly based on the `tuning fork' principle [Stema Survey Services BV, 2007]

Still measuring the sediment concentration near the bottom is not as easy as it might seem. The problem is that the bottom is not well-defined as the top mud layer is very soft. A criterion should be defined that distinguishes between the actual seabed and a possible mobile mud layer on top. Otherwise the concentration near the bottom and mud layer height cannot be measured. Next should be investigated whether or not the measurements are always conducted at the same height. The measuring device may sink into mud or the bottom level can vary in time due to wave forcing, consolidation, sedimentation and erosion. If the height varies, it should be studied if this variation is significant and to what extent it influences the mud infill prediction.

2. *Measure the lutocline or mud layer height when a mud layer is formed near the bottom* Also include the dependency of the layer height on the sediment concentration in the analysis, so measure these two parameters at the same moments in time.

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- 3. *Investigate the settling and consolidation behaviour of the mud*: Since the infill rate in case of scenario 2 is still considerable, it would be useful to investigate the settling and consolidation behaviour of the sediment in the channel.
- Investigate to feasibility of dredging techniques that are suitable for removing large quantities of mud from a channel Water injection dredging may be a feasible method for maintenance of the channel. Other non-conventional dredging techniques should be looked at as well.

6.3.3.4 Feedback on the considered course of action – monitoring infill of a trial trench

This research does not immediately support dredging a large-scale trial trench to monitor the actual infill as suggested in section 1.2. It is a good method to validate the models, but there is no immediate need to pursue this course of action. First the uncertainty surrounding the sediment state in the water needs to be resolved.

6.4 Summary of learning points and best practice for future projects

6.4.1 Key points of the discussion chapter

The key points of the discussion chapter are:

- 1. *Key uncertainties in the mud infill prediction sediment state and concentration data* The most important uncertainty is the uncertainty surrounding the sediment state in the water column. If the sediment is not to poorly flocculated, the infill is a factor 10 higher than if it is normally flocculated. The second most important uncertainty for both scenarios regards the lack of knowledge of the sediment concentration near the bottom.³¹ This also means that the key uncertainties in this thesis are epistemic and can be reduced by measurements.
- 2. Result of the modelling insight in uncertainties and an order of magnitude of the infill The used infill prediction models are simple, but do provide a good insight in which parameters and processes cause significant uncertainties. They also provide an order of magnitude of the channel infill which indicates what strategy should be adopted to deal with the infill and how to reduce the uncertainties, so the method applied in this thesis fulfilled its purpose. However for precise infill predictions they are not suitable and more sophisticated models should be used.
- Applicability of the uncertainty analysis
 The uncertainty analysis the sensitivity analysis and the probabilistic approach proved
 to be quite powerful in identifying uncertainties. In order to quantify the uncertainties the
 models first need to be validated and the quality of the input data has to be improved.
- 4. Strategy how to deal with the infill A strategy to deal with the uncertainties surrounding the mud infill is formulated. First the sediment state needs to be known; measuring the settling velocity is the most common method. In case the sediment in the water column is not to poorly flocculated, the infill rate is very high and it should be assumed that mud is always present in the channel. Research

³¹ For scenario 2 the specific mud layer mass is mentioned often, which is the sediment concentration times the mud layer thickness. The mud layer thickness is also uncertain, but it is correlated to the sediment concentration. It can therefore still be said that the uncertainty is due to lack of knowledge on the sediment concentration near the bottom.

should focus on how to deal with this: the settling and consolidation behaviour of the sediment needs to be investigated, the nautical bottom concept should be revised and maintenance strategies suitable for large infill rates need to be explored.

In case the sediment is normally flocculated, the sediment concentration and thickness of the layer should be measured to predict the mud infill more accurately. It is also recommended to investigate the settling and consolidation behaviour in case of this scenario considering the relatively high infill rate that is predicted.

6.4.2 Best practices for future projects

This final section of the discussion chapter provides best practices for future projects that were identified throughout the course of this thesis.

6.4.2.1 How to deal with uncertainties

This thesis was aimed at identifying, quantifying and reducing uncertainties. The main learning of this thesis is therefore how to deal with uncertainties in a mud infill prediction of an approach channel. Summarizing, this was done as follows:

- 1. Identify the relevant physical processes
- 2. Identify the parameters determining the infill
- 3. Derive a simple method to model the relevant processes based on the points above
- 4. Obtain the mean values of the parameters and their distributions (if possible)
- 5. Perform a sensitivity analysis
- 6. Perform a probabilistic analysis (note that this is only possible when the conditions as stated in section 5.4.1 are met)
- 7. Conclude which parameters cause the largest uncertainty
- 8. Identify the nature of the uncertainties
- 9. Devise measurements to reduce these uncertainties or accept them and deal with them

This method proved to be quite powerful in the case of the uncertainty analysis of the mud infill prediction of the OKLNG approach channel infill.

6.4.2.2 Data collection

Since the uncertainties in this thesis are mostly of epistemic nature, how to collect data and set up a measuring campaign should be paid close attention to in any project. These uncertainties can then be reduced as much as possible. The following points are recommended to consider if a measuring campaign needs to be set up or data has to be collected for a future project:

- Use a literature study to set up a measuring campaign:
 A literature study may be suitable as starting point for setting up a measuring campaign.
 For example Allen [1965b], Allersma and Tilmans [1993], Mascle [1976] and Olabode and Adekoya [2008] provide in-depth information on the geology, bathymetry, sediment distribution, metocean conditions and some mud characteristics in the Niger Delta area. Studying this beforehand may result in a more focused measuring campaign.
- Carefully analyze which parameters are required for the design and include them in the plan for the measuring campaign:
 Assess the physical processes and identify the parameters necessary to evaluate or compute the variable which needs to be predicted. Then determine a method to obtain data on the identified input parameters.
- *Choose measuring locations evenly distributed over the project length*: Evenly distributing measuring locations over the project site results in representative data being available for the entire project area.

- Obtain input data of the same quality.

Since the most unreliable parameter determines the reliability of the outcome, the data necessary to predict the channel infill should be of the same quality. This means that the uncertainties introduced by each data series have an impact of the same order of magnitude on the prediction.

6.4.2.3 Recommendations to improve the modelling

The most important issue regarding the modelling is the validation. For scenario 1 the model is quite straightforward, so validation can be done by either finding suitable reference projects, conducting scale tests in a laboratory or dredging a trial trench and monitoring the infill.

Other points of improvement are:

- Investigate and include the correlation between the current velocity and sediment concentration in the water column
- *Improve the choice of a representative time step*: Assess the timescales of the governing infill processes and analyse the data series of the current velocity, sediment concentration and wave height and period to decide upon a representative time step.
- Find a reliable and simple expression for the trapping efficiency of suspended sediment in the water column when crossing a channel
- Investigate the validity of the specific mud layer mass threshold

6.4.2.4 Recommendations for further investigation

Finally some recommendations for further investigation will be presented:

- Seasonal variation in infill

The seasonal variation in infill has not been properly investigated. The current velocities and wave heights are highest in July and August, so infill rates during this stormy season are expected to be higher than during the calm season. This is especially relevant in case the sediment is normally flocculated (scenario 2) and the risk of the channel being inaccessible due to a sudden large infill quantity is investigated as described in section 6.3.2.2.

The months that are part of the storm season have to be identified first. Then the data series should be split up and the same analysis as used in this thesis can be applied to predict the infill in a certain season, provided that the models are validated. The variation in infill quantity over the months can be investigated as well if the data series are split into monthly series.

- Longitudinal variation in infill – difference in infill time per channel section

The infill rate along the channel axis differs. The cross-section also varies. This combination might lead to the situation that the set depth for navigation is reached sooner in one channel part than in another. In a next project stage it should be investigated if this is the case and at which locations along the channel maintenance is required with a higher frequency.

The behaviour of the sediment in the channel should be included in this study. If the mud behaves viscous, it is possible that the mud distributes itself more or less evenly over the channel. Chances of uneven filling are highest in case of scenario 2, since the mud is not expected to be very viscous if it flocculated normally.

Ratio between the suspended sediment infill and mud layer infill.

The sensitivity analysis for scenario 2 also demonstrates that the infill prediction in this particular case is almost entirely due to mud layer infill. If this appears to be correct after validation of the model, the infill in case of scenario 2 can be computed according to equations (4.10) and (4.11) as well and using a more sophisticated model is not essential anymore.

Next, it can be studied what parameters determine the ratio in infill quantity between suspended sediment infill and mud layer infill. This might simplify the model even more; it may become possible to judge for each case if the infill generated by one of the two infill mechanisms is negligible compared to the infill generated by the other based on site-specific parameters. If not, both mechanisms still have to be analyzed.

7 Conclusions and recommendations

This chapter summarizes the main findings of this thesis regarding the analysis of the system around OKLNG, the sediment characteristics, the infill modelling, the uncertainty analysis and the probabilistic approach. The last section of this chapter contains recommendations on how to deal with uncertainties when predicting mud infill and some general recommendations. The general recommendations are limited to only two important ones, for more detailed recommendations on the modelling and data collection, one is referred to section 6.4.2.

7.1 Conclusions

The conclusions of this thesis are the following:

1. System description of the OKLNG area

The OKLNG project area is located at the north-western tip of the Niger Delta and 100 km east of Lagos in Nigeria, Africa. The area is dominated by persistent, fairly unidirectional and high-energy swell waves with an average wave height of 1.4 m and wave period of 14 s in the wet season. The Guinea Current and South Equatorial Counter Current induce ESE and WNW currents. The current magnitudes are small, roughly 5-10 cm/s near the bottom and tidal influence is negligible. The coastline east of the project area is dominated by the Niger Delta; it is formed by sediment transported by the Niger and Benue River to the coast. Two opposing longshore currents meet at the project site and the coastline has been advancing for millennia.

2. Seabed sediment characteristics

The top layer of the sea bottom around the future approach channel consists of several meters thick soft mud with a gentle slope. The mud has a very low strength of only several kPa when having a density of 1,370 kg/m³ and shows viscous behaviour. The settling rate is low.

3. Sediment state in the water column

In marine environments around the world, cohesive sediment is usually flocculated with resulting settling velocities in the order of 0.5 mm/s. However circumstantial evidence was found that the OKLNG sediment might not be fully flocculated. Evidence pointing to this hypothesis includes:

- a. Measured concentrations exceeding the saturation concentration in case of flocculated sediment
- b. A very low settling velocity measured 20 km west of the site
- c. A very low soil strength
- d. A low settling rate of OKLNG sediment samples
- e. The absence of a constant clay/silt ratio
- f. A high montmorillonite content

The possibility of naturally occurring unflocculated sediment is unexpected. To the best knowledge of the author and the consulted experts for this thesis these conditions have not been reported in literature before. One possible mechanism is that the continuous stresses induced by the persistent swell waves break down flocs over time and prevent forming new flocs. This state of the sediment in the water column is however highly uncertain, since no direct measurements are available. Moreover, the sediment state has a large impact on the prediction of the channel infill. For this reason, two scenarios have been investigated for the sediment infill prediction of the OKLNG approach channel. 4. Possible day-to-day sedimentations scenarios for OKLNG

Depending on the sediment state in the water column, two scenarios for OKLNG are possible. Because of the large uncertainty, they are both investigated.

In case of unflocculated conditions, a permanent mobile mud layer will be present near the seabed. Infill occurs when this mud layer flows into the channel. A force balance shows that mud flowing into the channel will not come out again, so the infill solely depends on the specific mud layer mass and near bottom current velocity. This is called scenario 1.

In scenario 2 suspended sediment is present in the water column which slowly settles when crossing the approach channel. Only during extreme events, such as a storm, it is expected that a mud layer is formed that temporarily results in a large infill rate.

5. Expected infill rate of the OKLNG approach channel in case of unflocculated sediment and a subsequent very low settling velocity (scenario 1)

The order of magnitude of the infill in this scenario is very large relative to the channel volume. If no dredging were carried out, the channel would be filled up within weeks with mud with a low density of around $1,030-1,080 \text{ kg/m}^3$.

The uncertainty analysis shows the channel will be full with low density mud in weeks regardless of any of the uncertainties in the input parameters. A more precise prediction of the infill is therefore not necessary. It should be assumed that there is always mud in the channel if the sediment is found to be not to poorly flocculated.

Note that the infill rate by itself does not provide insight in the accessibility of the channel for vessels. This depends on the infill rate, the density of the infill, the settling rate and the consolidation in the channel. So when determining a practical maintenance dredging strategy, settling and consolidation of the sediment in the channel will be just as important as the infill rate and mud density.

- 6. Expected infill rate of the OKLNG approach channel in case of normally flocculated sediment with a subsequent settling velocity of ~0.5 mm/s (scenario 2) The expected infill for scenario is in the order of several Mton of dry sediment per year. Due to the adopted infill model and lack of data a more precise prediction cannot be given. Nonetheless, this order of magnitude still corresponds to a large infill rate relative to the channel volume; the entire channel can accommodate 5.2 Mton of sediment if a mud density of 1,100 kg/m³ is assumed. Regular maintenance is therefore required.
- 7. Suitability of the used simple infill model to compute the infill of the two scenarios The simple method to schematise the infill is suitable for scenario 1. The infill mechanism is straightforward and all parameters of importance are included in the schematisation. However, the model does require validation before it can be used. For scenario 2 this is not the case. The largest problem is that no simple and reliable expression for the trapping efficiency is known. A more sophisticated model like DELFT 3D, MIKE 21 or FINEL 2D is therefore necessary to predict suspended sediment infill. The criterion to distinguish between when suspended sediment infill takes place and when mud layer infill takes place also needs to be more closely looked at. All in all, a simple model is not suitable to properly predict the infill in case two infill mechanisms take place alternately.
- 8. *Suitability of the used simple infill model to assess the uncertainties of the infill prediction* The purpose of using a simple model was to gain insight into the uncertainties and into which parameters influence the outcome most. The model proved to be suitable for this.
- Main uncertainties in the infill prediction and subsequent reduction of them The uncertainty in the sediment state in the water column – unflocculated or normally flocculated – causes the largest uncertainty in the infill prediction: the difference in

predicted infill rate is a factor 10. To reduce this uncertainty the sediment characteristics have to be measured. Afterwards it will be clear which scenario is the correct one for OKLNG.

The largest uncertainty regarding the input parameters for both scenarios is the concentration of the layer closest to the bottom and the corresponding layer height. Concentrations near the bottom above 8 kg/m³ were not registered during the measuring campaign at the project site, so the high concentrations had to be estimated. Fitting probability curves to the concentration data shows a 1% chance of exceeding a concentration of 50 kg/m³ and concentrations measured near the seabed approximately 20 km west of the site show concentrations up to 110 kg/m³ at 10 cm above the bottom. The frequency of occurrence and the chance of exceedance of these high concentrations have a large impact on the infill rate, so this lack of knowledge results in a large uncertainty in the infill prediction.

All other identified uncertainties, such as the distribution of the current velocity near the bottom, are of minor importance in comparison to the two uncertainties just mentioned.

10. Nature of the uncertainties

It is noteworthy that the main uncertainties in this thesis are epistemic uncertainties. These can be reduced by data collection, literature research, expert judgment and comparisons between tests, measurements and model results. The uncertainties identified in this thesis can best be reduced by conducting measurements.

11. Applicability of the probabilistic approach

A probabilistic analysis is a strong method to obtain a quantitative uncertainty analysis, but can only be applied if a relatively simple model is available that has reasonable predictive capacity, a probability distribution can be assigned to each input parameter with reasonable accuracy and correlations between parameters can be defined. If these requirements are met, a full probabilistic analysis can be applied to a sedimentation problem.

In this thesis only a partial probabilistic analysis could be conducted. For scenario 1 the distribution and mean value of the specific mud layer mass³² are not known and for scenario 2 the distribution of the concentration near the bottom had to be estimated. Also the deterministic model was not validated.

12. Added value of the probabilistic approach

Besides being able to quantify uncertainties, a probabilistic analysis has more advantages. A deterministic calculation using the mean values of the input parameters only provides the mean of the predicted parameter, it does not give insight into the symmetry and spread of the distribution.

In case of the OKLNG approach channel the probabilistic calculation shows that the probability distribution of the infill rate is strongly asymmetrical. The chance of eventually having a lower infill rate than the mean is quite large, but there is also a chance of having a much higher infill, which is important to know when designing a maintenance strategy. A deterministic calculation does not provide this insight.

7.2 Recommendations

7.2.1 Recommendations on reducing uncertainties and risk mitigation

1. *Reduce the uncertainty in the sediment state by conducting measurements*. First and foremost the OKLNG sediment characteristics need to be measured to resolve the uncertainty surrounding the sediment state in the water column. This can be done as follows:

³² The specific mud layer mass is defined as the concentration of the mud layer times the layer height

- a. *Measure the settling velocity of the sediment at different heights in the water column and at locations with a varying water depth along the channel*
- b. Investigate the flocculation behaviour
- c. Identify the mineralogy
- 2. Follow the mitigation strategy suitable for the relevant sediment state to deal with the mud infill

Based on the outcome of the measurements mentioned under 1 of this section, it will be known which scenario is the correct one for OKLNG. The mitigation strategy for scenario 1, unflocculated sediment, is as follows with the actions listed in order of importance:

- a. Investigate the settling and consolidation behaviour of the mud
- b. *Revise the nautical bottom concept*
- c. Identify and investigate maintenance strategies suitable for large infill rates of mud with a low density when entering the channel
- d. Validate the mud layer infill model
- e. *Measure the mud layer concentration and height*

The mitigation strategy for scenario 2, flocculated sediment in the water column, is as follows:

- a. Properly measure the concentrations near the bottom
- b. *Measure the lutocline or mud layer height when a mud layer is formed near the bottom*
- c. Investigate the settling and consolidation behaviour of the mud
- 3. Organize a brainstorm to do a complete risk analysis of the OKLNG channel infill Invite several stakeholders and experts on for example sedimentation, navigation, cohesive sediment, soil mechanics and the geology of the Niger Delta area to identify as many mechanisms that contribute to the infill as possible, their likelihood of occurrence and impact and subsequently conduct a complete risk analysis of the channel infill. Include the risk of the channel being inaccessible for vessels due to a large and sudden infill event and the possibility of channel destruction due to growth faults in the risk analysis. Also include the mud outflow at the end of the channel and the sand infill in the analysis of possible mechanisms that influence the amount of sediment in the channel.

7.2.2 General recommendations

- 1. *Consider the applicability of an uncertainty analysis for other morphological problems* The uncertainty analysis proved to be useful for the mud infill prediction of the OKLNG approach channel, but morphological uncertainties are frequently not analyzed probabilistically, although they are very important for marine projects. Applying the used method to other projects might benefit those projects as well.
- 2. Improve the used infill model

The modelling can be improved in several ways, but the most important recommendation is to try to validate the model. For scenario 1 the model is quite straightforward, so validation can be done by either finding suitable reference projects, conducting scale tests in a laboratory or dredging a trial trench and monitoring the infill. For scenario 2 first the specific mud layer mass threshold needs to be studied and a reliable expression for the trapping efficiency has to be found.

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Appendices

Appendix A	Gade's wave damping equation
Appendix B	Vinzon and Mehta's lutocline height equation
Appendix C	Hydraulic roughness height
Appendix D	Soulsby and Clark's bed shear stresses
Appendix E	Derivation of the standard deviation of an average
Appendix F	Confidential figures (not included)
Appendix G	Comparison of scenario 2 with previous studies (not included)

Appendix A. Gade's wave damping equation

A.1 Wave damping equation using Gade's [1958] wave damping coefficient

The decrease in wave height due to wave damping can be calculated using the following equation:

$$H_s(x) = H_0 \exp\left(-k_i x\right)$$

with
$$k = k_r + ik_r$$

Using Gade [1958] the wave damping coefficient on a horizontal bottom can be computed:

$$k = \pm \omega \left(\frac{\left(1 + \Gamma \frac{h_{m0}}{h_{w0}}\right) \pm \sqrt{\left(1 + \Gamma \frac{h_{m0}}{h_{w0}}\right)^2 - 4\gamma \Gamma \frac{h_{m0}}{h_{w0}}}}{2\gamma g \Gamma h_{m0}} \right)^{1/2}$$

with
$$\gamma = \frac{\rho_m - \rho_w}{\rho_w}$$

 $\Gamma = 1 - \frac{\tanh(mh_{m0})}{mh_{m0}}$
 $m = (1 - i)\sqrt{\frac{\omega}{2v_m}}$
 $\omega = \frac{2\pi}{T}$

A.2 Parameters to calculate the wave damping

The following values were used:

Mud layer height	h_{m0}	=	0.05-0.10	m	(Based on Figure 4-7and Figure 4-8)
Water depth	h_{w0}	=	17	m	(Start of channel, wave damping starts here)
Grav. constant	8	=	9.8	m/s ²	
Mud density	$ ho_{\scriptscriptstyle m}$	=	1,070	kg/m ³	(High value, the sediment concentration is equal to 82 kg/m^3 with this mud density.)
Sea water density	$ ho_{_{\scriptscriptstyle W}}$	=	1,020	kg/m ³	(See section 2.4.6)
Mud viscosity	V_m	=	5·10 ⁻⁴ -1·10 ⁻²	m²/s	
Wave period	Т	=	10-16	s	(Av. swell wave period, section 2.4.4)

A.3 Conclusion

The wave damping at OKLNG is found to be limited. The wave damping coefficient ranges from 0.7 to 1 after waves travelled for 9 km from the -16 m CD until the -5.5 m CD depth contour over a 5-10 cm thick mud layer with a sediment concentration of 82 kg/m³ and a viscosity of $5 \cdot 10^{-4}$ to $1 \cdot 10^{-3}$ m²/s. The mud at OKLNG is expected to be more viscous and to contain less sediment, but even under the stricter conditions as just mentioned the wave damping coefficient in the range of 0.85. A 15% wave height reduction over 9 km is very difficult to notice when observing the waves.

When combining the wave damping with shoaling, it is apparent from Figure A-1 that these effects approximately cancel each other out. Since shoaling will also occur, it is impossible to observe wave damping even if a mud layer is present on the seabed.



Figure A-1: The wave damping at OKLNG is limited, even with a high sediment content of 82 kg/m² and a low viscosity of 10^{-3} - 10^{-4} m²/s. When also taking shoaling into account, these effects cancel each other out

Appendix B. Vinzon and Mehta's lutocline height equation

B.1 Vinzon and Mehta's [1998] lutocline height equation

The thickness of the mud layer when the concentration profile collapses can be calculated using Vinzon and Mehta's [1998] equation for the equilibrium height of the lutocline in the water column:

$$H_{e} = 0.65 \left(\frac{\left(a_{b}^{3}k_{r}\right)^{3/2}}{T^{3}\Delta g w_{s} C_{v}} \right)^{1/4}$$
with $a_{b} = H/2 \sinh(kh)$
 $k = \frac{2\pi}{L}$
 $L = T\sqrt{gh}$ (Shallow water assumption is valid)
 $\Delta = \frac{\rho_{s} - \rho_{w}}{\rho_{w}}$
 $C_{v} = \frac{V_{s}}{V_{w}} = \frac{c/\rho_{s}}{1 - c/\rho_{s}}$ (Mean volumetric conc. of suspended solids measured at $H_{e}/2$; dry sediment volume per unit volume of water)
B.2 Parameters to calculate the mud layer height

The following values were used to construct Figure 4-7:

Wave height	H	=	1.4 m	(Av. wave height in July-Aug., section 2.4.4)
Wave period	Т	=	14 s	(Av. swell wave period, section 2.4.4)
Grav. constant	g	=	9.8 m/s ²	
Roughness height	k_r	=	0.0004 m	(See Appendix C)
Water depth	h	=	11 m	(Average water depth, see section 4.3.2)
Sea water density	$ ho_w$	=	1,020 kg/m ³	(See section 2.4.6)
Sediment density	$ ho_{s}$	=	2,600 kg/m ³	(Av. value of 25 samples, see section 3.4.3)
Settling velocity	W _s	=	~0.004 mm/s	
Sediment concentration	on c	=	Varied kg/m ³	

B.3 Conclusion

The outcome of the calculation is depicted as Figure 4-7 in section 4.4.2 of the report.

Appendix C. Hydraulic roughness height

C.1 White-Colebrook [1937] friction coefficient

White-Colebrook used the following relation for the bottom shear stress:

 $\tau_0 = \rho_w c_f u^2$

This formula is analogue to what Soulsby and Clark [2005] used (see Appendix D.2), so it can be stated that $c_f = C_{DS}$.

The roughness height can subsequently be calculated using White-Colebrook:

$$\frac{1}{\sqrt{c_f}} = 5.75 \log\left(\frac{12h}{k_r}\right)$$

C.2 Parameters to calculate the roughness height

The following values were used to estimate the roughness height in the OKLNG area:

Friction coefficient	c_{f}	=	0.0025	(See Appendix D.2)		
Water depth	h	=	11 m	(Average water depth, see section 4.3.2)		

C.3 Conclusion

This results in a roughness height $k_r = 0.02-0.07$ m. Although the bottom is very smooth, the waves cause the roughness height to increase considerably. When only taking the current into account and thus using $c_f = 0.001$, the roughness height is only 2 mm. To compute the mud layer height in section 4.4.2 a roughness height $k_r = 0.04$ m will be used. It should be kept in mind that the waves can influence this height to a large extent; a very calm period will result in a roughness height of only millimetres and a storm event in a roughness height of a decimetre. Other parameters such as the Reynolds number do not cause a large variation of the roughness height.

Appendix D. Soulsby and Clark's bed shear stresses

D.1 Soulsby and Clark's [2005] shear stress

Roughness coefficients and wave friction factor

Soulsby and Clark [2005] have come up with an equation to calculate the roughness coefficient for hydraulically smooth and freshly-deposited mud beds in turbulent flows:

$$C_{Ds} = 0.0001615 \exp(6 \cdot \operatorname{Re}_{c}^{-0.08})$$

With $\operatorname{Re}_{c} = uh/v$
 $v = \mu/\rho_{w}$

The wave friction factor under the same circumstances can be found as follows:

$$f_{ws} = 0.0521 \operatorname{Re}_{w}^{-0.187}$$

With $\operatorname{Re}_{w} = u_{w}A/\upsilon$ $A = \frac{u_{w}T}{2\pi}$

Smooth-turbulent wave and current shear stress

The mean value of the shear stress under the combination of waves and currents is calculated as follows:

$$\tau_{mean} = \rho_w C_{Dmean} u^2$$

With
$$C_{Dmean} = \left(\left(A_1^2 + A_2 \right)^{1/2} - A_1 \right)^2$$

 $A_1 = \frac{T_3 \left(\ln T_2 - 1 \right)}{2 \ln T_1}$
 $A_2 = \frac{0.40T_3}{\ln T_1}$
 $T_1 = 9 \cdot 0.24 \cdot \left(\frac{f_{ws}}{2} \right)^{1/2} \left(C_{Ds}^2 \left(\frac{u}{u_w} \right)^4 + \left(\frac{f_{ws}}{2} \right) \right)^{1/4}$
 $T_2 = \left(\frac{\text{Re}_c}{\text{Re}_w} \right) \cdot \left(\frac{u}{u_w} \right)^4 \cdot \frac{1}{0.24} \cdot \left(\frac{2}{f_{ws}} \right)^{1/2}$

$$T_3 = \left(C_{Ds}^2 + \left(\frac{f_{ws}}{2}\right)^2 \cdot \left(\frac{u_w}{u}\right)^4\right)^{1/4}$$

The maximum value of the shear stress under the combination of waves and currents is calculated according to:

 $\tau_{\rm max} = \rho_w C_{D\,{\rm max}} u^2$

With
$$C_{D\max} = \left(\left(C_{Dm} + T_3 \cdot \frac{u_w}{u} \cdot \left(\frac{f_{ws}}{2} \right)^{1/2} \cdot \cos \left| \phi \right| \right)^2 + \left(T_3 \cdot \frac{u_w}{u} \cdot \left(\frac{f_{ws}}{2} \right)^{1/2} \cdot \sin \left| \phi \right| \right)^2 \right)^{1/2}$$

D.2 Parameters to calculate the shear stress coefficient

The following values were used to find the shear stress coefficient in the OKLNG area:

Average mid-depth current velocity	и	=	0.18	m/s	(See section 2.4.5)
Water depth	h	=	11	m	(Average water depth, see section 4.3.2)
Dynamic viscosity	μ	=	8.5·10 ⁻⁴	Pa's	(See section 2.4.6)
Sea water density	$ ho_{\scriptscriptstyle w}$	=	1,020	kg/m ³	(See section 2.4.6)
Wave orbital velocity amplitude at sea bed	u_w	=	0.8	m/s	(See section 2.4.5 and Figure 2-27)
Wave period	Т	=	14	S	(Av. swell wave period, section 2.4.4)
Angle	ϕ	=	Varies	0	(Between current and wave direction)

D.3 Conclusion

The current velocity, water depth, wave orbital velocity, wave period and angle between the current and waves have been varied. Computed parameters are:

Re _c	=	1-6·10 ⁶
Re _w	=	1-4·10 ⁶
C_{Ds}	=	0.001
f_{ws}	=	0.0035
C_{Dmean}	=	0.0025
f_{ws}	=	0.02-0.03
	${ m Re}_{c}$ ${ m Re}_{w}$ ${ m C}_{Ds}$ ${ m f}_{ws}$ ${ m C}_{Dmean}$ ${ m f}_{ws}$	$Re_{c} = Re_{w} = C_{Ds} = f_{ws} = C_{Dmean} = f_{ws} = f_{ws} = 0$

It should be noted that the influence of the waves on the friction coefficient is much higher -a factor 3.5 - than the influence of the flow. This will result in a large roughness height when also taking waves into account.

Appendix E. Derivation of the standard deviation of an average

E.1 Starting points and definitions

We assume a random variable *X* with an assigned distribution with a mean μ and standard deviation σ . The mean is defined as the weighted average or expected value of a random variable *X* and is expressed as $\mu = E[X]$. The standard deviation is defined as a function of the variance:

$$\sigma^2 \equiv Var(X)$$

With the variance defined as:

$$Var(X) \equiv E\left[\left(X - E[X]\right)^2\right]$$

E.2 Mean and variance of an average value

Call X_1 , X_2 , X_3 ,... an independent³³ and identically distributed sequence. The sum of the sequence $\sum_{n=1}^{i=1} X_i$ is a function of n random variables and thus a random variable itself. The average of n random variables is then:

$$\overline{X} = \frac{X_1 + X_2 + \ldots + X_n}{n} = \frac{1}{n} \sum_{n=1}^{i=1} X_i$$

Using linearity of expectations this results in:

$$E\left[\overline{X}\right] = E\left[\frac{1}{n}\sum_{n}^{i=1}X_{i}\right]$$

$$= \frac{1}{n}E\left[X_{1} + X_{2} + \dots + X_{n}\right]$$

$$= \frac{1}{n}\left(E\left[X_{1}\right] + E\left[X_{2}\right] + \dots + E\left[X_{n}\right]\right) = \frac{1}{n}\left(\mu + \mu + \dots + \mu\right)$$

$$= \frac{1}{n}\left(n \cdot \mu\right)$$

$$= \mu$$

³³ The outcome of the first draw at $t = t_i$ does not influence the outcome of the next draw at $t = t_{i+1}$.

In case $X_1, X_2, X_3,...$ are independent, the following is valid for the sum:

$$Var(\sum X_{i}) = Var(X_{1} + X_{2} + ... + X_{n})$$

= $Var(X_{1}) + ... + Var(X_{n}) + 2Cov(X_{1}, X_{2}) + ...$
+ $2Cov(X_{1}, X_{n}) + ... + 2Cov(X_{2}, X_{n}) + ... + 2Cov(X_{n-1}, X_{n})$
= $Var(X_{1}) + Var(X_{2}) + ... + Var(X_{n})$

The covariance is zero in case X_1 , X_2 , X_3 ,... are independent.

The variance of a random variable multiplied by a constant, in this case 1/n, is:

$$Var\left(\frac{1}{n}X\right) = E\left[\left(\frac{1}{n}X - E\left[\frac{1}{n}X\right]^{2}\right)\right]$$
$$= E\left[\left(\frac{1}{n}X - \frac{1}{n}E[X]\right)^{2}\right]$$
$$= E\left[\left(\frac{1}{n}\right)^{2}\left(X - E[X]\right)^{2}\right]$$
$$= \left(\frac{1}{n}\right)^{2}E\left[\left(X - E[X]\right)^{2}\right]$$
$$= \frac{1}{n^{2}}Var(X)$$

Thus the standard deviation in this case is $\frac{1}{n}\sigma$.

Using the variance of the sum, the variance of a random variable multiplied by a constant and independence of $X_1, X_2, ..., X_n$ the variance of the average \overline{X} is given by:

$$Var\left(\overline{X}\right) = \frac{1}{n^2} Var\left(\sum_{n=1}^{i=1} X_i\right)$$
$$= Var\left(X_1 + X_2 + \dots + X_n\right)$$
$$= \frac{1}{n^2} \left(\sigma^2 + \sigma^2 + \dots + \sigma^2\right)$$
$$= \frac{1}{n^2} \left(n \cdot \sigma^2\right)$$
$$= \frac{\sigma^2}{n}$$

Thus $\sigma_{\overline{X}} = \frac{\sigma_X}{\sqrt{n}}$.

Appendix E Derivation of the standard deviation of an average

E.3 Relevance for this thesis

The mean yearly infill quantity based on one time step can be represented by a random variable X_i . The standard deviation when applying n time steps for the mean yearly infill quantity decreases with \sqrt{n} .