

Final Report

Master's Thesis:

Siltation of Approach Channel and Harbour Basin

Kyung-In Canal Project, South Korea

January 2006



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PREFACE

In order to achieve the degree of Master of Science in Civil Engineering a graduation project has to be finished. In January 2005 I looked for a challenging thesis, when possible within an international context. The engineering company DHV Environment and Transportation offered me everything I wished and I travelled to South Korea to define a subject. The subject had to be practical, broaden my knowledge and had to contain a modelling exercise. This resulted in my subject that comprises a quantitative analysis of the processes that cause siltation due to the construction of a navigational route and a terminal area in Kyunggi Bay. All characteristics mentioned above were present, so I started my study.

This document is the final report of my Master Thesis research. This research is carried out in cooperation with Delft University of Technology and DHV Environment and Transportation. The members of my graduation committee are:

Prof. dr. ir. M.J.F. Stive	DUT, Civil Engineering, Coastal Engineering (chairman)
Dr. ir. Z.B. Wang	DUT and WL Delft Hydraulics
Ir. W. Klomp	DHV Environment and Transportation
Ir. G.J. de Boer	DUT, Civil Engineering, Fluid Mechanics

I would like to thank Prof. dr. ir. M.J.F. Stive for his guidance and advices throughout this Master Thesis research. I would like to thank Dr. ir. Wang for helping me to understand the principles of modelling an estuary. I would like to thank Gerben de Boer for all his time, advices and good conversations. Last but not least, I would like to thank Wim Klomp everything, but especially for the pleasant way of working together.

I also would like to thank my family and friends for their support during all the years of my study. Without their help it would be far more difficult to finish my study. Last but not least, I would like to thank Corianne for her support and the pleasant times we had together during my study.

January 2006, Joost van der Lans

SUMMARY

Seoul Metropolitan Area is the heart of the fast growing South Korean economy. Nowadays, Incheon Port is the only harbour for this area and is expanding very fast. The present harbour capacity already causes delays for ships that have to wait for berthing. Subsequently, all the goods must be transported from Incheon Port to their final destination. This causes large congestion problems on the roads from Incheon Port to Seoul. To solve these problems the Korean government decided to investigate the feasibility of an inland waterway to Seoul. This waterway must provide direct canal access from the sea to Seoul Metropolitan Area, enhancing coastal shipping, mitigating environmental unfriendly road traffic and alleviating the pressure on the adjacent Port of Incheon.

On August 28th 2004 a contract was signed for the feasibility study and master plan of the "Kyung-In Canal project" between the Korean Water Resources Cooperation (KOWACO) and the consortium DHV Environment and Transportation and SAMAN Engineering Consultants Co. The project consists of:

1. The Kyung-In Canal connecting the sea with the Han River;
2. Two terminal areas, named Incheon Terminal and Seoul Terminal, at both ends of the canal;
3. The dredging of an Approach Channel.

The figure shows the sea side of the Kyung-In Canal (for whole project Figure 1 on page XVII)



This study focuses on the siltation of Incheon Terminal basin and the Approach Channel. The annual siltation is an important factor in the economical feasibility of the project. To guarantee sufficient water depth for vessels entering Incheon Terminal maintenance dredging or other measures are required. These measures are money consuming and may form an obstacle for navigation. The siltation of Incheon Terminal basin depends on the amount water that enters the harbour basin per tidal cycle and the sediment

content of the water. This sediment influx in Incheon Terminal basin is governed by three mechanisms: tidal prism, horizontal eddies in the harbour entrance and density currents. Given a tidal range in Kyunggi Bay that is reaching up to 9 metres in the Project Area, the study mainly focuses on the siltation caused by tidal filling. This mechanism includes two processes. The tidal filling via the Approach Channel into Incheon Terminal and tidal filling via the inter-tidal area in front of Incheon Terminal basin. The latter is involved with the sediment influx in Incheon Terminal basin caused by the flood current across the inter-tidal area. In the study the siltation due to tidal filling will be considered in relation to the influence of other mechanisms as part of an overall Analytical Approach. This results in the following objectives:

Make a quantitative assessment of the influences of tidal filling on the siltation of 'Incheon Terminal basin' and 'Approach Channel' due to the execution of the Kyung-In Canal project.

Determine the influence of tidal filling in relation to the other mechanisms that cause siltation in 'Incheon Terminal basin'.

For this study use is made of the one-dimensional network model 'SOBEK River & Estuary' (SOBEK RE). The model SOBEK RE provides insight in the mechanisms that are caused by tidal filling. In SOBEK RE the main branches in Kyunggi Bay are schematised. For the schematisation of the inter-tidal area in front of Incheon Terminal an individual branch is used. To prevent drying of the branch with low water the 'dry bed procedure' in SOBEK RE is used, since SOBEK RE cannot calculate with dry branches. Although SOBEK RE is suitable to simulate the tidal wave, the capabilities of SOBEK RE with respect to predicting siltation rates in Incheon Terminal basin are questionable. This results in the second objective of this study:

Determine if 'SOBEK River & Estuary' is suitable to predict the siltation in Incheon Terminal basin caused by tidal filling or can be used to improve the understanding of this siltation mechanism.

The Project Area is located in Kyunggi Bay, which is part of the Yellow Sea. Kyunggi Bay is a macro tidal embayment with a mean spring tidal range reaching up to 9 m. Kyunggi Bay is characterised by the presence of many islands, which provide a sheltered environment for extensive inter-tidal areas. About 10 kilometres north of the Project Area, Yeomha Waterway flows into Kyunggi Bay. The Yeomha Waterway is a branch of Han River and plays a significant role in determining the sediment transport and fresh water discharge in the Project Area during the rain season. Kyunggi Bay has a dynamic morphological character due to the many reclamation projects executed in the last decades.



The photo shows the Project Area with inter-tidal areas

In SOBEK RE a schematisation of the main channels in Kyunggi Bay is made in the so-called 'Autonomous Situation'. The objective of the 'Autonomous Situation' is to provide a correct representation of the tidal propagation, since this is the main hydrodynamic process in Kyunggi Bay determining the sediment transport in the Project Area. In the Project Area a correct simulation of the phase differences between the horizontal and vertical tide is considered important. This simulates the flood current that causes sediment influx in Incheon Terminal basin. After calibration of the 'Autonomous Situation' all the proposed interventions in the Kyung-In Canal project are schematised in the so-called 'Project Situation' (Appendix X).

In the execution of the analysis, a distinction is made between the Analytical Approach and the modelling approach based on the application of SOBEK RE. The Analytical Approach is involved with a desk study of the relevant theory, aiming to provide an insight in the relative importance of the relevant siltation processes and a first quantitative assessment. The Analytical Approach is used as a reference for the modelling based on SOBEK RE. Within the results of SOBEK RE, a distinction is made between the 'far field' and 'near field' results. The 'far field' results show the hydrodynamic and morphological changes due to the execution of the Kyung-In Canal project at a large spatial scale (including the siltation of the Approach Channel). The 'near field' results include the influence of tidal filling and the inter-tidal area on the siltation in Incheon Terminal basin.

The Analytical Approach shows a significant annual siltation of 0.5 m in Incheon Terminal basin caused by tidal prism. However, density currents during the rain season show a comparable annual siltation of 0.6 m. Although not further investigated in the modelling part of this study, the influence of the latter mechanism cannot be neglected in the feasibility study of the Kyung-In Canal project. The annual siltation (0.1 m) in Incheon Terminal basin due to horizontal eddies is only limited.

The 'far field' results show the differences between the 'Autonomous Situation' and 'Project Situation'. This results in quite reasonable hydrodynamic and morphological changes due to the execution of the Kyung-In Canal project on a large spatial scale. The tidal prism increases due to the construction of Incheon Terminal basin and the Entrance Channel, which connects the Approach Channel with Incheon Terminal basin. This leads to a small increase in flow velocities and an increase in tidal range, which results in a change in sediment transport in the main channel between Youngjong Island and the Korean mainland. Subsequently, this leads to erosion in the areas north and south of the Project Area. In the Approach Channel a large, concentrated siltation occurs due to the instantaneous behaviour of SOBEK RE, causing a large amount of sediment to settle at the location where flow velocities are reduced. When distributing the sediment over the whole area with low flow velocities this results in an annual siltation rate of 1.5 meter. However, this is an overestimation of the siltation rates, since in reality not all sediment will have enough time to settle in the Approach Channel.

The instantaneous behaviour of SOBEK RE results in significantly lower suspended sediment concentrations in front of Incheon Terminal basin compared with reality. Consequently the 'near field' results show lower annual siltation in Incheon Terminal basin than the Analytical Approach. The calculated annual siltation rates in SOBEK RE and the Analytical Approach are 0.2 m and 0.5 m, respectively. Probably the siltation rates in Incheon Terminal basin lies in between these values. The sudden change in sediment concentration in SOBEK RE is an overestimation of what happens in reality, since sediment needs time to settle. However, a reduction in sediment concentrations in front of Incheon Terminal basin can be expected. The siltation rates determined in the Analytical Approach are pessimistic, since this approach assumes that all sediment influx settles in the harbour basin. In the Entrance Channel the siltation is expected to be lower than in the harbour basin, since this area is less sheltered. In summary, the instantaneous behaviour of SOBEK RE makes the model less suitable to determine the annual siltation rates in this specific case. However, in SOBEK RE also the annual siltation rates in the existing Incheon North Port (approximately 15 km south of the Project Area) are calculated. For this open harbour basin both SOBEK RE and the Analytical Approach

determine approximately the same annual siltation of 0.3 m, since no dredging work and thus decrease in sediment transport capacity takes place in this area.

The 'near field results' show that the influence of the inter-tidal area in front of Incheon Terminal basin is very sensitive to the simulation of the hydrodynamics in the Project Area. This is caused by the small distance between both sides of the inter-tidal area compared with the length of the tidal wave. In this study it is concluded that the influence of the inter-tidal area is smaller than initially expected. The flooding of the inter-tidal area starts from both sides of the branch, which results in a dead tide (point with no flow velocities) in the middle of the inter-tidal area. Gradually, this point of no flow velocities moves in the direction of Incheon Terminal basin and finally results in a flood current. This flood period only occurs during a short period and therefore results in a rather small annual siltation of less than 0.1 m.

In summary, it can be concluded that SOBEK RE has proven to be suitable to describe the 'far field' changes due to the execution of the Kyung-In Canal project in the macro-tidal Kyunggi Bay. Furthermore, SOBEK RE is suitable to predict the siltation due to tidal prism in Incheon North Port. However, in the specific case of the Incheon Terminal project, the instantaneous behaviour of SOBEK RE results in some shortcomings, leading to an overestimation of the siltation in the Approach Channel. In addition, the instantaneous behaviour of SOBEK RE results in an underestimation of the siltation in Incheon Terminal basin caused by 'direct' tidal filling. With respect to the influence of the tidal filling via the inter-tidal area, SOBEK RE suffers from some severe limitations in properly schematising and describing this mechanism. Although some indicative results and insight could be obtained, it should be concluded that SOBEK RE is not really suitable for this purpose.

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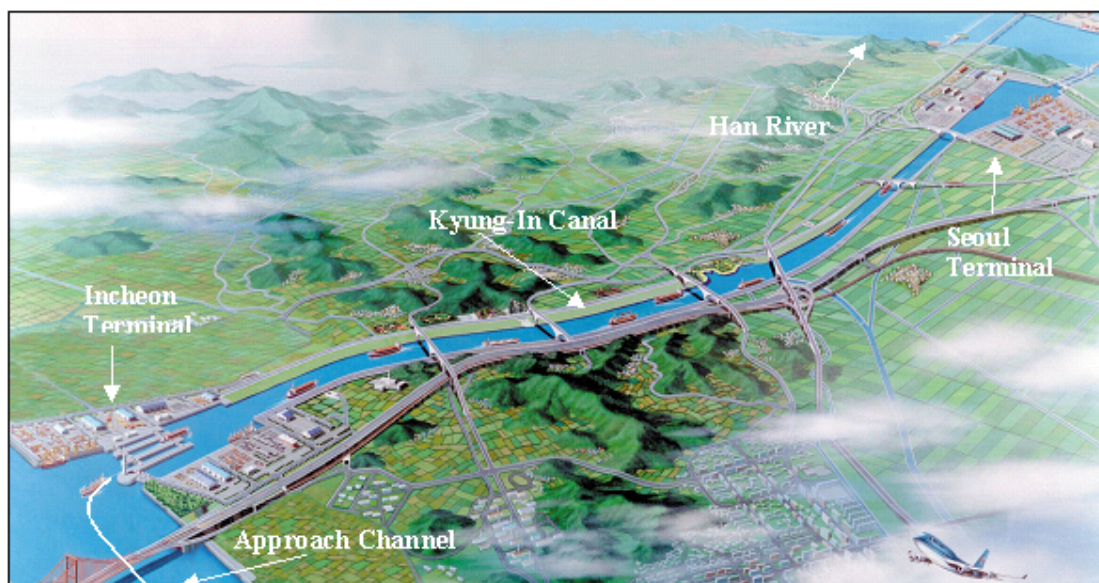
GENERAL INTRODUCTION

Background

The South Korean economy is one of the fastest growing economies in the world. Consequently, in South Korea high quality infrastructure is demanded. This holds especially in Seoul Metropolitan Area, where the heart of the South Korean economy is established. In theory ship traffic to Seoul Metropolitan Area is possible via Han River. However, Han River flows through restricted North Korean area and can therefore not be used for navigation. Nowadays, Incheon Port is the only harbour for this area and is expanding very fast. This already causes delays for ships that have to wait for berthing. Subsequently, all the goods must be transported from Incheon Port to its final destination. This causes large congestion problems on the roads from Incheon Port to Seoul.

To solve these problems, a project is formulated to create an inland waterway to Seoul. This so-called Kyung-In Canal project must provide direct canal access from the sea to Seoul Metropolitan Area, enhancing coastal shipping, mitigating environmental unfriendly road traffic and alleviating the pressure on the adjacent Port of Incheon. 0 shows a future presentation of the Kyung-In Canal project. The project consists of:

1. The Kyung-In Canal connecting the sea with the Han River;
2. Two terminal areas, named Incheon Terminal and Seoul Terminal, at both ends of the canal;
3. The dredging of an Approach Channel.



Overview of the Kyung-In Canal project [208]

Problem definition

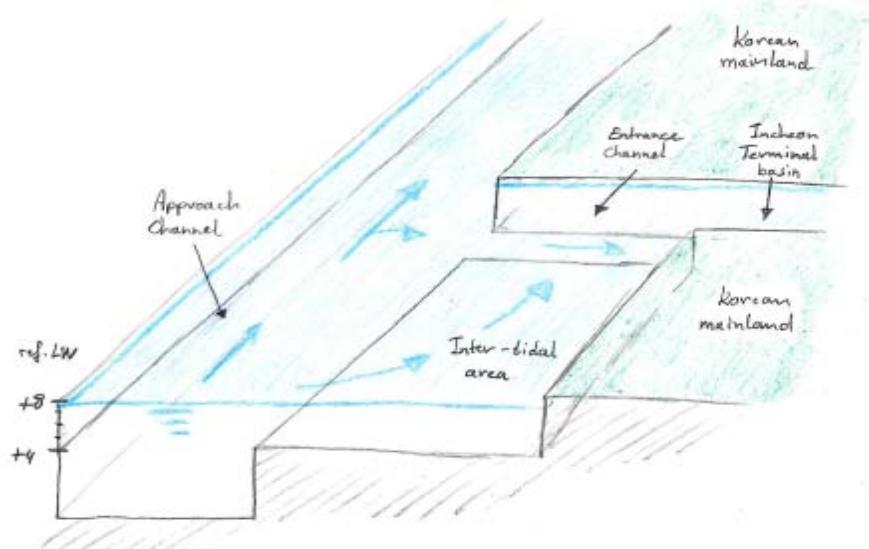
Siltation in the Project Area can be an important factor in the economical feasibility of the Kyung-In Canal project. The dredging of the Approach Channel and the construction of Incheon Terminal basin causes siltation. However, sufficient water depth for vessels entering Incheon Terminal must be guaranteed at all times to compete with other harbours in the region. This requires money consuming maintenance dredging or other measures to prevent siltation, which may form an obstacle for navigation.

This study focuses on the siltation of Incheon Terminal basin and the Approach Channel. The processes resulting in siltation of Incheon Terminal basin and the Approach Channel cannot be adequately addressed by only considering the Project Area. Also the area further away from the Project Area needs to be taken into account, since the presence of the Kyung-In Canal project will have impacts on a large spatial scale. This is the reason why the study is separated in a 'far field' investigation and a 'near field' investigation.

The 'far field' area reaches from 8 km upstream Yeomha Waterway to 5 km south of Incheon North Port and includes the new Approach Channel to Incheon Terminal basin (Appendix IX). The tidal wave enters this area from the south. The macro tidal character of Kyunggi Bay causes large sediment transports in the main channel. The execution of the Kyung-In Canal project will change both hydrodynamics and morphology on a large spatial scale. These changes are studied in the 'far field' investigation.

In the 'near field' investigation an open harbour basin for Incheon Terminal is considered. This basin forms a sheltered area in which the transport capacity of the water reduces and siltation occurs. Based on the literature about sedimentation in open harbour basins [5] the amount of sediment entering an open harbour basin depends on the volume of water that enters the harbour basin per tidal cycle and the sediment content of the water. This water exchange between estuary and harbour basin is governed by three mechanisms: tidal prism, horizontal eddies in the harbour entrance and density currents. It is expected that from these three mechanisms the tidal prism is most significant. Due to the large tidal range in Kyunggi Bay reaching up to 9 metres in the Project Area, this study mainly focuses on the siltation caused by tidal filling.

In Incheon Terminal basin, not only 'direct' tidal filling via the Entrance Channel causes siltation. In front of Incheon Terminal basin an inter-tidal area is situated. The flood current that enters Incheon Terminal basin via this inter-tidal area may cause a large influx of fine sediment from the inter-tidal area into the open harbour basin. This mechanism is an important aspect in this study.



Flood current across inter-tidal area (blue arrows)

Objective

The study focuses on the siltation of the Approach Channel and Incheon Terminal basin caused by tidal filling. To gain insight in the relative importance of all mechanisms, the siltation due to tidal filling will be considered in relation to the other mechanisms causing siltation in open harbour basins as part of an overall Analytical Approach. This results in the following objectives:

Make a quantitative assessment of the influences of tidal filling on the siltation of 'Incheon Terminal basin' and 'Approach Channel' due to the execution of the Kyung-In Canal project.

Determine the influence of tidal filling in relation to the other mechanisms that cause siltation in 'Incheon Terminal basin'.

In this study use is made of the one-dimensional network model 'SOBEK River & Estuary' (SOBEK RE). SOBEK RE is based on the process equations for conservation of mass and momentum. Given these equations SOBEK RE is suitable to simulate the main hydrodynamic processes in Kyunggi Bay driven by the tidal wave. The use of the one-dimensional model SOBEK RE will make it easier to gain insight in the specific physical processes compared with a more laborious 3-dimensional model. Moreover, it is easier to calibrate SOBEK RE with the relatively limited amount of data available for this study.

Although SOBEK RE is suitable to simulate the tidal wave, the capability of SOBEK RE regarding the prediction of siltation rates in open harbour basins is questionable. The morphological calculations of SOBEK RE are instantaneous, which means that the sediment transport directly reacts on changes in the flow velocity. Other uncertainties are involved with the schematisation of the inter-tidal area in front of Incheon Terminal. Because the shallow inter-tidal area falls dry with low tide and SOBEK RE cannot handle branches that do not hold water, the so-called 'dry bed procedure' is applied. This procedure establishes a small, deep, funnel shaped channel in the middle of the cross sectional area, which prevents completely drying of the branch. The correctness of simulating the influence of the inter-tidal area in this way is again questionable. This leads to the second objective of this study:

Determine if 'SOBEK River & Estuary' is suitable to predict or improve the understanding of siltation in Incheon Terminal basin caused by tidal filling.

To determine the suitability of SOBEK RE in predicting the siltation in Incheon Terminal basin caused by tidal prism, the Analytical Approach is used as reference. For the model results regarding the influence of the inter-tidal area no reference is available.

Siltation will automatically lead to the need of periodic maintenance dredging. However, maintenance dredging is a very cost consuming activity, hinders ship traffic and has negative impacts on the marine environment. For this reason the study also considers the possibility of applying certain mitigating measures.

Overview of the study

This study is divided in five parts (A – E). The relation between these parts is shown at the end of this section. The references for this study are mentioned with numbers between squared brackets, which are related to the references at the end of this report. Part A gives an overview of what the Kyung-In Canal project is about. In part B the most relevant theory from the literature study is presented. This theoretical knowledge deals with the hydrodynamics and morphology in estuaries. Furthermore, the

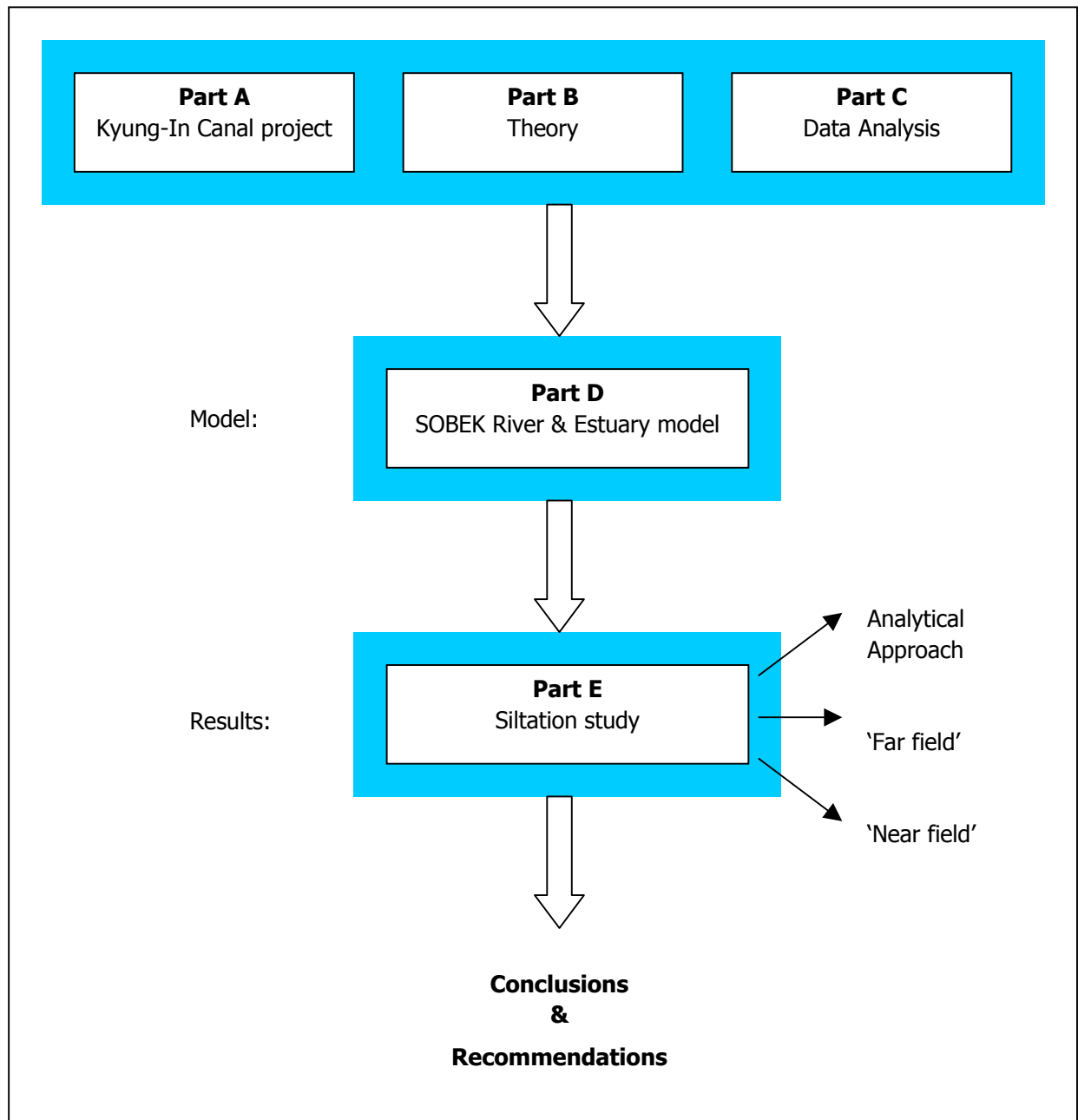
theory about water exchange mechanisms in open harbour basins is described, since these mechanisms drive the siltation in open harbour basins.

Part C starts with a description of the main characteristics of Kyunggi Bay and the Project Area. This is followed by a desk study in which the main processes that determine the hydrodynamics and morphology in Kyunggi Bay are described. Papers and company visits in South Korea provided the data presented in Part C. The information in Part A, B and C is used to set up and calibrate the model in Part D.

Part D starts with a description of the capabilities of the one-dimensional network model SOBEK Rivers & Estuary. In SOBEK RE a schematisation of the main channels in Kyunggi Bay is made in the so-called 'Autonomous Situation' (Appendix IX). This is followed by the calibration of the 'far field' hydrodynamics, which focuses on a correct propagation of the tidal wave. The calibration of the 'near field' hydrodynamics focuses on a correct simulation of the horizontal tide, since the horizontal tide is mainly responsible for the sediment transports in the Project Area. In addition, the calibration of the 'near field' hydrodynamics focuses on a correct simulation of the phase difference between the horizontal and vertical tide. This is important to simulate the flood current across the inter-tidal area, which causes sediment influx into Incheon Terminal basin. The calibration of the morphology focuses only on the 'near field' area, since no data for a 'far field' calibration are available. The objective of the 'near field' calibration is a correct simulation of the sediment transport in the Project Area. Part D ends with the schematisation of the so-called 'Project Situation' in which all the proposed interventions of the Kyung-In Canal project are included (Appendix X).

Part E deals with the overall results of the study. First the results of the *Analytical Approach* are described. The Analytical Approach provides an insight in the importance of the different processes causing siltation in Incheon Terminal basin. Furthermore, the Analytical Approach is used as reference for the SOBEK RE study. Subsequently, the SOBEK RE results are presented and distinguished in 'far field' and 'near field' results. The *'far field' results* show the hydrodynamic and morphological changes due to the execution of the Kyung-In Canal project at a large spatial scale. Because the Approach Channel is located in the main channel through which the tidal wave is propagating, the siltation of the Approach Channel is also treated in this chapter. Within the *'near field' results* both the influence of the tidal prism and the influence of the inter-tidal area on the siltation in Incheon Terminal basin are considered. For determining the influence of the tidal prism, the siltation of the harbour basins of Incheon Terminal is compared with the siltation of the existing harbour basin of Incheon North Port. Furthermore, the influence of the nodal point relation is investigated, since the nodal point relation is important in simulating the sediment influx into open harbour basins. With respect to the inter-tidal area, the 'near field' results are analysed to make further interpretations of the correctness of the schematisation of the flood current and the related sediment flows into Incheon Terminal. Based on the correctness of this schematisation the influence of the inter-tidal area can be determined. In the *discussion* all SOBEK RE results are compared with the results of the Analytical Approach. Where possible the study results are also linked to the consequences in reality. Part E ends with suggestions for *mitigation measures*.

The last part of the report is involved with the Conclusions and Recommendations. The conclusions deal with the answers to the objectives of the study and provide a summary of the main conclusions of the different parts of the study. The recommendations outline the main subjects that need further research.



Overview of study and structure of report

PART A

Kyung-In Canal project



Figure A: Animation of Project Area [208]

A.1 BACKGROUND KYUNG-IN CANAL PROJECT

The Kyung-In Canal (KIC) has been under study for 15 years now. It all began after a major flood hits Gulpo Chun area to the west of Seoul, on the West bank of the Han River in 1987, which affected 1.5 million people. After the flood temporary measures were taken. Firstly, a weir and Shinkok pumping station in Gulpo River were constructed in 1992. The pumping station can pump floodwater into the Han River. Secondly, a drainage channel to the Yellow Sea with a floodgate at the Incheon side of the channel was constructed in 1997 (Tailrace drainage channel in Figure A.1-1). From then on the drainage of the Gulpo Chun area was partially pumped into the Han River and partially flowing through the Tailrace drainage channel into the Yellow Sea.

The plan for a navigational function of the drainage channel was proposed in the nineties. This could provide direct canal access to the Seoul metropolitan area, encouraging coastal shipping and mitigating environmental unfriendly road traffic. Furthermore a navigation channel will alleviate the pressure on the adjacent Port of Incheon due to the expected growing economy. Due to objectives of environmentalists and Non-Governmental Organisations the project was postponed in 2000. Amongst others two problems of the environmentalists were:

1. Water pollution in the navigation canal from the more polluted Han River
2. Negative marine impact by fresh water influx into the Yellow Sea.

Another concern was the economical feasibility of the project due to lack of cargo through the canal.



Figure A.1-1 Birthview on the Tailrace drainage channel [208]

After some studies the Korean government decided in 2003 to construct a wider Tailrace drainage channel as a final solution for the flooding. Furthermore, a new feasibility study was recommended to analyse all different opinions about a navigational function of Kyung-In Canal. On August 28th 2004 a contract was signed for the feasibility and master plan of the Kyung-In Canal Project between the Korean Water Resources Cooperation (KOWACO) and the consortium of DHV Environment and Transportation and SAMAN Engineering Consultants Co. Main items of the reassessment were:

- Review of the cargo volume, transportation system and facilities already planned in the Kyung-In Canal project.
- Propose a facility plan and assess environmental effects.
- Economical and financial feasibility study of the recommended plan.

Based on the results of this reassessment the consortium defined a conceptual design of the total project. This so-called Master Plan incorporates the various aspects for effective usage of the canal.

A.2 DESCRIPTION OF KYUNG-IN CANAL PROJECT

A.2.1 Introduction

The project area is situated in the Gyeonggi Province in the north of South Korea (Figure A.2-1). The Kyung-In Canal runs from the Kyunggi Bay in the Yellow Sea, also known as West Sea, to the Han River. This 17 km long canal crosses paddy fields and rocky hills. Several bridges and road underpasses are necessary to cross the Kyung-In canal. The canal will optimally use of the existing Tailrace drainage channel.



Figure A.2-1 Map of Kyunggi Bay (in Yellow colour Gyeonggi Province and in blue the KIC project) [208]

The details of the project in this chapter have been obtained from the Master Plan executed by the consortium DHV Environment and Transportation and SAMAN Engineering Consultants Co. The project consists of three parts:

1. The Kyung-In Canal, which runs from the Yellow Sea in eastward direction to the Han River.
2. Two Terminal areas, named Incheon Terminal and Seoul Terminal, at both sides of the canal, which provide loading and unloading facilities.
3. The dredging of an Approach Channel that provides a navigational connection between the existing access channel to Incheon North Port and Incheon Terminal.



Figure A.2-2 Animation of current situation [208]

A.2.2 Kyung-In Canal

To guarantee smooth passage of fully loaded sea-river vessels, the Kyung-In Canal is proposed with a bottom width of 80 m and a minimum depth of 6.3 m. Figure A.2-3 gives a cross section of the proposed canal and some important water levels. The upgrading and widening of the existing Tailrace drainage channel for the first 14 kilometres from the Yellow Sea is now under construction. The last 3 kilometres have to be excavated in the future to realize a connection with the Han River. The canal crosses hard rock and soft material and where necessary a slope protection will be executed to prevent scour. The profile of the canal varies, since slopes along rocky areas are steeper (1:2) than in soft soil areas (1:3). The large quantities of material from the excavations can be used for road foundation, land reclamation or to construct dikes.

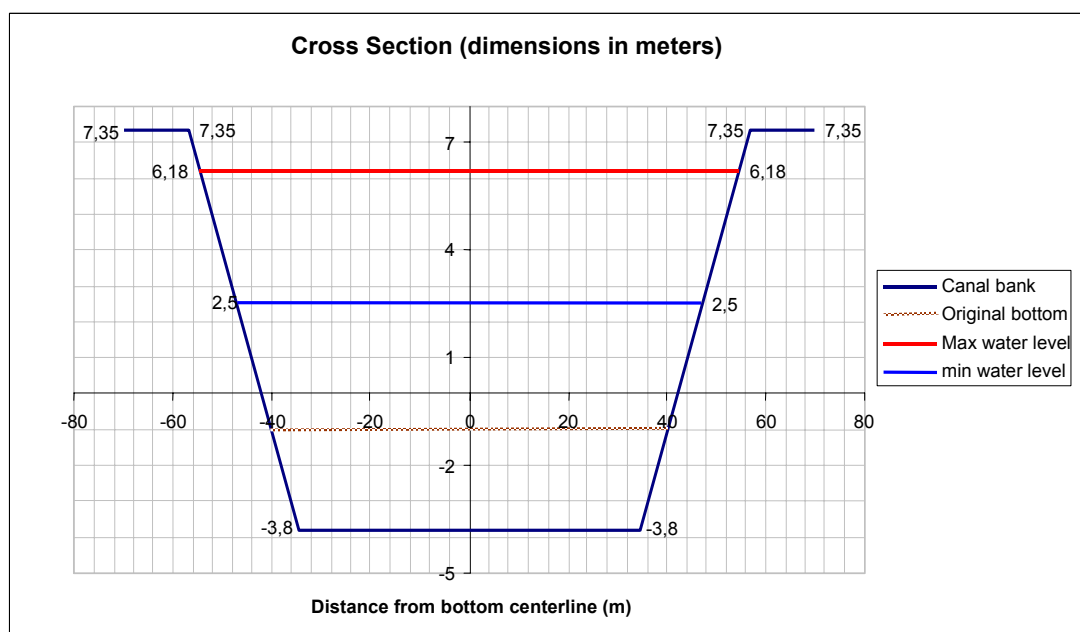


Figure A.2-3 Cross section of proposed navigation channel [201]

A.2.3 Terminal areas

Incheon Terminal is planned at the seaside of the Kyung-In Canal. In the planned terminal area a floodgate is already situated for drainage of the Gulpo Chun area during the rain season. The terminal includes cargo-handling facilities for containers, steel, vehicles and other cargo. Probably these facilities will be located at both sides of a lock system. Several hundreds of meters of quays provide berth for vessels (Figure A.2-4).

The total area of Incheon Terminal is approximately 230 ha of which the terminal basin takes approximately 53 ha. The depth of the basin is DL -10 m (Datum Level = Approximate Lower Low Water at Incheon) and the dredged material can be used for the reclamation of the terminal area. The composition of the soil in the basin is silty, so upgrading the soil quality will be necessary for reclamation. To ensure safety against flooding the terminal height must be EL +6.5 m. More information about Datum Level and Elevation Level is included in Appendix I.

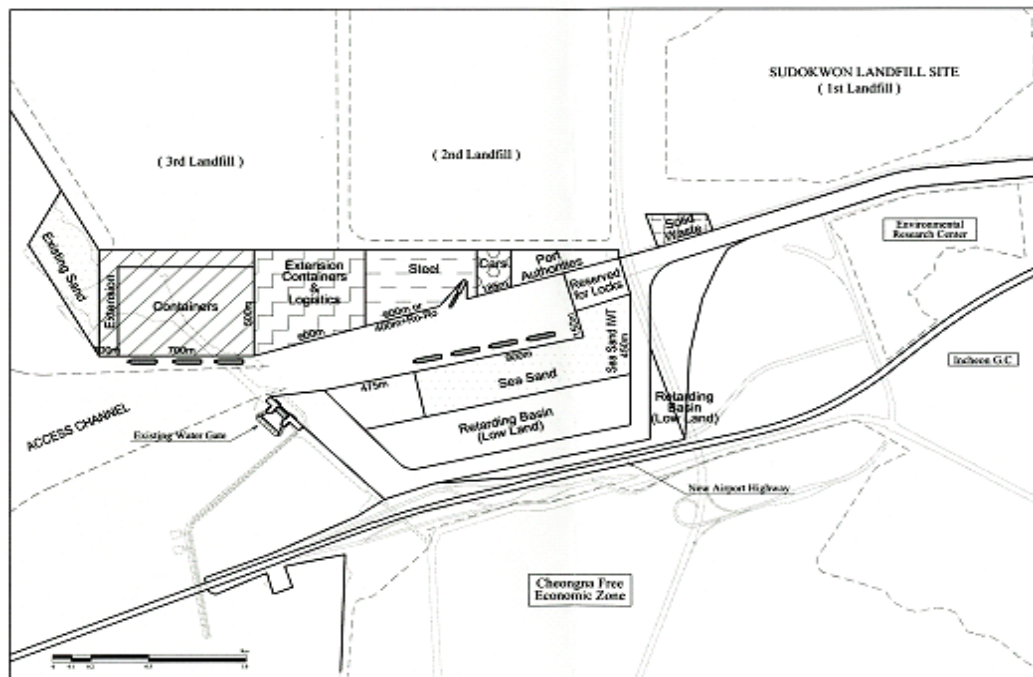


Figure A.2-4 Lay-out of open harbour basin Incheon Terminal [208]

At the Han River side of the canal Seoul Terminal is situated. This inland terminal provides the same facilities as Incheon Terminal and will be approximately 200 ha. It is necessary to heighten the terminal area to EL +7 m to be safe against maximum flood (EL +6.18 m). As for Incheon Terminal, dredged soil can be used for reclamation or heightening. At Seoul Terminal the canal will be connected to the Han River by a lock system. These locks provide passage for sand barges to reach one of the three planned sand wharfs along Han River and to transport waste from Seoul to the huge landfill site along the Kyung-In Canal.

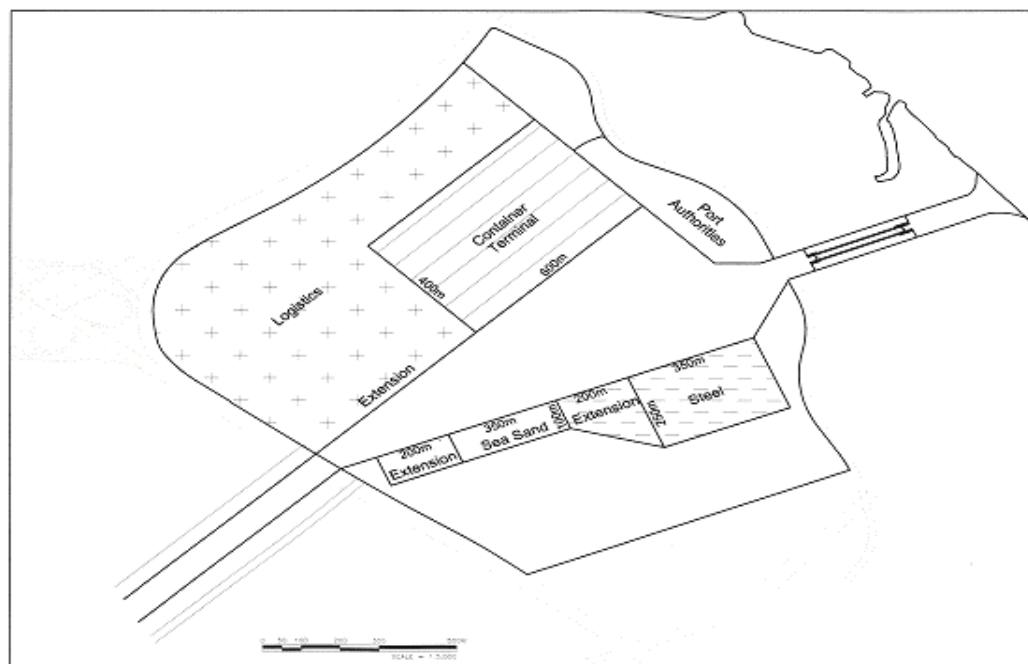


Figure A.2-5 Lay out Seoul Terminal [208]

A.2.4 Approach Channel

A dredged Approach Channel, an extension of the navigation channel to Incheon North Port, creates access to Incheon Terminal. The Approach Channel incorporates four sections, which are indicated by the blue lines in Figure A.2-6:

1. Main Channel: The Main Channel is accessible during all phases of the tide. This two-way channel is 200 meters wide and has a length of 5.7 km. The cross sectional slopes are 1:7 and the depth is DL -10 m.
2. Sub-Channel: The majority of the vessels expected are sand barges. These barges sail slowly, do not require much water depth and have poor manoeuvring capacity. These vessels can use an already existing sub-channel. This two-way route is 130 m. wide, 4 km. long and has got a minimum depth of DL -4 m.
3. Turning Basin: ships need a turning basin in which they can turn and align themselves to the entrance channel because of the strong north-south current. Probably use will be made of tugboats to support the vessels into the open terminal basin.
4. Entrance Channel (is Acces Channel in Figure A.2-6): connects Incheon Terminal with the main channel. The defined depth is DL -10 m. just like the Main Channel.

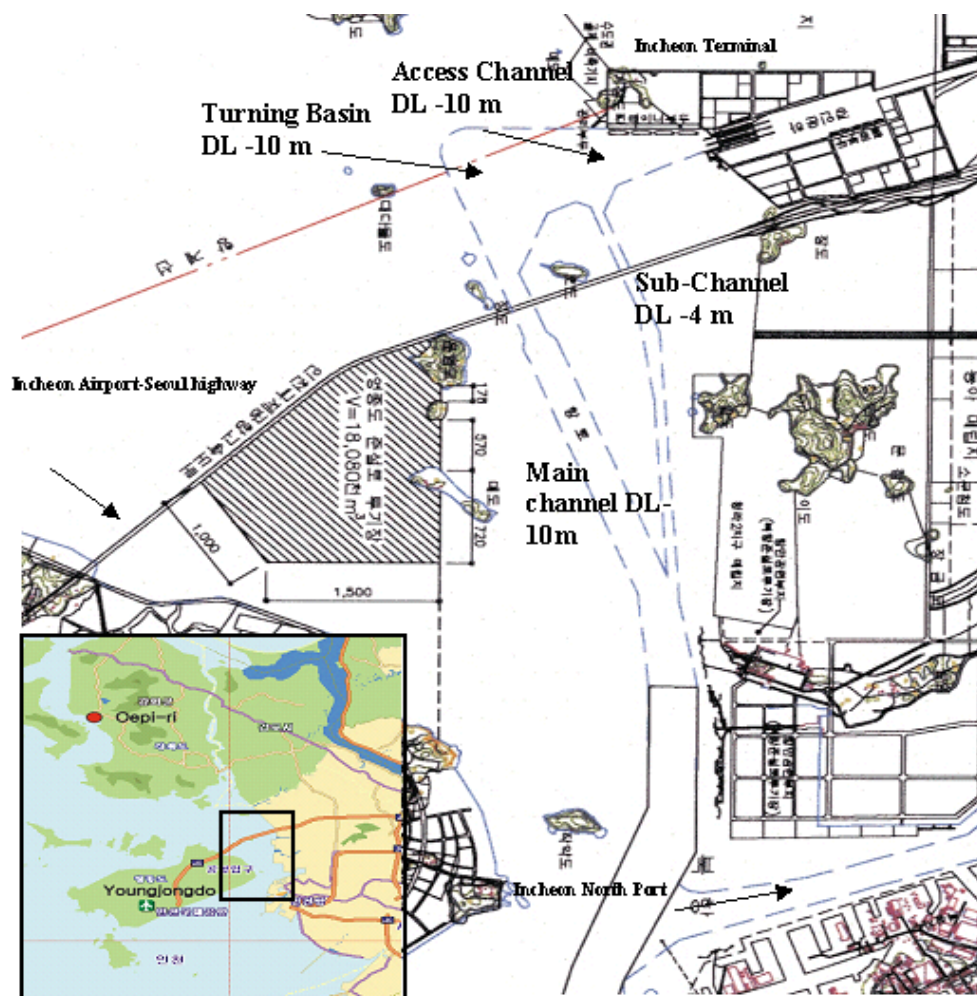


Figure A.2-6 Lay out of Approach Channel [207]

The soil characteristics of the Access Channel can be divided in two parts:

- 1) Main Channel
- 2) Turning Basin and Entrance channel (Access channel).

The Main Channel lies in a naturally scoured channel and is already deepened due to the strong tidal current. That is why the alignment of the channel is relatively straightforward. Here sand and gravel can be found. The turning basin and entrance channel lie in an inter-tidal sedimentation zone with fine silt and mud. Here more siltation is expected, because the currents are directed perpendicular to the channel. The total amount of dredging work for the access channel is estimated at 15.5 million m³, divided in 10% of medium sand and 90% of fine silt and mud [203].

PART B

Theory

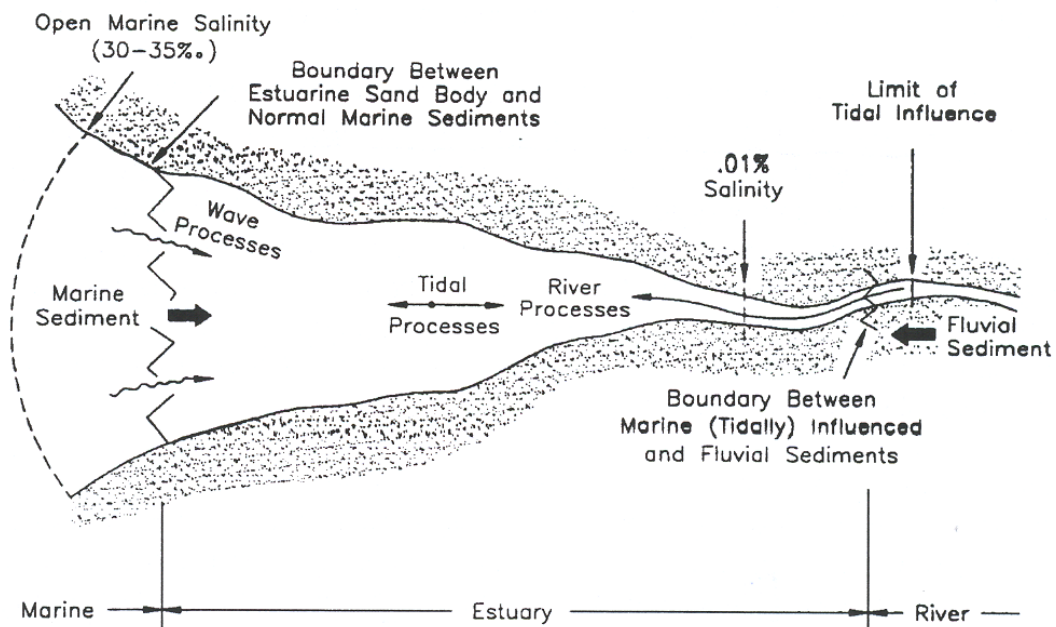


Figure B: Physical processes in estuaries [1]

B.1 PHYSICAL PROCESSES

Most morphodynamic processes that occur in front of the coast are a response to external hydrodynamic processes. Flow in estuaries can be generated by tidal motion, wind, waves, density differences and river discharge. The main hydrodynamic process in this study is the tidal motion, but also the flow, wind waves, wind currents, density flows and relative sea level rise are treated in this chapter. Every process is treated in a separated section (B.1.1 - B.1.5). In addition, non-hydrodynamic processes induce morphological changes. The most significant non-hydrodynamic influence is human interference, which is treated in section B.1.6.

B.1.1 Tidal motion

The generation of the astronomical tide is the result of the gravitational interaction between the Sun, Earth and Moon. The tidal wave (ebb and flood cycle) generated by gravitational forces induces two different water movements. A vertical movement (tidal elevation) when the tidal wave is passing and a horizontal current resulting from the vertical variation of the water level. The latter depends on the

friction of the water in the estuary and the tidal prism. When the horizontal current changes direction and no flow velocities occur a slack tide appears.

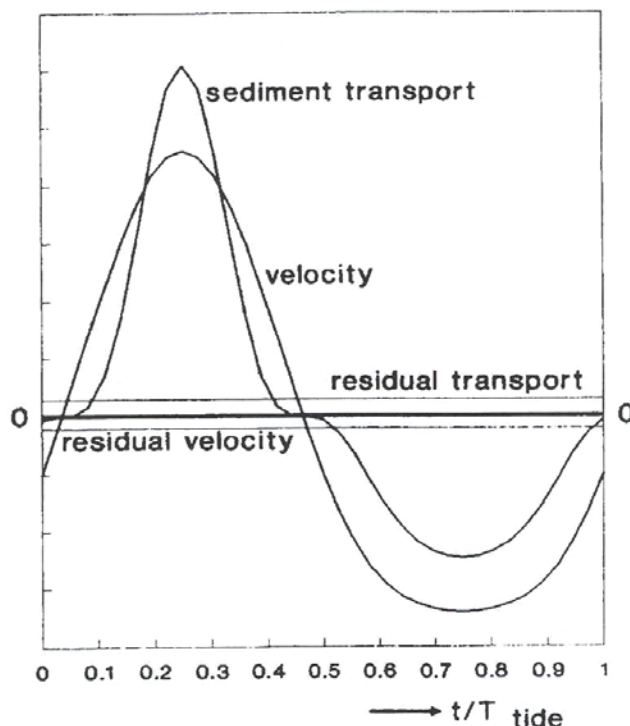


Figure B.1-1 Sediment transport vs. flow velocities [4]

The attraction of both the sun and the moon causes a spring-neap tidal cycle with a period of approximately 14 days. Every tidal signal contains several harmonic constituents, which are diurnal (K1, O1 etc.), semi-diurnal (M2, S2 etc.) or contains other features. The influence of these constituents depends on the location on the world. Due to an angle between the turning-axis of the earth and the rotation of the moon and sun around the earth there also exists a daily inequality between ebb and flood tide.

The morphological shape of an estuary and many other local factors also influences the tide, resulting in tidal asymmetry and many non-tidal constituents. The reason for tidal asymmetry is the non-linear interaction between the tidal wave and the geometry of the estuary. This causes a difference in flow velocities during rising sea level and falling sea level (Figure B.2-3). The tidal currents are very important for the sediment transport in an estuary, since the sediment transport is proportional to the flow velocity above a certain threshold of motion.

Two types of physical processes give rise to tidal asymmetry:

1. The average magnitude of the flood currents differs from the average magnitude of the ebb currents, accompanied by a difference in the duration of the flood and the ebb periods of time, according to Luijendijk (2001).
2. The velocity variation around slack tide before ebb (*SBE*) differs from the velocity variation around slack tide before flood (*SBF*) (Dronkers (1986)).

B.1.2 Flow

Main and secondary flows

When water flows through a bend or around a shoal the flow is basically three-dimensional. The flow can be divided in a main flow and secondary flow. The main flow is in longitudinal direction and the secondary flow is perpendicular to the main flow in lateral direction. The secondary flow is induced by curvature of the main flow and is always directed from the inner bend towards the outer bend in the upper layers and towards the inner bend in the lower layer (Figure B.2-2, meandering channels).

Residual flows

When the x- and y-component of a current-vector at a specific location are averaged over a tidal cycle, a residual current is usually apparent, because the vector curve is not closed. The tidal related residual currents are relatively small, but they are important for the transport of various fine materials as silt and mud. Basically, residual currents are generated by interaction of the tidal currents with the bottom topography (mud flats) and coastal geometry (islands causing reflection, recirculation patterns, density flows or wind driven flows).

B.1.3 Waves

The shear stress between the wind and the water surface causes wind waves. When the waves travel towards the coast the waves break where the depth is approximately two times the wave-height. When the waves approach the coast in an angle, a long shore current will be generated, due to breaking of the waves in the breaker zone. Along with this current sediment can be transported.

Wave set up occurs inside the breaker zone where breaking waves cause a net shoreward mass transport. A gradient in the waterline creates an undertow along the bottom towards the sea, which may carry sediment (Figure B.1-2).

When waves are small they still can play an important role in the erosion of shallow areas. Even waves generated by passing ships have influence on shallow inter-tidal areas.

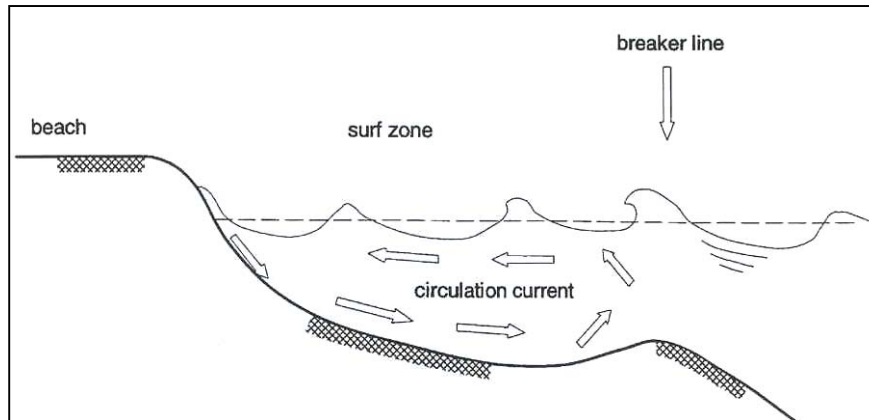


Figure B.1-2 Vertical circulation cell with undertow [2]

B.1.4 Density flows

Density flows or stratified flows are related to spatial density gradients due to variations of water temperature, salinity and/or sediment content.

An estuary is a semi-enclosed water body, connected to the sea, within which salt seawater is significantly diluted by fresh water. The amount of salt, which is totally dissolved in the water, determines the salinity of the water. This leads to three common classifications for salinity of estuaries.

1. Stratified estuary; No mixing of salt and fresh water occurs because of the weak tidal action.
2. Partially mixed estuaries; Tidal currents are the dominant mixing factor and cause only mixing in the interface between salt and fresh water.
3. Well mixed estuaries; Mixing by waves and tidal currents is very intense and an almost homogeneous salinity profile is formed over the depth.

The rate between river discharge and the intrusion of salt water from the sea plays an important role in this classification. The tidal currents and wave action from the sea and the river outflow of fresh water at the head of the estuary are closely interrelated with the sediment movement in the estuary (see figure at title page Part B).

B.1.5 Relative Sea level rise

Relative sea level rise is the sum of subsidence of the land area and absolute sea level rise by the changing climate. Studies on the effect of relative sea level rise stated that the bathymetry follows the water level variation [19].

This can be explained by the slight depth increase of the system, which causes a slight deceleration of the current in the estuary. This reduced flood stream has a smaller transport capacity for sediment and thus results in the settlement of sediment inside the estuary. The reduction of ebb tidal currents lowers the capacity to bring sediment into suspension and the settled sediment will not be transported out of the system.

To follow the relative sea level rise the bottom of the estuary needs sediment. This sediment can be supplied from outside the system by rivers or from the sea. If the sediment supply is insufficient the depth of the estuary will increase and causes a lot of morphological changes. At the end it might be possible that inter-tidal areas disappear.

B.1.6 Human interference

Human activities can be considered as a perturbation on the existing geometry. Due to this perturbations the flow characteristics are changed and this leads to a response of the bed configuration. This again leads to new flow characteristics etc. In this way, the morphological system adjusts itself from an unstable to a (new) stable situation [11]. The following human activities took place in the study area.

Dredging

The dredging of a channel causes imbalances in the hydraulic system. The increased depth can change flow patterns. Furthermore, the dredged area may attract extra flow, if the scale is large enough and may alter the pattern of flood and ebb channels. The enlarged cross sectional area of the channel causes lower flow velocities in the channel. Consequently, this causes a reduction in transport capacity of the water and in sedimentation of the dredged channel.

Reclamation

Land reclamation may totally alter local geometry. The construction of artificial land area decreases the inter-tidal volume (tidal prism) in the estuary. This affects sedimentation and erosion patterns and thus (navigation) channel depths in the estuary (O'Connor, 1982).

Construction of a harbour basin

Constructing a harbour basin increases the inter-tidal volume of the estuary and thus the tidal prism. This gives rise to higher flow velocities through the entrance channels of thus causes erosion of the cross sectional area and sedimentation in other areas.

B.2 MORPHOLOGY AND DYNAMICS OF ESTUARIES

Morphological studies investigate the shape of landforms. An estuary is such a landform and generally consists of extensive inter-tidal areas with channels in between. Many researches investigated the morphology of estuaries amongst others Van Veen (1950). He made the distinction between ebb and flood channels and used the following definitions. A flood channel is a tidal channel open to flood current and exhibits a sill in the upstream end. An ebb channel is a tidal channel that is primary open to ebb

currents and that exhibits a sill at the seaward end (Figure B.2-1).

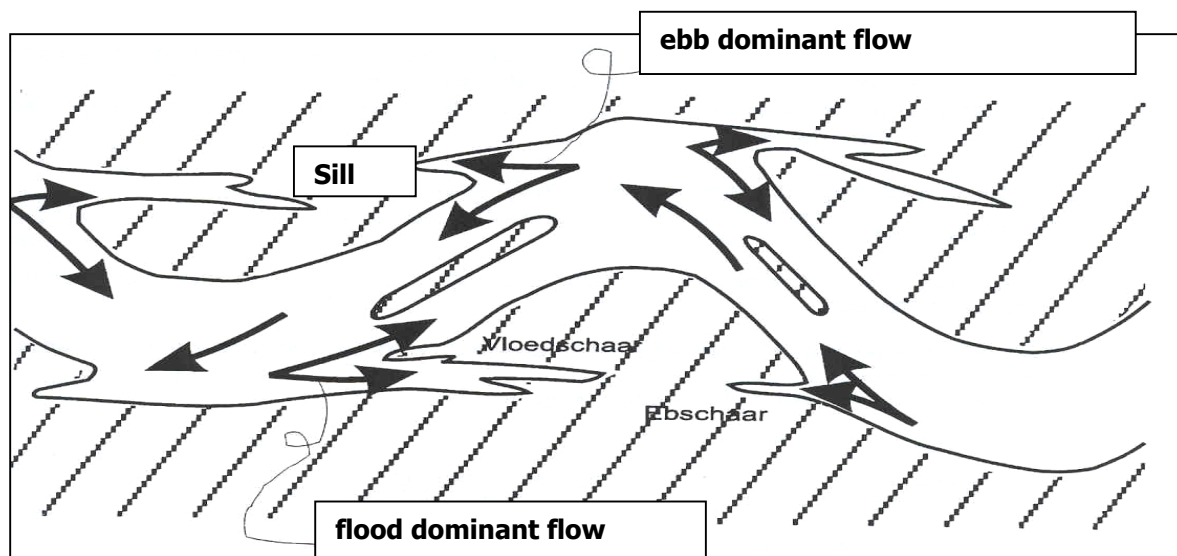


Figure B.2-1 Ebb and flood channels in meandering tidal channel [20]

Because a sill is formed at the end of the channels, it can be concluded that flood channels seem to avoid ebb channels and vice versa and only occasionally there will be a good connection between a main ebb channel and flood channel. When this connection is not formed in a natural way, unnatural measures like training works or dredging are necessary to realise navigation in the channels. For this kind of operations in a system of tidal channels, three main factors play an important role:

1. Meandering; explains morphological changes in the tidal system (section B.2.2);
2. Tidal prism; primary factor causing tidal currents in the tidal system (section B.2.3);
3. Sediment transport; caused by tidal currents and waves (section B.2.4).

Morphological development of estuaries is the result of gradients in sediment transport, which in return influences the hydraulic circumstances. Due to the non-linear interaction of water movement,

sediment transport and changing bathymetry, the morphological behaviour of estuaries is rather complex. This is the reason that the main results of many researches are empirical relations between the hydraulic circumstances and morphology. Most well known is the research by Escoffier (1940) (B.2.3). Moreover, the salinity distribution may influence the sedimentation processes and the behaviour of the muddy shoals in the project area. The theory on these subjects is discussed in section B.1.4 and B.2.5. Finally a description of the different spatial and time scales of morphodynamic processes is discussed in section B.2.6.

B.2.2 Meandering channels

The morphology of an estuary plays an important role in determining the flow characteristics. The meandering of the channels and bending of the flow due to coriolis forces cause these curvatures in the flow field. Averaging this flow over a tidal cycle results in transversal, residual flow circulations in a cross section perpendicular to the main flow direction. This results in a slightly higher water level in the outer bend compared with the inner bend. The transversal circulation causes erosion of the outer bend and sedimentation in the inner bend and a meandering shape of the channel. This difference in the cross sectional water level causes in his turn longitudinal residual flow circulation. This circulation is directed away from the outer bend and then directed towards the inner bend where the water level is slightly lower. This circulation in a horizontal plane, also called 'headland eddy', has the same effect on the bathymetry as the transversal circulation (Figure B.2-2).

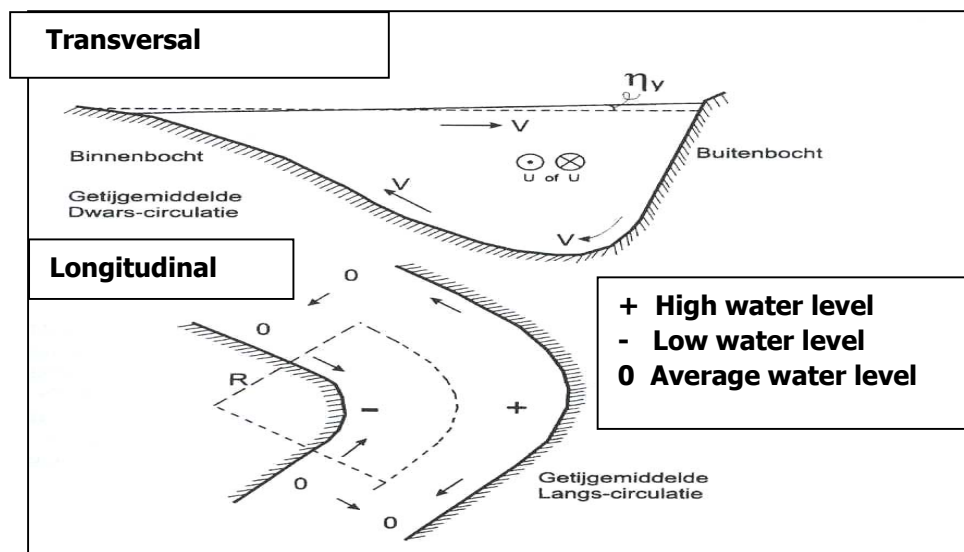


Figure B.2-2 Transversal and longitudinal circulations in channel bend [4]

When the ebb and flood current flow through the same channel, the ebb channels are in general deeper. This is caused by the time difference between high water (H.W.) and high water slack (kentering H.W.) and results in a higher flow velocity in a concentrated deeper part of the channel (Figure B.2-3).

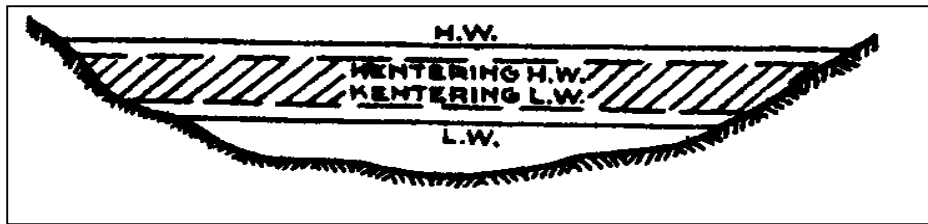


Figure B.2-3 Difference in water level between high water and high water slack or low water and low water slack [20]

B.2.3 Tidal prism

The tidal prism is the water entering the mouth of an estuary during rising tide. The tidal prism is especially important for the cross-sectional area of the channels connecting the estuary with the sea. The relation between the tidal prism and the cross-sectional areas depends on the theory of Escoffier, which says that every inlet has an equilibrium cross-sectional area:

$$A_c = c_A P$$

With: A_c = Cross-sectional area of the inlet below MSL [m^2]
 c_A = Coefficient of proportionality, dependent on the local conditions [-]
 P = Tidal prism [m^3]

When this equilibrium is disturbed, for instance by executing dredging works, a process of erosion and sedimentation is initiated until a new dynamic equilibrium is reached. Figure B.2-4 presents the relationship between the current velocity in a channel and the cross sectional geometry (x) of the channel. When the current comes above the critical velocity (V_{cr}), the current causes erosion. Now, the inlet gradually changes until the equilibrium condition in point D is reached. When the channel dimensions are smaller than in point B on the curve, the channel is too small and the friction is too high to maintain itself; so the channel will be closed by a natural process. When the geometry is situated in section D-E of the curve, the geometry becomes smaller and V increases until point D is reached (see arrows in Figure B.2-4).

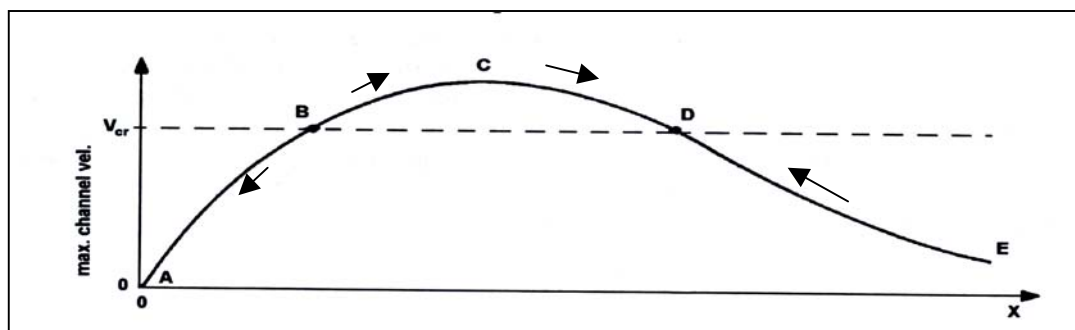


Figure B.2-4 Relationship between channel geometry and velocity [1]

B.2.4 Sediment transport

Sediment transport is the central process in morphological change [Hibma et al.]. Movement of sediment depends on the hydrodynamic forcing caused by currents, waves and pressure gradients and gravitational forces on a sloping bed. Sediment transport can be separated in bed load transport, across the sea bed and suspended transport, in the water column. By averaging the sediment transport over a certain time period the residual transport can be determined. The bathymetry and geometry are important factors in the residual transport pattern.

The movement of cohesive sediment can be described by a continuous transport cycle, consisting of: erosion, transport, deposition, consolidation and again erosion. The main hydrodynamic parameter that controls these states is the bed shear stress. Above a critical shear stress the bed erodes, while sediment settles out of the water column below a critical flow velocity (Krone, 1962; Patheniades, 1962). The four states of sediment in the transport cycle are linked to each other by the following processes: mobile suspended sediment, a high concentration near the bed which is sometimes referred as fluid mud, a newly deposited or partly consolidated bed and a consolidated bed (Figure B.2-5).

The transport processes of cohesive sediment are rather complex because of the strong interaction between waves and the mud bed, resulting in fluidization of the upper mud layers and weakening of the waves due to energy exchange between the wave motion and the mud bed. This is the reason that most studies about cohesive sediment are more site specific than of a fundamental nature.

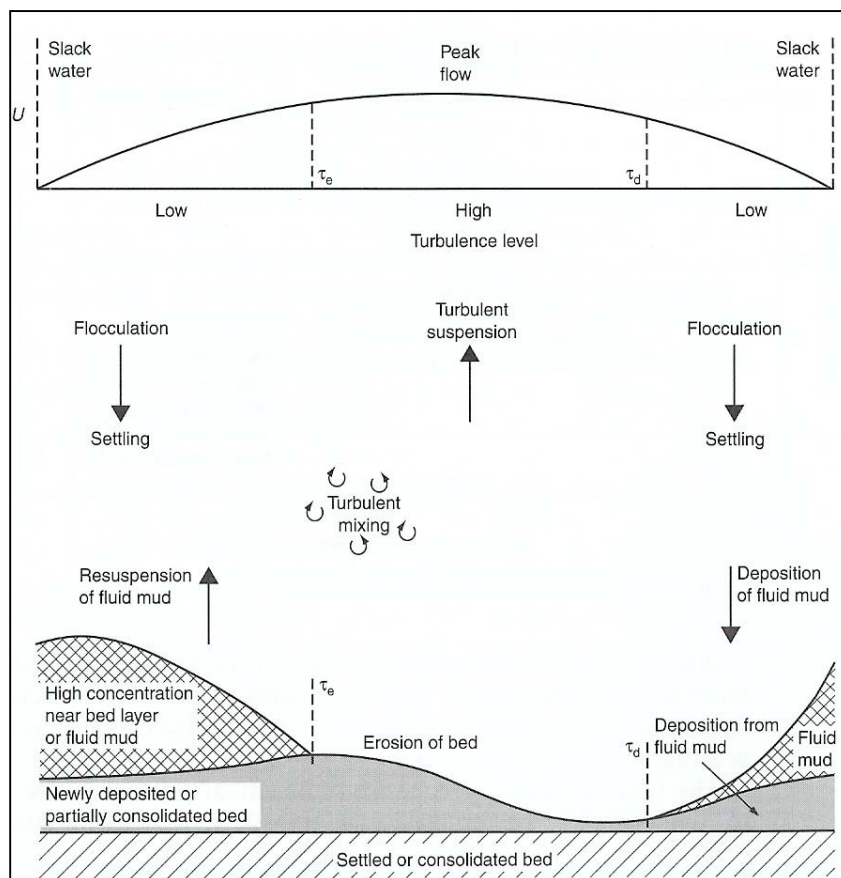


Figure B.2-5 Status of cohesive sediment [22]

B.2.5 Muddy shoals

Generally speaking sediment containing more than 10% of fine material (sieved material finer than 63 micron) may exhibit cohesive properties. Mud is such a cohesive material and is primarily composed of silt and clay. Mud contains a large proportion of very small particles, which have a large specific area such that the effect of surface physico-chemical forces becomes as important as the effect of gravity forces. Whereas in sandy sediment it is the particle size of the bed sediment, which controls the mobility and transport of sediment, in cohesive sediment individual particles stick together forming flocs, whose bulk properties determine the behaviour of the sediment. In salt water the formation of flocs (flocculation) even increases by attraction forces between positive salt ions and negatively charged clay particles.

Cohesive sediment is often found in hydraulically calm inter-tidal areas, also called shoals. Nevertheless, the effect of wave action on shallow shoals is more significant than in deeper areas. The disturbance of a settled bed of fine sediment by wave action can form a layer of fluid mud. Once a fluid mud layer is formed it can be moved by a gravity slope or by currents, or it can be mixed into the overlying water column by entrainment. This can result in high siltation rates in channels and harbour basins.

B.2.6 Morphological time scale

Because of the large variety of morphological elements, the morphodynamic processes have different spatial and temporal scales. On a smaller scale (micro scale) there is almost instantaneous an equilibrium. For example, changing of the bottom profile caused by flowing water. But when local activities are executed in channels, it may take 1 to 10 years before equilibrium is created (meso scale) and for large-scale adjustments over a distance of several kilometres, it can take 10 to 100 years until a new equilibrium is created (macro scale).

B.3 TERMINAL BASIN SILTATION

B.3.1 Water exchange mechanisms

The currents inside an open harbour basin are much weaker than the flow velocities in front of the harbour basin. Since the sediment transport capacity of flowing water is exponentially related to the flow velocity, the reduction of transport capacity of the water when entering the harbour basin is even stronger than the reduction in flow velocity. Consequently, the sediment-loaded water from the estuary enters the harbour basin and settles, due to much lower transport capacity. This is the reason that the open harbour basins suffer from siltation.

The amount of sediment entering the harbour basin depends on the volume of water penetrating the harbour basin per tidal cycle and the sediment content of the water. Furthermore, it depends on the trapping efficiency of the basin. This is determined by quantities such as the rate of flow reduction inside the harbour relative to the area outside the harbour, the fall velocity of the suspended sediment, the depth of the harbour and the retention time of the penetrated water in the basin.

The regular exchange of relatively clear harbour water with silt-laden water from outside the estuary is an important quantity in the mechanism of siltation in an open harbour basin. This water exchange may be governed by three mechanisms: the tidal prism, horizontal eddies in the harbour entrance and density currents. In his study the influence of tidal prism is separated in direct tidal filling and tidal filling via an inter-tidal area in front of the harbour basin.

Understanding of the mechanisms described above is important to predict the amount of siltation for the harbour basin and to evaluate the effectiveness of possible mitigation measures to reduce the siltation in the harbour.

Tidal prism

The tidal prism is the volume of water that is flowing into the harbour basin during a flood period. Because the dimensions of the basin area are very small compared to the length of the tidal wave, it is assumed that the water surface in the basin moves horizontally (Figure B.3-1). The tidal prism can easily be determined:

$$V_t = 2\eta A \quad [B.4-1]$$

V_t = Tidal prism of harbour basin [m^3]

η = Tidal amplitude [m]

A = Storage area of the basin [m^2]

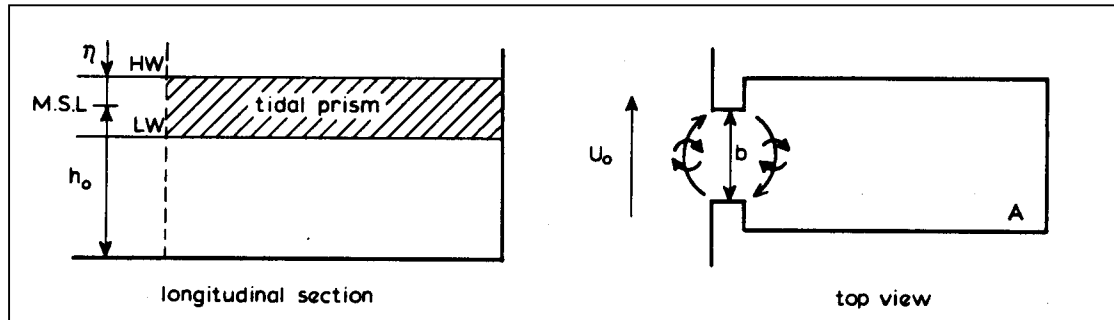


Figure B.3-1 Definition of horizontal exchange mechanism and tidal prism [5]

Horizontal eddies in the harbour entrance

A current passing the entrance of a basin generates an eddy in this entrance. Due to the difference of flow velocities a velocity gradient generates an exchange of water by turbulence. Conservation of mass implies that the separating streamline between the water in the harbour basin and the water in the estuary is directed into the harbour basin (Figure B.3-2). So, the silt-laden water from the estuary reaches an area with weak flow velocities in the harbour basin. At this location, there is insufficient turbulence to keep the sediment in suspension and hence siltation occurs.

The rate of water exchange depends on the flow velocity in front of the harbour basin, the size of the entrance and the water exchange due to tidal variations. This can be approximated by the following formula:

$$V_h = \frac{f_1 h_0 b u_{0,\max}}{\pi T} - f_2 V_t \quad [B.4-2]$$

V_h = Total volume of water exchange per tidal cycle by horizontal exchange flow [m^3]

V_t = Tidal prism of harbour basin [m^3]

h_0 = Water depth at entrance relative to MSL [m]

b = Width of entrance [m]

$u_{0,\max}$ = Maximum flow velocity in front of entrance [m/s]

T = Tidal period [s]

The coefficients f_1 and f_2 generally are within the ranges 0.01-0.03 and 0.1-0.25 respectively and can be estimated based on existing knowledge from comparable situations.

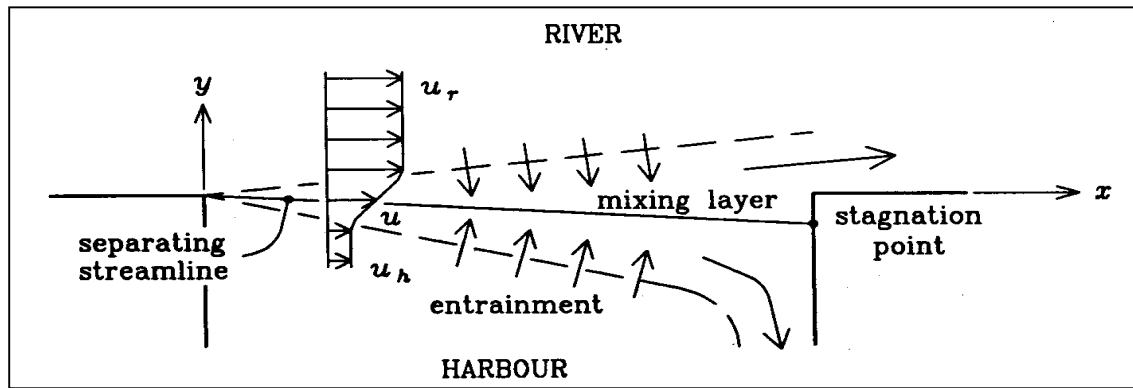


Figure B.3-2 Mixing layer in harbour entrance [5]

Density currents

Water exchange is also caused by density differences between the water inside and outside the harbour basin. When fresh or brackish water is discharged to the sea near the water surface, salt water with higher density enters the harbour basin along the seabed due to density differences occur in the harbour basin. Tidal filling and emptying of the harbour basin reduces water exchange by density currents due to tidal flow velocities through the entrance of the harbour (second part of equation [B.4-2]).

$$V_d = f_4 h_0 b \left(\frac{\Delta \rho_{\max}}{\rho} g h_0 \right)^{\frac{1}{2}} T - f_5 V_t \quad [\text{B.4-3}]$$

$$\text{with: } \Delta \rho_{\max} = \frac{1}{2} (\rho_{0,\max} - \rho_{0,\min})$$

V_d = Exchange volume per tide due to density currents [m^3]

V_t = Tidal prism of harbour basin [m^3]

h_0 = Water depth at entrance relative to MSL [m]

b = Width of entrance [m]

T = Tidal period [s]

g = Gravitational force [m/s^2]

ρ = Density of the water in the harbour basin [-]

$\Delta \rho_{\max}$ = Maximum density difference outside the harbour [kg/m^3]

$\rho_{0,\max}$ = Maximum density outside the harbour [kg/m^3]

$\rho_{0,\min}$ = Minimum density outside the harbour [kg/m^3]

f_4 = coefficient depending on V_{d0}/V_{ha} with V_{ha} being the volume of the basin below MSL

f_5 = coefficient depending on V_{d0}/V_t and phase lag ϕ_t between $u_{d(\text{ensity})o}$ and $u_{t(\text{idal})}$

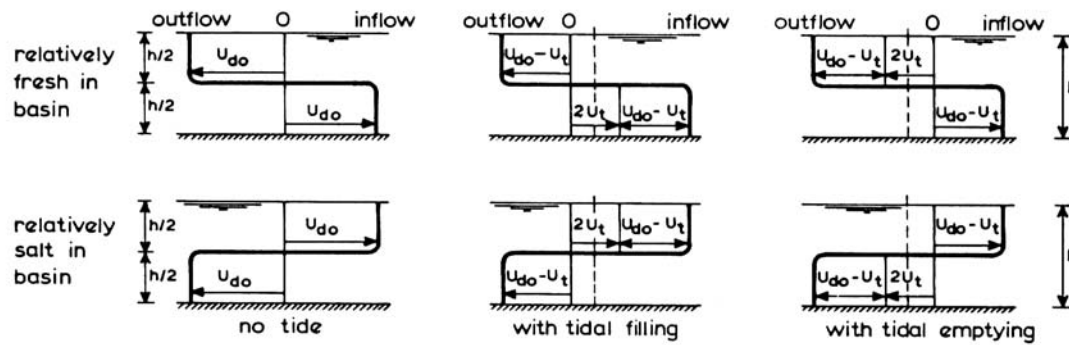


Figure B.3-3 Flow profiles indication reduction of density induced exchange during tidal cycle [5]

In case of a small harbour basin the density of the water inside the harbour may follow the density fluctuations outside. This results in a reduction of density difference induced currents. This effect has been included in the coefficient f_4 and is estimated on a theoretical basis. More explanation about the coefficients is included in Appendix XII.

Total water exchange

The total water exchange is the sum of the results of the three water exchange mechanisms.

$$V_e = V_t + V_h + V_d \quad [B.4-4]$$

B.3.2 Sediment trapping

As already mentioned in the previous section the amount of sediment entering a harbour basin depends on the total water exchange per tidal cycle in the harbour basin and the sediment concentration of the water. Now, the siltation of the harbour basin can be determined, when the settling factor of the incoming suspended sediment is known.

Defining the settling factor is not easy. The following aspects and processes influence the settling velocity:

- Particle fall velocity
- Sediment flow interactions
- Secondary effects

Particle fall velocity

Sediments can be divided in non-cohesive bed material (sand) and cohesive material (clay and silt). Most of the time the cohesive material is dominant in sheltered areas, like harbour basins, because this relatively fine material needs calm areas to settle. Based on experiments, W.D. Eysink estimated in 1989, that the relative sand content in deposits is 5% in existing harbours.

Based on experiments found in literature, the fall velocity of a single fine particle (floc) can be assumed at $1 \cdot 10^{-4}$ m/s. Investigations by Richardson and Zaki (1954) [15] have shown that the fall velocity of a single particle strongly reduces with higher concentrations, because of hindered settling.

Sediment flow interactions

Winterwerp, Uittenbogaard and de Kok (2001) [23] have analysed conditions at which rapid siltation from saturated mud suspension in navigation channels and harbour basin takes place. The maximum suspended sediment concentration that can be carried by turbulent flow is called the saturation concentration. When the sediment concentration exceeds the saturation concentration value, a complete collapse of the turbulence and the concentration profile occurs. This phenomenon may occur when sediment loaded water enters the relatively calm Incheon Terminal basin. This may lead to very fast siltation in the harbour basin.

Secondary effects

In harbours a circulation flow (called gyre) arises as a result of water that enters the harbour basin via the mixing layer. Sediment in the basin deposits in the center of the gyre due to secondary currents, already observed by Rohr (1933) [13]. The secondary current consists of a flow towards the centre near the bottom, where flow velocities are less, and a flow in the opposite direction near the free surface. The amount of gyres in a harbour basin depends on the geometry of the basin (Figure B.3-4)

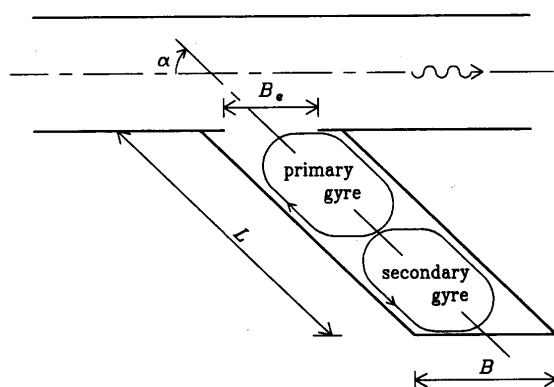


Figure B.3-4 Flow pattern in harbour [13]

PART C

Data Analysis



Figure C: Tidal station Incheon [209]

C.1 INTRODUCTION

When applying a model to gain insight in the processes that cause siltation due to the execution of the Kyung-In Canal, a correct representation of the main processes in Kyunggi Bay is important. In general, a model only produces useful results when correct input is used. Part C presents the main characteristics and environmental conditions of the Project Area regarding the objective of this study.

Chapter C.2 starts with a short description of the Yellow Sea and the propagation of the tidal wave through the Yellow Sea. This tidal wave is used as boundary condition in the schematisation of 'Autonomous Situation' of Kyunggi Bay. Subsequently, the main characteristics of Kyunggi Bay and the Project Area are described. The chapters C.3-C.7 present the results of a desk study in which the environmental conditions that determine the hydrodynamics and morphology in Kyunggi Bay are described. In the last chapter also the expected morphological effects due to the execution of the Kyung-In Canal project are mentioned. Part C finalises with conclusions.

The information in this chapter is provided by the following companies: The consortium DHV Environment and Transportation and SAMAN Engineering Consultants Co, The Korea Agricultural & Rural Infrastructure Cooperation (KARICO), The Korea Ocean Research & Development Institute (KORDI), The Ministry of Maritime Affairs and Fisheries (MOMAF), Korean Water Resources Cooperation (KOWACO), Geosystem Research Cooperation and Seil Engineering. In addition, use is made of a considerable amount of papers about researches in Kyunggi Bay. Unfortunately, the project area is situated close to the frontier with North Korea, which is a restricted area. Therefore data of this part of the area is scarce.

C.2 SITE DESCRIPTION

C.2.1 Yellow Sea

Kyunggi Bay is a part of the Yellow Sea, which is about 1000 km long and 700 km wide. The Yellow Sea is situated on the continental shelf and since post-glacial sea level rise the present basin developed in about 8000 years. The average water depth of the sea is 44 m. The sea is oversupplied with silty clays especially from the Yangtze and Yellow River in China.

In the Yellow Sea predominantly a semi-diurnal tide exists. The tidal wave is generated at the southern hemisphere and propagates through the Pacific Ocean. When entering the shallower Yellow Sea the wave is partly transmitted on the shelf and partly reflected back to the ocean. The (tidal) wave propagation direction changes at the shelf edge due to the refraction effect. Reflection and Coriolis effects give rise to the generation of amphidromic systems in the Yellow Sea (Figure C.2-1).

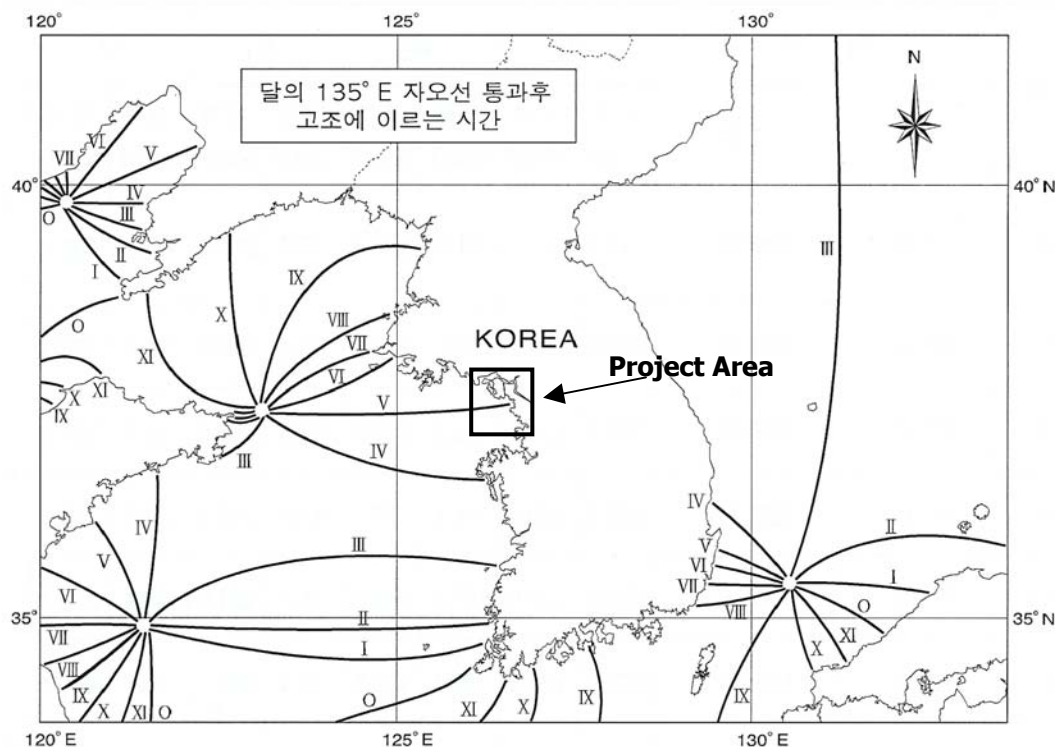


Figure C.2-1 Movement of tidal wave through the Yellow Sea [206]

C.2.2 Kyunggi Bay

The Project Area is situated in Kyunggi Bay at the northern part of the west coast of South Korea. Kyunggi Bay is one of the largest macro tidal embayment along the Korean peninsula and filled with many islands. Kyunggi Bay is a part of the Han River estuary. The Han River is the largest river on the west coast of South Korea. The discharge of the Han River and his branches (amongst others: Imjin River, Hantan River and Yessaong River) enters Kyunggi Bay through two pathways: The Yeomha Waterway east of Kanghwa Island and the main waterway north of Kanghwa Island. Since the waterway north of Kanghwa Island is the borderline between South and North Korea, access is limited in this area and so are field data. The same holds for the water that flows through Yeomha Waterway [103].

The large tidal range and funnel shape of the Han River mouth prevent the formation of a large active growing delta [105]. The Han River transports large amounts of deposited material during the wet summer season. Therefore Kyunggi Bay is defined as a tidal bay with a tide-dominating system. Wave energy is restricted by limited fetch and sheltering of offshore islands. The strong tidal current causes significant sediment transports, which dominate the coastal morphology in Kyunggi Bay. This can be recognised in the funnel shape of the embayment and the large linear sand bodies oriented parallel to the tidal current.

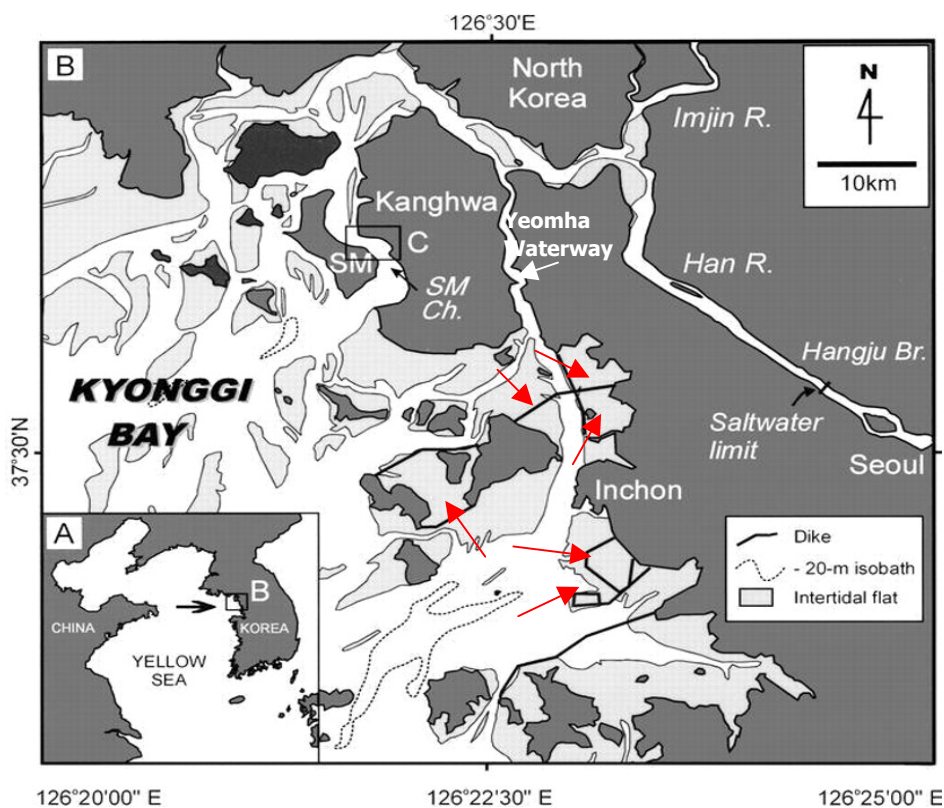


Figure C.2-2 Kyunggi Bay approximately 15 years ago (arrows show already reclaimed areas) [101]

Kyunggi Bay can also be classified as a mud coast consisting of predominantly inorganic sediment of median size less than 63 micron. This fine sediment originates from terrestrial sources in Korea as well as China, carried downstream by rivers. In the sheltering of the off shore islands the fine sediment settles and forms the extensive inter-tidal mudflats in Kyunggi Bay. Between the inter-tidal flats the morphology of Kyunggi Bay shows a meandering and branched channel systems with ebb and flood chutes. The interaction between the bottom morphology and tidal motion causes complex three-

dimensional processes of residual circulations and spiralling flows. Sedimentation and erosion on the inter-tidal flats are connected with these flow structures. Within Kyunggi Bay the tidal current is deformed by bottom friction and other non-linear effects associated with the complex geometry of the basin. These distortions cause asymmetry between high and low water flows, which have large influence on the net movement of sediment.

There has been extensive coastal development in Kyunggi Bay over the last twenty years and the shoreline and morphology have been changed progressively [105]. Since 1992, several reclamations and dredging works were executed in Kyunggi Bay. The largest reclamation was the construction of a new international airport on the inter-tidal flats between Youngjong Island and Youngyou Island. For this reclamation the dredged material of the approach channel to Incheon North Port was used.

The reclamation works resulted in a decrease in tidal prism, because a part of the inter-tidal area was replaced by land. Now less water had to move into Kyunggi Bay every tidal cycle, which resulted in a reduction of the current velocities in the ebb and flood channels. Consequently, the morphology in these channels changed, since the flow velocities in the channels determine the sediment transport capacity of the water. The reduction of the flow velocities causes settlement of sediment in the channels and lowers the capacity to bring sediment into suspension and transport the sediment out of the system.

These processes occur on a meso-morphological time scale of 1 to 10 years or even longer. Because the reclamation works in Kyunggi Bay followed each other in a rapid tempo, the morphological changes are still going on [101]. This makes Kyunggi Bay a highly dynamic system. The red arrows in Figure C.2-2 show the reclamation works, which are executed now (see Figure A.2-1). The dark colored pieces in Figure C.2-2 are land area and the light colored pieces are inter-tidal area.

C.2.3 Project Area

The Project Area is situated between Youngjong Island and the Korean Mainland (see Figure A.2-1). Directly north of the Youngjong Grand Bridge (the highway connection between the Youngjong Island and Seoul [110]) Incheon Terminal basin is planned and 15 kilometres south of the Youngjong Grand Bridge the port of Incheon is situated. Incheon Port is the fourth harbour in South Korea and expanded with Incheon North Port a few years ago. To provide access to Incheon North Port an approach channel was dredged. In the Kyung-In Canal project this approach channel to Incheon North Port will be extended to provide navigation to Incheon Terminal.

The Project Area is influence by one of the two connections of the Yeomha Waterway with the Yellow Sea. The northerly connection between Kanghwa Island and Youngjong Island takes care of most of the discharge of Yeomha Waterway [103]. Less tidal current is expected through this relatively shallow connection. The southerly connection comprises the main channel to Incheon Port. This connection is deep and straight caused by the strong tidal current and periodic dredging operations [107]. At the end of the dredged approach channel to Incheon North Port in northward direction the bottom level gradually rises, but the channel still remains relatively straight. After passing the Project Area the water depth in the channels reduces more quickly caused by a decrease in tidal discharge. The flow velocities in this area are more or less constant and equilibrium exists in this area. Many ending flood channels can be distinguished north of Youngjongdo Islands, which are formed by the tidal current moving via the southerly connection.

The tidal prism in the study area reduced substantially during the last decades, especially by reclaiming more land around Youngjong Island. This causes a reduction of the channel depths due to the decrease in tidal prism. However, also channels disappeared by reclaiming more land around Youngjong Island, which compensates this effect.

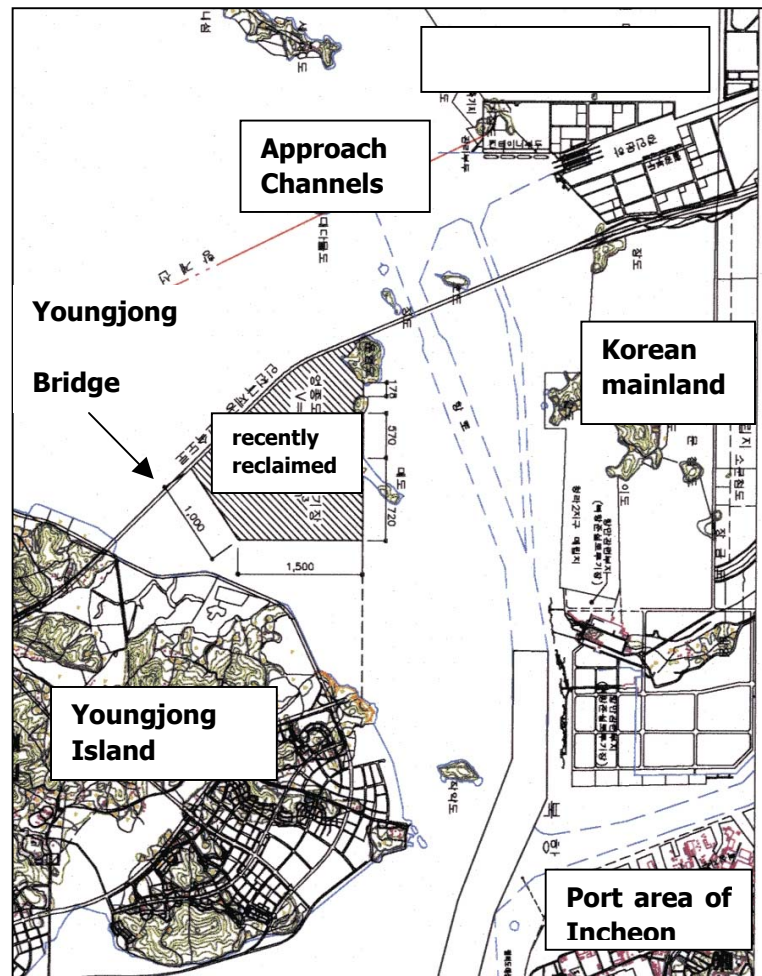


Figure C.2-3 Project Area (the Approach Channel is indicated by the blue dotted line) [207]

C.3 CLIMATE

The project is influenced by a continental climate as well as an oceanic climate. The climate is marked by cold and dry winters with an average temperature of -2.6°C and minima of -18.5°C and hot and humid summers with an average temperature of 25°C and maxima of 37.2°C . The annual rainfall in the project area is approximately 1300 mm, which is not exceptional. Important is that almost half of the annual rainfall occurs in the months July and August (rain season), causing large fresh water discharge in rivers. The average evaporation is by far not enough to reduce the effects of this large fresh water discharge (Figure C.3-1).

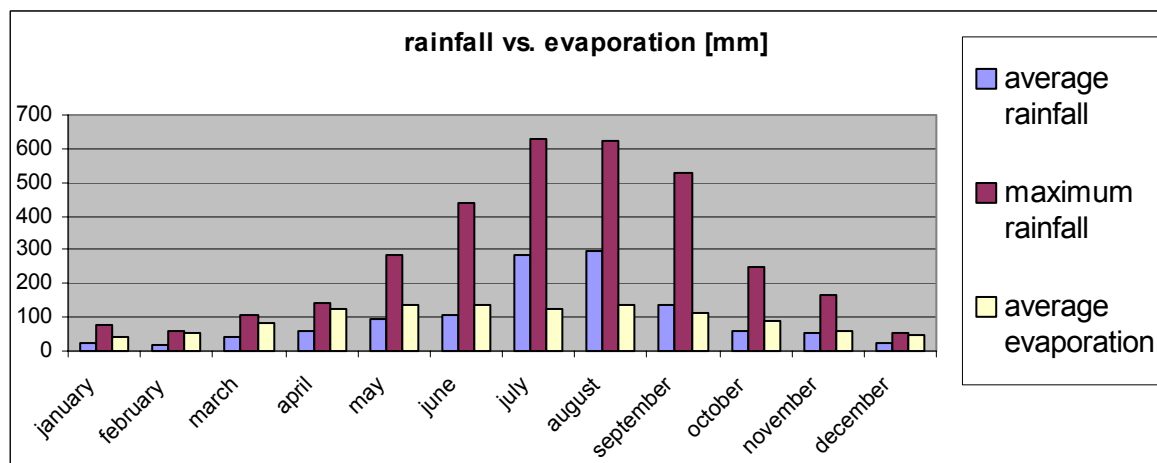


Figure C.3-1 Rainfall vs. evaporation in Incheon [210]

Normally winds are from the southwest during summer and northwest during winter (Korea Meteorological Administration 1998). The monthly maximum wind speed is varying between 16 and 21 m/s during the year (Figure C.3-2), but extreme conditions appear during the almost annual typhoons in the area. Typhoons frequently occur and move in northern direction with wind speeds that can rise from 50 up to 95 m/s at the centre.

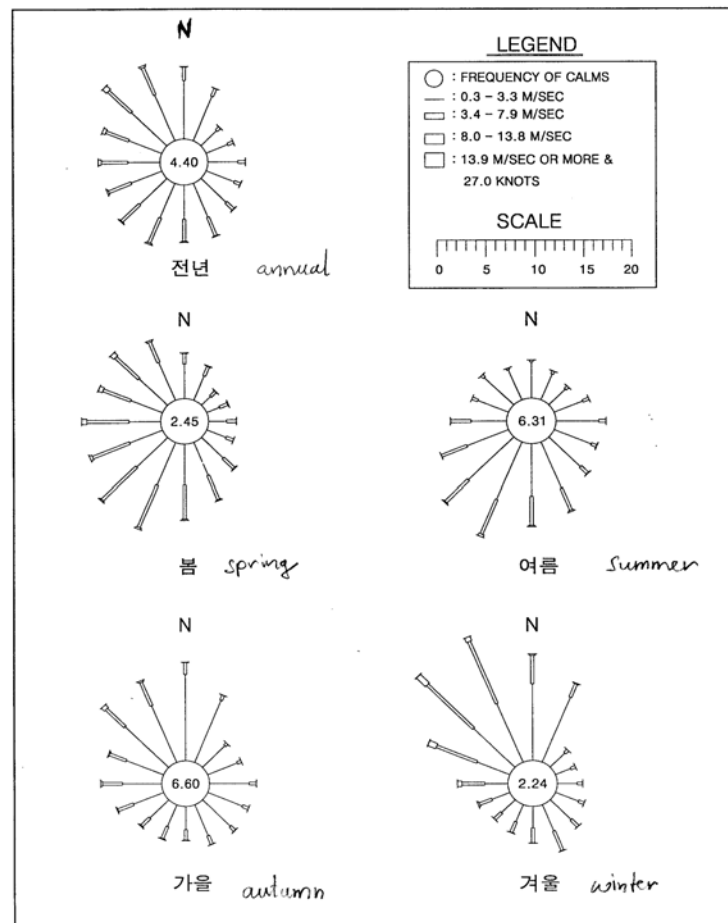


Figure C.3-2 Wind rose
Incheon [202]

C.4 HYDRODYNAMICS

C.4.1 Tidal elevation

The tidal elevation in Incheon is included in Appendix I. Predominantly a semi-diurnal tide acts along the West coast of South Korea moving in northward direction. By geometrical effects shoaling occurs, yielding a significant increase in tidal range when entering Kyunggi Bay (Figure C.4-1 and Appendix II). The mean spring tidal range can reach up to 9 meter (Office of Hydrographic Affairs 1992) and can be classified as macro-tidal (> 4 m).

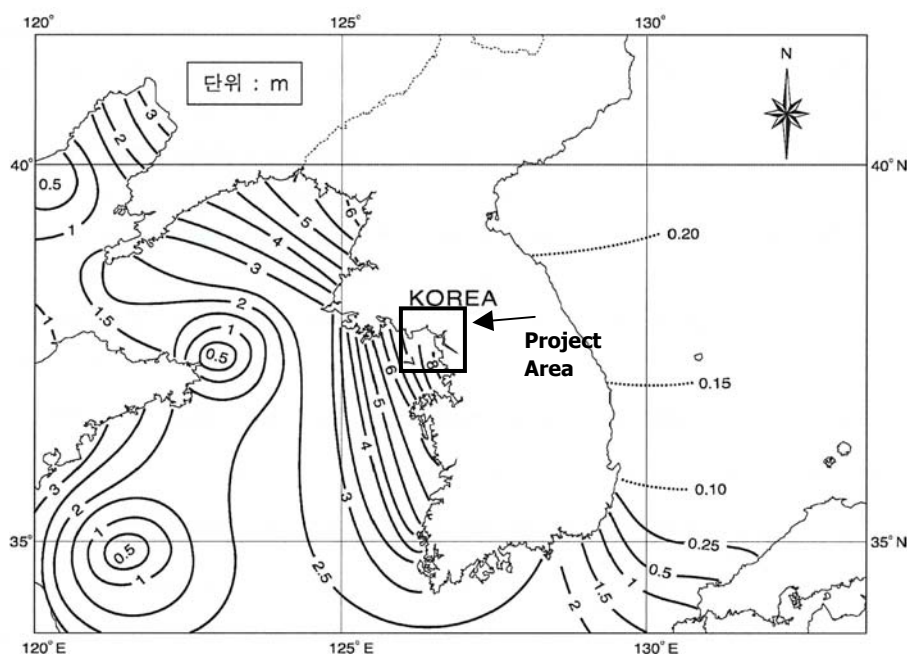


Figure C.4-1 Development of tidal range in the Yellow Sea [206]

For this study use is made of the water level measurement at the tidal station in Incheon. This is a time series of high water and low water levels for the period of June 27th to July 27th 2005. In addition, use is made of the harmonic constituents M2, S2, O1 and K1, at several locations in Kyunggi Bay. These tidal data are included in Appendix VI. Table C.4-1 presents the characteristics of the tidal constituents in Incheon.

			Angular velocity (°/hr)	Period (hr)	Half tide range (cm)	Phase (°)
M ₂	Main	lunar	28.98	12.42	286.2	129.5
	Semi-diurnal					
S ₂	Main	solar	30.00	12.00	112.7	179.1
	Semi-diurnal					
O ₁	Main	lunar	13.94	25.82	39.4	295.3
	Diurnal					
K ₁	Main	solar	15.04	23.93	25.2	266.4
	Diurnal					

Table C.4-1 Characteristics of the harmonic constituents in Incheon [201]

C.4.2 Tidal current

The tidal currents have the same characteristics as the local water level variations (semi-diurnal). The large vertical tidal difference causes considerable (horizontal) tidal currents in Kyunggi Bay. The flood tidal current moves in northeast direction and increases due to narrowing of the flow area between Youngjong Island and Incheon Harbour. During spring tides, the velocity of flood tidal currents in the main tidal channel between Youngjong Island and Incheon Harbour ranges between 0.9 and 1.8 m/s and ebb currents range between 1.2 and 2.3 m/s (Bong 1978; Office of Hydrographic Affairs 1992) [101].

In the Project Area the flood tide current flows in northeast-northwest (21°-334°) direction and the ebb tide current flows in south-southeast (134°-188°) direction. In front of the Project Area a phase difference between high water and slack water of 1.1 hour exists and the maximum velocity for mean spring tide is 120 cm/s about 3.6 hours after low tide. The phase difference between low water and slack water is 1.0 hour after high tide and the maximum velocity for mean spring tide is 116 cm/s about 3.8 hours after high tide. More information about tidal current direction, (maximum) tidal current velocities and tidal current transition time is included in Appendix IV.

When moving further in the direction of the mouth of the Yeomha Waterway the tide becomes non-symmetric. Here the tide turns from low tide to high tide suddenly and from high tide to low tide slowly. So, flood time is short and flood tidal velocity is high. Another feature of the Yeomha Waterway is that high tide level is almost fixed but low tide level is higher and the tidal range is smaller upstream.

C.4.3 Wind induced waves and currents

The Project Area is sheltered behind the North Korean main land and many islands, the length on which the wind is active is disturbed and the effect of wind during the year is minimal. The average significant wave height at Incheon varies from 1.3 m in winter to 0.3 m in summer, but periods with no waves are quite normal during summer. Other research found significant wave heights of more than 2 meter during winter but less than 1 meter during summer (Korea Administration 1998) [101]. The design wave height at Incheon Harbour for 10 m water depth and a southwest direction is 2.0 m [201].

It is expected that shallow inter-tidal areas respond more rapidly to wind stresses, but no data about the effect of wind-induced currents are known. Also wind generated waves cause turbulent activities at the bottom of shallow areas, stirring up fine material.

Wave heights associated with typhoons can be considerable in Kyunggi Bay (Ministry of Agriculture and Fisheries 1989). Storm surges also result in positive and negative sea level anomalies of as much as 0.6 m (Lee and Oh 1994) [101], this is still small compared with the tidal variation.

C.4.4 Density induced currents

The water temperature in the Project Area varies seasonally, ranging from 3.2-5.0 °C in February to 20.0-21.7 °C in June. Big influences of these variations on the current velocities are not expected because changes take place very gradually.

More significant is the discharge of fresh water from Yeomha Waterway into the salt water in the Project Area. Yeomha Waterway is a branch of Han River, which is the largest river on the west coast of Korea with a 468 km long main channel and large catchments area of 26219 km² [111]. The annual discharge of the Han River reaches 23 km³/year with nearly 60 % of the discharge occurring in the three-month period from July to September (MCT 2001). Due to regulation by dams the discharge of fresh water is restricted.

In the paper about mass transport mechanisms in Kyunggi Bay [103] the residual volume transports through Yeomha Water for both the rain season and the dry season are mentioned (see Figure C.4-2). When the maximum discharge of Yeomha Waterway (743 m³/s) is compared with water exchange by the tide in the Project Area, it is assumed that even in the rain season the strong tide mixes the fresh water with the salt water and a homogeneous salinity profile occurs.

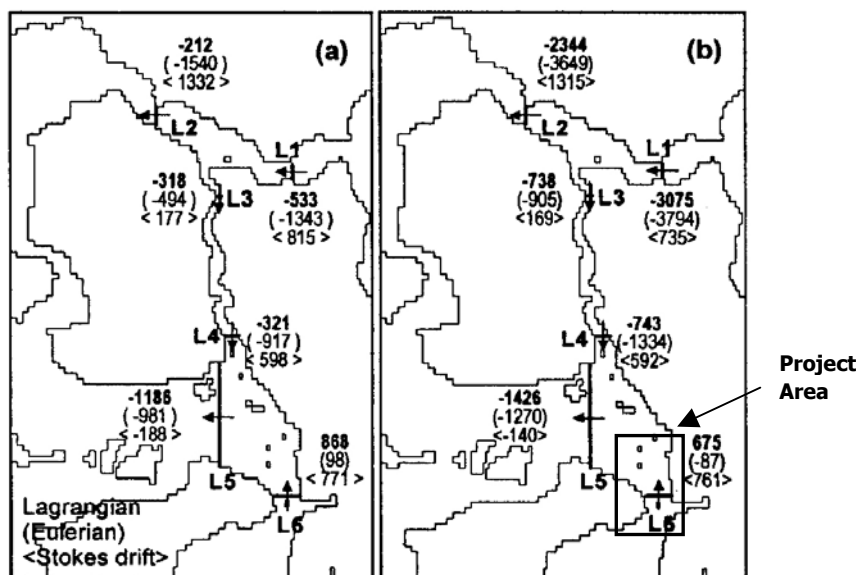


Figure C.4-2 Residual volume transport rates [m³/s] at six cross sections near the project area in the normal period (a) and wet period (b). Arrows indicate transport direction and positive and negative values indicate flood and ebb direction, respectively. The values include tide (M2, S2, K1 and O1 constituents), fresh water inflows and solving salt and heat balance equations [103].

However, measurements in the Project Area resulted in salinity rates of 24.0 to 27.8 parts per thousand in February and 17.9 to 28.3 parts per thousand in July (Appendix IV and [201]). The values in July indicate that the salinity decreases during the rain season due to higher fresh water discharge of Yeomha Waterway.

The salinity in the Project Area shows fluctuations with the tidal cycle, reaching its maximum during high tide and its minimum during low tide [108]. In the rain season peak discharges of Yeomha Waterway causes density currents in the Project Area. Figure C.4-3 shows the longitudinal density gradient in the main channel between Youngjong Island and the Korean main land [205].

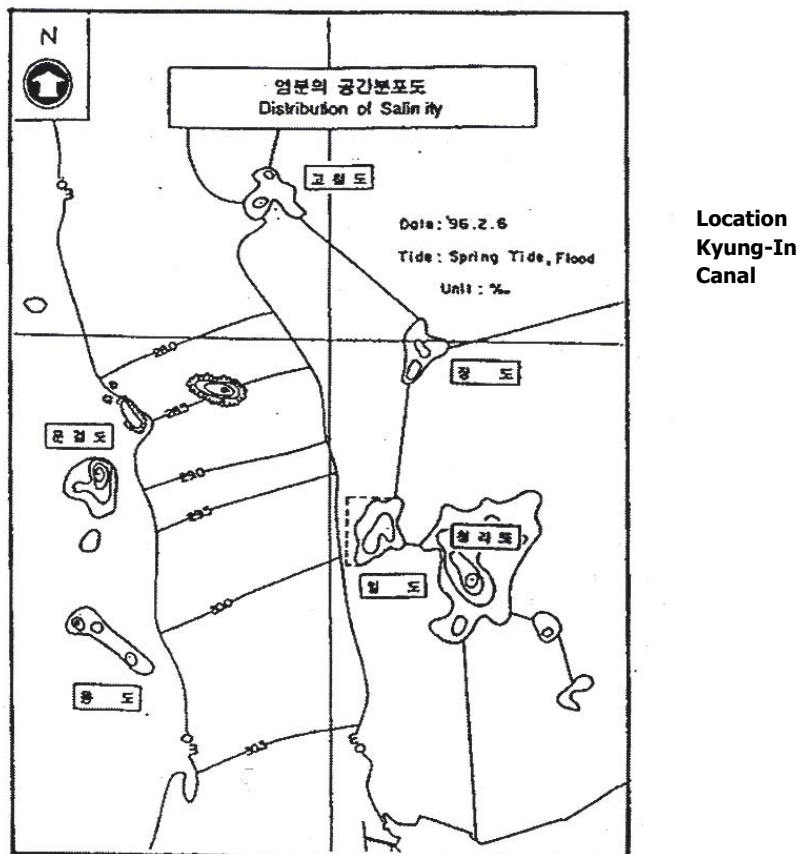


Figure C.4-3 Longitudinal density gradients with spring tide in Project Area [205]

For this reason, density currents cannot be neglected in Incheon Terminal basin. In addition, chapter C.3 showed a large difference between rainfall and evaporation in the rain season. To prevent flooding of Gulpo Chun area the rainwater is drained through the existing floodgate besides Incheon Terminal basin into the Project Area and also causes density gradients. Finally, the water exchange due lockage of vessels between Incheon Terminal basin and the Kyung-In Canal causes extra fresh water in the Project Area (Appendix XIII).

C.5 GEOLOGY

Korea is a mountainous peninsula extending south-southeast from the north-eastern part of the Chinese mainland. The terrain is rugged and steep and only near the west and southwest coasts extensive flat alluvial or diluvial plains and rolling hilly lands are formed.

The basement of South Korea is lying on a layer of hard rock from the Precambrian époque, tectonically related to China. A long period of temperature fluctuations, concentrated summer rains and chemical reactions induced intense weathering and erosion of surface material, deposited by the Han River in Han River estuary. Nowadays at some places sedimentary deposits up to 40 meter thick immediately overlie the basement of rock (Korea Airport Construction Authority 1996) [101].

These sedimentary deposits form the upper sedimentary soil layers, also called transport layers. They are variable in thickness and are increasing towards the edge of the peninsula. These layers are present both in the bottom of the Approach Channel and in the bottom of Incheon Terminal basin. The transported soils have been subdivided into an: upper, middle and lower layer, defined by the sea level movement in the past. In more recent years, the transport layers have been filled by softer deposits (reclaimed soils) as a result of the increasing sea level. When making a borehole near Incheon Terminal the following soil layers can be found:

- Reclaimed soil layer (depth: 0 – 10 m): consists of clay and mixed silt sand, mixed silt fine-grained sand or coarse-grained sand.
- Upper sedimentary layer (depth: 0 – 10m): consists of clay and silt layers.
- Middle sedimentary layer (depth: 5 – 10m): mainly consist of clay and silt layers
- Lower sedimentary layer (depth: 10 – 25m): composed of sand and gravel layers
- Weathered soil layer (16 – 34m): consists of clay and mixed silt sand, mixed silt fine grained sand or coarse grained sand
- Weathered rock layer (17 – 38m): completely weathered
- Soft rock layer (0 – 40m): highly and moderately weathered

Intermezzo:

Engineers and geologists do not agree with each other about the true origin of the mudflats along the west coast of South Korea and Kyunggi Bay. Geologists believe the Chinese Rivers are the origin of the mud. During sea level rise in the last 8000 years, the fine material easily could be transported to the west coast of South Korea in the shallow Yellow Sea. Engineers believe that the fine sediment is deposited by the Han River. Geologists found out by sampling that the composition of the fine sediment in Kyunggi Bay is the same as the sediments from the Chinese rivers. At the moment another study is executed to find out the true origin [106].

C.6 SEDIMENT

C.6.1 Sediment properties

The type of sediment found in Kyunggi Bay is so called lithogenous; sediments (quartz and clay minerals) entering the sea as discrete particles (gravel, sand, silt and clay). Most of the marine sediments are derived from the weathering of rocks on land by the action of wind, water and ice under the influence of temperature, pressure and chemical reactions. As already mentioned in chapter C.6 these layers are at many places covered by a mud layer.

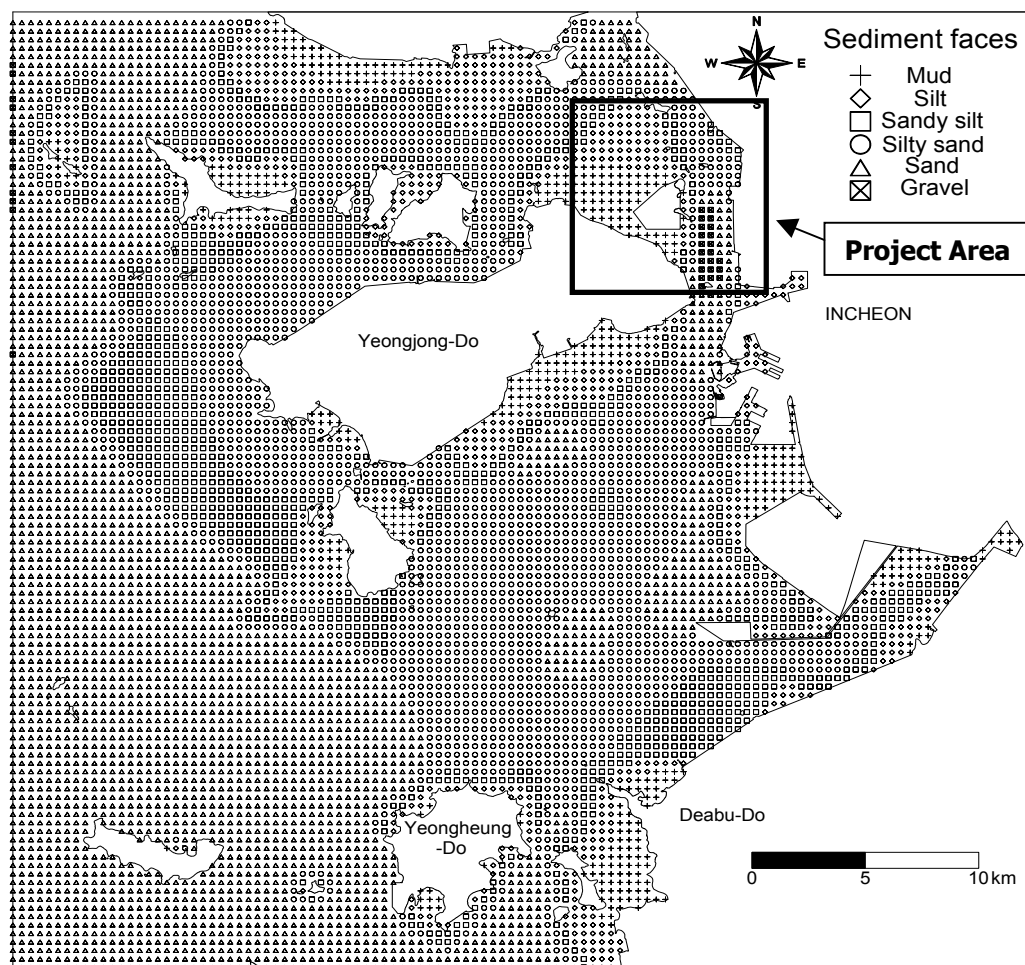


Figure C.6-1 Sediment facies in Kyunggi Bay [213]

When the composition of the sediment is known, the movement of the sediment can be determined using the knowledge about the hydrodynamics in the estuary. Figure C.6-1 shows the types of sediment on the sea bottom of Kyunggi Bay. In this figure it becomes clear that the planned Incheon Terminal Basin is situated in a sandy silt or silty sand area. Nevertheless, more detailed data show a silty or even muddy sediment in front of Incheon Terminal basin. The channel fill succession consists of silty sand, sandy silt, silt and mud. In the channel between Youngjong Island and the main land gravel lags appear caused by erosion due to high flow velocities.

Lee et al. 1992 found the following data: The sub-tidal sediment at the bottom of the main channel consists mostly of silty sand ranging between 0.3 and 4.5 phi (0.044-0.812 mm). The turning basin and the entrance channel lie in an inter-tidal sedimentation zone composed of sandy silt to mud with a mean size ranging between 4.1 and 7.7 phi (0.005-0.058 mm) [101]. D_{50} is approximately 10 μm with 10 - 30% of mud.

C.6.2 Suspended sediment

The tidal current is the main cause of sediment transport in front of Incheon Terminal. Concentrations of suspended particulate matters (SPM) in the main channel between Youngjong Island and the Port of Incheon show a large temporal variability, ranging from 12 mg/l in summer to 421 mg/l in winter (Korea Electric Power Corporation 1990). The increase in SPM during winter is attributable to resuspension by wind-induced waves [101]. Change and Oh (1991) found suspended sediment concentrations up to more than 500 mg/l in the upper layer near the surface, during the periods of high rainwater discharge in the wet summer [101].

For the Kyung-In Canal also sediment transport measurements are carried out. The suspended load of the ebb and flood tide are monitored for spring and neap tide at 3 layers and 20 stations in the Project Area. Table C.6-1 shows the suspended load measurements at February 23th 1996 right in front of Incheon Terminal. Appendix IV shows all results and the locations of the three measurement stations between Incheon Terminal and Incheon North Port.

		Spring tide 23-2-1996		
		Outer layer	Middle layer	Lower layer
Flood tide	max	377	372	370
	min	95	123	141
	mean	163	214	227
Ebb tide	max	413	419	436
	min	138	141	140
	mean	227	232	238

Table C.6-1 Suspended load with spring tide (mg/l) [201]

C.7 MORPHOLOGY

C.7.1 Autonomous Situation

The morphological development of Kyunggi Bay is tide dominated. The main navigation channels in Kyunggi Bay are in the direction of the tidal current. Consequently, low sedimentation rates occur and less maintenance dredging is required. The strong tidal current transports a lot of sediment through the channels. The slightly larger ebb current causes a net sediment transport in the seaward direction (from north to south). However, sediment influx from Yeomha Waterway causes only slight variation in the amount of sediment in the Project Area.

In addition, Kyunggi Bay contains extensive and open-coast muddy flats and silty inter-tidal regions. In these areas the fine sediment is easily brought into suspension due to the action of the tidal currents and waves. The sediments are carried over large distances due to the low settling rate of the fine sediment and settles in sheltered areas. In Kyunggi Bay a significant exchange of sediment between the inter-tidal areas and the channels is expected. The large tidal range creates forces in the direction lateral to the channel, which induce gravity infill from the inter-tidal area into the channel.

Historical charts show that in the last decennia a lot of reclamation works were carried out. After the reclamation the tidal flats lack extensive tidal marsh and actively migrating tidal channels. Muddy tidal flats grade into a sandy sub-tidal region where inter tidal channels loose their morphology (e.g. Wells at al. 1990). Since 1992 the tidal flats between Youngjong Island and Youngyou Island were reclaimed for the construction of the international airport (Figure C.2-2 and figure 3-1, part A). The sand for this reclamation was extracted from the dredging work for the first approach channel to Incheon Harbour. In addition, Youngjong Bridge was constructed to provide a road connection between Youngjong Island and the mainland and an island directly under this bridge was reclaimed. All these projects significantly disturbed the morphology in the Project Area due to the change in ratio between tidal volume and the cross sectional area of the tidal channels, in Kyunggi Bay. This resulted in larger flow velocities and erosion in the channel between Youngjong Island and the mainland and high siltation rates in newly created sheltered areas by the above-mentioned projects. Figure C.7-1 shows the numerical predicted siltation due to the reclamation of an island underneath Youngjong Bridge. In addition, this numerical study shows an estimation of the siltation rates at the inter-tidal area in front of Incheon Terminal and the siltation rates in Incheon North Port.

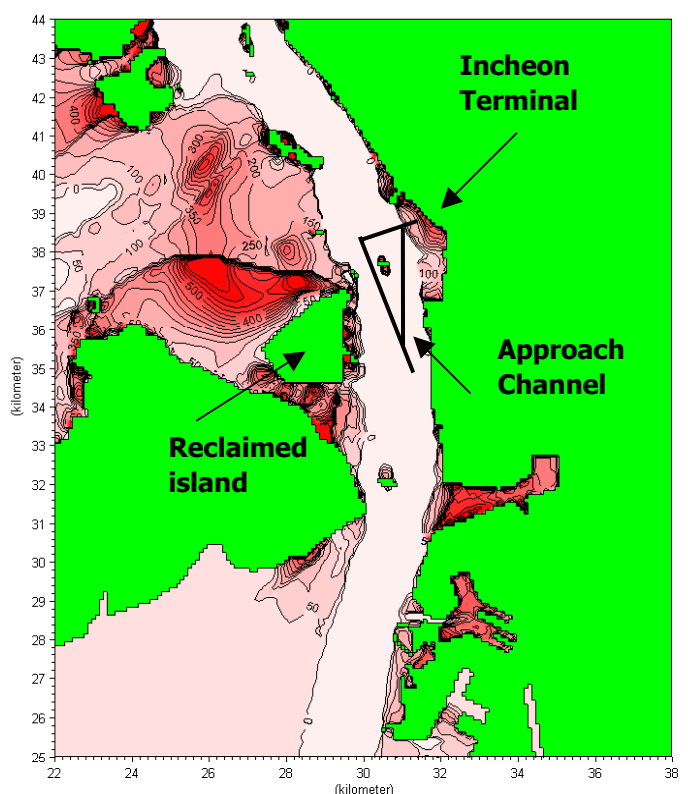


Figure C.7-1 Iso-lines indicating the annual siltation due to the reclamation of the island between Youngjong Island and the Korean Main land in mm. [207]

C.7.2 Expected impact of the Kyung-In Canal project

The Kyung-In Canal project will initiate changes in the hydrodynamics and morphology of Kyunggi Bay. The dredging of an Approach Channel causes a reduction of the flow velocities and thus sediment transport capacity. Consequently this will lead to siltation of the Approach Channel, but also the hydrodynamics and morphology of the neighbouring inter-tidal areas will change.

Siltation can be expected in the Entrance Channel (for locations see Figure A.2-6). The Entrance Channel penetrates a shallow inter-tidal area with low flow velocities. The sediment carrying tidal currents perpendicular to the Entrance Channel can easily deposit sediment in the Entrance Channel. Horizontal eddies at the border of the main channel and the Entrance Channel also cause influx of sediment loaded water. In addition, the behavior of the inter-tidal area in front of Incheon Terminal is important for determining the siltation of the Entrance Channel. The muddy sediment on the inter-tidal area can change in fluid mud due to hydrodynamic forces. This fluid mud can flow down hill along the gently sloping sides of the Entrance Channel under the effect of gravity. At last, flocculation of the cohesive material of the inter-tidal area could increase siltation rates due to higher fall velocities of the material.

Most siltation is expected in Incheon Terminal basin. Due to the large tidal range every tidal cycle large quantities of sediment loaded water enters Incheon Terminal basin. In the sheltered basin the sediment can easily accumulate. Also fresh water discharge of Yeomha Waterway during the rain season causes density currents and thus siltation in Incheon Terminal basin. The same holds for fresh water discharge and lockage water from the Kyung-In during the rain season. During the year this

effect is minimal because the Kyung-In Canal has got almost the same salinity as the harbour basin. Finally, the inter-tidal area in front of Incheon Terminal basin may also cause siltation in Incheon Terminal basin.

Furthermore, the construction of Incheon Terminal basin causes an increase in tidal prism of Kyunggi Bay. Although this increase in tidal prism is very small in comparison with the total tidal prism, still this might influence the hydrodynamics and morphology in the Project Area. Besides the Kyung-In Canal project is not the only planned project in the region. Also other reclamation projects and the construction of a second bridge connecting Youngjong Island to the mainland are already planned. These projects also cause changes in hydrodynamics and morphology in Kyunggi Bay.

C.8 CONCLUSIONS

The Project Area is located in Kyunggi Bay, which is part of the Yellow Sea. Kyunggi Bay is a macro tidal embayment with a mean spring tidal range reaching up to 9 m. Kyunggi Bay is characterised by many islands, which provide sheltering for extensive inter-tidal areas. This results in large quantities of fine sediment, median size less than 63 micron. 10 kilometres north of the Project Area Yeomha Waterway flows into Kyunggi Bay. The Yeomha Waterway is a branch of Han River and plays a significant role on daily sediment transport in the Project Area during the rain season. Kyunggi Bay has got a dynamic morphological character due to the many reclamation projects that are executed in the last decades.

The tidal wave propagating from the south is the main hydrodynamic process in the estuary. The large tidal range causes considerable tidal currents in Kyunggi Bay. Tidal asymmetry causes an ebb-dominated estuary and thus slightly higher ebb tidal currents. Most of the year, the effect of wind and waves is small due to the many islands in Kyunggi Bay. Nevertheless, in the shallow areas the effect can be significant and generate turbulent activities that stir up the fine material. Furthermore, storm surges and typhoons cause more extreme hydrodynamic conditions, but still small compared with the tidal variations. When comparing the tidal prism with the fresh water discharge from Yeomha Waterway, the estuary is assumed well mixed. However, in the rain season peak discharges from Yeomha Waterway cause density currents in the Project Area.

The Project Area mainly consists of sandy silt and silty sand, but also silty and even muddy sediment is present on the inter-tidal areas. The strong tidal current causes large suspended sediment concentrations up to more than 500 mg/l in the upper layer. This is the main cause of the morphological changes in Kyunggi Bay. In addition, the large number of projects in the last two decades causes a highly dynamic morphological environment in Kyunggi Bay.

The execution of the Kyung-In Canal project changes the hydrodynamics and morphology in the Project Area. The dredging of an Approach Channel causes a reduction of the flow velocities and thus sediment transport capacity. Consequently this will lead to siltation of the Approach Channel. In addition, the large tidal range causes a significant water exchange between the sea and Incheon Terminal basin. In sheltered area of Incheon Terminal basin the sediment can settle and causes siltation, but also in the Entrance Channel siltation is expected. Furthermore, fresh water discharge during the rain season causes density currents, which induce siltation in Incheon Terminal basin and finally also the inter-tidal area in front of Incheon Terminal basin may cause siltation in Incheon Terminal basin.

PART D

SOBEK River & Estuary model



Figure D: Start screen SOBEK River & Estuary [211]

D.1 INTRODUCTION

The objective of this study is to quantify the influences of tidal filling on siltation of Incheon Terminal basin and Approach Channel due to the execution of the Kyung-In Canal project. Nowadays, these kind of complex hydrodynamic and morphological problems are often solved with three-dimensional numerical models. However, this study is especially interested in the influence of the tidal filling. Furthermore insufficient data are available for a detailed study. So taking into account the objective of the study it is decided to use the one-dimensional network model 'SOBEK River & Estuary' (SOBEK RE). [Chapter D.2](#) explains more extensively why SOBEK RE is used and what the possibilities of SOBEK RE are.

SOBEK RE consists of a hydrodynamic and morphological module. [Chapter D.3](#) deals with the schematisation of Kyunggi Bay, the so-called 'Autonomous Situation'. After creating an appropriate schematisation of Kyunggi Bay, the calibration of the hydrodynamics starts. The calibration is described in section D.3.2 and separated in a 'far field' and 'near field' calibration. The 'far field' calibration focuses on a correct representation of tidal wave. The 'near field' calibration focuses on a correct simulation of the phase difference between the horizontal and vertical tide. This is important to investigate the influence of the inter-tidal area in front of Incheon Terminal later in this study. Furthermore a correct representation of the flow velocities in the Project Area is important, since this determines the sediment transporting capacity of the water. Chapter D.3 finalizes with conclusions.

After calibrating the hydrodynamics in Kyunggi Bay, the morphological module of SOBEK RE can be activated. [Chapter D.4](#) deals with the schematisation of the morphological characteristics of Kyunggi Bay. The calibration of the morphological model is discussed in section D.4.2. The calibration focuses on a correct representation of the 'near field' sediment transport. Chapter D.4 finalizes with conclusions.

[Chapter D.5](#) presents the schematisation of the 'Project Situation'. In the 'Project Situation' all the interventions that are included in the Kyung-In Canal project are schematised. In this chapter special attention is given to the schematisation of the inter-tidal area in front of Incheon Terminal basin. This schematisation must provide insight in the siltation due to the inter-tidal area in front of Incheon Terminal basin.

D.2 SOBEK RIVER & ESTUARY

D.2.1 Model choice

The most important reason for choosing a model is, which objective needs to be fulfilled. In addition, the availability of numerical models, the order of detail of the available data, the computational resources and the available time span determine which model is most appropriate.

The objective of this study is; "Classify the influences of the different processes that cause siltation in Incheon Terminal basin and Approach Channel due to the execution of the Kyung-In Canal project". So, this study is not interested in detailed quantitative results but is a qualitative study. Furthermore, the available data for this study are insufficient to execute a detailed study.

Based on the objective of this study, together with the available data and time span, it is decided to use the one-dimensional network model "SOBEK River & Estuary" for this study. SOBEK RE is a relatively less complicated model that makes it easier to gain insight in the physical processes compared with a more laborious and complex 3-dimensional model. Moreover, SOBEK RE is based on process equations and uses the equation for conservation of mass and the equation of momentum. This means that SOBEK RE is appropriate to simulate the far most significant process in Kyunggi Bay, the tidal propagation, in a correct way. Furthermore, Kyunggi Bay is characterized by a clear structure of main channels, which makes the use of a 1D-model appropriate.

The specific purpose of the model is to investigate the relative differences between the autonomous situation in Kyunggi Bay and the situation after executing the Kyung-In Canal project. This must lead to insight in the qualitative influences of the different hydrodynamic and morphological processes on siltation in the surrounding of the Project Area. In addition, the siltation due to the inter-tidal area in front of Incheon Terminal basin is investigated with the model.

Regarding the objective of this study SOBEK RE also contains limitations, which are described in section D.2.3. This is the reason also an analytical method is used later in this study. This analytical method is used as reference for SOBEK RE. In this matter, this study also investigates the appropriateness of the one-dimensional SOBEK RE in solving this siltation problem. SOBEK RE forms an instrument between 2D/3D-models and an expert opinion in this study.

D.2.2 Description of SOBEK River & Estuary

SOBEK River & Estuary is a one-dimensional network morphodynamic model for tidal basins and can be seen as an extension of the existing one-dimensional morphological model for rivers. WL/Delft Hydraulics developed SOBEK RE in full partnership with the Institute for Inland Water Management

and Waste Water Treatment (RIZA) of the Netherlands government. Also major Dutch consulting companies, city authorities, research institutes and water boards took part in developing SOBEK RE.

SOBEK RE is a process-based model. This model tries to make a prediction fully based on process equations and therefore requires detailed data. SOBEK RE is a one-dimensional model, which implies SOBEK RE works with cross sectional averaged values of parameters and variables. As input SOBEK RE uses the specific aspects of the estuary, amongst others bathymetry, tide and sediment characteristics, to simulate the water flow, sediment transport and morphology.

SOBEK RE consists of a hydrodynamic and morphological module. The hydrodynamics in estuaries are described by the equation of conservation of mass and the equation of momentum. The balance equations read:

$$\frac{\delta A_t}{\delta t} + \frac{\delta Q}{\delta x} = 0 \quad [\text{D.2-1}]$$

$$\frac{\delta Q}{\delta t} + \frac{\delta}{\delta x} \left(\alpha_B \frac{Q^2}{A_f} \right) + g A_f \frac{\delta h}{\delta x} + \frac{g Q |Q|}{C^2 R A_f} = 0 \quad [\text{D.2-2}]$$

In which:

- Q = discharge [m³/s]
- t = time [s]
- x = distance [m]
- α_B = Boussinesq constant [-]
- A_f = cross section with flow [m²]
- A_t = total cross section [m²]
- g = gravitational acceleration [m/s²]
- h = water level [m]
- C = Chézy-coefficient [m^{1/2}/s]
- R = hydraulic radius [m]

In the morphological module, SOBEK RE uses an equation for sediment transport, for example Van Rijn. Many formulations exist for the sediment transport. These formulations can roughly be divided into two groups: the 'total transport formulae' and 'the formulae that make a distinction between bed load and suspended load transport'.

For calculating the bottom profile SOBEK RE uses a third balance equation. This balance equation solves the sediment transport for each cross section:

$$\frac{1}{1 - \varepsilon_p} \frac{\partial A}{\partial t} + \frac{\partial S}{\partial x} = 0 \quad [\text{D.2-3}]$$

In which:

- A = cross-sectional area [m²]
- S = sediment transport per cross section [m³/s]
- ε_p = porien volume of bottom [-]

SOBEK RE iteratively determines all non-linear components for every grid point using the above-mentioned balance and the sediment transport equations.

D.2.3 Limitations

SOBEK RE is an extension of the existing one-dimensional morphological model for rivers. However, in estuaries the driving forces for morphological development is much more complicated than in the case of non-tidal rivers [4]. For this reason it is important to be aware of the limitations of SOBEK RE related to this study. Underneath the relevant limitations and the consequences of this limitations in the study are described.

- Even with model simplifications the morphological equilibrium state of a system under influence of the tide cannot yet be derived in a straightforward way with the equations governing water motion and sediment transport. Also in reality it is not clear whether a morphological equilibrium exists or not.
In this study is assumed that the schematised bathymetry of the 'Autonomous Situation' is in equilibrium. In this matter only the morphological consequences of executing the Kyung-In Canal project, in which this study is interested, can be investigated. By analysing the relative differences between the 'Autonomous Situation' and the 'Project Situation' is tried to reduce the effect of an unstable morphological state, because this instability occurs in both the 'Autonomous Situation' and the 'Project Situation'.
- In SOBEK RE the aspects: upstream discharge, tidal motion, bathymetry and sediment characteristics are included. But also density currents may play a significant role on siltation in Incheon Terminal basin and Approach Channel. This is the reason also an Analytical Approach is applied in this study, which includes the effect of density currents.
- In principle, SOBEK RE cannot handle inter-tidal areas, because the physical effects of inter-tidal areas are different than for floodplains, which are included in SOBEK RE. Inter-tidal areas are characterised by mud shoals with meandering channels in between. These meandering channels are characterised by a complex hydrodynamic and morphological behaviour, which is difficult to model and not included in SOBEK RE [11]. However, this study still uses the floodplains to schematise the inter-tidal areas. This assumption may influence the hydrodynamics and morphology in the model.
- One of the objectives of this study is to determine the influence of the inter-tidal area in front of Incheon Terminal basin on siltation. This inter-tidal area is schematised with a special branch for which the 'dry bed procedure' is used. The 'dry bed procedure' establishes a small, deep, funnel shaped channel in the middle of the cross sectional area, which prevents complete drying of the cross section. This so-called Preismann funnel is used because SOBEK RE cannot handle dry branches.
- In Kyunggi Bay many inter-tidal areas cause lateral movement of sediment from inter-tidal areas into the main channels. This fine sediment is transported away and settles in sheltered areas. The one-dimensional SOBEK RE model cannot handle this phenomenon in lateral direction.
In this study the 'near field' sediment transports are calibrated with the field data in this area, in which sediment from the inter-tidal areas is included. So, it is assumed that the consequences of this limitation are small on the 'near field' siltation results.
- In a network model for a tidal area each bifurcation represents a confluence as well as a bifurcation, since the flows during ebb and flood are in opposite direction. The nodal point relation in case of a bifurcation has got an important influence on the distribution of sediment

at the nodal point. Physically the sediment distribution at a bifurcation is a complex three-dimensional problem.

Since, the distribution of sediment at bifurcations is important in this study to determine the net sediment transport in both North Port and Incheon Terminal basin. In this study, the sensitivity of the nodal point relation on the distribution of sediment at the bifurcation in front of Incheon North Port is investigated. Of course, this does not result in correct schematisation of the reality, but will at least lead to an indication of the sediment influx in Incheon North Port.

- In Kyunggi Bay many inter-tidal area are situated, which contain large volumes of fine cohesive sediment. Whereas in sandy sediment it is the particle size of the sediment, which controls the mobility and transport of sediment, with fine cohesive sediment the bulk properties of the admixture determine the behaviour of the sediment [22]. These phenomena are not included in SOBEK RE, which must be kept in mind when analysing the siltation results.
- At last, the morphological simulations in SOBEK RE are instantaneous. This means that the sediment transport directly reacts on changes in the flow velocities, which results in sudden erosion or deposition of sediment. This phenomenon is compensated in this study by using existing knowledge about settling velocities.

D.3 'AUTONOMOUS SITUATION'

D.3.1 Schematisation

Topography

The schematisation of the 'Autonomous Situation' of Kyunggi Bay is included in [Appendix IX](#). It is recommended to hold Appendix IX next to the text while reading this chapter. The schematised topography consists of the main channels in Kyunggi Bay and the Yeomha Waterway. This topography is detailed enough to investigate the 'far field' consequences of the Kyung-In Canal project. For the input of the bathymetry use is made of the nautical chart of Kyunggi Bay [204], which is used as background for the schematisation of the 'Autonomous Situation' in Appendix IX. By converting the nautical chart into a three-dimensional drawing, several cross sections of the channels are made and implemented in the schematisation (Appendix XIV). Because the nautical chart stops at the border between North Korea and South Korea the topography of Yeomha Waterway is determined by using satellite images. For the depth of Yeomha Waterway the depth at the mouth of the river is assumed constant. The mouth of the river is just visible at the nautical chart.

The topography has two open boundaries at the seaside (no. 5 and 8) and one open boundary on the Yeomha Waterway (no. 1). A third seaside boundary (no. 9) is eliminated at an early stage of the study. This boundary is strongly influenced by the discharge of the Han River, which makes it very complicated to define a correct boundary condition. In addition, the Han River does not influence the Project Area and the effect of the propagating tidal wave through this boundary can be neglected compared with the tidal wave entering Kyunggi Bay via 'South Channel'. To prevent the boundary conditions change due to the project, the seaside boundaries are located outside the influence area of the Kyung-In Canal project. In addition, at the location of the seaside boundaries proper boundary conditions are available.

For the upstream boundary of 'Yeomha Waterway', it is important to prevent influence of reflection effects of the tidal wave, since reflection might influence the hydrodynamics in the Project Area. The boundary is located 16 kilometres upstream 'Yeomha Waterway'. At this location Yeomha Waterway diverts from Han River. If this is far enough from the Project Area to prevent reflection effects is discussed in D.3.2. At last a closed boundary is defined at the end of the open harbour basin of 'Incheon North Port'.

Forcing

Both seaside boundary conditions comprise a time series of water levels during a period of two spring-neap tidal cycles. The time series are generated from the amplitudes and phases of the most

important harmonic constants M2 and S2 (Appendix VI). This simplification makes it easier to analyse the model results and has got no far reaching consequences for the objective of the study, since the hydrodynamics are calibrated later in this study.

For the boundary condition upstream 'Yeomha Waterway' a time series of discharges is used. The period of this time series is one year and thus includes the peak discharge during the rain season in August. For the discharges the residual volume transport rates from Figure C.4-2 are used [103].

	Discharge
Yeomha Waterway: 11 month	300
1 month (rain season)	900

Table D.3-1 Boundary condition discharge Yeomha Waterway [m³/s]

(Physical) model parameters

In the hydrodynamic module, on all branches a grid must be defined. For the 'far field' area a grid size of 500 meter is used. However, for the 'near field' area, which contains the branches 'Navigation 1' and 'Navigation 2', a denser grid size of 200 meter is used to provide more exact results. For accurate morphological calculations SOBEK RE demands that cross sections are defined at a grid point. For this reason, cross sections are located at a grid point.

Due to the presence of many inter-tidal areas in Kyunggi Bay, the cross-sectional profiles of the branches are divided in a main channel and floodplains. These floodplains simulate the inter-tidal areas and are defined as that part of the cross section that becomes dry with Lowest Low Water Spring. This division makes it slightly possible to model the inter-tidal area by defining another friction for this part of the cross section. Despite the division of main channel and floodplains, initially one uniform roughness for the whole bottom profile is defined. This overall Chezy coefficient is defined at 55 m^{1/2}/s and based on comparable situations. The friction coefficient will later be adjusted by the calibration of the hydrodynamics in the Project Area. The initial water level in Kyunggi Bay is defined at Datum Level +4.635 m, which indicates Mean Sea Level in Incheon Port.

D.3.2 Calibration

The calibration is separated in a 'far field' and a 'near field' calibration. The tide is the most important process in Kyunggi Bay and thus the 'far field' calibration focuses on a correct representation of tidal propagation. In the 'near field' calibration focusses on a correct simulation of the phase difference between the horizontal and vertical tide. This is important to investigate the influence of the inter-tidal area in front of Incheon Terminal later in this study. Furthermore, a correct representation of the flow velocities in the project area is important for a correct simulation of the sediment transport.

Available 'field' data

The following 'field' data are used to calibrate the hydrodynamic model:

- Time series of High Water and Low Water in Incheon for the period of June 27th to July 27th, 2005 (Appendix VII)
- The phase and amplitude of the tidal constants M2, S2, O1 and K1 at several locations in Kyunggi Bay (Appendix VI)
- A co-tidal chart of Kyunggi Bay indicating the increase in tidal range of the propagating tidal wave in Kyunggi Bay (Appendix II).
- Tidal charts indicating the tidal current every 1:02 hours during spring, mean and neap tide for one tidal period (Appendix II).

Calibration parameters

Many model parameters used in the schematisation of Kyunggi Bay are variables. Changing the initial values of these parameters results in a change of the hydrodynamics in the model. The following model parameters can be used during calibration of the hydrodynamic model:

- *Amplitude of tidal constants*
- *Phase of tidal constants*
- *Length of Yeomha Waterway*
- *Friction of Yeomha Waterway (both directions)*

As already mentioned, the cross-sectional profile of the branches is divided in a main channel and floodplains (inter-tidal areas) in SOBEK RE. In both parts of the branches it is possible to formulate different *friction coefficients* for as well the ebb as flood direction of the branches. Moreover, it is possible to define a *flow width* in the cross section. The part of the cross-sectional profile outside the flow width is storage area, in which no flow is possible at all. Figure D.3-1 conveys an example of a cross-sectional profile in SOBEK RE.

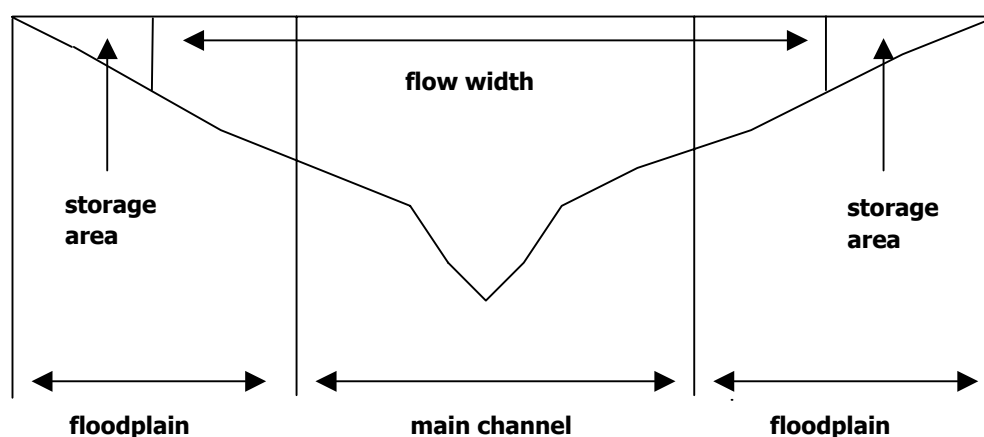


Figure D.3-1 Example of cross section in SOBEK RE

In most cases the *branch length* is also used as calibration parameter in SOBEK RE. However the bathymetry in this study is assumed accurate, because an official nautical chart is used.

'Far field' hydrodynamics

The 'far field' calibration focuses on a correct representation of the propagation of the tidal wave, the amplitude of the tidal wave and the increase in tidal range in the estuary, since the tidal propagation is the main process in Kyunggi Bay. For the calibration the time series of High Water and Low Water levels in Incheon, for the period of June 27th to July 27th, 2005, are compared with the SOBEK RE results at the same location in the same time period. The calibration succeeds when the propagating tidal wave in SOBEK RE is similar to the measured tidal wave in Incheon.

The results of this comparison are presented in Figure D.3-2. The figure shows only small phase differences between the measured data and the model results. So, propagation speed of the tidal wave from seaside boundary (no 5) to Incheon is simulated correctly in the model. The amplitudes in Figure D.3-2 show more or less the average value of the measured data, which is also a good result. Nevertheless, the amplitudes of both tidal waves show small differences. These differences are caused by the simplification that in this study only the most important tidal constituents M2 and S2 govern the hydrodynamics of Kyunggi Bay. Other tidal constituents are not used in this study, but might have a significant influence in reality. The importance of the other tidal constituents in reality is investigated in the Matlab module t-tide. However, these results are not relevant in this study and therefore included in Appendix VIII. It is important to keep the consequences of the simplification in mind, especially during interpretation of the model results later in the study.

At last, the increase in tidal range in the SOBEK RE model is checked. The results of comparing the SOBEK RE results with the data of the co-tidal chart of Kyunggi Bay are presented in Appendix II.

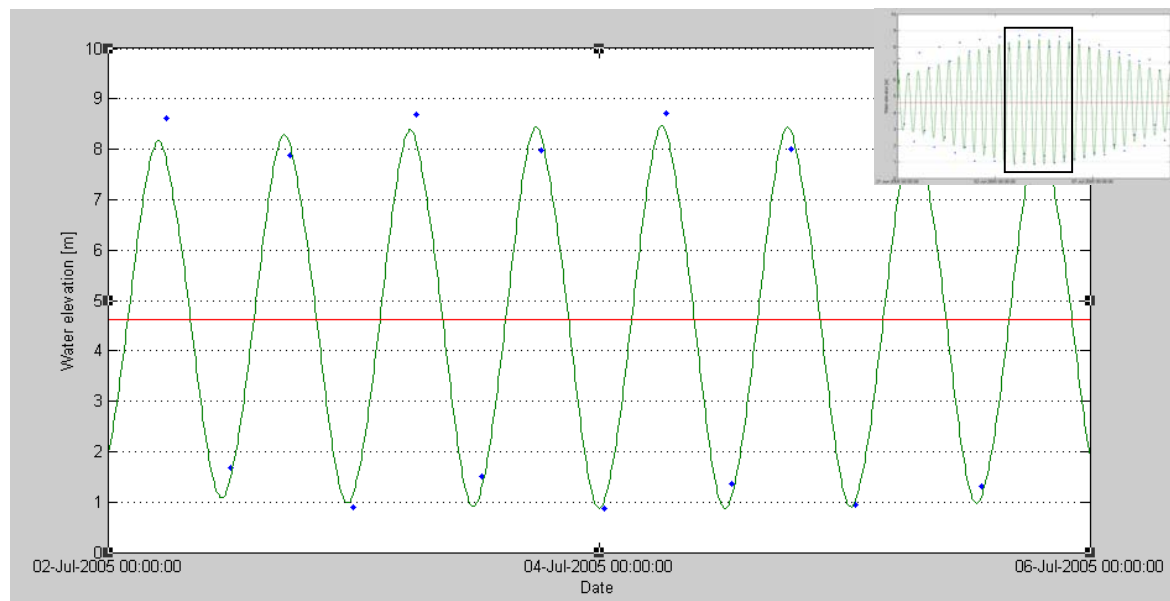


Figure D.3-2 Comparison of the tidal wave in Incheon with spring tide; SOBEK RE (green), tidal station (blue), mean tide (red) [212]

'Near field' hydrodynamics

A correct representation of the 'near field' hydrodynamics is important to quantify the processes causing siltation in Incheon Terminal basin due to the execution of the Kyung-In Canal project. The tide in the main hydrodynamic process in Kyunggi Bay and causes two different movements. A vertical movement (tidal elevation) when the tidal wave is passing and a horizontal movement (tidal current)

resulting from the vertical variations of the water level. This section focuses on these two characteristics of the tide. A correct reflection of the tidal current is very important because this determines the sediment transport capacity in the Project Area. The desired current velocities in respectively ebb and flood direction are 1.6 and 1.5 m/s. In addition, the phase difference between the horizontal and vertical tide is important, since this study also investigates the influences of the inter-tidal areas in front of Incheon Terminal. A correct representation of the phase difference generates a flood current across the inter-tidal area in front of Incheon Terminal basin in the harbour basin. This current transports sediment in the direction of Incheon Terminal basin and causes siltation. In the calibration procedure a difference between horizontal and vertical tide of 1.1 hours is desired. A more elaborated explanation of the importance of the phase differences between horizontal and vertical tide in this study is described in chapter D.5.

In the schematisation of the 'Autonomous Situation' the horizontal and vertical tidal movement do not present the reality. An important explanation for this incorrect reflection of the reality is the extensive inter-tidal areas, with totally different hydrodynamic and frictional behaviour, in Kyunggi Bay. The following procedure is used to fulfil the purpose of the calibration. The step sequence in this procedure is specified iteratively, by observing the influence of all the hydrodynamic calibration parameters separately. In this way, the calibration procedure also created insight in the influence of the different model parameters. Appendix XV includes a table with all the model parameters that are used and the values that are investigated during the calibration. In addition, appendix XV shows the resulting graphs of the calibration steps. Table D.3-2 below summarises the results of the calibration procedure.

1. Examine the effect of changing the lengths of Yeomha Waterway:

Initially the phase difference between the horizontal and vertical tide is too small in the Project Area. This can be caused by the characteristics of the tidal wave in Kyunggi Bay. By extending the length of Yeomha Waterway the tidal wave in Kyunggi Bay will change from a standing wave to a progressive wave (Appendix XV). This results in more accurate reflection of the phase difference between horizontal and vertical tide. Furthermore, an extension of Yeomha Waterway results in larger distance between the Project Area and the model boundary at the end of 'Yeomha Waterway'. This decreases the reflection effects of the tidal wave on the boundary. A negative effect of extending the length of Yeomha Waterway is the increase in tidal prism.

2. Divide the cross sectional area in a flow area and storage area:

The initial flow velocities are far too low, when comparing with the flow velocities in reality. Concentrating the flow in a smaller area causes an increase in flow velocities in the Project Area. In addition, a smaller flow width has got a positive effect on the phase difference between horizontal and vertical tide, because the flood period increases.

3. Change the friction of the main channel:

In the model, the flow velocities in as well the flood as the ebb direction are not reflecting the reality. Especially the flood velocities in the model are too low. Probably, the inter-tidal areas with totally different hydrodynamic behaviour are an important reason for this difference between the schematisation in SOBEK RE and reality. In SOBEK RE hydrodynamic characteristics of inter-tidal areas is not included (also section D.2.3).

To create correct current velocities the friction coefficient of the main channel is used as calibration parameter. In the schematisation use is made of the friction coefficient of Chezy. Because the current velocities with flood tide are far too low, a rather drastic change in the friction coefficient is used to calibrate the current velocities in flood direction. This resulted in a Chezy friction coefficient of $110 \text{ m}^{1/2}/\text{s}$ in flood direction and $52 \text{ m}^{1/2}/\text{s}$ in ebb direction. It is important to keep in mind the use of this extraordinary and direction dependent friction coefficients, because it may have effects on other processes.

4. Change the friction of Yeomha Waterway:

The friction of Yeomha Waterway has got minimal effects on the hydrodynamics in the Project Area. Nevertheless, a higher friction coefficient on Yeomha Waterway has got small positive effects on the ratio between the period of flood velocities and ebb velocities. Because there are no inter-tidal areas in Yeomha Waterway, the flood and ebb friction are assumed equal.

5. Change the friction of the floodplains:

In calibration step 2 the flow width was defined at Datum Level +3 meter. Consequently, the floodplains are only a small part of the cross-sectional profile. Therefore the friction coefficient of the floodplains is used for fine-tuning the model. Of course the friction of the floodplains is supposed to be lower than in the main channel.

As mentioned before Table D.3-2 summarises the results of the calibration procedure. The second column shows the initial values of the 'Autonomous Situation'. The following columns show the same calibration steps as mentioned above. The bold values in the orange cells show the model parameter that result from the calibration step in concerning column. The last column shows the final values of the calibration procedure. The last three rows show the improvement of the parameters that must be calibrated.

Calibration step	Initially	1	2	3	4	5	Finally
Length Yeomha Waterway [km]	16	48	48	48	48	48	48
Flow width [ref. LLWS]	+8	+8	+3	+3	+3	+3	+3
Main channel ebb direction	55	55	55	52	52	52	52
Main channel flood direction	55	55	55	110	110	110	110
Friction Yeomha Waterway	55	55	55	55	70	70	70
Floodplains ebb direction	55	55	55	55	55	20	20
Floodplain flood direction	55	55	55	55	55	55	55
Phase difference [hours]	0.20	0.7	0.9	0.95	1.0	1.0	1.0
Ebb current velocity [m/s]	1.14	0.99	1.02	1.37	1.41	1.44	1.44
Flood current velocity [m/s]	1.44	1.64	1.64	1.58	1.64	1.64	1.64

Table D.3-2 Summary of the results of the calibration procedure

A graph of the final calibration result is presented in Figure D.3-3. The result shows that the flow velocities for both ebb and flood tide are represented correctly in the model. Unfortunately, a correct reflection of phase difference between horizontal and vertical tide is not reached. The resulting 1.0-hour is still not the 1.1-hours that was found by field measurements (Appendix IV and [201]). The most important model parameter to obtain a correct reflection of the phase difference between the horizontal and vertical tide is the length of Yeomha Waterway. Finally, this parameter is defined at 48

kilometres. More extension of Yeomha Waterway did not have a positive effect on the phase difference. Probably, the reduction of reflection effect at the boundary of Yeomha Waterway resulted in the change in the phase difference. The length of 48 kilometres was chosen because at this location exists a weir in the Han River and in reality the tidal wave also reflects at this location.

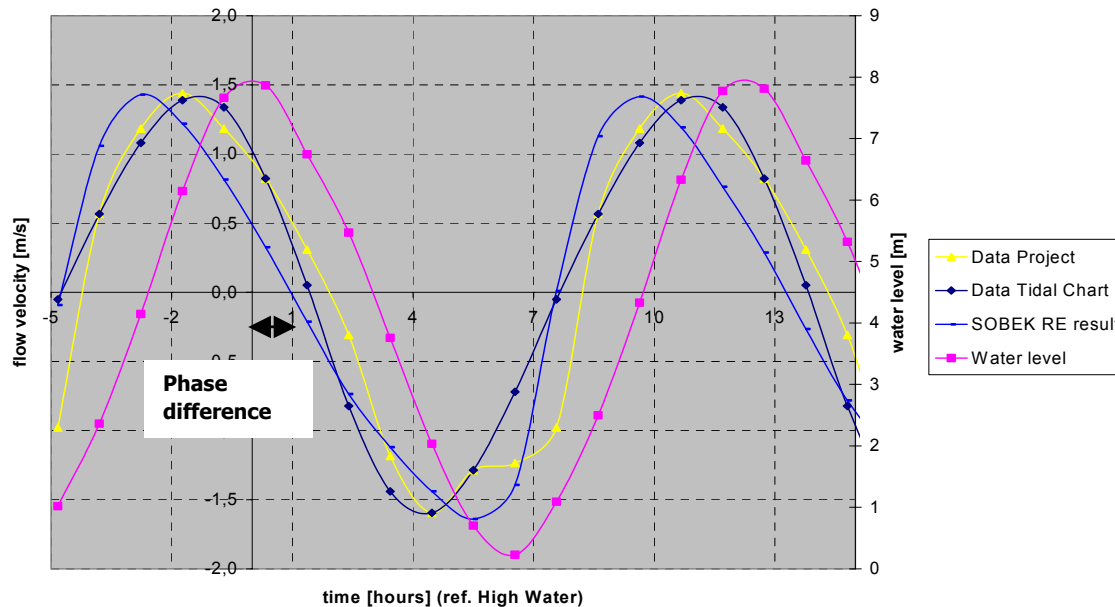


Figure D.3-3 Final calibration result [211]

D.3.3 Conclusions

Kyunggi Bay is characterised by many hydrodynamic processes. However the main process in Kyunggi Bay is the tide. This is the reason the purpose of this calibration is a correct simulation of the tidal movement for both 'far field' and 'near field'. Secondary hydrodynamic effects are not included in the model because these effects are assumed to be limited.

For the 'far field' calibration the model initially shows quite correct results. The tidal propagation as well as the amplitude of the tidal wave and the increase in tidal range shows quite similar results as the 'field' data. For the 'far field' calibration of the hydrodynamics in the 'Autonomous Situation' no adjustments of the model parameters turned out to be necessary.

The initial 'near field' hydrodynamics show large differences with the field observations. The calibration of the horizontal flood current required a quite drastic increase of the friction coefficient in flood direction from 55 to 110 $\text{m}^{1/2}/\text{s}$. Furthermore, the field observations show a phase difference between the horizontal and vertical tide of 1.1 hours, while the phase difference initially computed was 0.2 hours. Mainly the extension of the Yeomha Waterway, but also the narrowing of the flow width, finally resulted in a phase difference of 1.0 hour. This is still not exactly the 1.1 hours from the field investigations, but this result is assumed to be sufficiently accurate to simulate the flood current across the inter-tidal area. Nevertheless, the model results should be used with caution.

D.4 MORPHOLOGICAL MODEL OF KYUNGGI BAY

D.4.1 Model schematisation

The schematisation of the morphology comprises the definition of boundary conditions, nodal point relations, sediment transport formula and morphological model parameters.

At the model boundaries a sediment influx must be defined. The boundary conditions are based on an existing numerical model in which also siltation in Kyunggi Bay was investigated [206]. Table D.4-1 presents the boundary conditions.

	Sediment influx [mg/l]
Sea side boundaries	30
Yeomha Waterway: 11 month	150
1 month (rain season)	350

Table D.4-1 Boundary conditions of sediment influx [m^3/s]

The nodal point relation determines the sediment distribution at bifurcations. Especially the nodal point relation at the bifurcation in front of Incheon North Port (no. 4) is important. This nodal point relation determines the net sediment influx and thus the siltation rates in the open-harbour basin of Incheon North Port. The siltation rates in Incheon North Port will later be used as reference for the siltation rates in Incheon Terminal basin. Initially is chosen for a distribution proportional with the discharge. This same distribution is used in the Analytical Approach that is used in this study and makes comparison of both methods easier. The second nodal point north at the mouth of Yeomha Waterway (no. 2) has also a proportional sediment distribution with the discharge. This nodal point relation determines the sediment transport that passes the Project Area. These sediment transports are calibrated later in section D.4.2.

For the sediment transport in the model use is made of the sediment transport formula of Van Rijn. The reason to choose the sediment transport formula of Van Rijn is that in this formula the Chezy coefficient is not included. This friction coefficient is already used during calibration of the hydrodynamic characteristics in the model. This resulted in a numerical friction that has nothing to do with the reality. Applying a transport formula, which includes this friction coefficient results in incorrect sediment transport volumes. In addition, the sediment transport formula of Van Rijn contains both suspended bed material and bed load fraction and thus contains total sediment transport. The formula for the bed load fraction is as follows:

$$\frac{s_b}{u_m d} = \frac{1}{1 - \varepsilon} 0.0005 \left(\frac{u_m - u_c}{\sqrt{g \Delta_d D_{50}}} \right)^{2.4} \left(\frac{D_{50}}{d} \right)^{1.2} \quad [\text{D.4-1}]$$

The formula of suspended load fraction is as follows:

$$\frac{s_s}{u_m d} = \frac{1}{1 - \varepsilon} 0.0012 \left(\frac{u_m - u_c}{\sqrt{g \Delta_d D_{50}}} \right)^{2.4} \left(\frac{D_{50}}{d} \right)^{1.2} (D_g)^{-0.6} \quad [\text{D.4-2}]$$

In which:

s_b = Bed load sediment transport [m^2/s]

s_s = Suspended load sediment transport [m^2/s]

d = Water depth [m]

u_m = Average flow velocity in main channel [m/s]

u_c = Critical flow velocity [m/s]

ε = Packing factor of bed material [-]

g = Gravitational acceleration [m/s^2]

Δ_d = Relative density of sediment [-]

D_{50} = Grain size for which 50% of the material is smaller [m]

D_g = Dimensionless grain size parameter [-]

The D_{50} value of the grain size is approximately 300 μm in the main channel in front of Incheon Terminal basin (Appendix IV). Because SOBEK RE does not keep up the exchange of sediment between different branches, initially a model wide D_{50} value of 300 μm is used. Furthermore, a uniform grain size prevents large morphological changes at the nodal points in the model. In the basin areas a finer D_{50} grain size of 50 μm is used. This is approximately the grain size found by measurements on the inter-tidal area in front of Incheon Terminal (Appendix IV). In reality also grain sizes of 10 μm are present in the open-harbour basin of Incheon North Port. For the sediment transport formula of Van Rijn, SOBEK RE also requires a D_{90} -value. In the main channels a value of 500 μm is used and in the basin 100 μm . The sediment transporting width is defined as the width of the main channel at Datum Level.

D.4.2 Calibration

Because it is impossible to calibrate the sediment transport in whole Kyunggi Bay with the available data, the calibration of the morphological module focuses on the sediment transport in the Project Area. A correct simulation of the suspended sediment concentration in front of Incheon Terminal is important to determine the amount of sediment influx in Incheon Terminal basin. Every flood tide the water transports sediment into Incheon Terminal basin. In the sheltered basin area the sediment can settle causing siltation of the basin.

Available 'field' data

The amount of useful field data about the morphology in Kyunggi Bay is limited. The following field data are used to calibrate the morphological model:

- The suspended sediment concentration of the tidal current in front of the Project Area for the outer, middle and lower layer (Appendix IV, location SB-2).

Calibration parameters

For the calibration of the morphology only the model parameters that have no effect on the hydrodynamics can be used. This results in the following calibration parameters:

- Grain size (D_{50})
- Nodal point relation

In section D.4.1 is already decided to use a proportional nodal point relation to makes the comparison of the SOBEK RE result with the Analytical Approach easier later in this study. For this reason the nodal point relation is only used for calibration when necessity.

'Near field' suspended sediment transport

For this calibration the sediment concentration for the middle layer at spring tide are used at measurement station SB-2. To transform the data into the right dimensions the sediment concentration with flood tide is multiplied with the discharge in the channel. This resulted in maximum sediment transport of $5.1 \text{ m}^3/\text{s}$ for spring tide. Subsequently, is investigated what effect D_{50} has on the sediment transport (Figure D.4-1). In the figure the positive axe represent the flood direction. Especially the sediment transport in flood direction must be simulated correct since sediment influx in the harbour basin occurs with flood tide. Figure D.4-2 shows a close up of the sediment transport with spring tide for a D_{50} of $300 \text{ }\mu\text{m}$. This results in almost correct representation of the maximum sediment transport in flood direction in front of the Project Area. The d_{50} of $300 \text{ }\mu\text{m}$ results in a net sediment transport in ebb direction of approximately $200,000 \text{ (m}^3/\text{tidal cycle)}$.

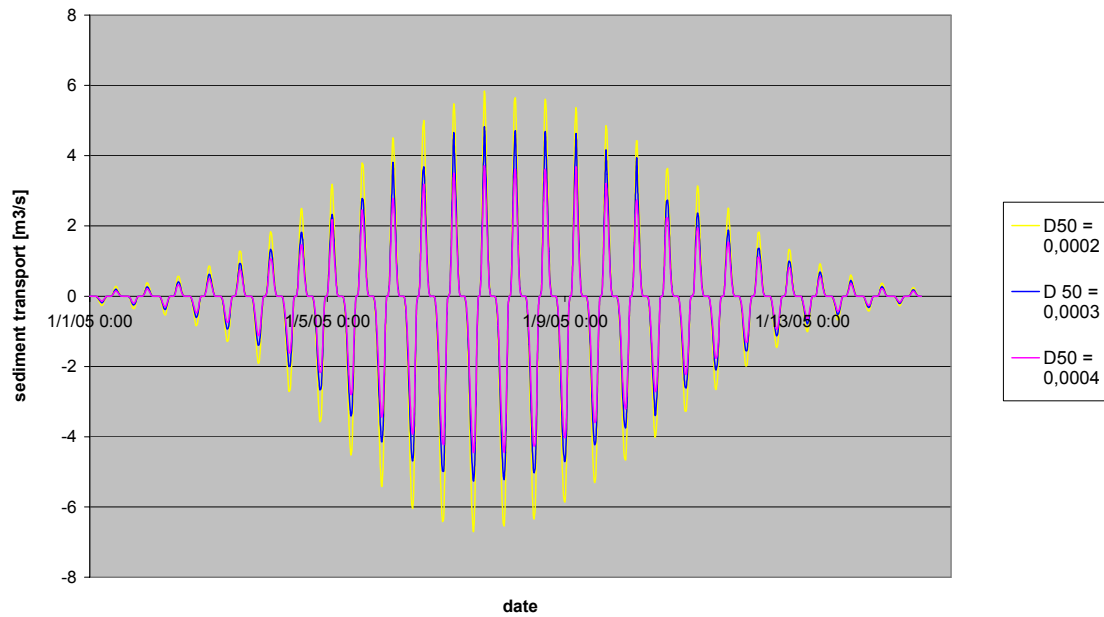


Figure D.4-1 D_{50} versus sediment transport in Navigation 2_0 for one spring-neap tide cycle [211]

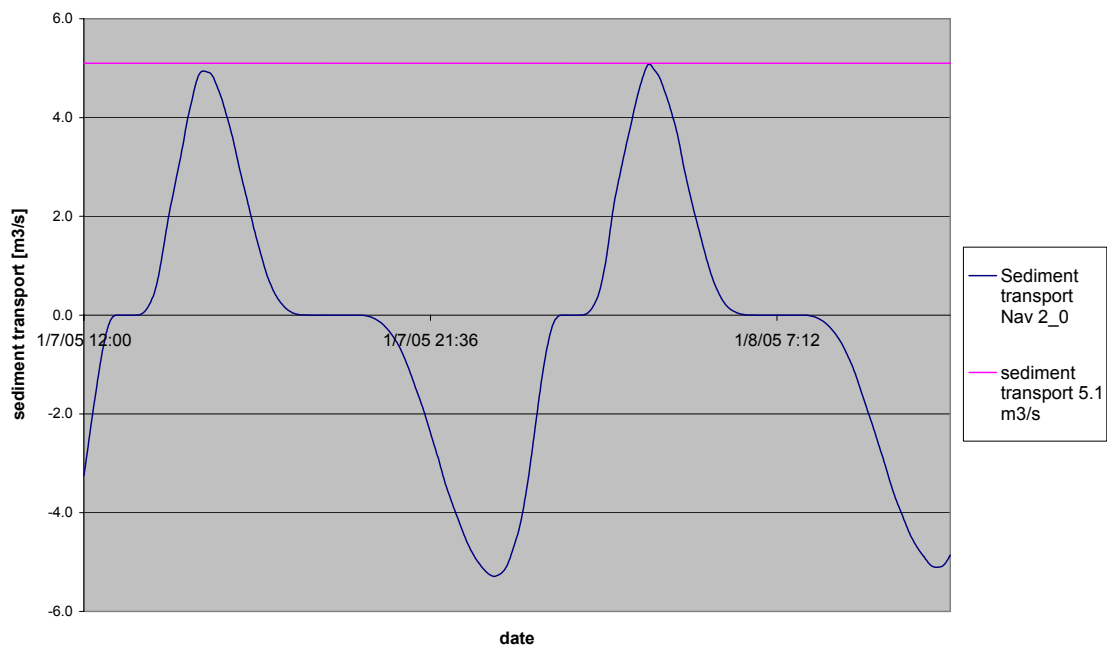


Figure D.4-2 Close up of sediment transport at spring tide for D_{50} of 300 μm [211]

D.4.3 Conclusions

The calibration of the morphological module focuses on a correct simulation of the sediment transports. For the calibration use is made of the maximum sediment transport during spring tide. The only model parameter that could be used is the D_{50} grain size. The calibration results in a D_{50} of 300 μm , which is approximately the grain size that is present in reality.

D.5 'PROJECT SITUATION'

This chapter presents the schematisation of the 'Project Situation'. In the 'Project Situation' all the interventions that are included in the Kyung-In Canal project are schematised. By comparing the 'Autonomous Situation' with the 'Project Situation' the 'far field' and 'near field' influences of the Kyung-In Canal project are investigated later in this study. For a better understanding of this chapter it is recommended to keep the schematisation of the 'Project Situation' next to the text ([Appendix X](#)). When branches are mentioned in this chapter the name of the branch is placed between quotes. Sometimes the name of the branch is followed by an underscore. The value behind the underscore indicates the location on the branch from the beginning of the branch (m). The positive direction of all branches is the direction of the ebb current.

In the 'Project Situation' three new branches are added to the schematisation of the 'Autonomous Situation'. In addition, the branch 'Navigation 2' is separated in two parts named: 'Navigation 2.1' and 'Navigation 2.2'. A branch of 1600-meter schematises the 'Entrance Channel'. This branch connects 'Navigation 2.1_0' with the second new branch in the 'Project Situation' that schematises 'Incheon Terminal'. A third new branch named 'Inter-tidal area' schematises the flow across the inter-tidal area in front of Incheon Terminal. This branch is 2200-meter long and 900 meter wide and creates a short cut from 'Navigation 2.2_0' to 'Entrance Channel_0'. Because the inter-tidal area was also included in the cross sectional area of 'Navigation 2' in the 'Autonomous situation', the cross sectional area of 'Navigation 2.1' in the 'Project situation' is adjusted by subtracting the inter-tidal area and also a part of the Entrance Channel. In this manner a correct reflection of the increase in tidal prism due to the Kyung-In Canal project is created. For all bifurcations that are created by adding these branches the nodal point relation for sediment transport is proportional to the distribution of water discharge. The grid distance of all branches is 200 m.

The newly created 'Inter-tidal area' is very shallow and dries with ebb tide. Because SOBEK RE cannot calculate with dry branches the 'dry bed procedure' in SOBEK RE is applied. The 'dry bed procedure' establishes a small, deep, funnel shaped channel in the middle of the cross sectional area, which prevents complete drying of the cross section. Figure D.5-1 shows the lay-out of this so-called Preismann funnel.

The shape of the Preismann funnel is semi-automatically created. The user only has to specify the averaged width W_{dry} of the Preismann funnel as well as its depth below the lowest bed level in the branch z_b to prevent drying of the cross sectional area. This artificially created cross section guarantees mass conservation and no effect on the flow computations in the cross section if the cross section is not dry.

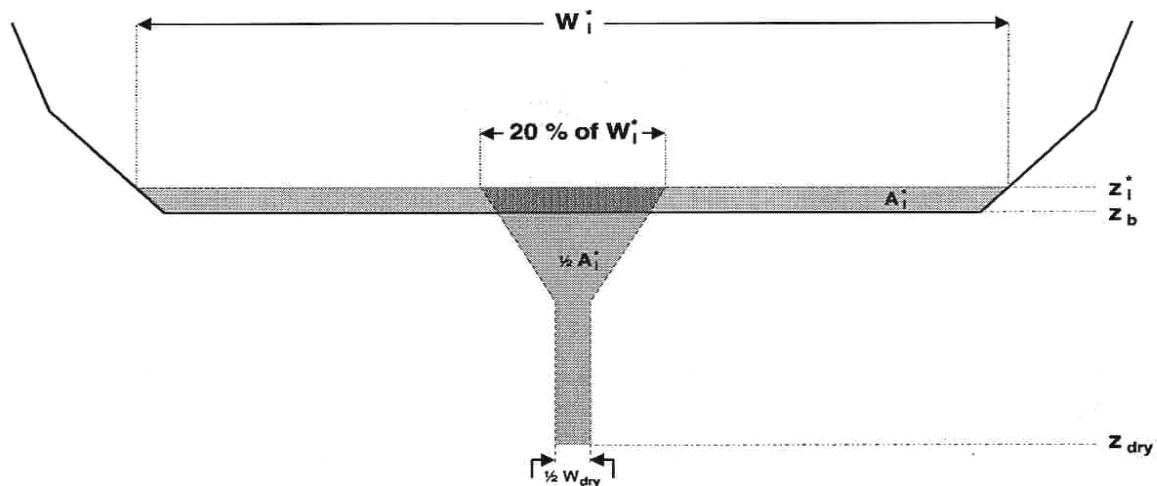
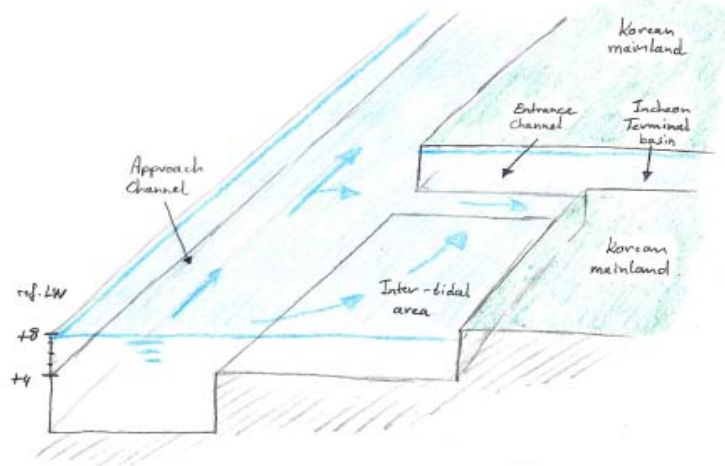


Figure D.5-1 Preismann funnel [24]

The schematisation of the 'Inter-tidal area' as described above is intended to create the following hydrodynamic processes. A flood current across the 'Inter-tidal area' caused by a phase difference between both ends of the 'Inter-tidal area'. This flow across the 'Inter-tidal area' brings sediment into



suspension and transports the sediment in the direction of 'Incheon Terminal'. Here, the flow velocities decrease and the sediment can settle causing siltation in Incheon Terminal basin. So, by creating this branch it is tried to simulate the effects of siltation caused by the inter-tidal areas in front of Incheon Terminal basin in the schematisation (Figure D.5-2).

Figure D.5-2 Flow across the inter-tidal area

This explanation also makes clear, why a correct reflection of the phase difference between horizontal and vertical tide during calibration of the hydrodynamics was so important. Due to a phase difference in front Incheon Terminal basin, the water level starts lowering at the moment there is still a flood current. At the moment of high water slack (flow velocities are zero) the water level on the inter-tidal area is lower than with flood, which results in less ebb discharges across the inter-tidal area compared with flood discharge.

In addition, the Kyung-In Canal project comprises the dredging of an Approach Channel and Turning Basin. This dredging work must guarantee a depth of Datum Level -10 m. The area that has to be dredged stretches over 'Navigation 1', 'Navigation 2.1' and 'Navigation 2.2' in the schematisation of the 'Project Situation'. To realise the necessary depth in this area, the dredging module in SOBEK RE is used. The dredging volumes are determined by handmade calculations for sections of 400 meter and than substituted in the model. The defined sections cannot be part of two different branches, because this is not possible in SOBEK RE. When the dredging volumes are substituted, SOBEK RE dredges an Approach Channel and Turning Basin in the 'Project Situation' in a time span of 17 hours.

PART E

Siltation study

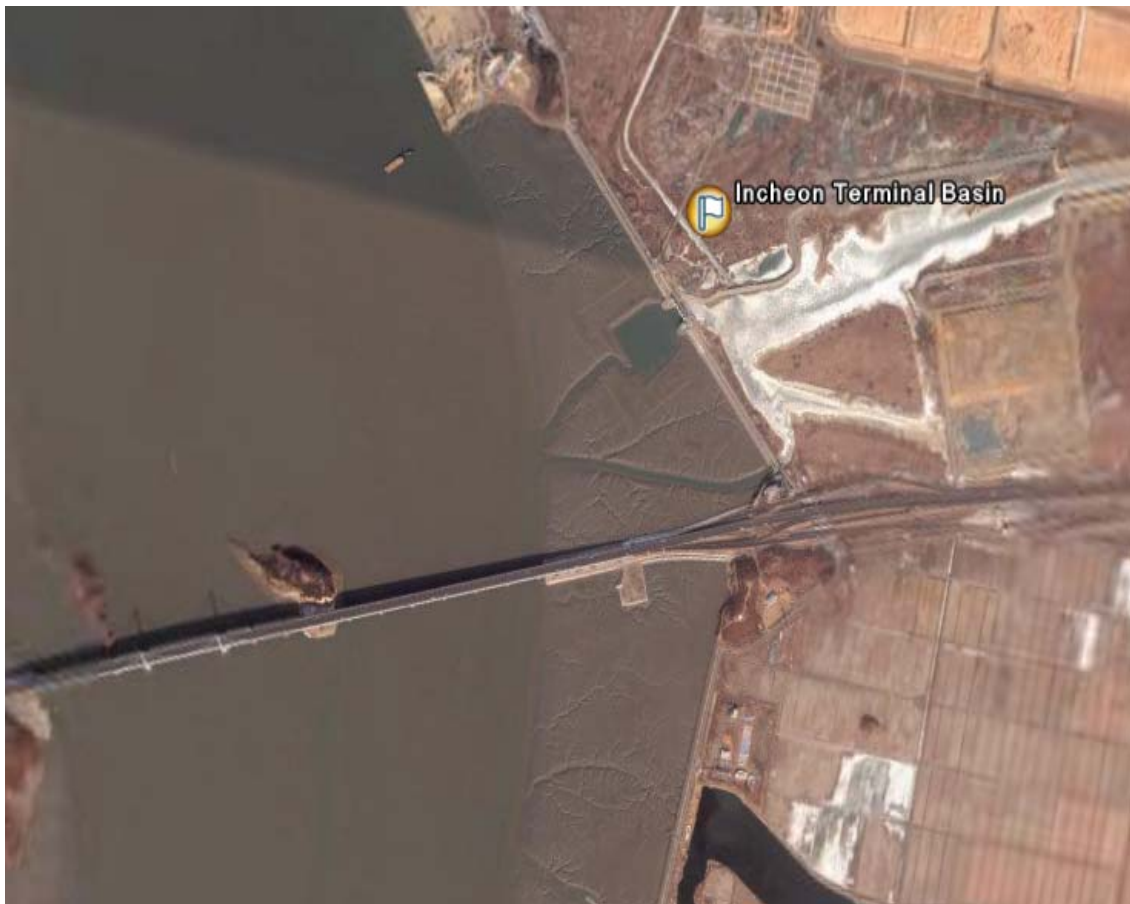


Figure E: Satellite photo of Project Area [214]

E.1 INTRODUCTION

Part E deals with the results of this study. In chapter E.2 the results of an Analytical Approach are presented. The Analytical Approach is based on the theory about water exchange mechanisms, which is described in chapter B.3. The Analytical Approach creates insight in the influences of the different mechanisms causing siltation for both Incheon Terminal basin and Incheon North Port.

In chapter E.3 the results of the 'far field' consequences of the Kyung-In Canal project are presented. In two different sections the hydrodynamic and morphological results are discussed. The consequences of the Kyung-In Canal are investigated by comparing the model calculations for the 'Project Situation' and the 'Autonomous Situation'. In this investigation the relative differences between the 'Project Situation' and the 'Autonomous Situation' are analysed. It is assumed that possible inaccuracies occur in both the 'Project Situation' and the 'Autonomous Situation'. By analysing the relative differences between the two situations these inaccuracies have less effect on the results.

Chapter E.4 describes the 'near field' results. The 'near field' results analyses the siltation of Incheon Terminal basin and Entrance Channel caused by tidal prism ('direct' filling via the Entrance Channel) in section E.4.1. Furthermore, influence of the nodal point relation on the sediment influx in Incheon North Port is investigated. In section E.4.2 the influence of the inter-tidal area (tidal filling via the inter-tidal area) is analysed.

In chapter E.5 the model results and the connection with the reality are discussed. This chapter also treats the comparison of SOBEK RE with the Analytical Approach. Based on the results of chapter E.5 in chapter E.6 some mitigating measures are suggested.

The study finalises with Conclusions and Recommendations. The Conclusions deal with the answer to the objective of this study. Furthermore the conclusions form a summary of the main conclusions of the different parts of this study. The Recommendations outline the subjects that need further research.

E.2 ANALYTICAL APPROACH

The objective of applying an Analytical Approach in this study is two fold. At first, an Analytical Approach gives insight in the influence of different processes causing siltation in harbour basins. Secondly, the Analytical Approach is used as reference for the 'near field' siltation calculations with SOBEK RE, since the appropriateness of SOBEK RE in siltation cases is questionable. W.D. Eysink published the Analytical Approach used in this study [5]. The Analytical Approach determines the siltation of harbour basins, based on three water exchange mechanisms (section B.3.1). In this chapter the siltation in both Incheon North Port and Incheon Terminal basin are determined.

For a correct comparison of the Analytical Approach with the results of SOBEK RE discussed later in this study, water exchange due to tidal prism is treated separately from water exchange due to horizontal eddies and density currents. This is done because only water exchange due to tidal prism is included in SOBEK RE. In addition, the Entrance Channel and Incheon Terminal basin are both defined as sheltered areas in the Analytical Approach. Again this is done for a correct comparison with SOBEK RE. SOBEK RE is an instantaneous model and thus all sediment directly settles when the sediment transport capacities are too low. This occurs in the Entrance Channel and thus no sediment is transported into Incheon Terminal basin in SOBEK RE. Afterwards the net sediment influx in the Entrance Channel is distributed over Entrance Channel and Incheon Terminal basin. In reality, it is expected that more sediment settles in Incheon Terminal due to less hydrodynamic effects in Incheon Terminal basin. However, in the Analytical Approach it is assumed that the sediment is distributed evenly over the Entrance Channel and Incheon Terminal. The siltation results of the Analytical Approach for water exchange due to tidal prism are presented in Table E.2-1. The average suspended sediment concentrations used in the Analytical Approach are determined with SOBEK RE.

	North Port	Entrance Channel + Incheon Terminal	Dimension
Volume tidal prism	12.9	6.2	*10 ⁶ m ³ /tide
Average suspended sed.	0.13	0.21	kg/m ³
Total siltation	0.7	0.6	*10 ⁶ m ³ /year
Siltation	0.3	0.5	m/year

Table E.2-1 Siltation caused by water exchange due to tidal prism

From Table E.2-1 it becomes clear that the Analytical Approach predicts more siltation in Incheon Terminal and the Entrance Channel. The main reason for this difference is a lower concentration of suspended sediment in front of Incheon North Port, since the tidal range at both locations is more or less the same. However, for the suspended sediment concentrations in front of the Entrance Channel the values before the dredging of the Approach Channel are used. Probably, the sediment transporting capacity decreases due to the dredging of the Approach Channel and so does the suspended sediment concentration. In this case the siltation in Table E.2-1 over-estimates the reality.

Below the Analytical Approach is applied to determine the siltation caused by horizontal eddies and density currents. In Incheon Terminal basin the influence of horizontal eddies is assumed nil. The inter-tidal area in front of Incheon Terminal basin disturbs the current velocities in such a way that eddies do not occur. However, in the mouth of the Entrance Channel horizontal eddies occur, which is shown in Table E.2-2.

The determination of siltation caused by density gradients for Incheon Terminal basin is more complicated than for Incheon North Port. In front of Incheon Terminal weak longitudinal density gradients, caused by peak discharge of Yeomha Waterway, occur in the rain season. In addition, the floodgate causes discharge of less saline water from Kyung-In Canal into Incheon Terminal area during the rain season and finally, there is also the effect of water exchange due to lockage of vessels between Incheon Terminal basin and the Kyung-In Canal. In North Port, the effect of density gradients caused by peak discharge from Yeomha Waterway is very small. Furthermore, no fresh water discharge from the land flows out in Incheon North Port. Table E.2-2 shows the siltation caused by all three water exchange mechanisms.

	North Port	Entrance Channel + Incheon Terminal	Dimension
Volume tidal prism	12.9	6.2	*10 ⁶ m ³ /tide
siltation due to Vt	0.3	0.5	m/year
Volume eddies	0.7	1.2	*10 ⁶ m ³ /tide
siltation due to Ve	0.03	0.1	m/year
Volume density	28.6	79.6	*10 ⁶ m ³ /tide
siltation due to Vd	0.1	0.6	m/month
Total siltation	0.5	1.2	m/year

Table E.2-2 Siltation caused by all three water exchange mechanisms

Table E.2-2 shows a small influence of horizontal eddies in Incheon North Port. This is caused by the large influences of the tidal prism in Incheon North Port, which is negatively correlated with the effect of horizontal eddies. For the determination of siltation caused by density gradients the salinity measurements in Appendix IV are used. This results in a significant effect on the sediment influx and thus siltation in Incheon Terminal basin. In the determination is assumed that the density difference only occur one month a year during the rain season. This results in 0.6 m/year extra siltation above the already determined siltation caused by tidal prism.

From the results of this section can be concluded that density differences can have significant influence on siltation in Incheon Terminal basin. However, for this study density differences are not important, because this process is not included in SOBEK RE. More background about the results of this section is included in Appendix XIII.

E.3 'FAR FIELD' RESULTS

In this chapter the 'far field' results of the execution of the Kyung-In Canal project are discussed. In two different sections the hydrodynamic and morphological results are discussed. The consequences of the Kyung-In Canal are investigated by comparing the model calculations for the 'Project Situation' and the 'Autonomous Situation'. In this investigation the relative differences between the 'Project Situation' and the 'Autonomous Situation' are analysed. It is assumed that possible inaccuracies occur in both the 'Project Situation' and the 'Autonomous Situation'. By analysing the relative differences between the two situations these inaccuracies have less effect on the results.

For a better understanding of this chapter, it is recommended to hold the schematisation of the 'Project Situation' next to text (Appendix X). The horizontal axe of the figures in this chapter represents the 'far field' area. This area stretches from the north 'Yeomha_40000' ('Name of branch _ location on branch [m]') in southern direction and ends at 'Nav 3_4503' south of the bifurcation with 'North Port'. This area includes the hydrodynamic effects of 'Gangwado' in the north and the area of 'North Port' in the south. Along the horizontal axe of the figures the important locations for the 'far field' investigation, from north to south, are mentioned from left to right. On the left and right end of the horizontal axe the grid distance is multiplied with 10 and 2.5, respectively.

During the analysis of the 'far field' results in this chapter, three parts can be distinguished. The Project Area, which stretches from 'Navigation 1_3824' to 'Navigation 2_3207', the area north of the Project Area and the area south of the Project Area. In this way, also the changes in the Approach Channel are presented in this chapter. The arrows in the figures show the location of the bifurcations with the Entrance Channel (no 3) and the inter-tidal area (no 13).

E.3.1 Hydrodynamics

Discharge

In Figure E.3-1 and Figure E.3-2 show an increase in flood discharge of 10 million m³ caused by the execution of the Kyung-In Canal project. The construction of Incheon Terminal basin and the Entrance Channel create an extra tidal prism of approximately 5 million m³ in SOBEK RE. The remaining difference can be ascribed to the increase in tidal range due to the Kyung-In Canal project. This is noticeable north of the project area at the location 'Nav 1_3834', where the increase in flood discharge is still approximately 4 million m³ compared with the 'Autonomous Situation'. The average relative difference in discharge between the 'Autonomous Situation' and 'Project Situation' is approximately 3% (Figure E.3-3).

In the Project Area a significant increase in flood discharge is perceptible. This is caused by the schematisation of the inter-tidal areas, which generates a circulation of the flood current from

'Navigation 2.1' into the 'Entrance Channel' into the 'Inter-tidal area' and back into 'Navigation 2.1'. This effect is less with low tide because the water level with low tide are already lower due to the phase difference between the horizontal and vertical tide. However, still a small decrease of discharge is perceptible at 'Nav 2_1600' because a part of the relatively increased ebb discharge returns across the 'Inter-tidal area'. More about this phenomenon is described in chapter E.4, about the 'near field' results.

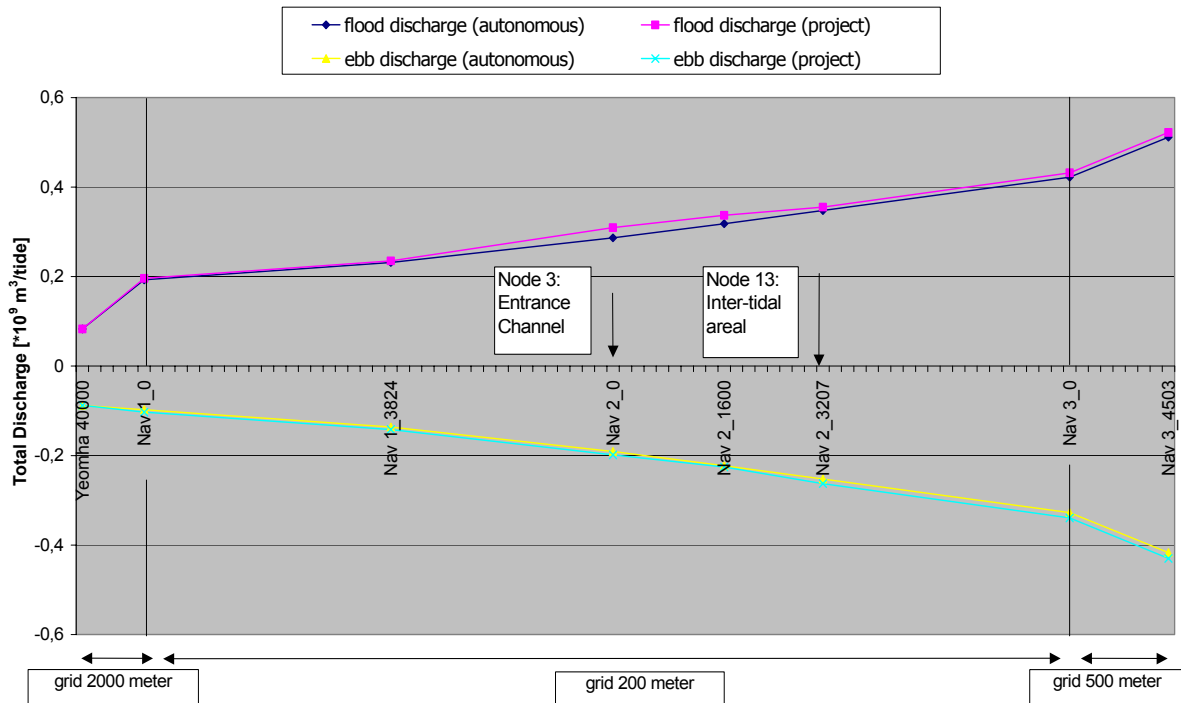


Figure E.3-1 Change in total discharge due to the execution of the Kyung-In Canal project [211]

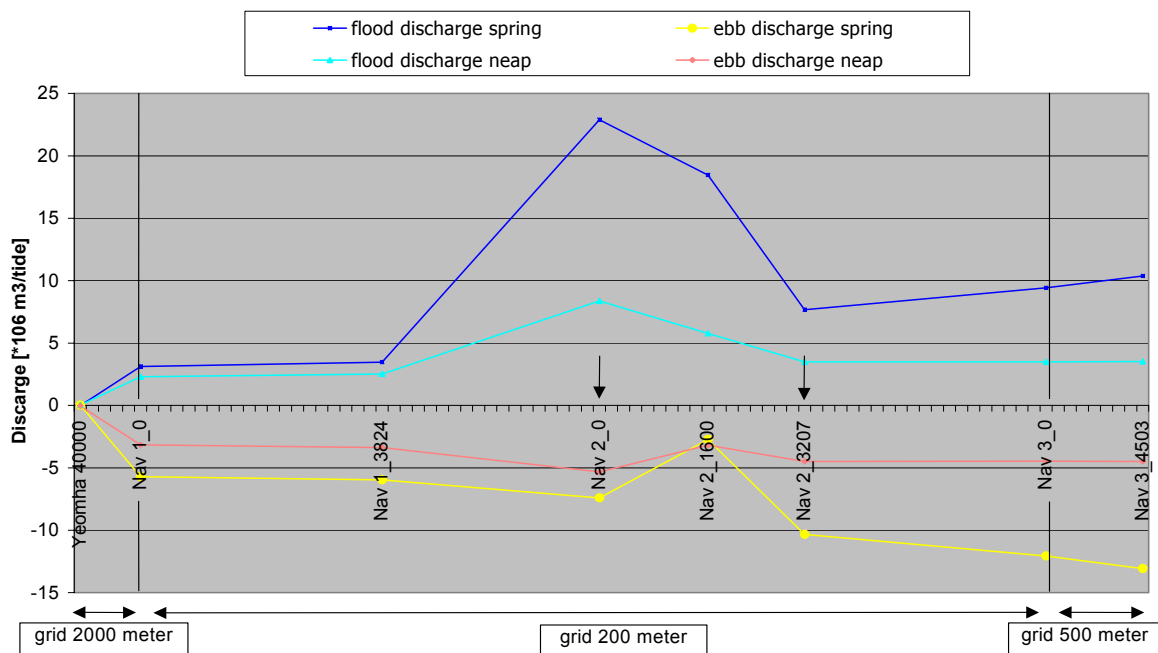


Figure E.3-2 Absolute difference in discharge due to the execution of the Kyung-In Canal project [211]

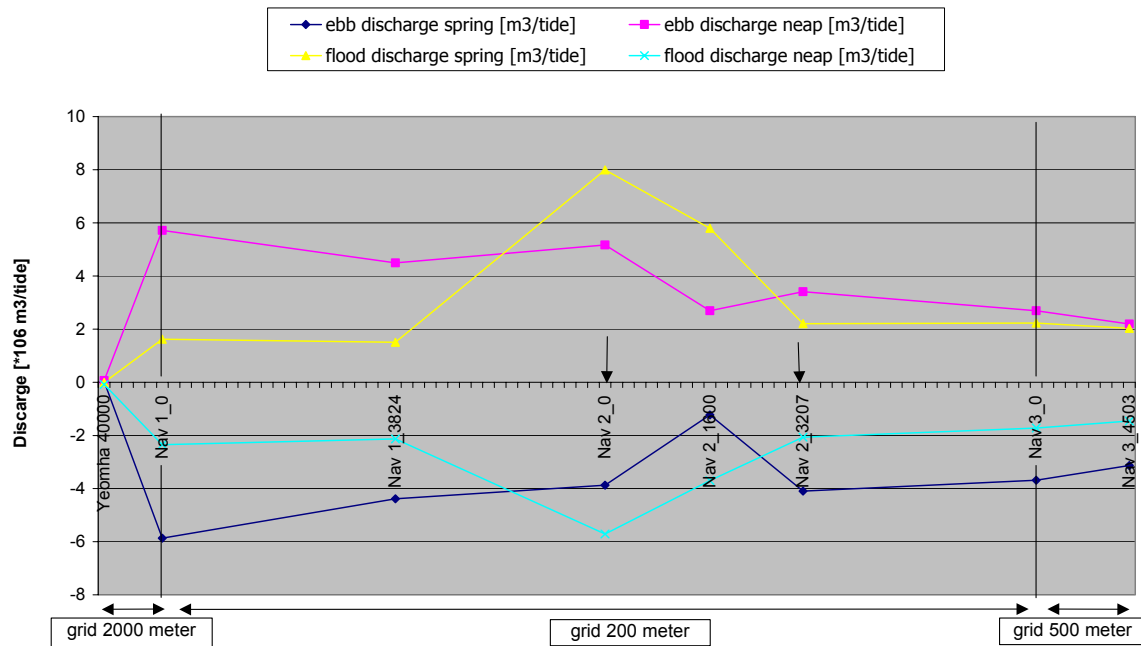


Figure E.3-3 Relative difference in discharge due to the execution of the Kyung-In Canal project [211]

Figure E.3-4 shows the relative differences in net discharge. Again the figure shows a large relative increase in flood direction in the Project Area due the circulation of the flood currents. However, also an overall extra discharge with low tide is perceptible. This extra discharge has entered Kyunggi Bay through 'Gangwado' and return with low tide via the 'Navigation 1' in southward direction. Perhaps, the reduced friction due to the dredging of the Approach Channel and Turning Basin causes this extra discharge with low tide, since the Chezy coefficients depends on the water depth.

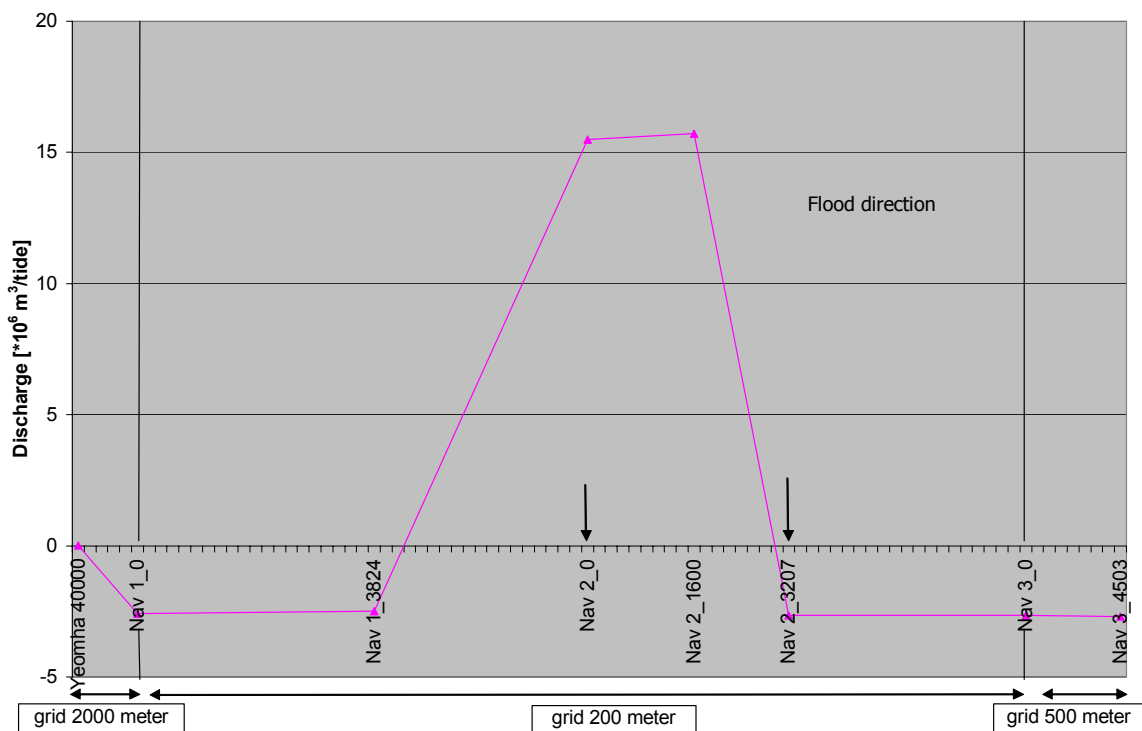


Figure E.3-4 Absolute change in net discharge after executing the Kyung-In Canal project [211]

Water level

Figure E.3-5 shows the change in tidal range caused by executing the Kyung-In Canal project. The figure shows a significant increase in spring tidal range, which is caused by lowering of low water level (Δh_{ebb}). It is difficult to find a plausible qualitative explanation for this phenomenon. Probably the dredged Approach Channel and Turning Basin is an important reason for this phenomenon. At first, the dredging work causes a steeper slope in low water levels from north to south, which is shown in Figure E.3-6. Consequently, the ebb flow velocities in 'Navigation 1_3834' increase, which is shown in the next section. Secondly, the dredging works create relatively more extra cross sectional area with ebb currents than with flood current due to the difference between horizontal and vertical tides in the Project Area. This causes a reduction of the friction for the ebb current and the already mentioned extra net discharge with low tide. Thirdly, a shorter time period between High Water level and Low Water level can be observed in the 'Project Situation', which is shown in Figure E.3-7. These three facts may be the reason the significant deviation of Δh_{ebb} in the 'Project Situation'.

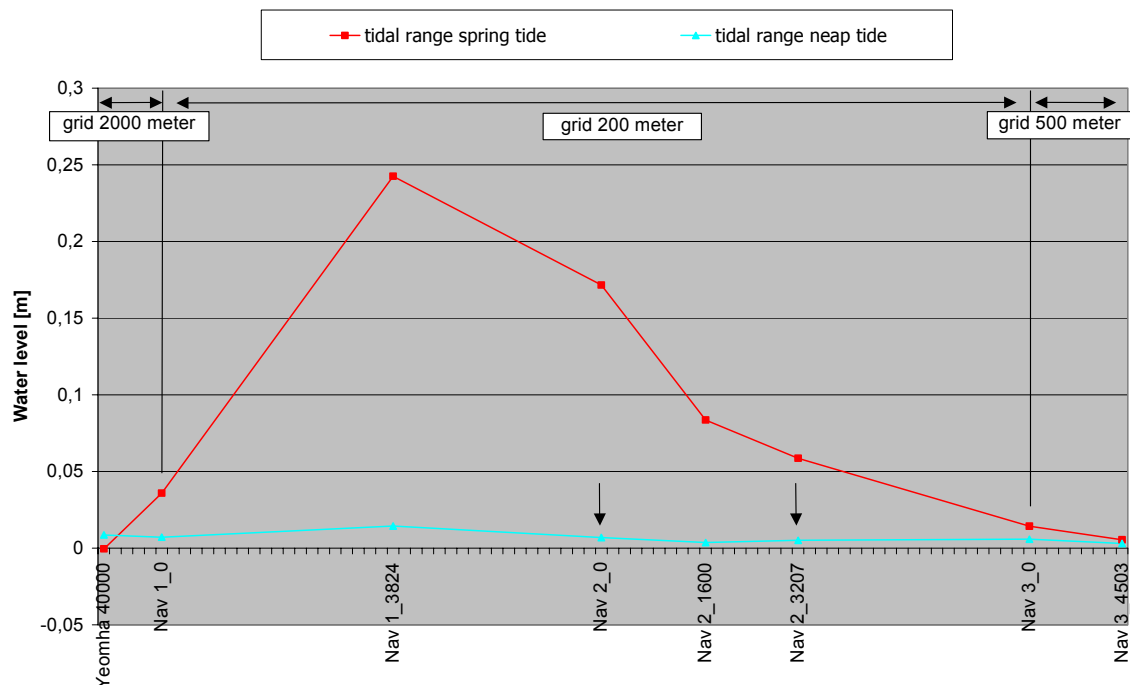
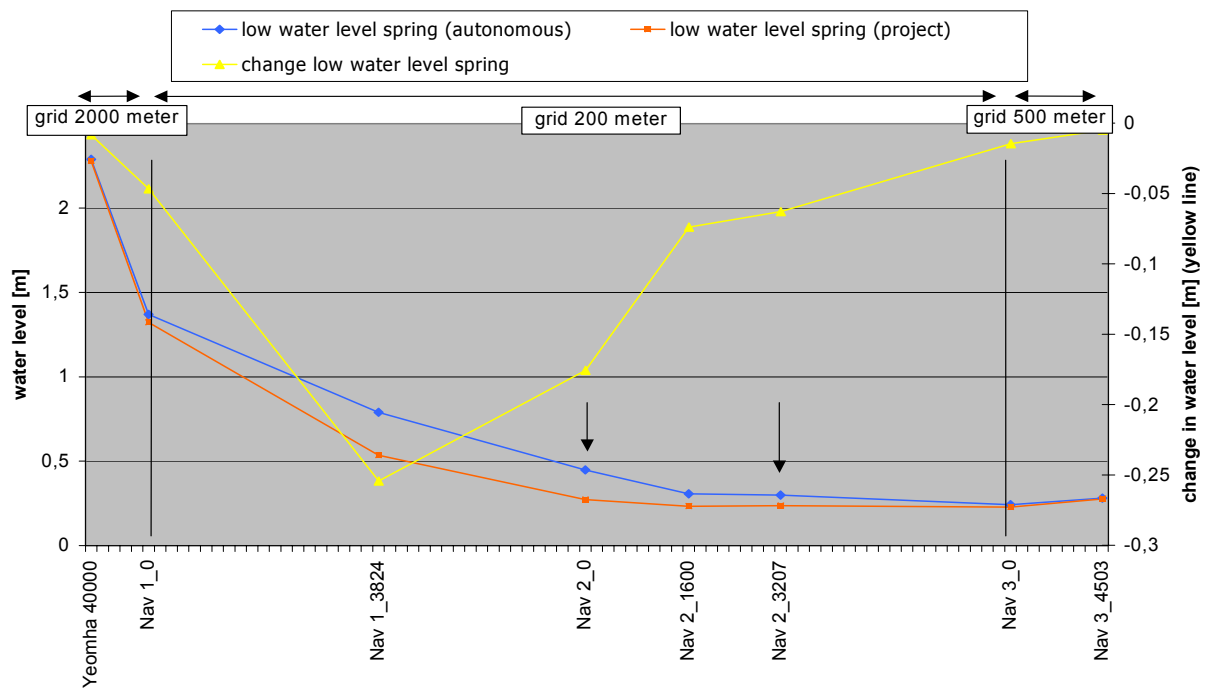
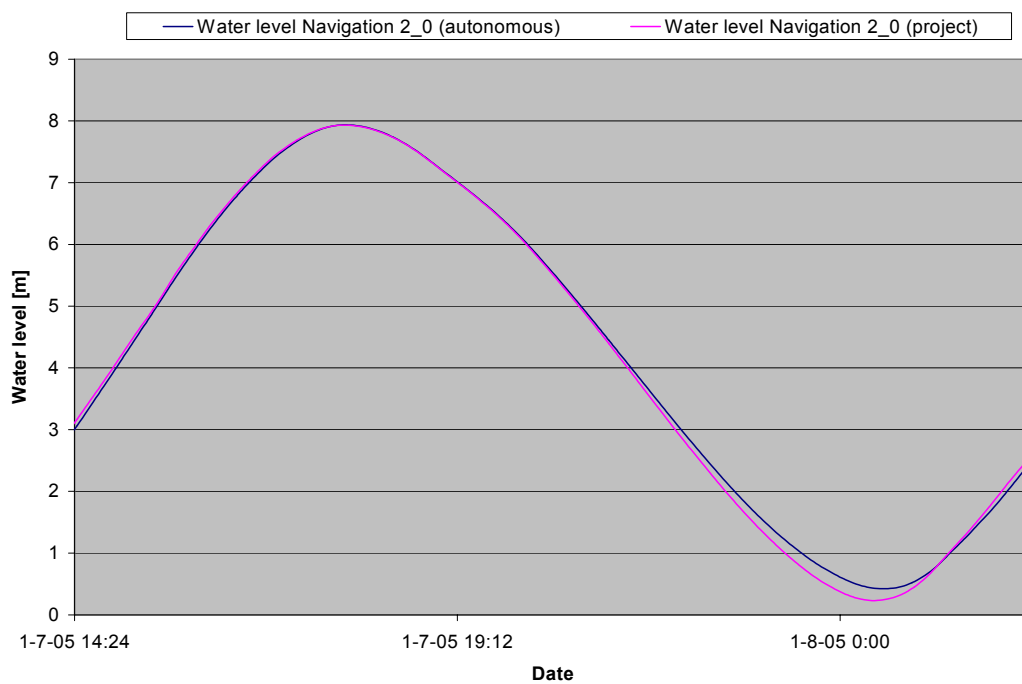


Figure E.3-5 Change in tidal range due to the execution of the Kyung-In Canal project [211]

Figure E.3-6 Change in low water level (Δh_{ebb}) and slope in low water levels [211]Figure E.3-7 Change in low water level (Δh_{ebb}) after executing the Kyung-In Canal project [211]

Flow velocities

Figure E.3-8 and Figure E.3-9 show an increase in flow velocities south of the Project Area. In this area the increase in tidal prism due to the Kyung-In Canal project passes every tidal cycle. The extra tidal discharge flows through approximately the same cross sectional area, which causes an increase in flow velocities. The same phenomenon occurred a few years ago, after the dredging work for the Approach Channel of Incheon North Port.

In the Project Area, where the Approach Channel for Incheon Terminal is dredged, the opposite happens. The dredging work for the Approach Channel creates a substantial increase in cross sectional area. Obviously, the discharge in this area is increasing too, but compared with the increase in cross sectional area this effect is only small. This causes a significant decrease in flow velocities in the Project Area and especially at the location of the Turning Basin, because here the largest depth has to be dredged. In the Turning Basin the ebb velocities decrease even more than the flood velocities. In the Turning Basin the extra cross sectional area due to the dredging work is larger with low tide compared with high tide. For this reason, the ebb velocities decrease more than the flood velocities.

North of the Project Area a small increase in flow velocities can be noticed. This can be ascribed to the increase in discharge, which was shown in Figure E.3-1. This causes an increase in flow velocities because the cross sectional area stays unchanged or even decreases, because of the lowering of Mean Sea Level with low tide. Probably, this is also the explanation why the ebb flow velocities increase a little more than the flood flow velocities.

In Appendix XVI the flow velocities in the 'Autonomous Situation' (old), 'Project Situation' (new) and the absolute differences between both situations are included.

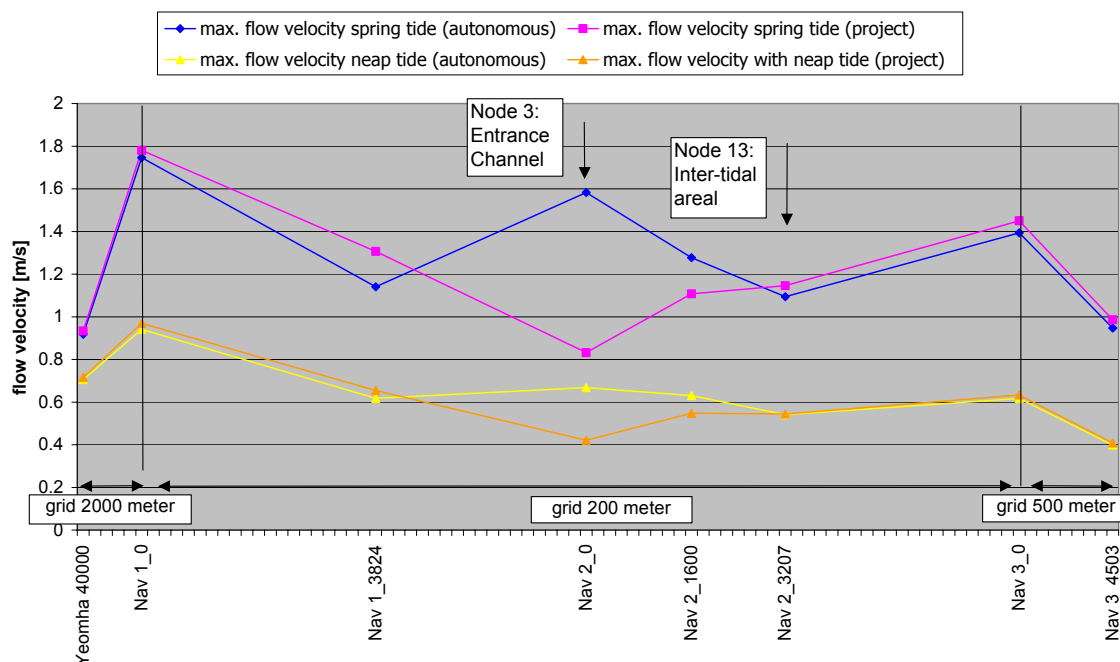


Figure E.3-8 Change in flow velocities with ebb tide [211]

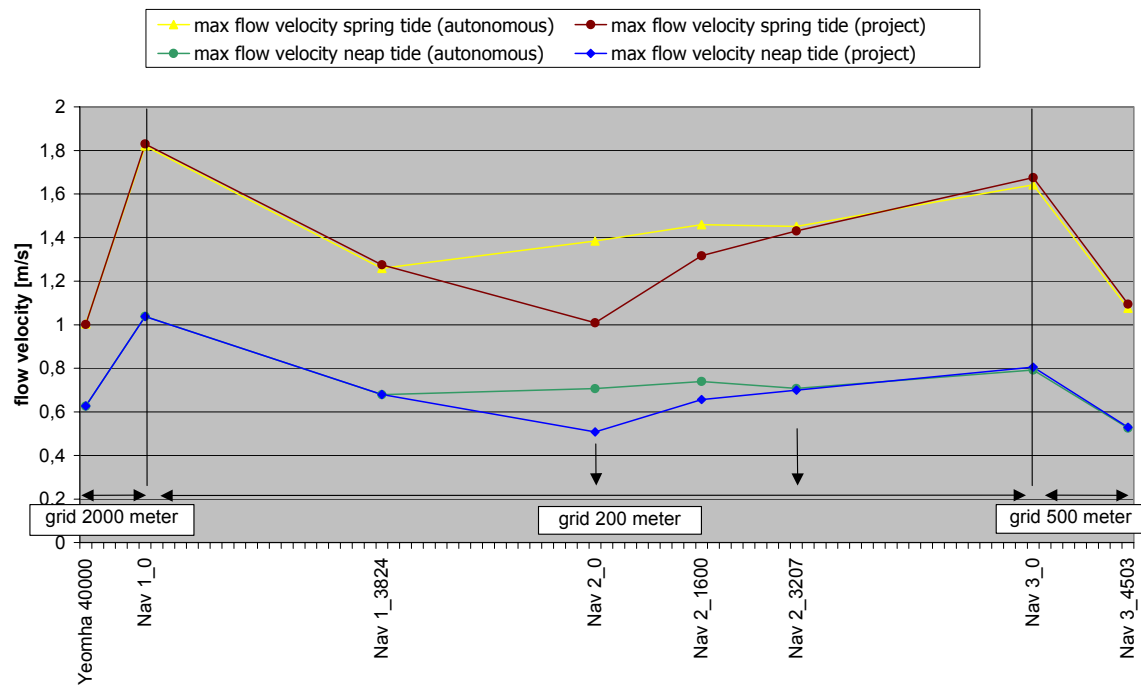


Figure E.3-9 Change in flow velocities with flood tide [211]

E.3.2 Sediment and Morphology

Sediment transport

The change in total sediment transport due to the execution of the Kyung-In Canal are presented in Figure E.3-10 and Figure E.3-11. The figures show more or less the same behaviour as the flow velocities. North of the Project Area the sediment transport in flood direction stays more or less the same, since the flow velocities also stay unchanged. The sediment transport in ebb direction again follows more or less the change in flow velocities. When superposing the relative differences in ebb and flood direction, this shows a net increase in sediment transport in ebb direction north of the Project Area.

In the Project Area a significant reduction in sediment transport is perceptible caused by the reduction in flow velocities and thus sediment transporting capacity. Figure E.3-10 shows even a reduction to nearly zero in total sediment transport at 'Navigation 2_0'. Here, the sediment transport abruptly stops and sediment settles due to the instantaneous behaviour of the model.

In Appendix XVI the sediment transport in the 'Autonomous Situation' (old), 'Project Situation' (new) and the absolute differences between both situations are included.

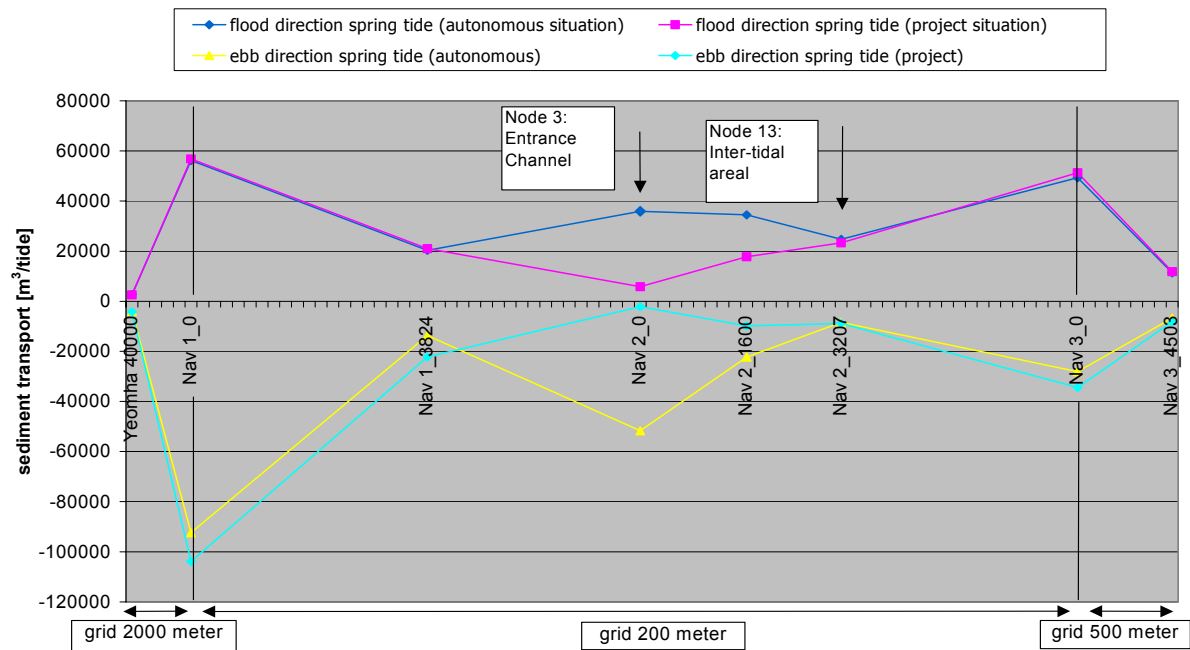


Figure E.3-10 Change in total sediment transport [211]

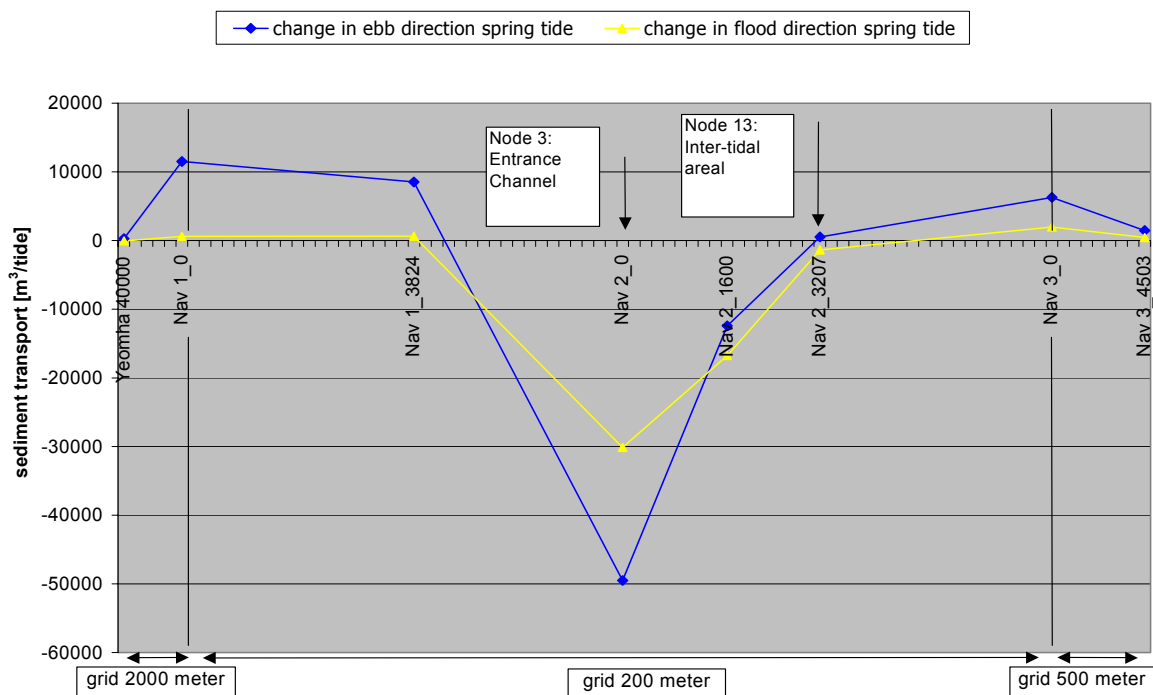


Figure E.3-11 Difference in total sediment transport with spring tide [211]

Figure E.3-12 shows the change in bottom profile over one year. South of the Project Area unexpected siltation is noticeable right in the middle of the locations 'Navigation 2_3207' and 'Navigation 3_0'. Furthermore, right in the middle of 'Navigation 2_0' and 'Navigation 2_3207' unexpected erosion is noticeable. The reason for this erosion is an incorrect tuning of the initial

bathymetry and hydrodynamics in the 'Autonomous Situation'. In the 'Autonomous Situation' erosion occurs at the location where in the 'Anticipated Situation' the Approach Channel is dredged. So this erosion does not occur in the 'Project Situation'. In the 'Autonomous Situation' this eroded sediment is transported in ebb ward direction and settles in the middle of 'Navigation 2_3207' and 'Navigation 3_0'. These processes are small in the 'Autonomous Situation', because in reality the bottom level is more or less in equilibrium.

North of the Project Area erosion occurs, which is expected due to the increase in sediment transport in ebb direction and not in flood direction. When the transported sediment in ebb direction reaches the Turning Basin the flow velocities decrease and the sediment settles in the Turning Basin. Because of the instantaneous behaviour of SOBEK RE all the sediment directly settles at the start of the Approach Channel at the location of the Turning Basin. This results in the excessive high siltation rates in the Turning Basin (see Figure E.3-12).

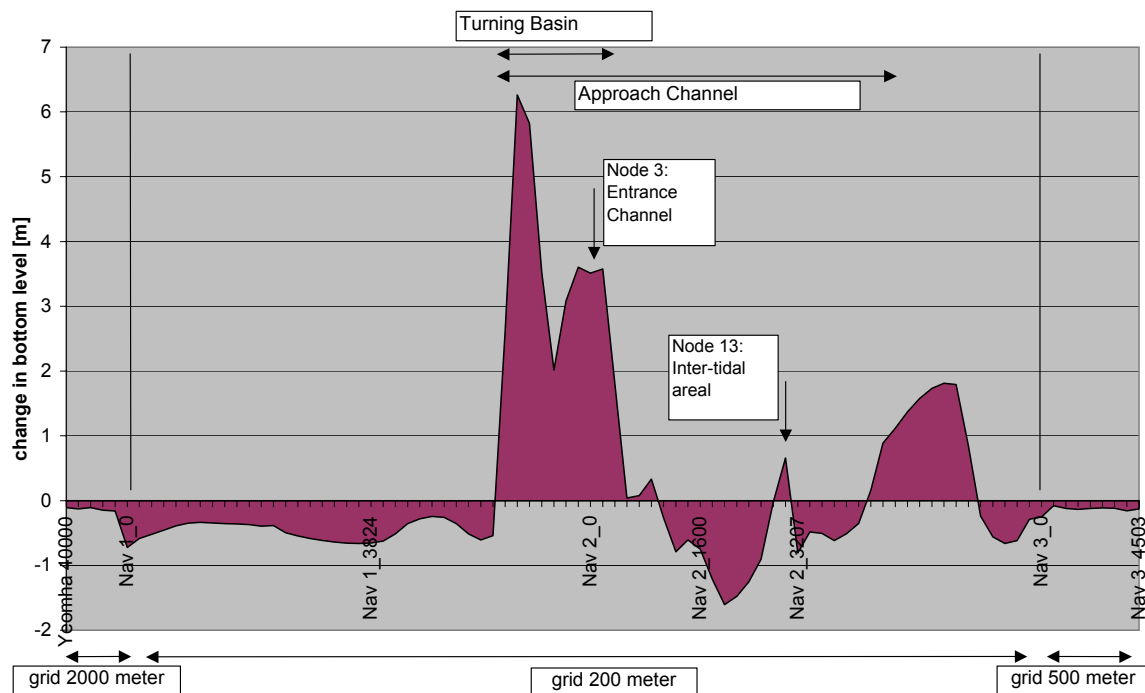


Figure E.3-12 Absolute change in bottom level over one year [211]

In reality the siltation gradually distributes over the area with low flow velocities. This area of low flow velocities stretches from the start of the Turning Basin approximately 3000 meter in southward direction. When assuming all the sediment, which is now depositing in the Turning Basin, distributes over this area a yearly siltation rate of approximately 1.5 meter occurs. However, this is an overestimation of the siltation rates, since in reality there is not enough time for all sediment to settle in the Approach Channel and Turning Basin.

E.4 'NEAR FIELD' RESULTS

The 'near field' results focus on the area that is newly created in the schematisation of the 'Project Situation'. So it is not possible in this chapter to compare the results with the 'Autonomous Situation'. In section E.4.1 the siltation caused by water exchange due to tidal prism for both Incheon Terminal basin and Incheon North Port basin is discussed.

Section E.4.2 shows the SOBEK RE results of the schematisation of the inter-tidal areas on siltation in the surrounding area. For this analysis no reference can be used. In Appendix X a good overview of the 'near field' area is included. For a good understanding of this chapter it is recommended to hold this overview next to the text.

E.4.1 Tidal prism

Siltation of Incheon North Port

The water exchange due to the tidal prism is the fundamental process in SOBEK RE and one of the processes that cause siltation in open harbour basins. For an estimation of the influence of this process in Incheon Terminal basin, the already existing harbour basin of Incheon North Port is used as reference. As already mentioned, a proportional nodal point relation at the bifurcation in front of Incheon North Port is chosen, because this same sediment distribution is also used in the Analytical Approach and makes comparison of the results easier. When the sediment enters the sheltered area of Incheon North Port, the sediment will directly settle due to the instantaneous behaviour of SOBEK RE. For this reason the sediment influx in Incheon North Port is directly measured at the entrance of Incheon North Port. The return ebb current in Incheon North Port is relatively small and only less sediment is distributed back from the harbour basin into the sea. This results in a net sediment influx in Incheon North Port of 719,585 m³/year. Figure E.4-1 shows the SOBEK RE results of the sediment exchange caused by tidal prism at the mouth of Incheon North Port.

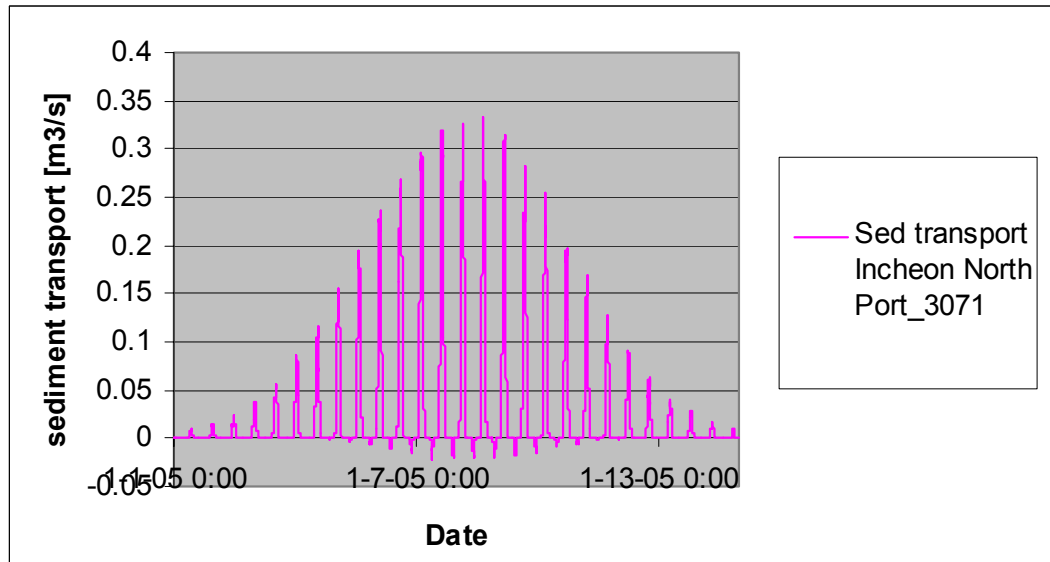


Figure E.4-1 Sediment transport at the mouth of Incheon North Port [SOBEK RE]

However the sediment influx strongly depends on the nodal point relation at the bifurcation (no. 4) of Incheon North Port. For this reason the sensitivity of the nodal point relation on the sediment influx into Incheon North Port is investigated underneath. Figure E.4-2 visualises a nodal point, the following nodal point relation is applied:

$$\frac{S_2}{S_3} = \left(\frac{B_2}{B_3}\right)^{1-k} \left(\frac{Q_2}{Q_3}\right)^k \quad [E.4-1]$$

S = Sediment transport [m^3/s]

B = Channel width [m]

Q = Discharge [m^3/s]

k = Parameter [-]

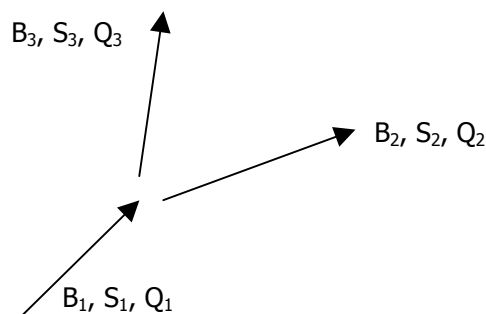


Figure E.4-2 Distribution of sediment transport and discharge at nodal point

Figure E.4-3 shows the relation between the k -value and the net sediment transport into Incheon North Port. When the k -value is one, the sediment is distributed proportional to the discharge. When the k -value increases, less sediment influx in Incheon North Port occurs. When the k -value stays lower

than 5/3 this results in closing of Incheon North Port due to sedimentation (Wang 1993) [21]. This is the reason that in reality maintenance dredging is required in open harbour basins.

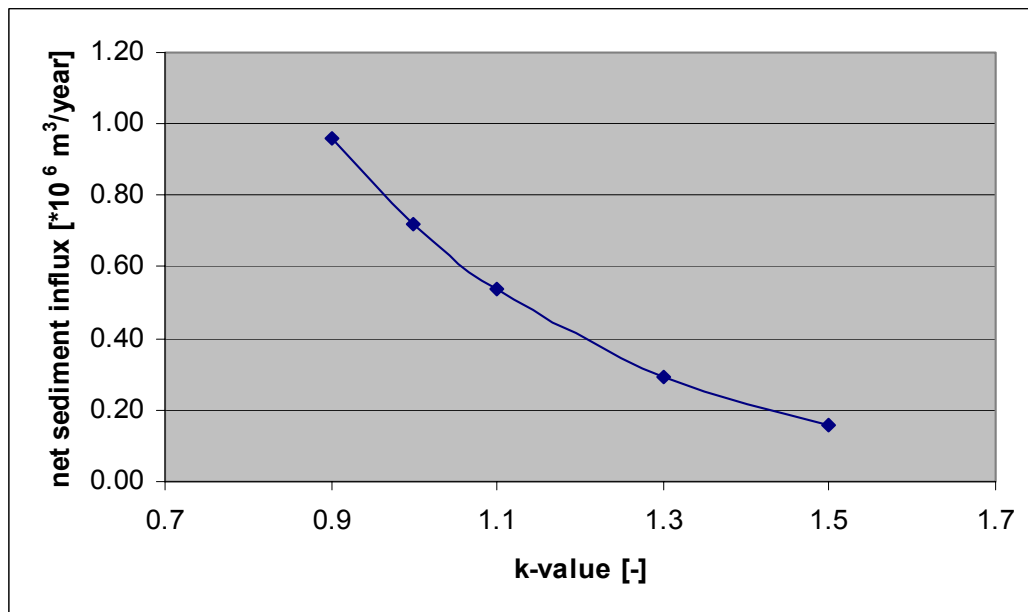


Figure E.4-3 Net sediment influx Incheon North Port [211]

Siltation in Incheon Terminal basin

In Incheon Terminal basin also siltation caused by water exchange due to tidal prism occurs. Because the Entrance Channel is modelled in front of Incheon Terminal, all the sediment influx directly settles in the Entrance Channel due to the reduced sediment transporting capacity in the Entrance Channel. For this reason the net sediment transport into the Entrance Channel must later be distributed over both the Entrance Channel and Incheon Terminal. Furthermore, the branch that schematises the inter-tidal area is removed in this analysis. By removing this branch the significant influences of the water exchange due to the circulation current is not taken into account.

The annual net sediment transport into the Entrance Channel is $118,390 \text{ m}^3/\text{year}$. This is considerably lower than for Incheon North Port. This is mainly caused by the instantaneous behaviour of SOBEK RE. The strong reduction in flow velocities due to the dredging of the Approach Channel causes a lower sediment transporting capacity. Consequently the suspended sediment concentration is reduced, which means less sediment influx into the Entrance Channel. In reality, the sediment needs more time to settle and higher sediment concentrations can be expected at the bifurcation with the Entrance Channel.

E.4.2 Inter-tidal area

The second source of siltation investigated in SOBEK RE is the inter-tidal area in front of Incheon Terminal basin. In chapter D.5 is described how the inter-tidal area is schematised and how this schematisation should create a flood current across the inter-tidal area into Incheon Terminal basin. However, the model does not show a flood current with high tide, but a current in the opposite direction (Figure E.4-4 and Figure E.4-5).

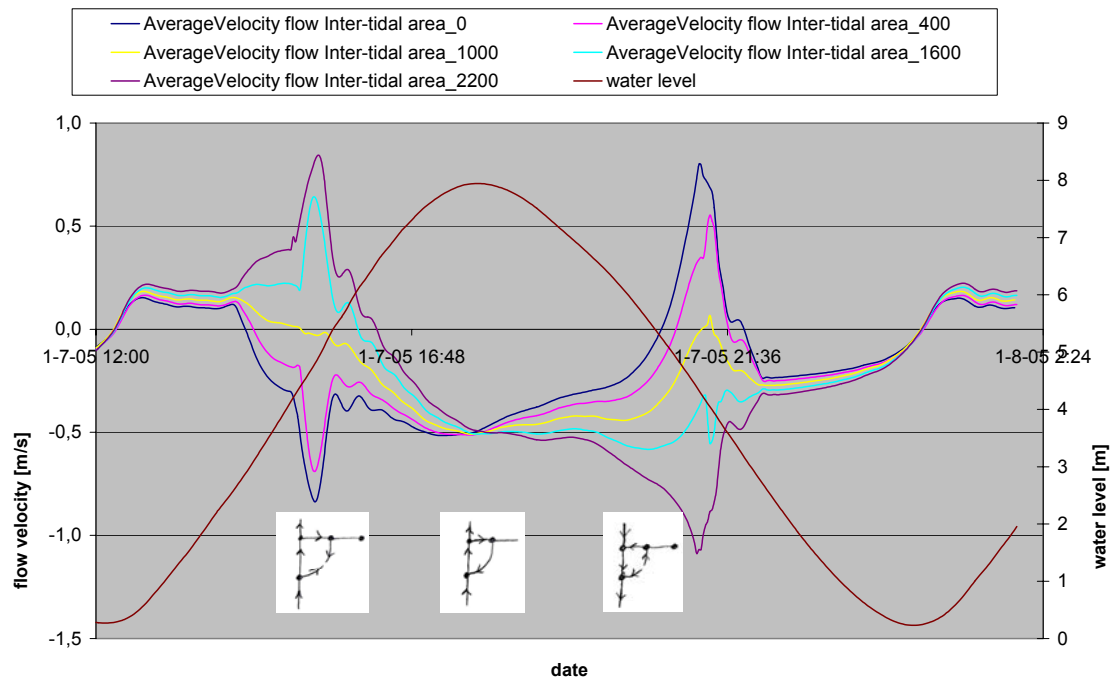


Figure E.4-4 Flow velocities across 'Inter-tidal area' with spring tide. (Positive velocity = flood) [211]

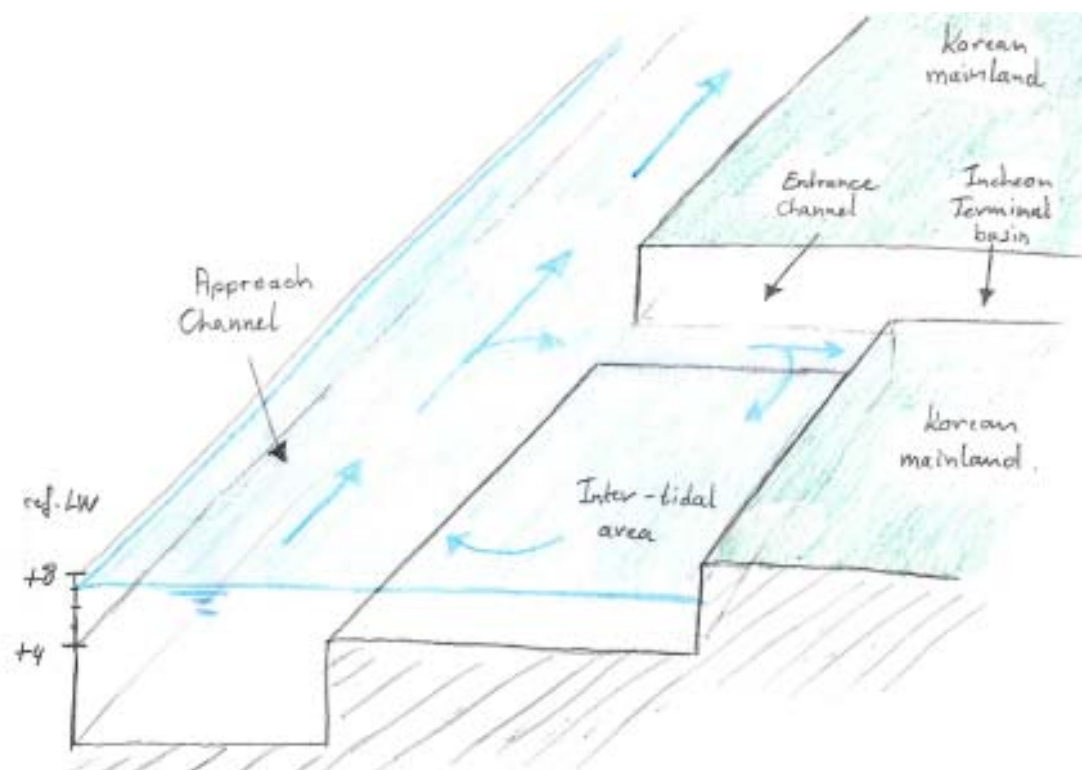


Figure E.4-5 Current in opposite direction across the inter-tidal area

The bottom level of the 'Inter-tidal area' is defined at 4 meter; so when the water level reaches 4 meter the flood currents start to flow across the 'Inter-tidal area'. This occurs at approximately 15:30 hour, where Figure E.4-4 shows peak velocities. These peak velocities are not realistic but an artefact

created by the 'dry bed procedure', which uses a Preismann funnel as cross-section profile. It is noticeable in Figure E.4-4 that the inflow of the flood current starts at both ends of the 'Inter-tidal area', which results in a point of no flow velocities in the middle of the branch. This point of no flow velocities moves in southward direction and finally results in a current in ebb direction through the whole branch, which is the opposite of what was expected beforehand.

The unexpected flow direction across the 'Inter-tidal area' resulted in an investigation to the origin of this phenomenon. This investigation concluded that the model does not represent the high water levels in the Project Area correct. High water level at bifurcation 1 (Appendix X) occurred earlier than at bifurcation 13. The main reason for this phenomenon is the method that is used to calibrate the horizontal tide, which resulted in unrealistic direction-dependent friction coefficient in the Project Area. When using the same friction coefficient in both the ebb and flood direction the high water levels in the Project Area show the expected behaviour. Now, the high water level at bifurcation 13 is slightly higher than at bifurcation 3 and the expected flood current across the 'Inter-tidal area' occurs. This results in the flow velocities across the 'Inter-tidal area' presented in Figure E.4-6 and also sketched in Figure E.4-7.

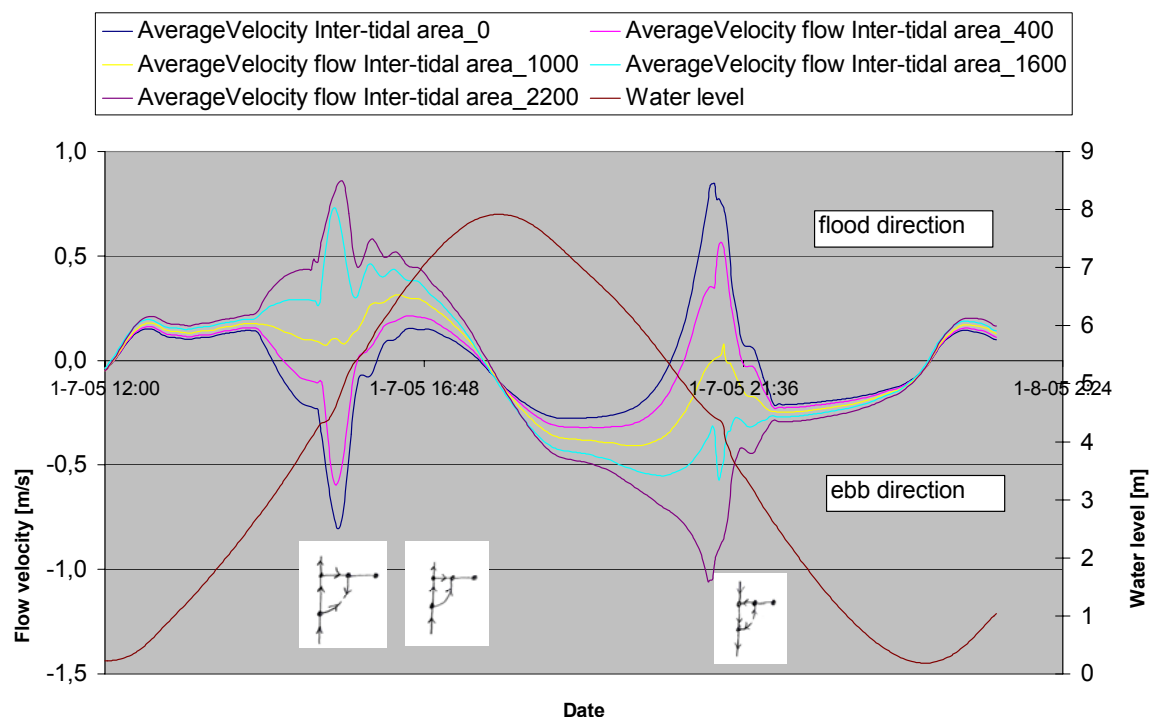


Figure E.4-6 Current velocities across 'Inter-tidal area' with spring tide. (Positive velocity = flood) [211]

Figure E.4-6 shows a flood current through the channel from approximately 16:00 until 17:30. Approximately at high water level, this flood current changes in an ebb current for a period of 2.5 hours. Figure E.4-6 shows more realistic results, although the phase difference between horizontal and vertical tide, which occurs in reality, is not simulated. This hydrodynamic behaviour leads to the sediment transport presented in Figure E.4-8.

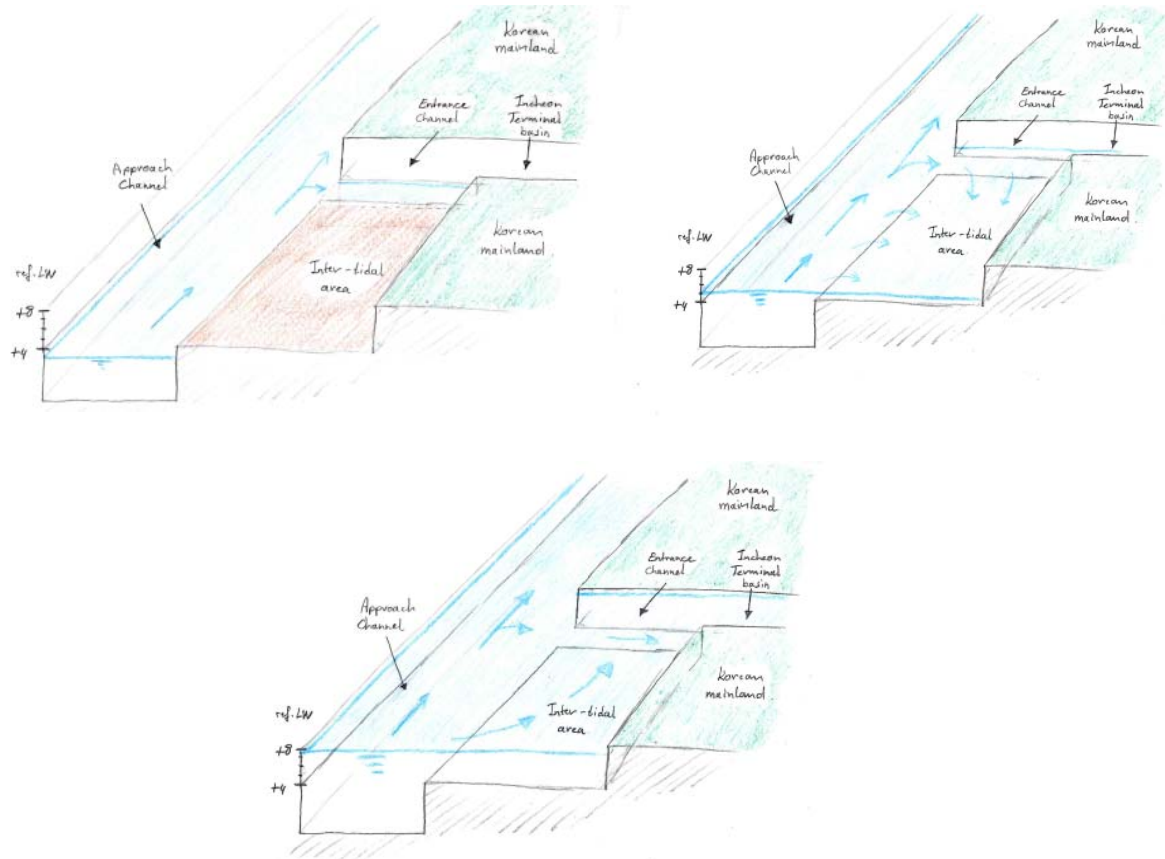


Figure E.4-7 Flood current in Project Area with rising tide

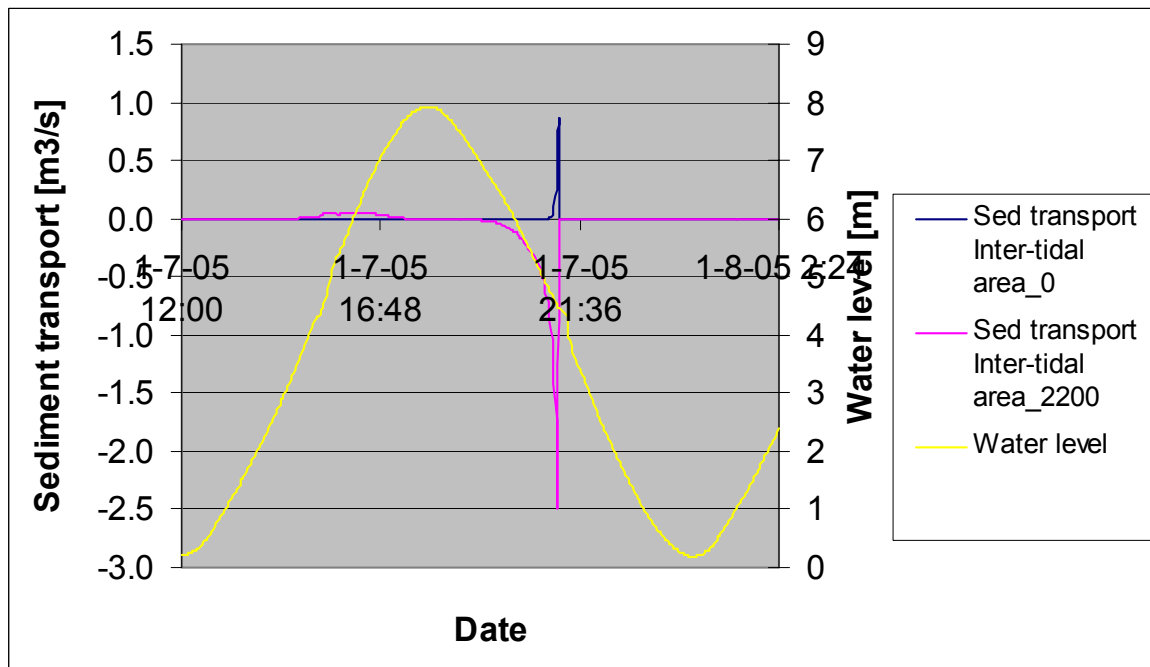


Figure E.4-8 Sediment transport at the ends points of the 'Inter-tidal area' (Positive transport = flood)
[211]

Figure E.4-8 shows peak values of sediment transport at the moment that peak values in the flow velocity appear (Figure E.4-6). These peak values are an over-estimating of the sediment transport in reality, because the Preismann funnel artificially created high flow velocities around a water level of 4 meter. However the sediment transport in flood direction already starts at approximate 19:30 hours and at this time no influence of the Preismann funnel occurs. When assuming the peak sediment transport does not occur, the annual sediment transport into Incheon Terminal basin is estimated at 11,000 m³/year. This would result in an annual siltation in Incheon Terminal basin of less than 0.1 m. With ebb tide the sediment transport into the Approach Channel is estimated at 266,000 m³/year.

A sensitivity analysis has been executed to find out if extreme conditions could result in larger sediment transport in the direction of 'Incheon Terminal'. In this analysis the friction coefficient of Chezy in flood direction has been decreased to 110 m^{1/2}/s and the friction coefficient in ebb direction has been increased to 30 m^{1/2}/s. This indeed causes extra sediment transport in the direction of Incheon Terminal, but most of the increase can be ascribed to extra transport due to the use of the Preismann funnel. The estimated annual siltation will be around 0.1 m.

Furthermore the siltation in Incheon Terminal is estimated based on the flood water discharge that enters Incheon Terminal basin via the inter-tidal area. This leads to an annual discharge of 80 million m³ which would result in a siltation rate of less than 0.1 m. Appendix XVII shows the discharge across the inter-tidal area with spring tide.

In summery can be concluded that the inter-tidal area shows less influence of the inter-tidal area than initially expected. The flood current across the inter-tidal area has more friction than the flood current through the deeper Entrance Channel. Consequently the inter-tidal area is flooded from two directions and a dead tide appears. This results in a short period of flood currents across the inter-tidal area and less siltation due to tidal filling via the inter-tidal area.

E.5 DISCUSSION OF SILTATION RESULTS

This chapter discusses the results of Part E. In the discussion the result of SOBEK RE are compared with existing data or other reference material, for example the Analytical Approach that is used in this study. Again the separation between 'far field' and 'near field' is used. When relevant the consequences of the results in the reality are mentioned.

Discussion of 'far field' results

The 'far field' results show the differences between the 'Project Situation' and the 'Autonomous Situation'. South of the Project Area an increase in tidal prism occurs due to the execution of the Kyung-In Canal project. Subsequently, the water levels show the expected increase in tidal range. This results in an increase in flow velocities and in erosion of the cross sectional area of the main flood and ebb channels. Directly north of the Project Area the increase in tidal prism reduces because most of the increased tidal prism flows into Incheon Terminal basin. Further north of the Project Area erosion occurs. Here, the sediment transport in ebb direction increases more than the sediment transport in flood direction. This is caused by extra ebb discharge that flows through the Project Area due to the execution of the Kyung-In Canal project. This discharge enters via the flood channels north of Youngjong Island and return via the Project Area. It can be concluded that the change in 'far field' hydrodynamics shows quite reasonable results.

The well-simulated hydrodynamics results also in a quite reasonable 'far field' morphology. However, the morphological changes in the 'far field' area show quite sudden changes. This is caused by the instantaneous behaviour of SOBEK RE, which means that the sediment transport directly reacts on changes in the flow velocity. In reality sediment needs time to settle, which depends on the fall velocity of the sediment and results in a smoother bottom profile than SOBEK RE shows.

Discussion of the 'near field' results

The flow velocities in the Project Area show a significant decrease due to the dredging of the Turning Basin and the Approach Channel. Due to the reduced flow velocities the transport capacity of the water decreases and thus settlement of sediment in the Turning Basin and Approach Channel occurs. SOBEK RE predicts an annual siltation rate in the Turning Basin of approximately 1.5 meter. However, this is an overestimation of the siltation rates, since in reality there is not enough time for all sediment to settle in the Approach Channel and Turning Basin. The siltation requires annual dredging to guarantee enough navigation depth.

The instantaneous behaviour of SOBEK RE causes a quite sudden reduction in suspended sediment concentration at the bifurcation of the Approach channel with the Entrance Channel. This causes significantly lower suspended sediment concentrations in SOBEK RE compared with the reality, which results in less sediment influx due to water exchange caused by tidal prism into the Entrance Channel. In reality, the sediment needs more time to settle and higher sediment concentrations can be expected at the bifurcation with the Entrance Channel. This is the reason that in the Analytical Approach the suspended sediment concentration in the Autonomous Situation is used to predict the sediment influx due to water exchange caused by tidal prism. The siltation results for both the Analytical Approach and SOBEK RE are presented in Table E.5-1.

	Incheon North Port		Entrance Channel & Incheon Terminal	
	SOBEK River & Estuary	Analytical Approach	SOBEK River & Estuary	Analytical Approach
Net sediment influx [$\cdot 10^6$ m ³ /year]	0.7	0.74	0.1	0.6
Volume tidal prism (Vt) [$\cdot 10^6$ m ³]	10.8	12.9	5.0	6.2
Siltation rate [m/year]	0.3	0.3	0.2	0.5

Table E.5-1 Comparison of siltation in SOBEK RE with the Analytical Approach

The prediction of the siltation rates in SOBEK RE and the Analytical Approach show quite similar results for Incheon North Port in Table E.5-1. In SOBEK the net sediment influx is determined by calculating the net sediment influx for one spring-neap tidal cycle, whereas the Analytical Approach uses one average sediment concentration. The result shows that SOBEK is capable to predict siltation in harbour basins.

The instantaneous behaviour of SOBEK RE results in significantly lower suspended sediment concentrations in front of Incheon Terminal basin compared with reality. Consequently, SOBEK RE calculates lower siltation rates caused by tidal prism than the Analytical Approach. The calculated annual siltation rates in SOBEK RE and the Analytical Approach are respectively 0.2 and 0.5 m. Probably the results of the Analytical Approach are more reliable. The sudden change in sediment concentration in SOBEK RE is an overestimation of what happens in reality, since sediment needs time to settle. However a small reduction in sediment concentration can be expected, which would result in a slightly lower annual siltation rate than 0.5 m. Furthermore the determined siltation rates in this study are pessimistic, since this study assumes that all sediment influx settles in the harbour basin. In the Entrance channel the siltation is expected to be even lower than in Incheon Terminal, because this area is less sheltered than Incheon Terminal basin. In summary, there can be concluded that SOBEK RE is less suitable to predict the siltation rates in this specific case.

The siltation rate in Incheon Terminal shows differences between the two methods. As mentioned above this is caused by the instantaneous behaviour of SOBEK RE. Probably, the annual siltation in the Entrance Channel and Incheon Terminal is a little lower than 0.5 m, because the dredging of the Approach Channel will have some effect on the sediment transporting capacity of the flood current. However, the annual siltation of 0.2 m predicted by SOBEK RE is too low. So, for this specific open-harbour basin SOBEK RE is less suitable. Furthermore, it is expected that a larger part of the net sediment influx into the Entrance Channel will settle in the more sheltered Incheon Terminal basin.

In addition, the distribution of sediment at the bifurcation in front of Incheon North Port is investigated. This investigation shows that the nodal point relation has large influence on the net

sediment influx in the harbour basin. For this reason a more elaborated investigation to the nodal point relation in Incheon Terminal is recommended in a later phase of the Kyung-In Canal project.

Furthermore the 'near field' results show the influence of the inter-tidal area in front of Incheon Terminal on siltation in Incheon Terminal basin. However, the initially chosen schematisation of the inter-tidal area does not result in the expected hydrodynamics in this study. An incorrect simulation of the high water levels in the Project Area results in a current across the inter-tidal area in the opposite direction. In addition, this results in a significant extra relative difference in flood discharge in the Approach Channel. This effect is most significant with spring tide because with neap tide there is hardly flowing water across the shallow inter-tidal area.

The reason for the incorrect simulation of the high water levels in the Project Area is the direction-dependent friction coefficient, which is used to calibrate the horizontal tide in the Project Area. For a more realistic prediction of the influences of the inter-tidal area on siltation, a new simulation with the same friction coefficient in both ebb and flood direction has been executed. This indeed shows more realistic effects, but without the phase difference between horizontal and vertical tide, which is presented in reality. The investigation of the inter-tidal area results in following conclusions:

- The simulation of the flood current across the inter-tidal area is highly sensitive to the hydrodynamics in the Project Area. Since the distance between both sides of the inter-tidal area is only small compared with the length of the tidal wave, more detailed and accurate modelling is required to simulate the siltation effects due to the inter-tidal area.
- The Preismann funnel, which is used to schematise the inter-tidal area, shows large artificial effects on the sediment transport computations.
- The simulation with correct water levels at both sides of the inter-tidal area shows a net sediment transport across the inter-tidal area in ebb direction and even with spring tide only small sediment influx into Incheon Terminal basin.

Based on the results in this study the effect of the inter-tidal area on siltation in Incheon Terminal basin seems small. However, the relatively small waves in Kyunggi Bay still can play an important role in the erosion of shallow areas and even waves generated by passing ships can also have influence. The disturbance of a settled bed of fine sediment by waves can even form a fluid mud layer, which may cause high siltation rates. However, these issues are out of the scope of this study.

Furthermore, according to the Analytical Approach, density currents may play a significant role on the siltation in Incheon Terminal basin. This is caused by large fresh water influences in the surrounding of Incheon Terminal basin during the rain season. However, the influence of density currents in the Project Area is a side issue in this study.

E.6 MITIGATING MEASURES

Maintenance dredging is a very cost consuming activity. In addition, dredging hinders the flow of ships and can have a negative impact on the marine environment. These are just a few reasons that make it worthwhile to investigate mitigating measures that reduce the dredging frequency. Of course, a cost-benefit analysis must define if the suggested mitigating measures are feasible. However this study only give some qualitative descriptions of mitigation measures.

In this chapter the four processes causing siltation in Incheon Terminal are mentioned, followed by proposed mitigating measures to reduce the siltation effects caused by this process.

1. Siltation of Incheon Terminal caused by horizontal eddies is expected to be very small due to the location of an inter-tidal area in front of the basin. For this reason no mitigation measures are required.
2. It is difficult to reduce siltation caused by the tidal prism, assuming that the harbour lay out is already optimised. A possibility is a closed harbour basin, which is also used for one of the harbour basins of Incheon Port.
3. Preventive dredging of the inter-tidal area can prevent periodic maintenance dredging due to siltation caused by the inter-tidal area in front of Incheon Terminal. Another possibility is the construction of a 'hard' structure that stops sediment transport from the inter-tidal area into Incheon Terminal basin. Both possibilities seem rather drastic and expensive, so are only worthwhile if large siltation occurs due to the inter-tidal area.
4. The siltation caused by density currents can be significant in Incheon Terminal, especially during the rain season. The reduction of density currents from Kyunggi Bay is difficult to reduce, considering the experience of many others. A closed harbour basin is again a good solution. To reduce fresh water in Incheon Terminal basin from the Kyung-In Canal, a salt Kyung-In Canal is a good solution.

CONCLUSIONS

The Analytical Approach shows a significant annual siltation of 0.5 m in Incheon Terminal basin caused by tidal prism. However, density currents during the rain season show a comparable annual siltation of 0.6 m in addition to the siltation caused by tidal prism. Although not further investigated in the modelling part of this study, the influence of the latter mechanism cannot be neglected in the feasibility study of the Kyung-In Canal project. The horizontal eddies in the harbour entrance have only a minor influence on the siltation in Incheon Terminal with an annual siltation rate of 0.1 m. The focus of the modelling part of the study was on the influence of the hydrodynamic processes in Kyunggi Bay driven by the tidal wave. The tidal range in Kyunggi Bay can reach up to 9 m, which results in flood currents reaching up to 1.8 m/s and ebb currents reaching up to 2.3 m/s in the Project Area. The tidal current causes large sediment transport in the Project Area.

For the 'far field' calibration of the hydrodynamics in the 'Autonomous Situation' no adjustments of the model parameters turned out to be necessary. On the contrary, the initial 'near field' hydrodynamics show large differences with the field observations presented in Appendix IV and V. The calibration of the horizontal flood current required a quite drastic increase of the friction coefficient in flood direction from 55 to 110 m^{1/2}/s. Furthermore, the field observations show a phase difference between the horizontal and vertical tide of 1.1 hours, while the phase difference initially computed was 0.2 hours. Mainly the extension of the Yeomha Waterway, but also the narrowing of the flow width, finally resulted in a phase difference of 1.0 hour. This is still not exactly the 1.1 hours from the field investigations, but this result is assumed to be sufficiently accurate to simulate the flood current across the inter-tidal area. The calibration of the 'near field' sediment transport has resulted in a D50 of 300 µm, which is approximately the grain size that is present in reality.

SOBEK RE shows quite reasonable hydrodynamic and morphological changes due to the execution of the Kyung-In Canal project on a 'far field' scale. The tidal prism increases due to the construction of the Entrance Channel and Incheon Terminal basin. Subsequently, this leads to a small increase in flow velocities and an increase in tidal range, which results in a change in sediment transport in the main channel between Youngjong Island and the Korean mainland. This leads to erosion in the areas north and south of the Project Area.

The dredging of the Approach Channel results in a significant reduction of the flow velocities in the Project Area in the SOBEK RE simulation. Due to the instantaneous behaviour of SOBEK RE the sediment directly settles at the location where the flow velocity decreases due to the dredging works. This results in significant siltation in the Approach Channel at location of the Turning Basin in front of Incheon Terminal basin. In reality the sediment will gradually distribute across the area with low flow velocities. If it is assumed that all the sediment, which is deposited in the Turning Basin in the SOBEK RE computation, would be distributed across the area with low flow velocities, the annual siltation rate will be approximately 1.5 m. However, this is an overestimation of the siltation rates, since in reality

there is not enough time for all sediment to settle in the Approach Channel and Turning Basin. A part of the sediment will stay in suspension and is distributed to elsewhere.

The instantaneous behaviour of SOBEK RE results in significantly lower suspended sediment concentrations in front of Incheon Terminal basin compared with reality. Consequently the 'near field' results show lower annual siltation in Incheon Terminal basin than the Analytical Approach. The calculated annual siltation rates in SOBEK RE and the Analytical Approach are 0.2 m and 0.5 m, respectively. Probably the siltation rates in Incheon Terminal basin lies in between these values. The sudden change in sediment concentration in SOBEK RE is an overestimation of what happens in reality, since sediment needs time to settle. However, a reduction in sediment concentrations in front of Incheon Terminal basin can be expected. The siltation rates determined in the Analytical Approach are pessimistic, since this approach assumes that all sediment influx settles in the harbour basin.

In the Entrance Channel the siltation is expected to be lower than in the harbour basin, since this area is less sheltered. In summary, the instantaneous behaviour of SOBEK RE makes the model less suitable to determine the annual siltation rates in this specific case. However, in SOBEK RE also the annual siltation rates in the existing Incheon North Port (approximately 15 km south of the Project Area) are calculated. For this open harbour basin both SOBEK RE and the Analytical Approach determine approximately the same annual siltation of 0.3 m, since no dredging work and thus decrease in sediment transport capacity takes place in this area.

Initially, the influence of the inter-tidal area on the siltation of Incheon Terminal basin was not computed correctly. The drastic adjustment of the friction coefficient in flood direction to calibrate the horizontal current produced incorrect water levels in the Project Area and led to a current across the inter-tidal area in the opposite direction. Therefore, the large friction coefficient in flood direction was reversed to normal, which resulted in the expected flood current across the inter-tidal area. The flooding of the inter-tidal area starts from both sides of the inter-tidal area, which leads to a dead tide (point of no flow velocities) in the middle of the inter-tidal area. Gradually, this point of no flow velocities moves in the direction of Incheon Terminal basin and finally results in a flood current. This flood period only occurs during a short period and therefore results in a rather small annual siltation of less than 0.1 m in Incheon Terminal basin. Even when the friction on the inter-tidal areas in flood direction is extremely low the annual siltation rates due to the inter-tidal area are limited.

The schematisation of the inter-tidal area in front of Incheon Terminal has shown to be rather sensitive to the simulation of the hydrodynamics in the Project Area. This is caused by the small distance between both sides of the inter-tidal area compared with the length of the tidal wave. The investigation shows less influence of the inter-tidal area than initially expected. The flood current across the inter-tidal area has more friction than the flood current through the deeper Entrance Channel. Consequently the inter-tidal area is flooded from two directions and a dead tide appears. This results in a short period of flood currents across the inter-tidal area and less siltation due to tidal filling via the inter-tidal area. However, for a more reliable estimation of the siltation rates due to the inter-tidal area in Incheon Terminal basin a more detailed and accurate model is required.

In summary, it can be concluded that SOBEK RE has proven to be suitable to describe the 'far field' changes due to the execution of the Kyung-In Canal project in the macro-tidal Kyunggi Bay. Furthermore, SOBEK RE is suitable to predict the siltation due to tidal prism in Incheon North Port. However, in the specific case of the Incheon Terminal project, the instantaneous behaviour of SOBEK RE results in some shortcomings, leading to an overestimation of the siltation in the Approach Channel. Furthermore, the instantaneous behaviour of SOBEK RE results in an underestimation of the siltation in Incheon Terminal basin caused by 'direct' tidal filling. With respect to the influence of the tidal filling via the inter-tidal area, SOBEK RE suffers from some severe limitations in properly schematising and describing this mechanism. Although some indicative results and insight could be obtained, it should be concluded that SOBEK RE is not really suitable for this purpose.

RECOMMENDATIONS

- For a more correct prediction of the siltation of Incheon Terminal basin caused by the water exchange due to the tidal prism a more refined modelling approach is required. Due to the instantaneous behaviour of SOBEK RE, the dredging of the Approach Channel results in a sudden reduction in sediment transport capacity, leading to an incorrect simulation (underestimation) of the suspended sediment concentration in front of the Incheon Terminal basin. Since the suspended sediment concentration is an important parameter in the prediction of siltation rates, the annual siltation of Incheon Terminal basin is underestimated.
- The results of the investigation of the influence of the inter-tidal area on siltation in Incheon Terminal basin are not reliable. The flood current across the inter-tidal area is highly sensitive to the hydrodynamics in the Project Area. Since the distance between both sides of the inter-tidal area is small compared with the length of the tidal wave, more detailed and accurate modelling is required to properly simulate the siltation effects due to the inter-tidal area.
- An additional survey on the sediment concentrations in the vicinity of Incheon Terminal basin is required. The predicted sediment influx in Incheon Terminal due to water exchange caused by tidal prism is presently based on poor data. The data used in this study are the results of measurements from 1996, with only one location close to Incheon Terminal. These data are insufficient and also less representative since the sediment transports in the highly dynamic Kyunggi Bay have been influenced by many reclamation projects, which were executed in the last decade.
- In the present study little attention is paid to the influence of density currents on the siltation of Incheon Terminal basin. However, according to the results of the Analytical Approach, density currents may play a significant role on the siltation in Incheon Terminal basin. An important reason is that large fresh water discharges occur during the rain season. Therefore, a further investigation of the effects of density currents is recommended.
- Based on the results of the present study, the propagation of the tidal wave is the most significant process in Kyunggi Bay. However, the effects of other processes also need to be investigated. The relatively small waves in Kyunggi Bay can have an important effect on the erosion of the inter-tidal area and even waves generated by passing ships may have an influence. In particular, the disturbance of a settled bed of fine sediment by waves can form a fluid mud layer, which may cause high siltation rates in Incheon Terminal basin. Furthermore, flocculation of the cohesive fine sediment from the inter-tidal area can also have a significant effect on siltation. In view of these potentially important other processes it is required that a more elaborated study will be conducted in a later stage of the Kyung-In Canal project.

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APPENDICES

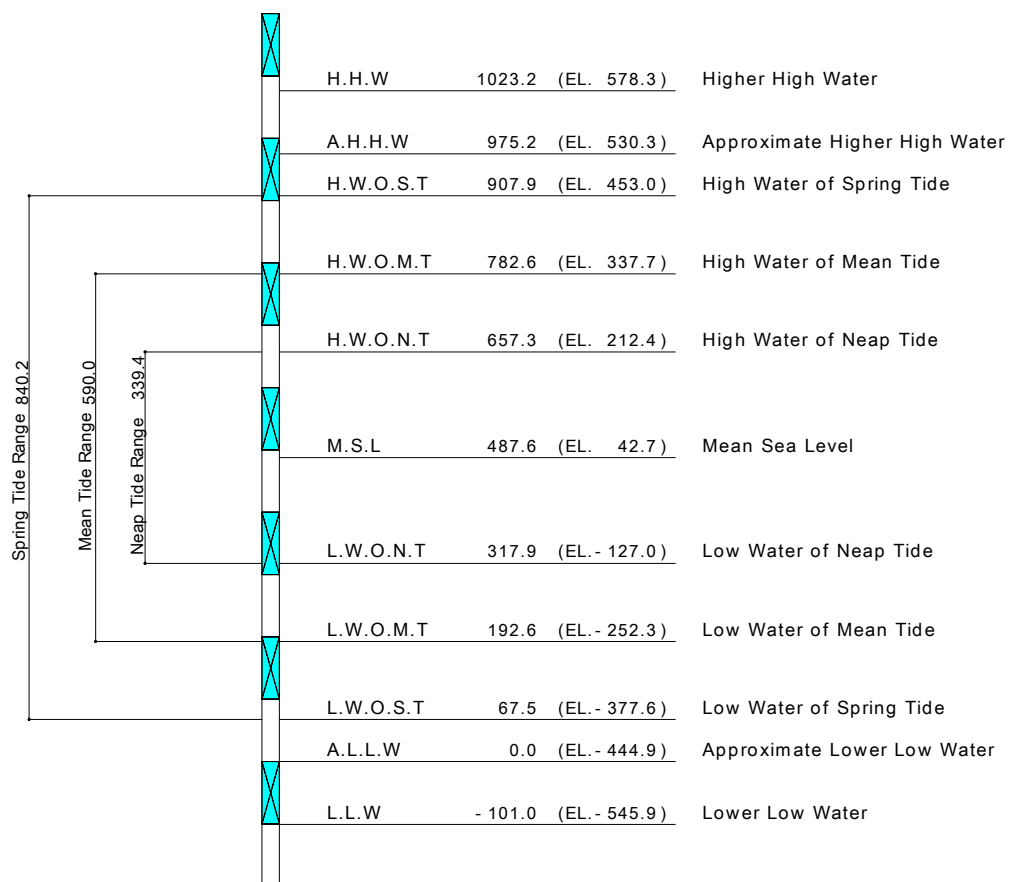
Appendix I: Tidal elevation

Two different reference levels are used in the project Figure I-1:

Datum Level (DL), in the first column, refers to "Approximate Lower Low Water" at Incheon. This standard is used for calculating bottom heights at sea.

Elevation Level (EL) is connected to Mean Sea Level (MSL) at Incheon. This standard is used throughout whole Korea for calculating surface level on land.

The conversion between the two levels is 4.45 m.



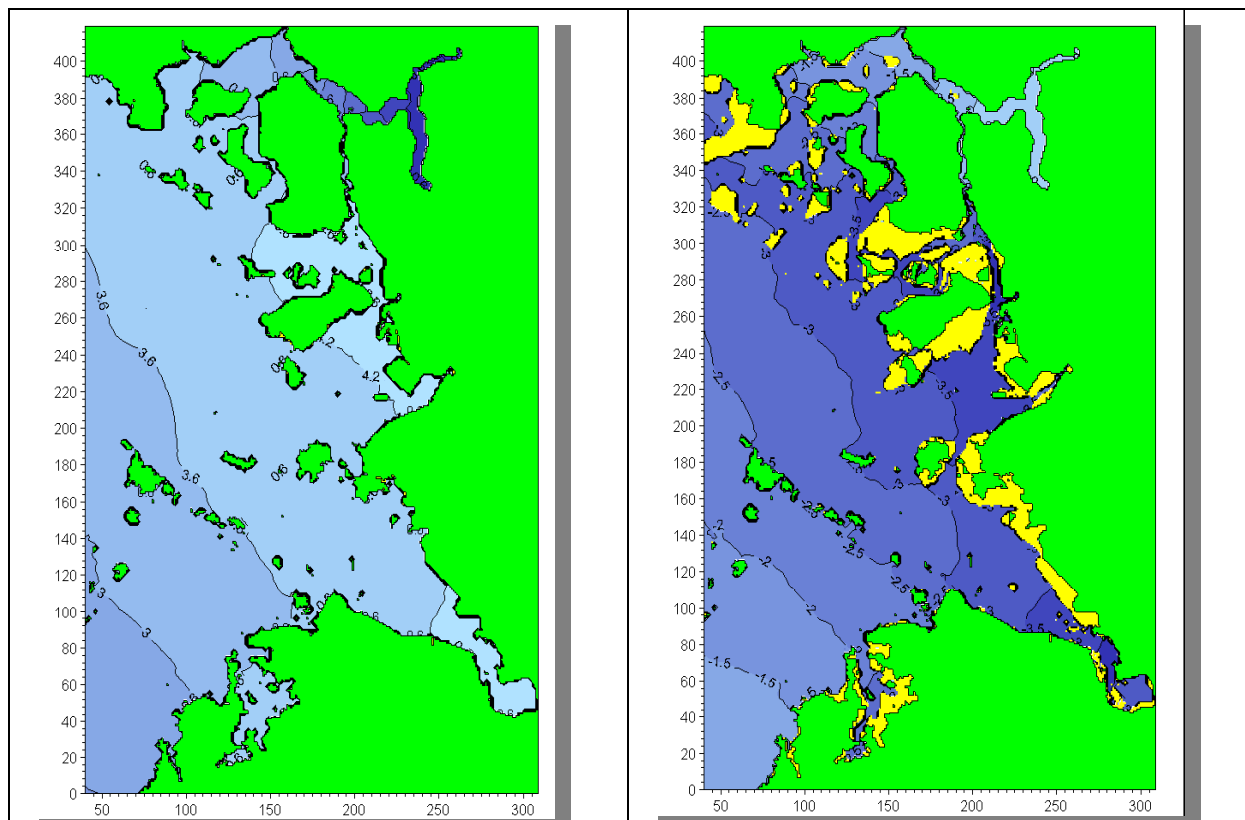
I-1: Water levels at Incheon (cm) [215].

Appendix II: Tidal range

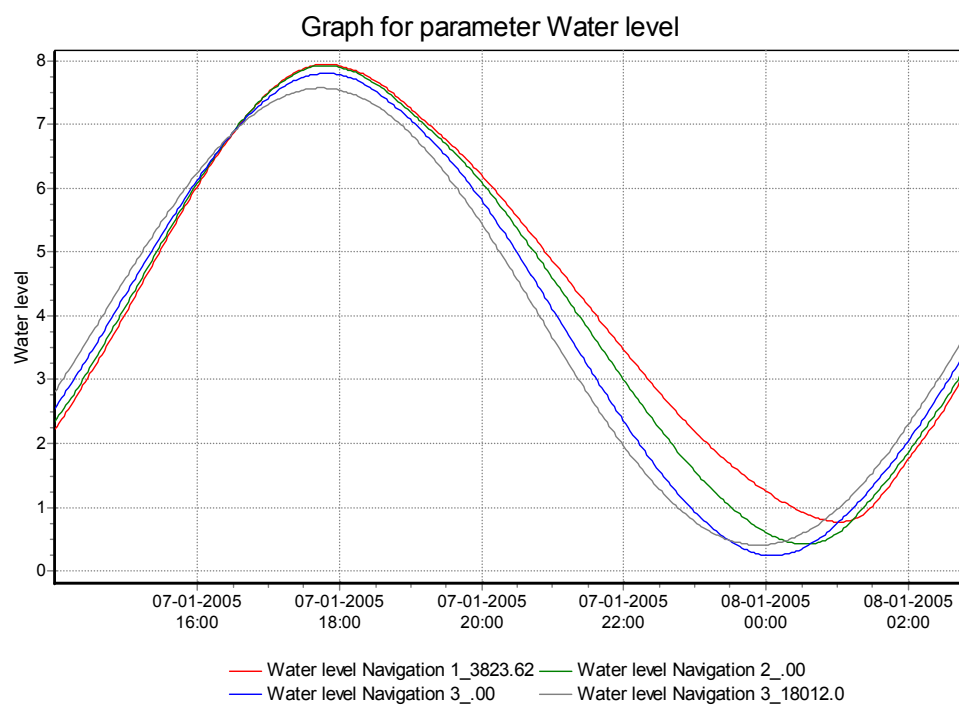
The Co-tidal and co-range lines show the propagation of the tidal wave and increase in tidal range.



II-1: Co-tidal and co-range lines [216]

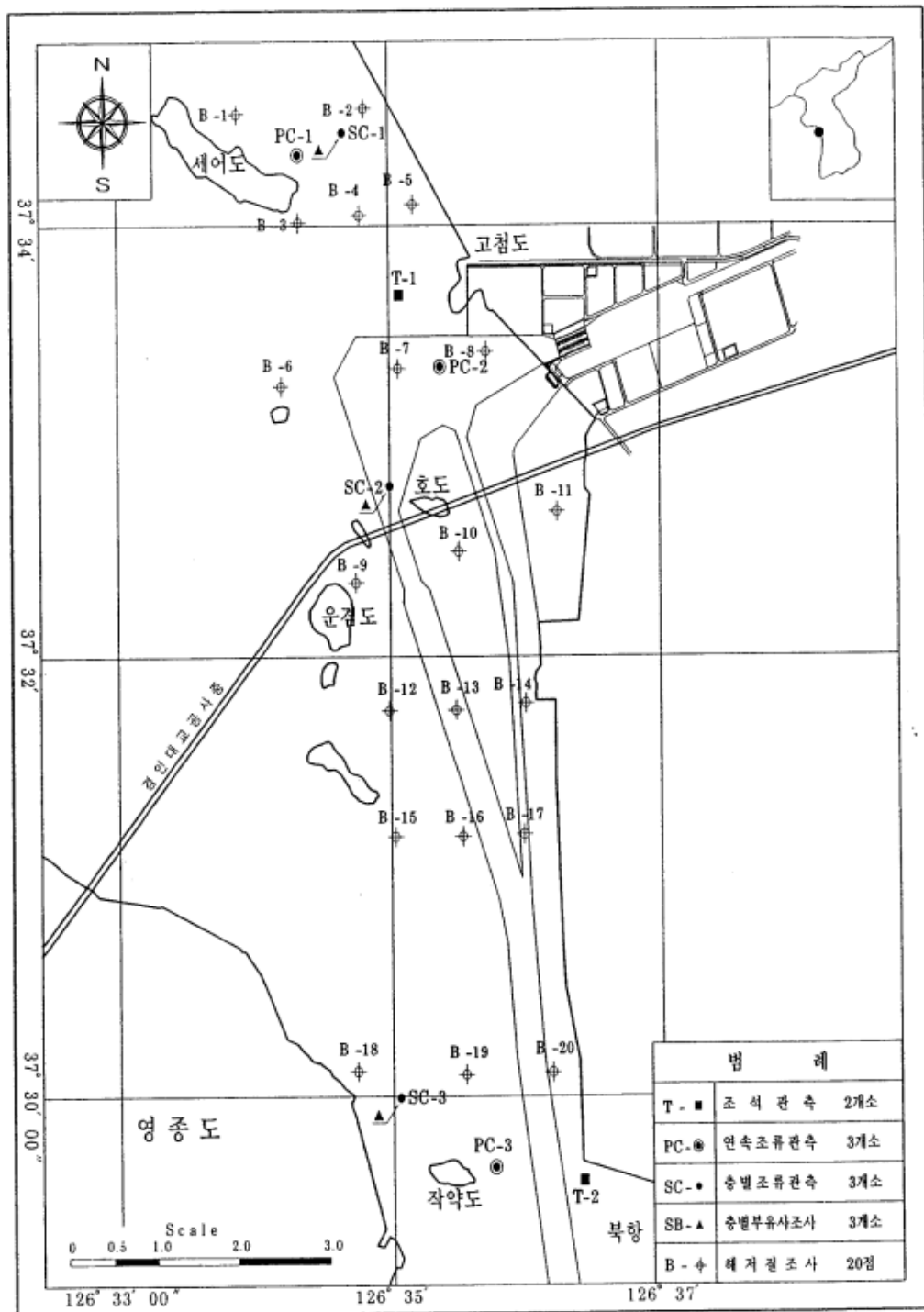


II-2: Tidal elevation at high tide (left) and low tide (right) with spring tide (reference level is MSL) [213]. The yellow areas in the right figure show the inter-tidal areas.



II-3: Increase in tidal range in 'Autonomous Situation' [211].

Appendix III: Locations maritime sea survey Incheon Sea

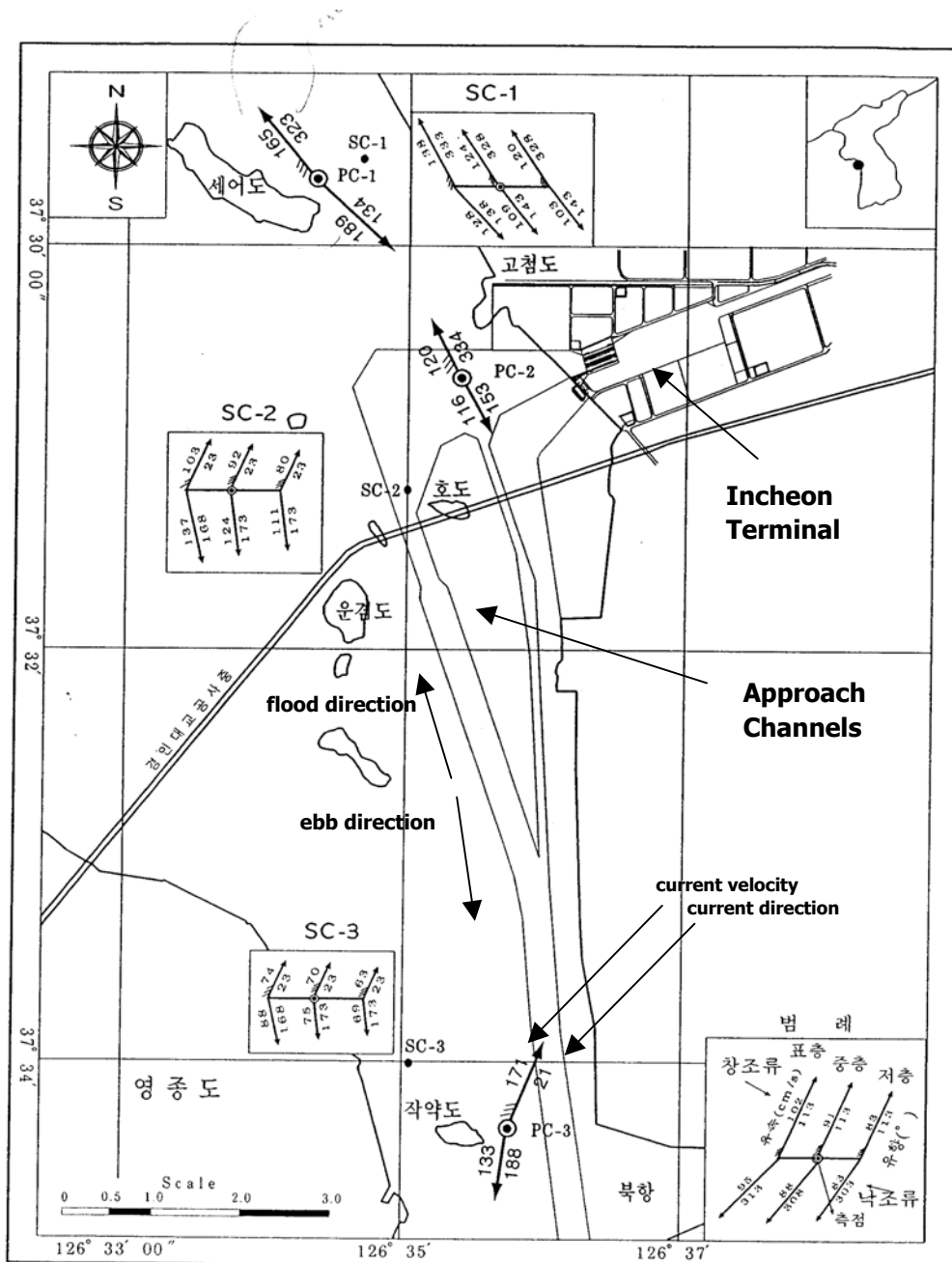


III-1: Locations maritime sea survey Incheon [201]

T = Tidal observation Gocheom Island and North Port
 PC = Tidal current
 SC = maximum current velocity & current transition time
 SB = Water temperature Salt and Suspended Sediment
 B = Mechanical analysis submarine soil

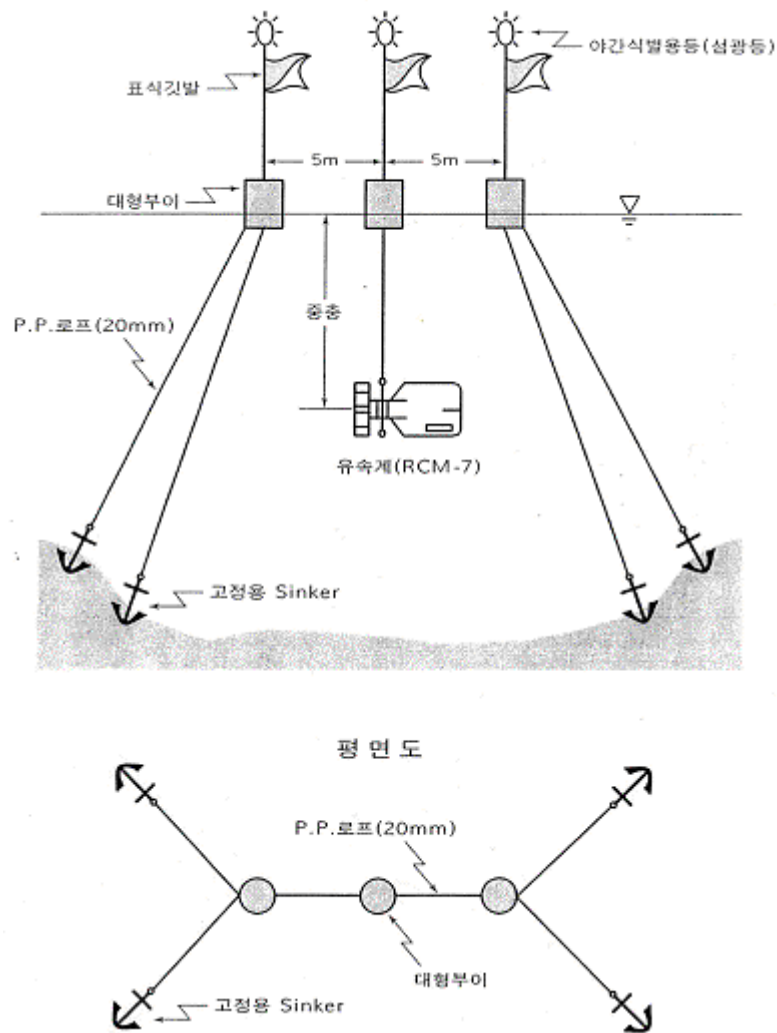
Appendix IV: Results maritime sea survey Incheon Sea

1. Tidal Current:



IV-1: Results tidal current [201]

The tidal current is continuous measured to grasp the tidal characteristics in the area between Incheon North Port and Incheon Terminal basin. The observations are carried out at 3 stations (PC 1,2,3) from 1-1-2005 until 15-1-2005. A RCM-7 recording current meter is moored at Middle Water Level ($1/2 \times \text{depth}$) at each station.



IV-2: Mooring method of the current meter [201]

2. Maximum Current velocity [201]

Station	Date	Tidal Range	Layer	direction	flood current	direction	ebb current
SC-1	8-1-2000	Fl: 759	Upper	333	138	138	128
		Eb: 682	Middle	328	124	143	109
			Lower	328	120	143	103
SC-2	9-1-2000	Fl: 759	Upper	23	103	168	137
		Eb: 668	Middle	23	92	173	124
			Lower	23	80	173	111
SC-3	10-1-2000	Fl: 733	Upper	23	74	168	88
		Eb: 674	Middle	23	70	173	75
			Lower	23	63	173	69

Table IV-1: Maximum current velocity [m/s]

3. Current transition time (phase difference) [201]

Station	Date	Layer	Current Transition Time	
			Flood [L.W.+hr]	Ebb [H.W.+hr]
SC-1	8-1-2000	Upper	1.2	1.4
		Middle	1.2	1.3
		Lower	1.2	1.3
SC-2	9-1-2000	Upper	1.1	1.2
		Middle	1.2	1.1
		Lower	1.1	1.0
SC-3	10-1-2000	Upper	0.2	0.1
		Middle	0.2	0.2
		Lower	0.2	0.2

Table IV-2: Current transition time (phase difference)

4. Suspended sediment [201]

SB-1		Spring tide 23-2-1996		
		Outer layer	Middle layer	Lower layer
Flood tide	max	668	710	752
	min	88	58	121
	mean	269	290	326
Ebb tide	max	696	763	864
	min	97	131	155
	mean	347	382	418

		Neap tide 2-3-1996		
		Outer layer	Middle layer	Lower layer
Flood tide	max	151	170	172
	min	63	73	81
	mean	109	123	135
Ebb tide	max	218	260	289
	min	111	118	128
	mean	178	215	245

Table IV-3: Suspended sediment concentration (mg/l) at location SB-1

SB-2		Spring tide 23-2-1996		
		Outer layer	Middle layer	Lower layer
Flood tide	max	377	372	370
	min	95	123	141
	mean	163	214	227
Ebb tide	max	413	419	436
	min	138	141	140
	mean	227	232	238

		Neap tide 2-3-1996		
		Outer layer	Middle layer	Lower layer
Flood tide	max	198	255	261
	min	74	85	97
	mean	121	138	152
Ebb tide	max	211	243	272
	min	84	96	103
	mean	153	183	212

Table IV-4: Suspended sediment concentration (mg/l) at location SB-2

		Spring tide 23-2-1996		
		Outer layer	Middle layer	Lower layer
Flood tide	max	362	371	379
	min	100	118	135
	mean	165	216	236
Ebb tide	max	359	372	373
	min	152	161	170
	mean	234	245	253

		Neap tide 2-3-1996		
		Outer layer	Middle layer	Lower layer
Flood tide	max	185	200	215
	min	75	106	138
	mean	133	161	183
Ebb tide	max	221	274	336
	min	143	164	177
	mean	174	201	230

Table IV-5: Suspended sediment concentration (mg/l) at location SB-2

5. Salt [201]

		Spring tide 23-2-1996		
		Outer layer	Middle layer	Lower layer
Flood tide	max	30,6	30,6	30,8
	min	27,2	27,2	27,4
	mean	29,3	29,3	29,5
Ebb tide	max	30,4	30,4	30,6
	min	27,3	27,4	27,5
	mean	29,3	29,3	29,5

		Neap tide 2-3-1996		
		Outer layer	Middle layer	Lower layer
Flood tide	max	31,5	31,5	31,6
	min	27,5	28	28,2
	mean	30,1	30,3	30,5
Ebb tide	max	31,3	31,4	31,5
	min	26,2	26,8	27,6
	mean	28,6	28,9	29,3

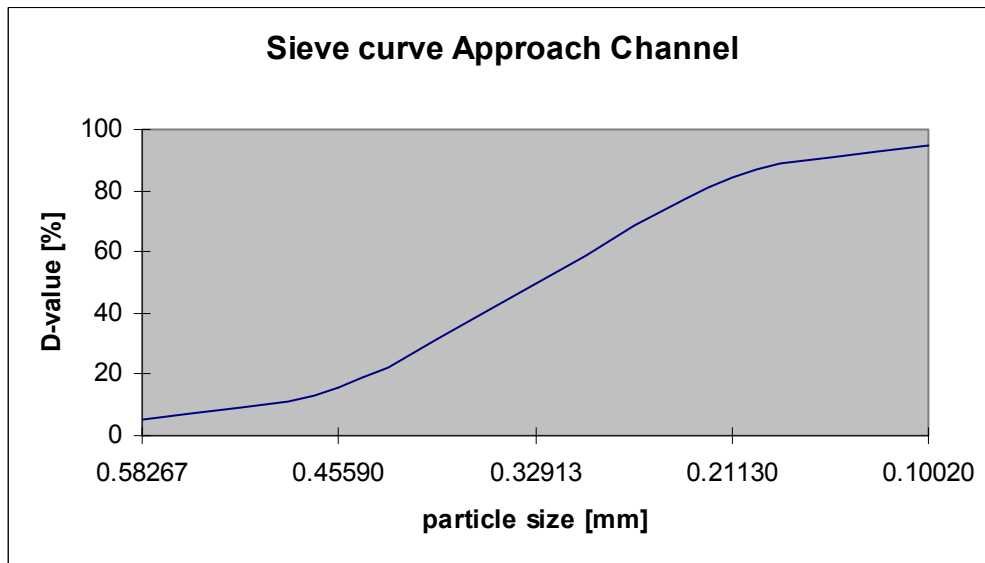
		Spring tide 23-2-1996		
		Outer layer	Middle layer	Lower layer
Flood tide	max	30,4	30,5	30,6
	min	27,4	27,5	27,6
	mean	29,2	29,3	29,4
Ebb tide	max	30,6	30,7	30,8
	min	27,8	28	28,4
	mean	29,9	30	30,1

		Neap tide 2-3-1996		
		Outer layer	Middle layer	Lower layer
Flood tide	max	30,6	30,6	30,7
	min	28,7	28,9	29
	mean	29,7	29,8	29,9
Ebb tide	max	31,1	31,1	31,1
	min	29,4	29,4	29,4
	mean	30,6	30,5	30,5

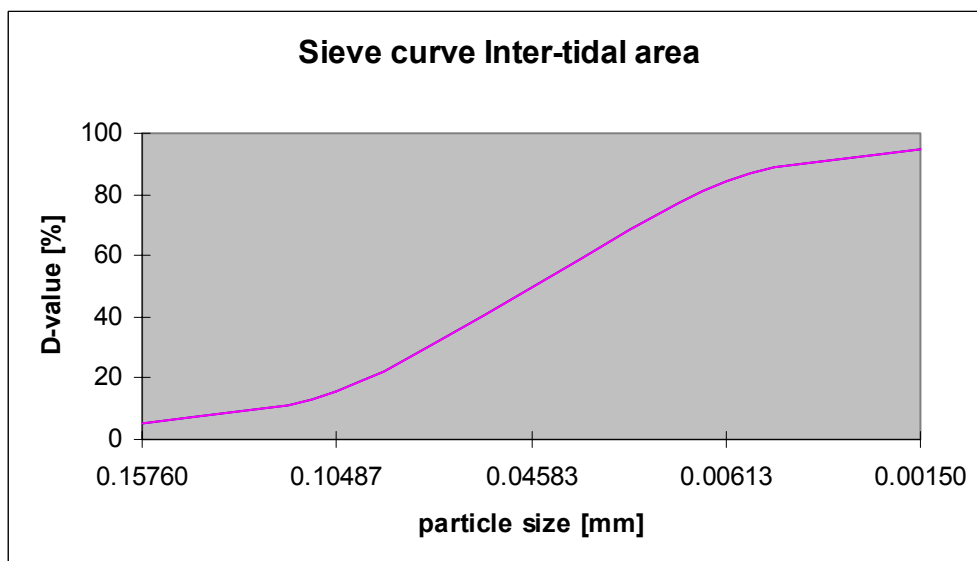
		Spring tide 23-2-1996		
		Outer layer	Middle layer	Lower layer
Flood tide	max	30,5	30,6	30,7
	min	27,8	28,1	28
	mean	29,5	29,7	29,8
Ebb tide	max	30,5	30,5	30,5
	min	27,5	27,5	27,8
	mean	29,7	29,7	29,8

		Neap tide 2-3-1996		
		Outer layer	Middle layer	Lower layer
Flood tide	max	30,5	30,6	30,7
	min	28,7	28,8	28,9
	mean	29,6	29,7	29,7
Ebb tide	max	30,8	30,9	30,9
	min	28,6	28,7	28,7
	mean	30,3	30,3	30,4

Table IV-6: Salinity of the sea at three locations near the Project Area (‰)

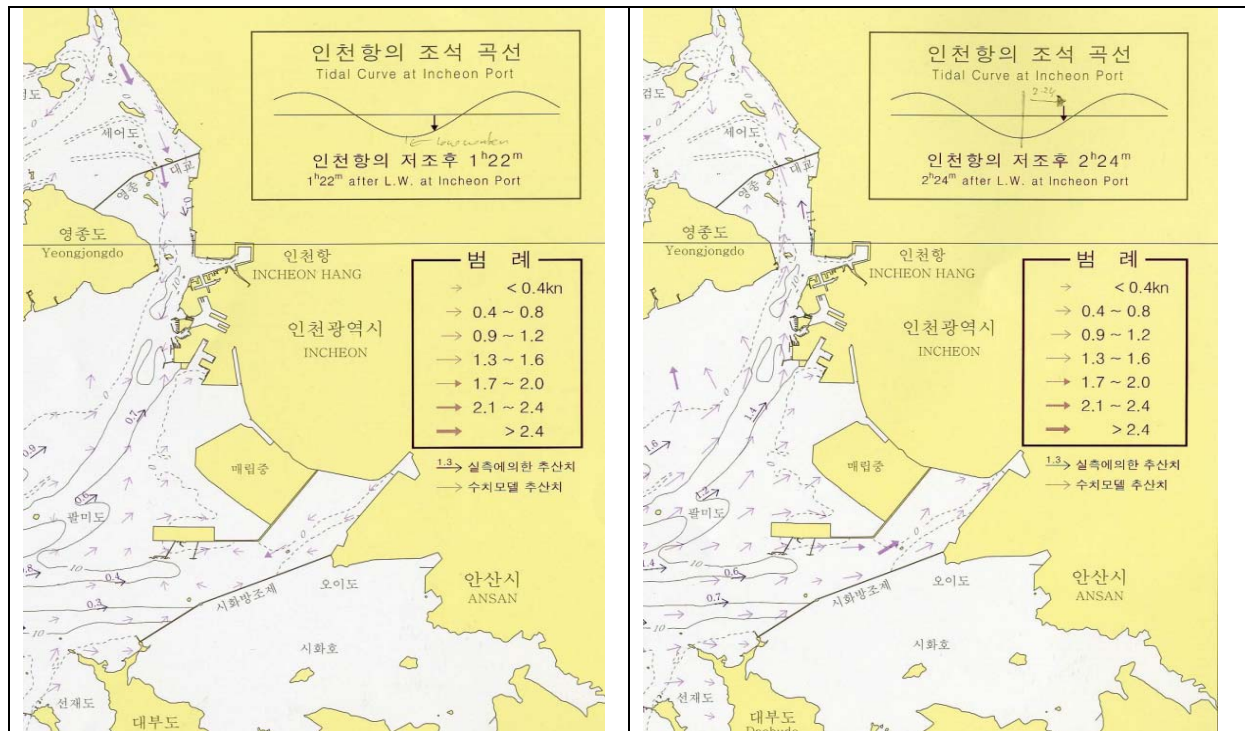
6. Submarine Soil [201]

IV-3: Average of observation points B-1 B-11 B-17 and B-18

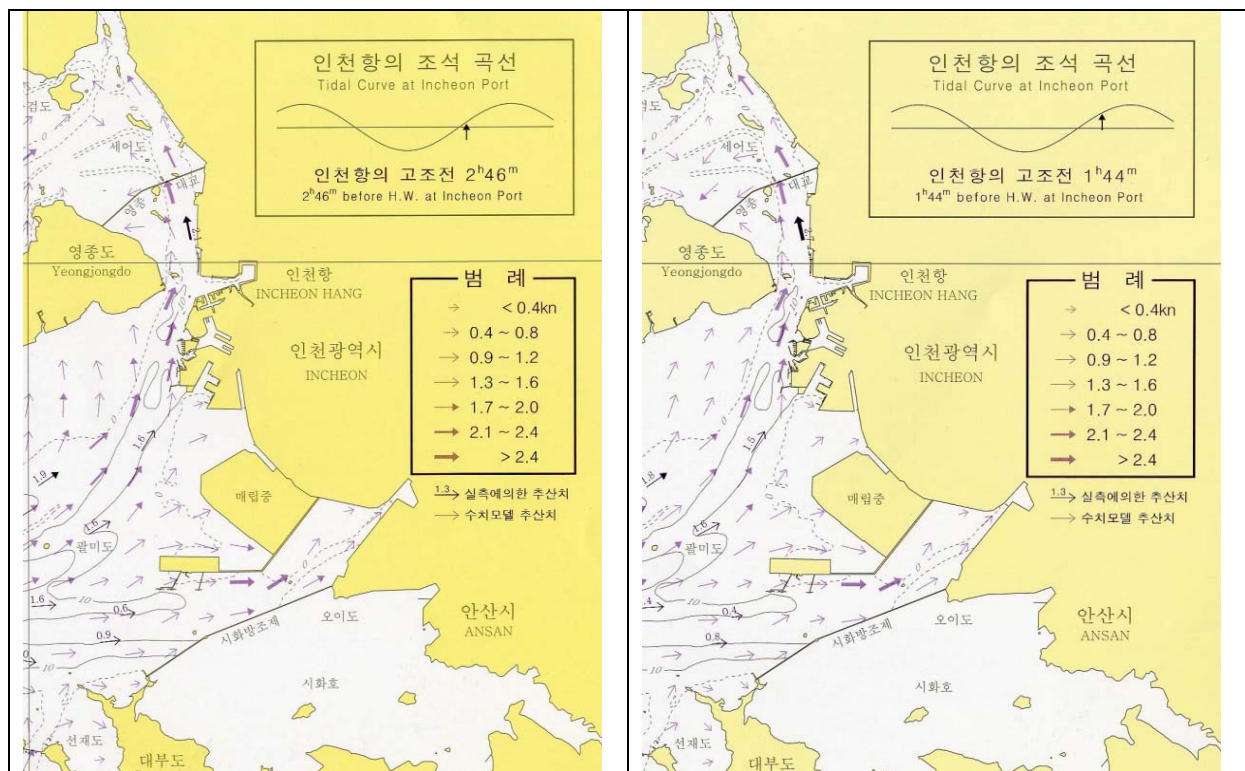


IV-4: Average of observation points B-13, B-16, B-19

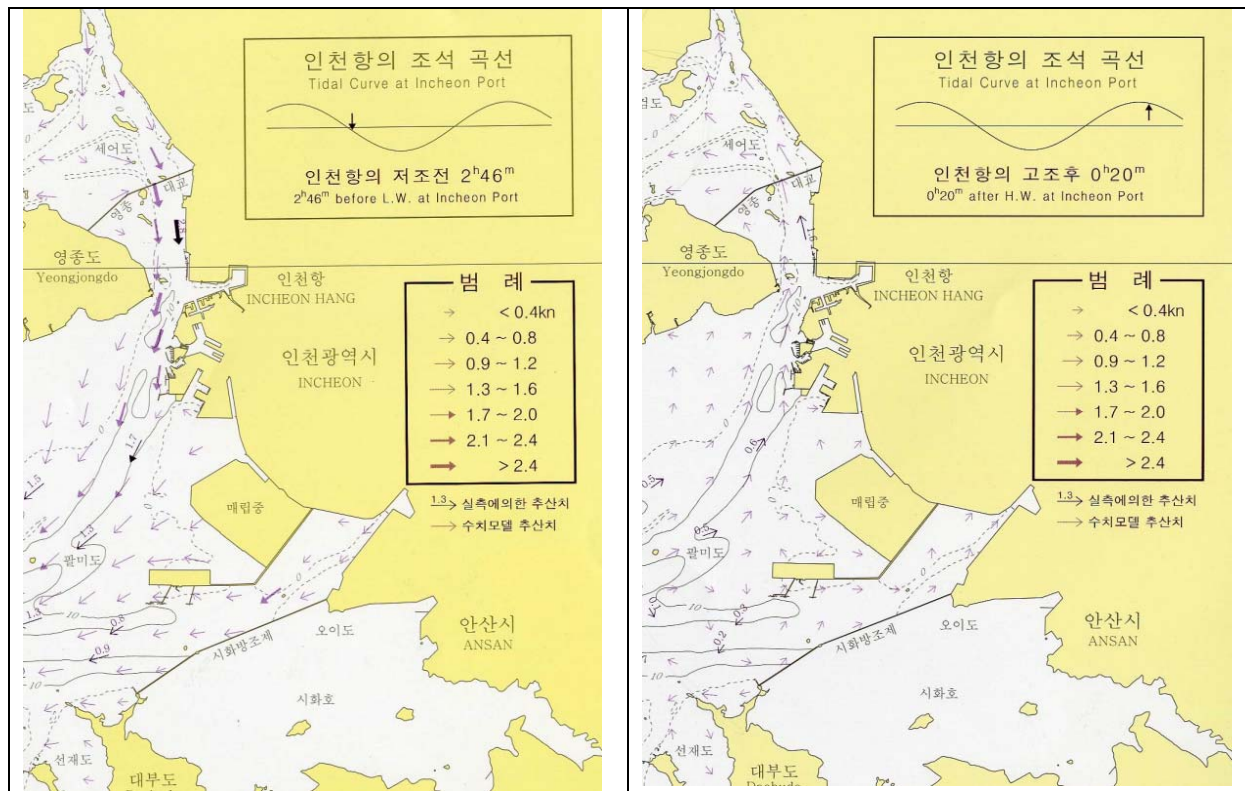
Appendix V: Flow velocities tidal chart



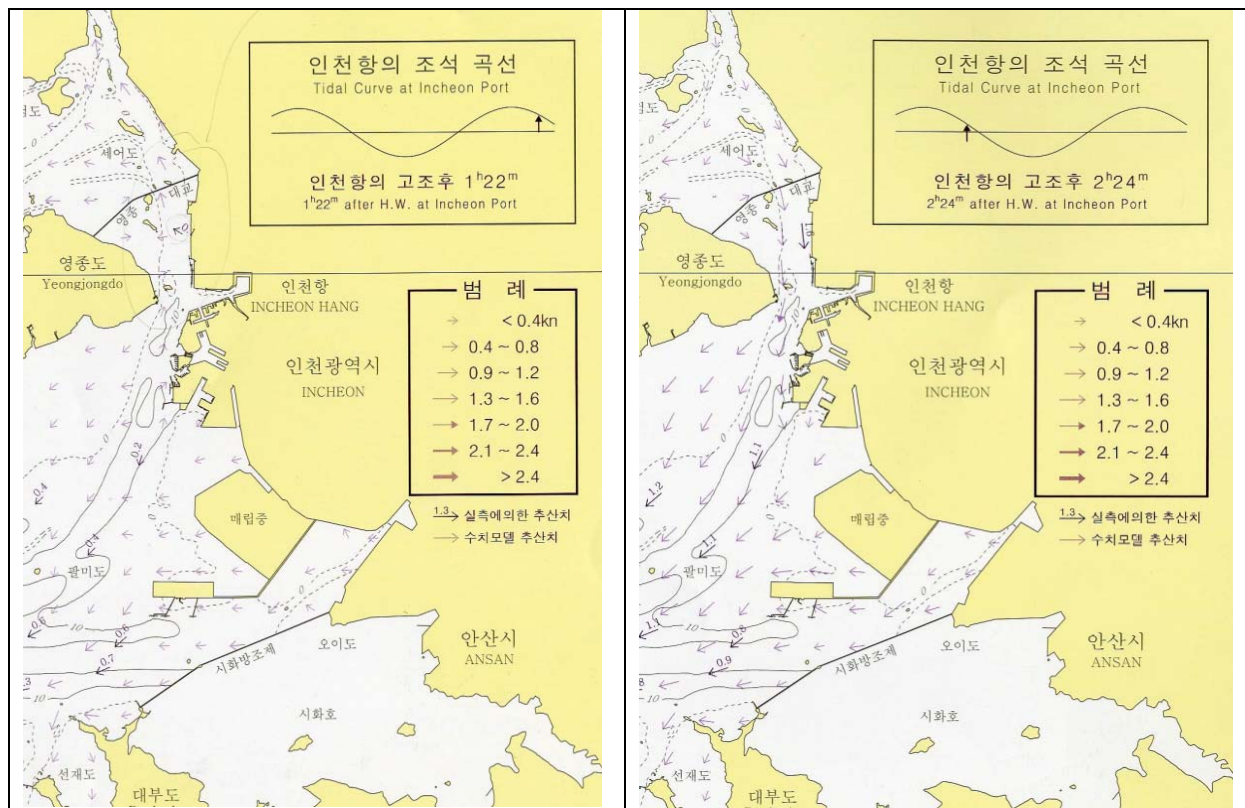
V-1: Tidal current 1:22 (left) and 2:24 (right) after Low Water at Incheon [216]



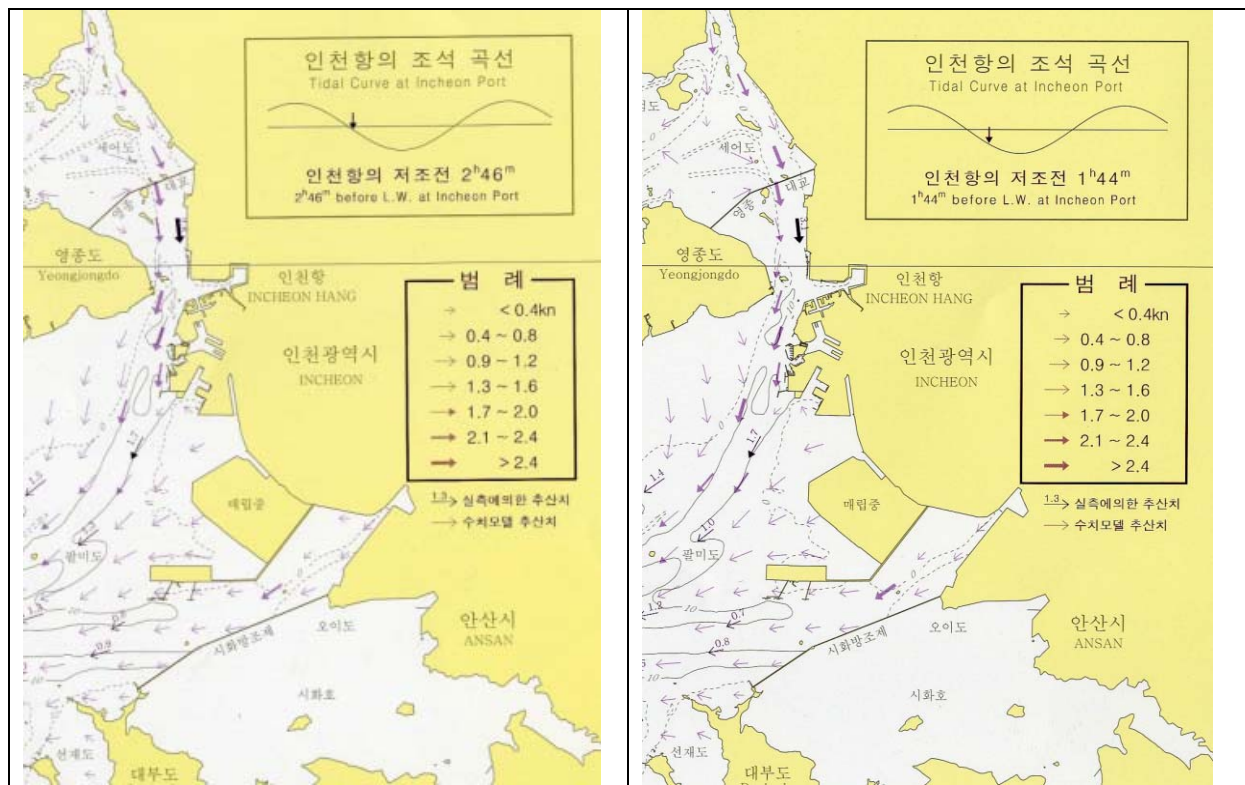
V-2: Tidal current 2:46 (left) and 1:44 (right) before High Water at Incheon [216]



V-3: Tidal current 0:42 before High Water (left) and 0:20 after Low Water (right) [216]



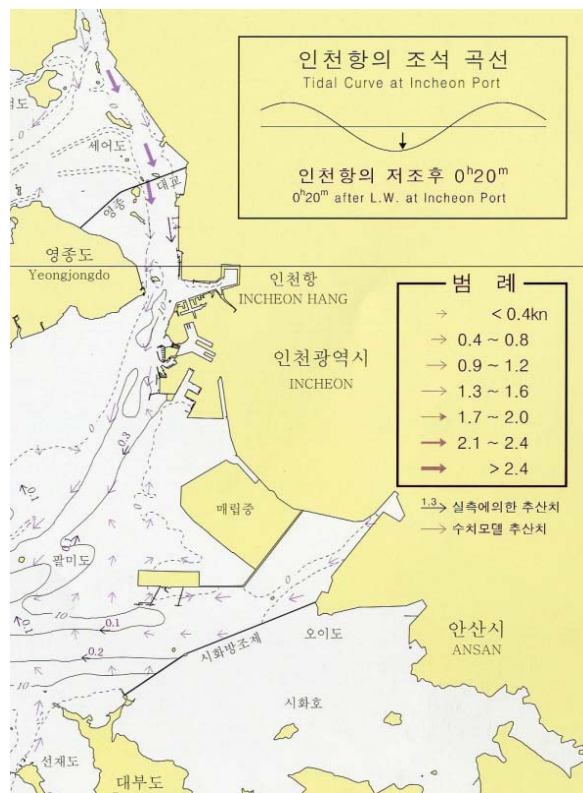
V-4: Tidal current 1:22 (left) and 2:24 (right) after High Water at Incheon [216]



V-5: Tidal current 2:46 (left) and 1:44 (right) before Low Water at Incheon [216]



V-6: Tidal current 1:44 (left) and 0:42 (right) before Low Water at Incheon [216]



V-7: Tidal current 0:20 after Low Water at Incheon Port [216]

Appendix VI: Harmonic constituents

The figure below shows the map of Kyunggi Bay. At the cross section of the horizontal and vertical lines with also a dot, the Korean Oceanographic Research and Development Institute (KORDI) provided tidal data. Probably the data are generated with a model that did not include all islands in Kyunggi Bay. This is the reason some cross sections are located at an island. The next page shows the provided tidal data.



VI-1: Overview Kyunggi Bay [204]

M2

latitude	longitude	amplitude(cm)	phase(degree)	phase(rad)
37,2813	126,375	254,44	131,98	-0,669
37,2813	126,4583	259,48	131,75	-0,666
37,2813	126,5417	264,8	131,65	-0,665
37,3438	126,375	258,15	133,24	-0,685
37,3438	126,4583	262,64	132,83	-0,680
37,3438	126,5417	267,49	132,94	-0,681
37,4063	126,375	261,71	134,62	-0,702
37,4063	126,4583	265,37	133,69	-0,691
37,4063	126,5417	269,41	133,88	-0,693
37,4688	126,375	265,35	136,64	-0,727
37,5313	126,375	269,71	138,18	-0,745
37,5313	126,4583	276,78	138	-0,743
37,5313	126,5417	281,68	137,77	-0,740
37,5938	126,375	271,8	139,29	-0,758
37,5938	126,5417	286,37	138,27	-0,746

Table VI-1: Tidal data for M2 at different location in Kyunggi Bay

S2

latitude	longitude	amplitude(cm)	phase(degree)	phase(rad)
37,2813	126,375	94,04	179,4	-1,000
37,2813	126,4583	95,96	179,25	-1,000
37,2813	126,5417	98,04	179,27	-1,000
37,3438	126,375	95,49	180,79	-1,000
37,3438	126,4583	97,21	180,45	-1,000
37,3438	126,5417	99,04	180,71	-1,000
37,4063	126,375	96,86	182,34	-0,999
37,4063	126,4583	98,26	181,38	-1,000
37,4063	126,5417	99,8	181,79	-1,000
37,4688	126,375	98,13	184,72	-0,997
37,5313	126,375	99,74	186,47	-0,994
37,5313	126,4583	102,47	186,57	-0,993
37,5313	126,5417	104,45	186,56	-0,993
37,5938	126,375	100,57	187,63	-0,991
37,5938	126,5417	106,27	187,24	-0,992

Table VI-2 : Tidal data for S2 at different locations in Kyunggi Bay

O1

latitude	longitude	amplitude(cm)	phase(degree)	phase(rad)
37,2813	126,375	22,06	270	-1,84E-16
37,2813	126,4583	22,17	269,81	-3,32E-03
37,2813	126,5417	22,29	269,83	-2,97E-03
37,3438	126,375	22,14	270,57	9,95E-03
37,3438	126,4583	22,21	270,35	6,11E-03
37,3438	126,5417	22,3	270,61	1,06E-02
37,4063	126,375	22,21	271,34	2,34E-02
37,4063	126,4583	22,25	270,72	1,26E-02
37,4063	126,5417	22,3	271,07	1,87E-02
37,4688	126,375	22,24	272,58	4,50E-02
37,5313	126,375	22,27	273,28	5,72E-02
37,5313	126,4583	22,37	273,6	6,28E-02
37,5313	126,5417	22,36	273,9	6,80E-02
37,5938	126,375	22,31	273,62	6,31E-02
37,5938	126,5417	22,42	274,3	7,50E-02

Table VI-3: Tidal data for O1 at different locations in Kyunggi Bay

K1

latitude	longitude	amplitude(cm)	phase(degree)	phase(rad)
37,2813	126,375	31,45	297,53	0,46
37,2813	126,4583	31,62	297,4	0,46
37,2813	126,5417	31,81	297,28	0,46
37,3438	126,375	31,61	298,08	0,47
37,3438	126,4583	31,75	297,78	0,47
37,3438	126,5417	31,85	298,02	0,47
37,4063	126,375	31,71	298,82	0,48
37,4063	126,4583	31,8	298,24	0,47
37,4063	126,5417	31,83	298,53	0,48
37,4688	126,375	31,69	300	0,50
37,5313	126,375	31,74	300,69	0,51
37,5313	126,4583	31,84	300,82	0,51
37,5313	126,5417	31,84	301,02	0,52
37,5938	126,375	31,83	301,16	0,52
37,5938	126,5417	31,87	301,37	0,52

Table VI-4: Tidal data for K1 at different locations in Kyunggi Bay

Appendix VII: Tidal station Incheon

	Time	Water level [cm]							
27-jun	2:10	729	7-jul	2:05	153	18-jul	0:25	26	
	8:38	332		8:05	812		6:33	958	
	14:19	633		14:24	144		12:55	25	
	20:32	224		20:28	773		18:52	907	
28-jun	3:11	765	8-jul	2:42	204	19-jul	1:05	1	
	9:38	290		8:36	767		7:08	928	
	15:21	672		14:59	167		13:29	31	
	21:27	190		21:12	750		19:30	891	
29-jun	4:00	799	9-jul	3:23	264	20-jul	1:43	51	
	10:25	250		9:18	713		7:41	880	
	16:46	712		15:43	199		14:01	59	
	22:53	155		22:09	723		20:08	858	
30-jun	4:39	827	10-jul	4:25	326	21-jul	2:19	124	
	11:36	190		10:15	657		8:14	818	
	16:46	772		16:46	232		14:33	104	
	22:53	104		13:31	708		20:48	809	
1-jul	5:12	847	11-jul	5:59	364	22-jul	2:57	210	
	11:36	190		11:48	619		8:48	746	
	17:20	772		18:17	240		15:08	164	
	23:28	104	12-jul	1:07	729		21:34	751	
2-jul	5:42	861		7:50	341	23-jul	3:43	300	
	12:05	168		13:31	634		9:29	669	
	17:51	788		19:48	204		15:51	233	
3-jul	0:01	90	13-jul	2:30	786		22:37	694	
	6:10	869		9:11	276	24-jul	4:53	378	
	12:34	150		14:51	692		10:33	597	
	18:22	797		21:03	139		17:05	295	
4-jul	0:32	86	14-jul	3:35	852	25-jul	0:16	665	
	6:38	871		10:06	202		6:59	400	
	13:00	137		15:51	763		12:30	566	
	18:51	801		22:03	70		18:57	308	
5-jul	1:03	94	15-jul	4:37	911	26-jul	1:57	688	
	7:06	863		10:55	132		8:35	354	
	13:27	130		16:42	828		14:12	603	
	19:20	798		22:56	12		20:21	268	
6-jul	1:35	116	16-jul	5:13	950	27-jul	3:02	738	
	7:33	844		11:38	76		9:29	293	
	13:54	132		17:28	876		15:12	666	
	19:52	789		13:42	22		21:17	211	
			17-jul	5:55	966				
				12:18	40				
				18:52	902				

Table VII-1: High water and Low water levels in Incheon from June 27th until July 27th 2005 [209]

Appendix VIII: Tidal analysis

A tidal signal is built up of different tidal constituents. The tidal constituents can be separated into principle tidal (M2 and S2), declination tides (e.g. Mf, fortnightly) and elliptic tides (e.g. Q1, diurnal lunar and N2). In addition, the tidal wave deforms in shallow seas due to the continents, inertia and currents and is even more disturbed in coastal areas due to bottom friction [Kalkwijk, 1976]. This induces 'shallow water constituents'.

Although, the tide in Incheon also contains many non-linear effects, it is possible to distillate the astronomical constituents from a tidal signal. The astronomical tides can be described with:

$$h(t) = h_0 + \sum_n f_n H_n \cos(\omega_n t + V_n + u_n - g_n)$$

$h(t)$ = Water level at time t

h_0 = Reference water level

f_n = Correction for nodal tide

H_n = Amplitude

ω_n = Angular velocity of the tidal constituent

V_n = Uniform change part of the astronomical argument

u_n = Correction for nodal tide (phase lag)

g_n = Phase adjustment

For the tidal analysis is made use of the MATLAB toolbox t-tide. There is only a time series of one-month available thus tidal cycles with a tidal period of less than 1 month can be extracted from the sea level record. The astronomical argument ($V+u$) and the nodal factor (f) are included in the determination of the constituents in t-tide. The results of the tidal analysis for only M2 and S2 are presented below:

```
* from TU Delft and WL | Delft Hydraulics
* Frequency and astronomical data from t_tide toolbox
* which is available at http://www2.ocgy.ubc.ca/~rich/
* This analysis is performed at: 31-Aug-2005 15:18:28
* based on 120 data points from
* 2005-06-27 02:10:00 to
* 2005-07-27 21:17:00
* with reference date
* 2005-07-12 10:39:01
*
* Amplitude   Phase   freq [dg/hr]  u+v   & f   at 2005-07-12 10:39:01
W
2 5
3.140  262.3  28.984104252  178.2  0.965  M2
1.148  188.2  29.999999988  319.5  1.002  S2
```

VIII-1: Result tidal analysis [212]

The results show 10% higher values for the amplitude than the constituents provided by KORDI in Appendix VI.

In addition, the same tidal analysis is performed for wider range of constituents (see figure below). This analysis shows the influence of many other constituents in the tidal signal at Incheon. The reliability of the result is questionable since these results show even higher differences with the data provided by KORDI. Consequently, the sum of all amplitudes shows a too high value.

* This analysis is performed at: 29-Aug-2005 10:00:25
 * based on 120 data points from
 * 2005-06-27 02:10:00 to
 * 2005-07-27 21:17:00
 * with reference date
 * 2005-07-12 10:39:01 (gem. tijd)

	Amplitude	Phase	freq [dg/hr]	u+v	&f	name	Kordi data
W							
number of constituents	0.058	151.6	13.399	309	1.181	Q1	
	0.238	85.9	13.943	181.8	1.178	O1	→ 0.22
	0.144	32.6	14.959	319.3	0.991	P1	
	0.504	273	15.041	357.8	1.109	K1	→ 0.32
	0.201	324.5	27.424	165.2	0.965	EPS2	
	0.851	41	27.895	73.1	0.969	2N2	
	0.802	165.5	27.968	37.7	0.964	MU2	
	1.247	329.6	28.440	305.7	0.969	N2	
	3.234	293.2	28.984	178.2	0.965	M2	→ 2.70
	0.356	210	29.528	248.3	1.143	L2	
	1.638	209	30.000	319.5	1.002	S2	→ 0.99
	0.037	51.5	57.424	123.9	0.935	MN4	
	0.156	341.4	57.968	356.4	0.931	M4	
	0.014	118.3	58.440	265.2	0.971	SN4	
	0.09	271.8	58.984	137.8	0.967	MS4	
	0.252	321.7	86.408	302.1	0.902	2MN6	
	0.812	7.5	86.952	174.7	0.898	M6	
	0.496	252.5	87.968	316	0.933	2MS6	
	0.14	148.8	88.984	97.3	0.969	2SM6	
	0.029	94.3	115.936	352.9	0.866	M8	
	0.201	62.5	144.921	171.1	0.836	M10	
summed:	11.5 m.						

→ te groot

VIII-2: Results tidal analysis [212]

Appendix IX: Schematisation of 'Autonomous Situation'

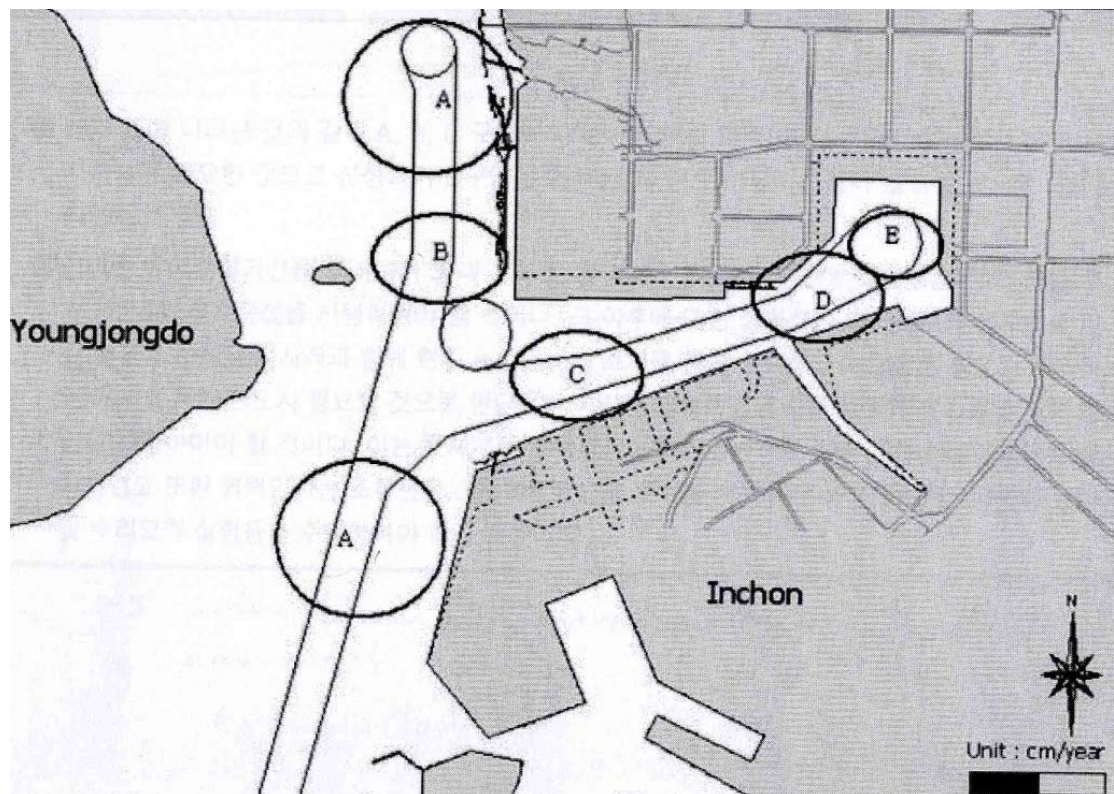
Rectangle:	Name of branches
Numbers:	Important nodal points
Small text:	Names of observation points in 'far field' analysis
Note 1:	North of the chart the mouth of Yeomha Waterway starts
Note 2:	The 'far field' area runs from 8 km stream upwards of Yeomha Waterway to Navigation 3_4503 south of Incheon North Port.
Note 3:	For the Project Area, see Appendix X

Appendix X: Schematisation of 'Project Situation'

Blue: Name of the branch
Red: Important subjects of the Kyung-In Canal project
Black: Important grid points in the schematisation
Numbers: Nodal points

Appendix XI: Dredging of Incheon North Port

A numerical model determined the dredging volumes in Incheon North Port in 2004. The results of this study resulted in a dredging plan for different areas around Incheon North Port.



XI-1: Dredging area North Port [206]

Area	Surface	Amount of deposition	Dredging frequency	Annual sedimentation
	[m ²]	[m ³ /year]	[1/year]	[m]
A	585,990	298,856	1	0.52
B	110,358	67,319	1	0.61
C	128,860	79,894	1	0.62
D	142,250	42,670	2	0.29
E	173,875	8,694	10	0.05

Table XI-1: Model results for dredging of Incheon North Port

This study resulted in an average siltation rate in Incheon North Port of 5 cm. This seems a little optimistically.

Appendix XII: Water exchange mechanisms

The Analytical Approach used in this study determines the siltation of open harbour basins, based on three water exchange mechanisms (see section B.4.1). W.D. Eysink publishes the Analytical Approach used in this study [5]. This appendix determines the siltation rates in Incheon Terminal basin and Incheon North Port based on these three mechanisms:

1. Tidal Prism

$$V_t = 2\eta A$$

V_t = tidal prism of harbour basin [m^3]

η = tidal amplitude [m]

A = storage area of the basin [m^2]

2. Horizontal Eddies

$$V_h = f_1 h_0 b * u_{0,max} / \pi * T - f_2 V_t$$

V_h = total volume of water exchange per tidal cycle by horizontal exchange flow [m^3]

V_t = tidal prism of harbour basin [m^3]

h_0 = water depth at entrance relative to MSL [m]

b = width of entrance [m]

$u_{0,max}$ = maximum flow velocity in front of entrance [m/s]

T = tidal period [s]

The coefficients f_1 and f_2 generally are within the ranges 0.01-0.03 and 0.1-0.25 respectively and can be estimated based on existing knowledge from comparable situations. Because this knowledge is not present in this study, both the maximum and minimum effects are determined.

3. Density currents

$$V_d = f_4 h_0 b \left(\frac{\Delta \rho_{max}}{\rho} g h_0 \right)^{\frac{1}{2}} T - f_5 V_t$$

$$\text{with } \Delta \rho_{max} = \frac{1}{2} (\rho_{0,max} - \rho_{0,min})$$

Where:

V_d = exchange volume per tide due to density currents [m^3]

V_t = tidal prism of harbour basin [m^3]

h_0 = water depth at entrance relative to MSL [m]

b = width of entrance [m]

T = tidal period [s]

g = gravitational force [m/s^2]

ρ = density of the water in the harbour basin [-]

$\Delta \rho_{max}$ = maximum density difference outside the harbour [kg/m^3]

$\rho_{0,max}$ = maximum density outside the harbour [kg/m^3]

$\rho_{0,min}$ = minimum density outside the harbour [kg/m^3]

Figure 3 demonstrates the mutual relationship of a number of relevant parameters concerning the density induced exchange.

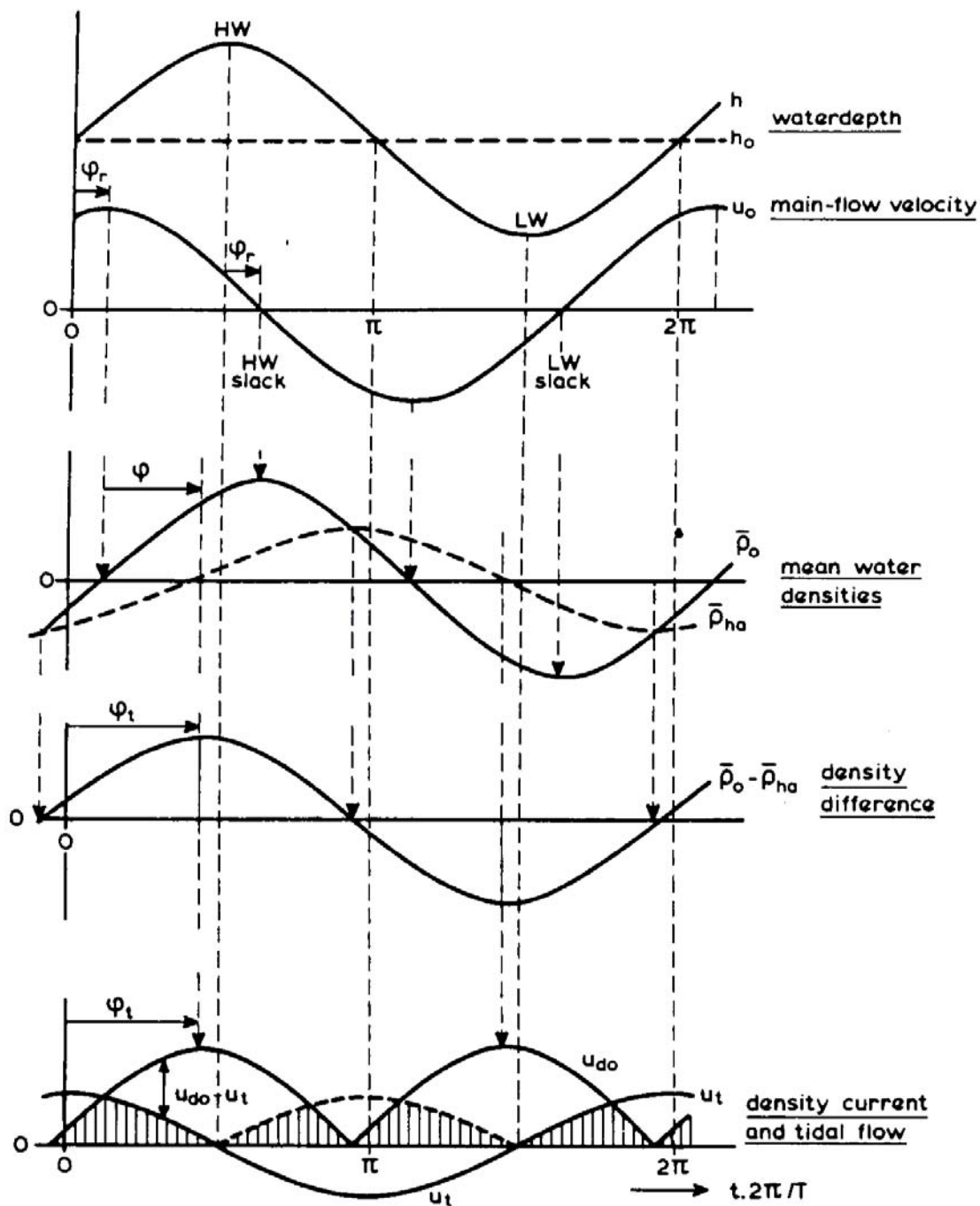


Figure 3. Effect of phase lag between tidal and density currents on the density induced exchange flow.

It is obvious that in a large harbour the average water density will hardly follow the density fluctuation of the water in front of the harbour. In smaller harbour basins the opposite is the case. This effect

has been included in the coefficient f_4 and has been estimated theoretically on the basis of linear harmonic theory assuming a constant water level and neglecting tidal flow (see figure 4)

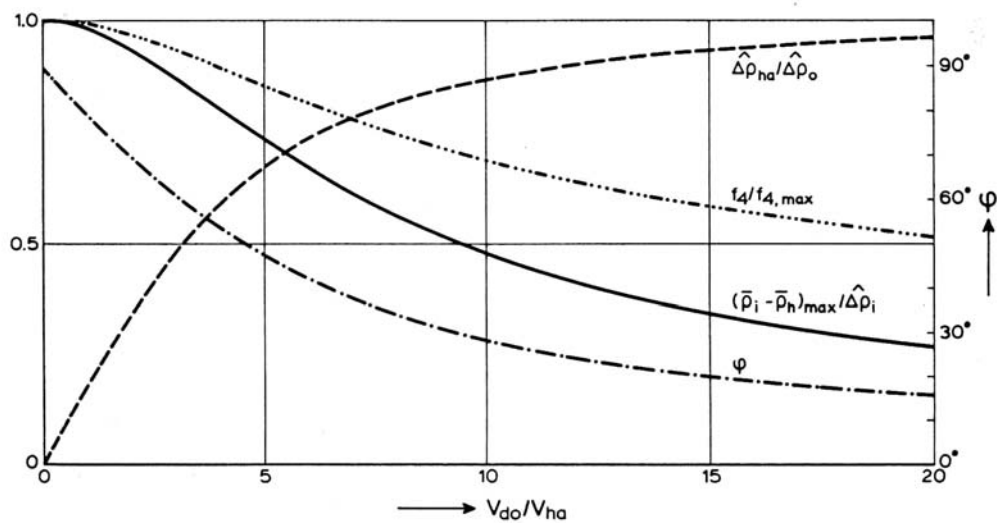


Figure 4. Effect of harbour volume on coefficient f_4

Also the coefficient f_5 has been derived theoretically assuming a constant water level ($h = h_0$) and is shown on figure 5.

The coefficient $f_{4,max}$, finally, is assumed to be 1.0 in this study. This is an averaged value derived from field data, model data and model investigations, which are shown in figure 6.

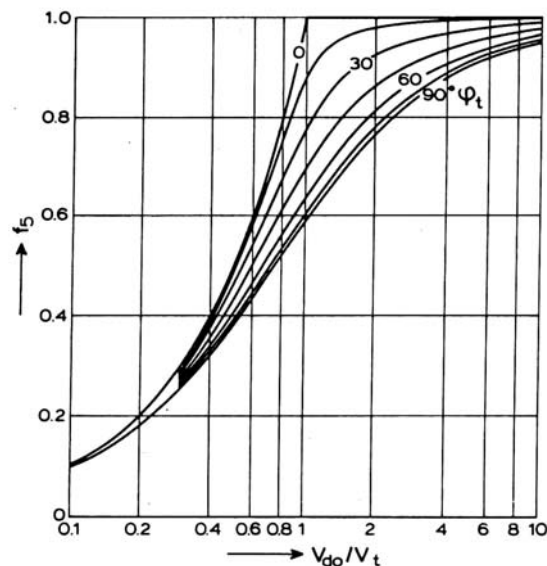


Figure 5. f_5 as a function of V_{d0}/V_t and phase lag ϕ_t

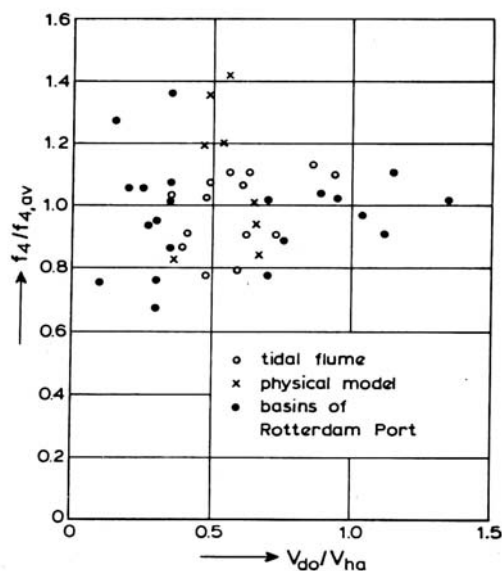


Figure 6. Relative variation in coefficient $f_{4,max}$ determined from model and field data

Results of Analytical Approach

1) Tidal Prism

length basin	3000	m
width basin	750	m
surface	2.250.000	m ²
MSL	4,635	m
spring tidal range	7,98	m
neap tidal range	3,47	m
depth entrance below DL	2	m
Tidal prism Vt	12.879.000	m ³ /tide

Table XII-1: Water exchange due to tidal prism in Incheon North Port

length Entrance Channel	1600	m
width Entrance Channel	450	m
length Incheon Terminal	1200	m
width Incheon Terminal	300	m
Total surface	1.080.000	m ²
MSL	4,635	m
spring tidal range	7,98	m
neap tidal range	3,47	m
depth entrance below DL	10	m
average Tidal prism (Vt)	6.181.920	m ³ /tide

Table XII-2: Water exchange due to tidal prism in Entrance Channel and Incheon Terminal

2) Horizontal eddies

f1 min.	0,01	
f1 max.	0,025	
f2 min.	0,15	
f2 max.	0,25	
depth in entrance below DL	2	m
h0	6,635	m
width harbour entrance	750	m
u0,max	1,5	m/s
tidal period	44700	s
max. horizontal eddies Vh	723.313	m ³ /tide
min. horizontal eddies Vh	-2.157.685	m ³ /tide

Table XII-3: Water exchange due to horizontal eddies in Incheon North Port

f1min.	0,01	
f1 max	0,025	
f2 min	0,15	
f2 max	0,25	
depth below DL	10	
h0	14,635	m
width harbour entrance	450	m
u0,max	1,5	m/s
tidal period	44700	s
max. horizontal eddies Vh	2.586.651	m ³ /tide
Average horizontal eddies	1.223.373	m ³ /tide
min. horizontal eddies Vh	-139.905	m ³ /tide

Table XII-4: Water exchange due to horizontal eddies in Entrance Channel and Incheon Terminal

3) Density currents

Incheon North Port

Volume basin below MSL (Vha)	14.928.750	m ³
f4,max (figure 6)	1	
f4 (figure 4)	0,1	
f5 (figure 5)	0,95	
h0	6,635	m
width harbour entrance (b)	750	m
rho max	30,7	‰
rho min	27,8	‰
delta rho max	1,45	‰
rho basin	28	‰
g	9,81	m/s ²
tidal period (T)	44700	s
Vd0	409.851.269	m ³
Vdo/Vha	27,45	m ³
Vdo/Vt	31,82	m ³
Vd	28.603.439	m ³ /tide

Table VII-5: Water exchange due to density current in Incheon North Port

Entrance Channel and Incheon Terminal:

Volume basin below MSL (Vha)	15.805.800	m ³
f4,max (figure 6)	1	
f4 (figure 4)	0,1	
f5 (figure 5)	0,95	
h0	14,635	m
width harbour entrance (b)	450	m
rho max	30,7	‰
rho min	27,4	‰
delta rho max	1,65	‰
rho basin	28	‰
g	9,81	m/s ²
tidal period (T)	44700	s
Vd0	865.586.195	m ³
Vdo/Vha	54,76	m ³
Vdo/Vt	140,02	m ³
Vd	79.753.359	m ³ /tide

Table XII-6: Water exchange due to density currents in Entrance Channel and Incheon Terminal

Appendix XIII: Less saline water from Kyung-In Canal

For Incheon Terminal the siltation study is a little more complicated compared with North Port. This is caused by water exchange through the lock gates between Incheon Terminal basin and Kyung-In Canal. In addition, water discharge through the already existing floodgate during the rain season has got effects on density differences. Table XIII-1 shows the influence of the water exchange caused by lockage compared with the tidal prism.

volume basin at MSL	7.902.900	m3
tidal prism (Vt)	3.090.960	m3/tide
length	195	m
width	32,5	m
depth	8	m
volume	50700	m3
lock passages per year	6026	vessels
operation level	300	days
lock passages per tidal cycle	10,39	
average water difference	2	m
lock water per tidal cycle	131.719	m3/tide
percentage of Vt	4	%
lock water exchange per year	92.928.502	m3/year

Table XIII-1: Water exchange through lock gates

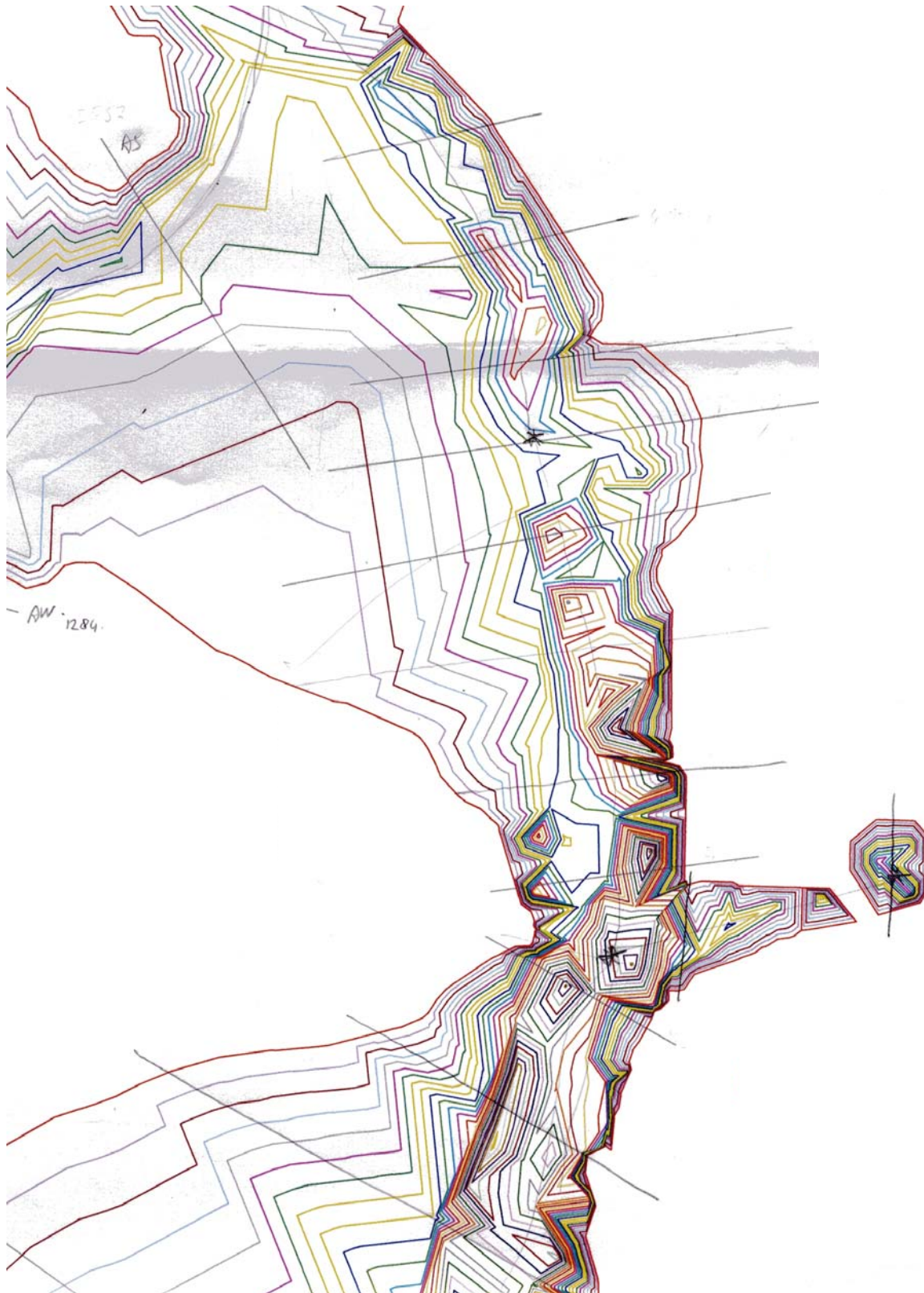
Table XIII-1 shows a relatively small water exchange by lockage compared with the tidal prism. Furthermore, the Kyung-In Canal also becomes salt due to lockage and thus the salinity difference is smaller. In addition, the relatively small volume less saline water from Kyung-In Canal has got a lower density and thus stays at the surface of the basin water. This causes less mixing and therefore a minimum effect of siltation due to density differences. Nevertheless, small density difference may have significant influences on siltation.

Discharge through the floodgate during the rain season causes a peak volume of rainwater with low salinity in front of Incheon Terminal basin. It is assumed that mixing takes place between the seawater in Incheon Terminal basin and the less saline water rainwater. This induces large density differences and thus introduces sediment influx contributing to extra shoaling in Incheon Terminal basin. Table XII-2 shows the influence of discharge through the floodgate, compared with the tidal prism.

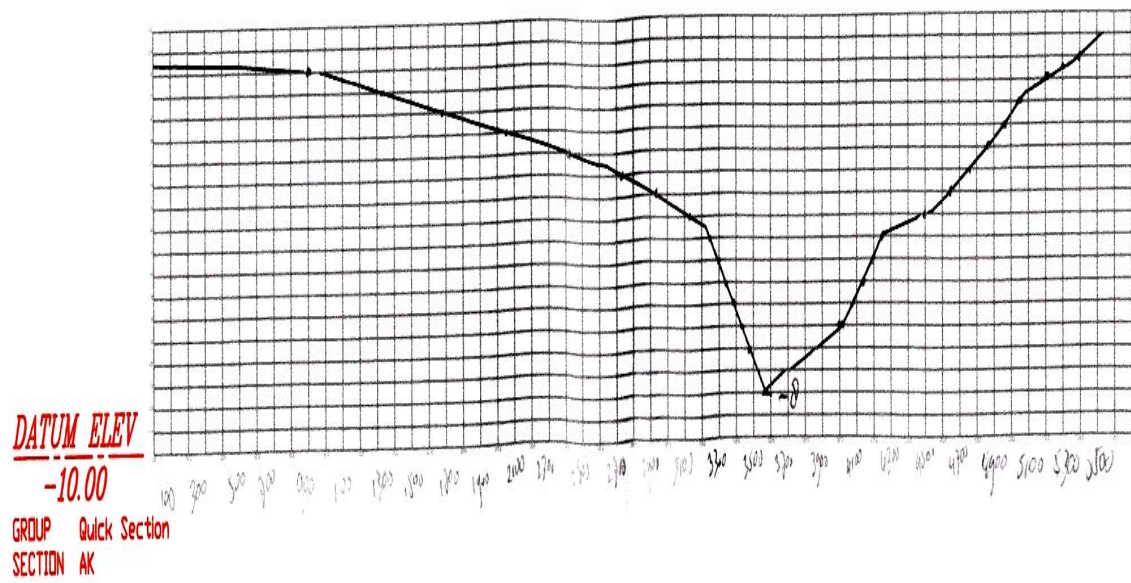
volume basin at MSL	7.902.900	m3
tidal prism (Vt)	3.090.960	m3/tide
tidal prism one month	185.208.674	m3/month
tidal prism one day	5.974.473	m3/day
Yearly rain fall	1,34	m
Yearly evaporation	1,086	m
yearly run off	0,254	m
catchment area	159.000.000	m2
average yearly run off	40.386.000	m3/year
tidal prism one year	2.180.682.769	m3/year
percentage of Vt	1,85	%
mean precipitation july	0,364	m
mean evaporation july	0,111	m
monthly run off	40.227.000	m3/month
percentage of Vt	22	%
mean precipitation august	0,295	m
mean evaporation august	0,122	m
monthly run off	27.507.000	m3/month
percentage of Vt	15	%

Table XIII-2: Discharge of rainwater through floodgate

Appendix XIV : Bathymetry in Autodesk 3d

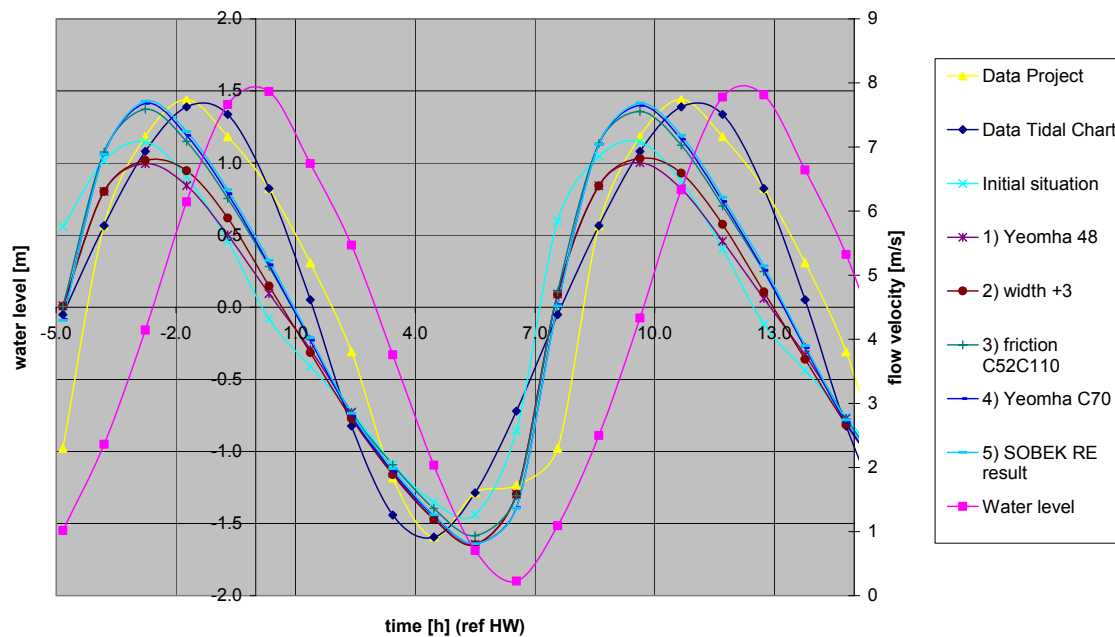


XIV-1: Bathymetry Kyunggi Bay in Autodesk 3d

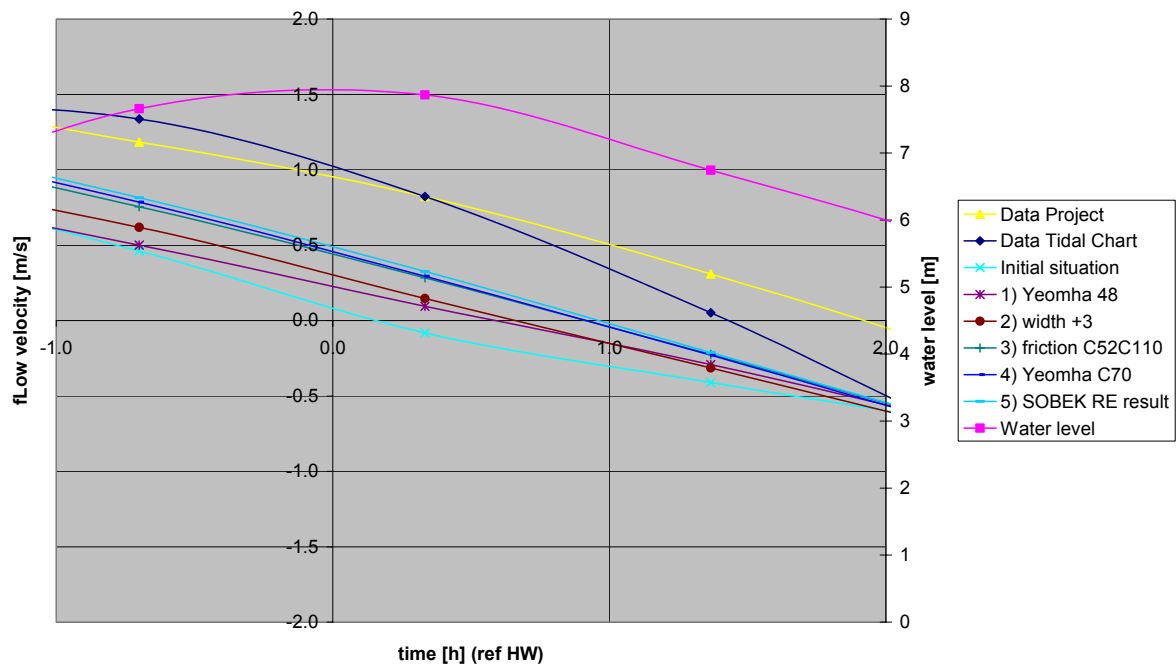


XIV-2: Cross sectional profile in Autodesk 3D

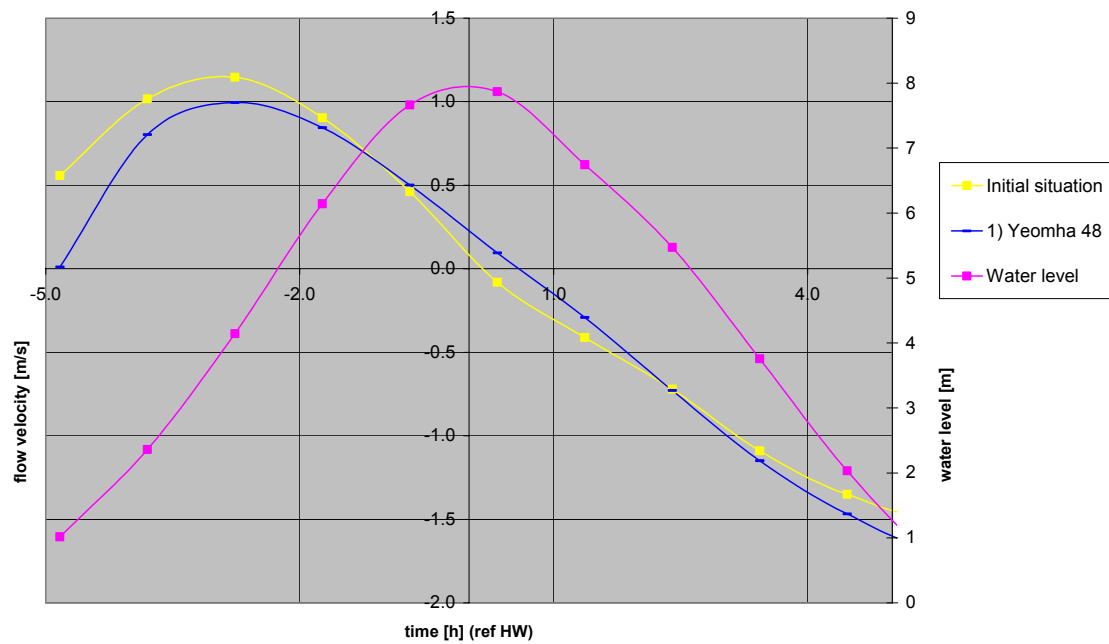
Appendix XV: Calibration hydrodynamics



XV-1: All the calibration steps in one figure (the legend does not show the step sequence)

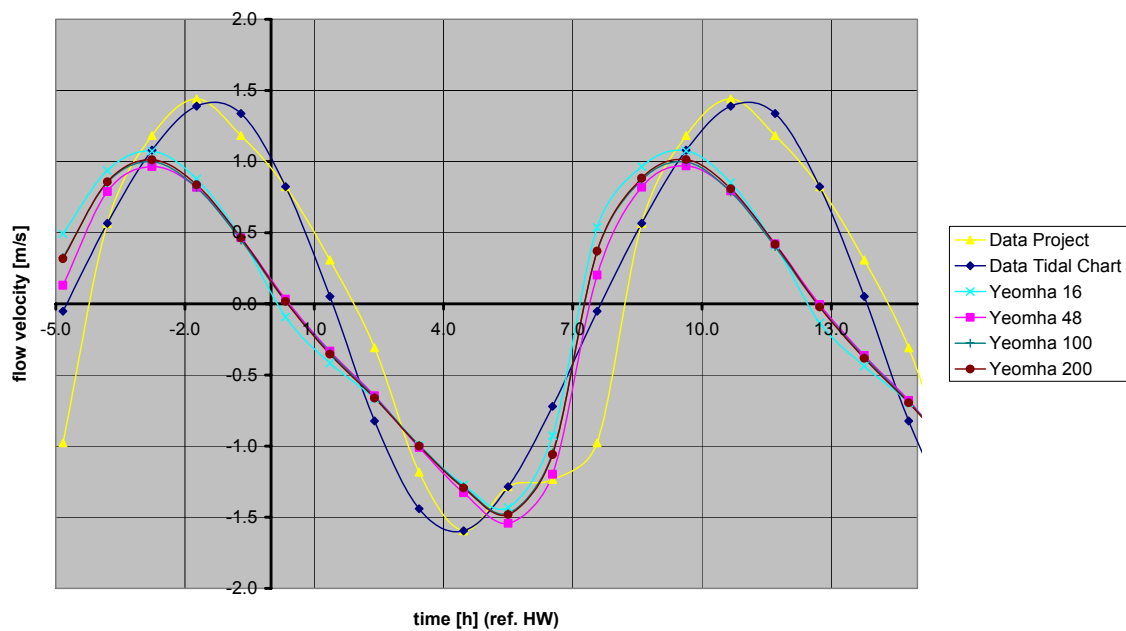


XV-2: Calibration results of the phase difference between horizontal and vertical tide

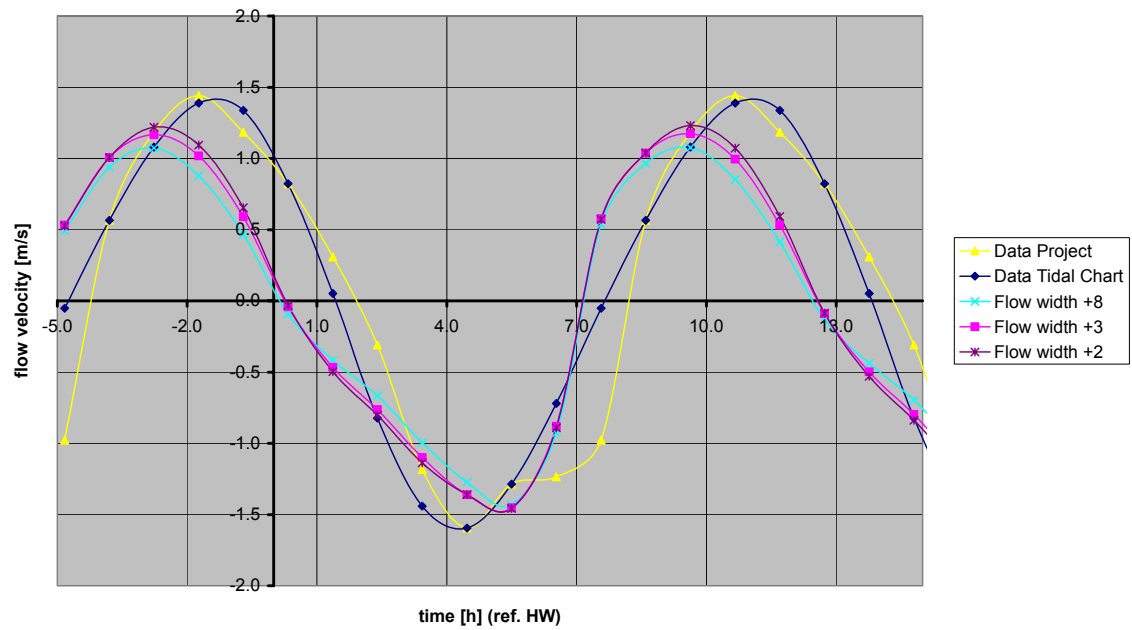


XV-3: The change in phase difference between horizontal and vertical tide due to the extension of Yeomha Waterway from 16 to 48 kilometres.

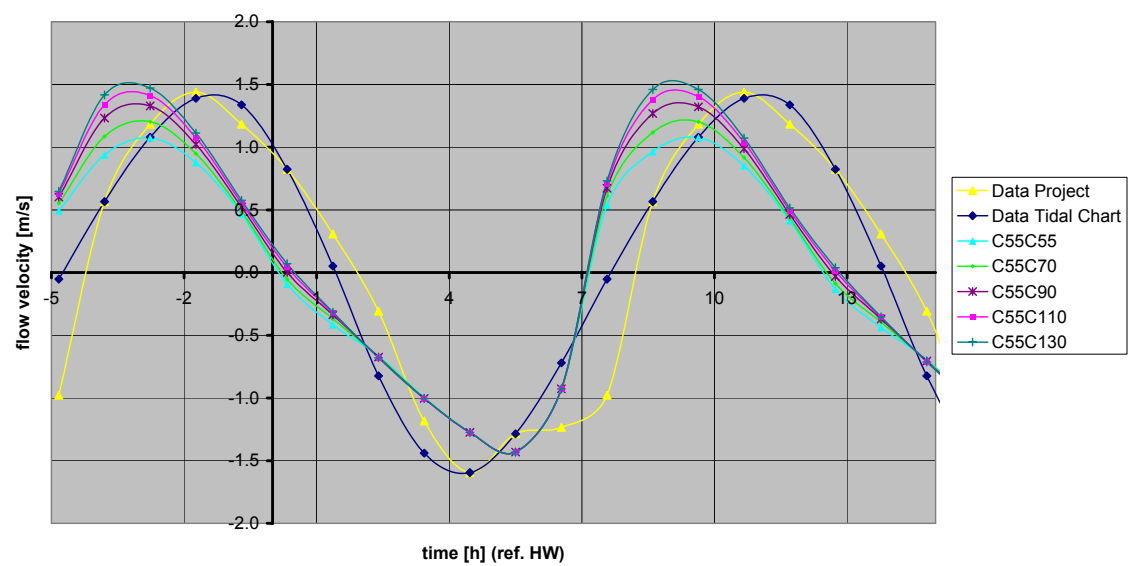
The calibration procedure created a lot of insight in the influence of the different model parameters. The following figures show the sensitivity of the different model parameters.



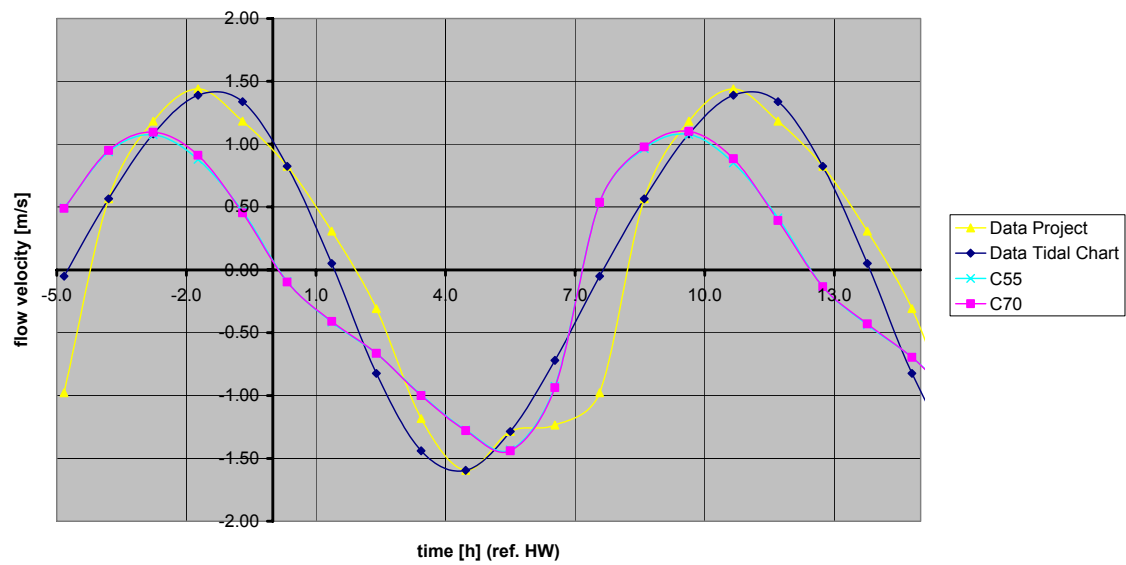
XV-4: Calibration step 1: Varying the length of Yeomha Waterway



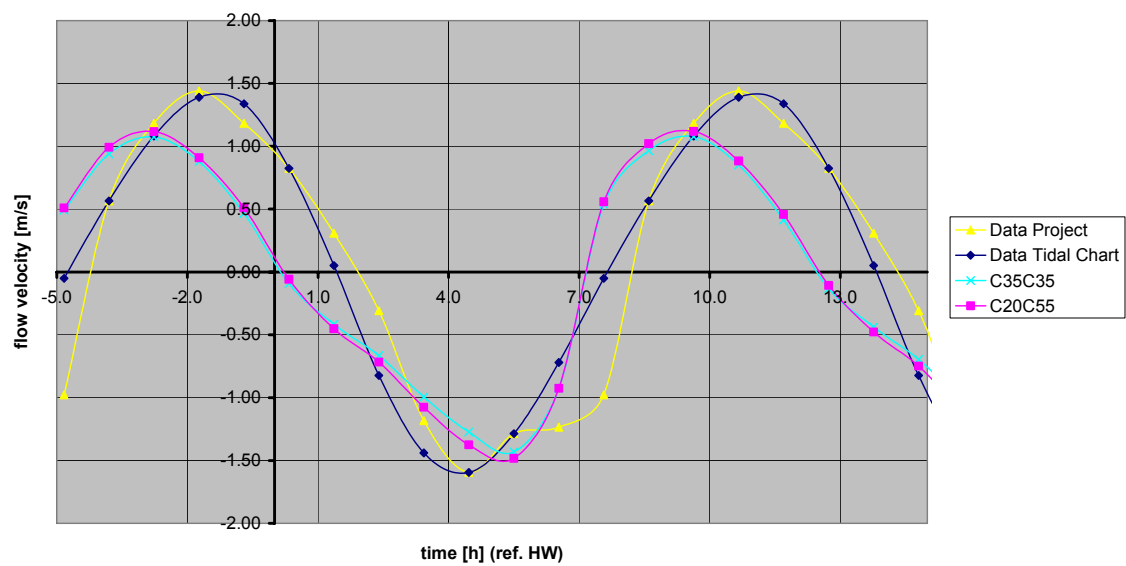
XV-5: Calibration step 2: Varying the flow width (ref. Lower Low Water)



XV-6: Calibration step 3: Varying the friction coefficient of the branches Navigation 1,2 and 3 (Cebb Cflood)



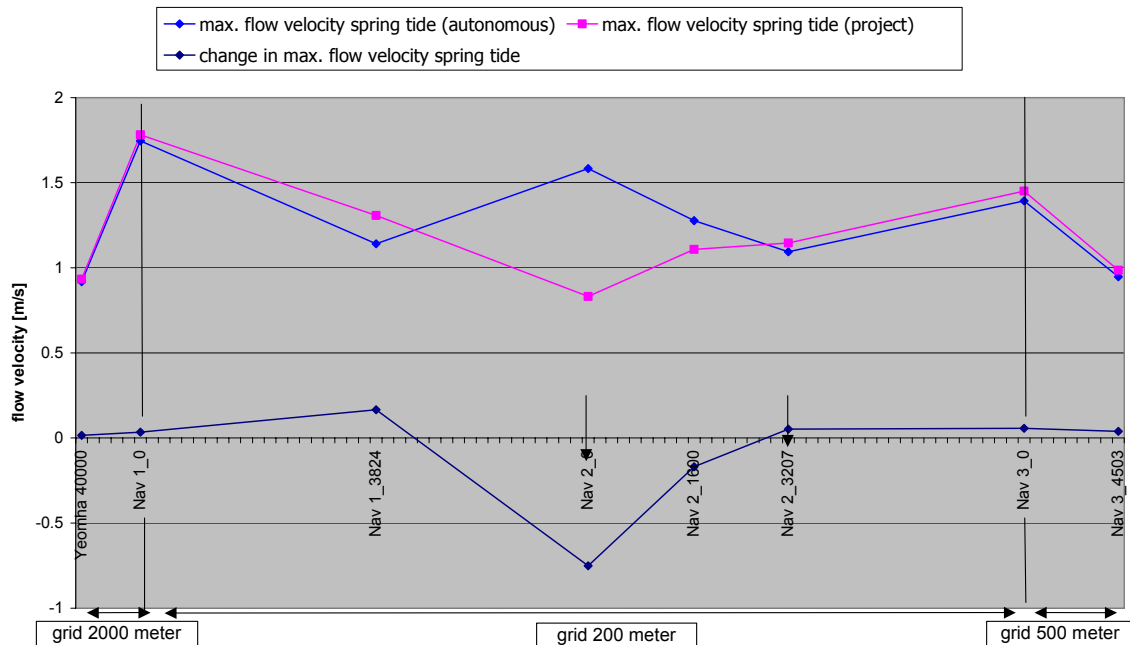
XV-7: Calibration step 4: Varying the friction coefficient of Yeomha Waterway



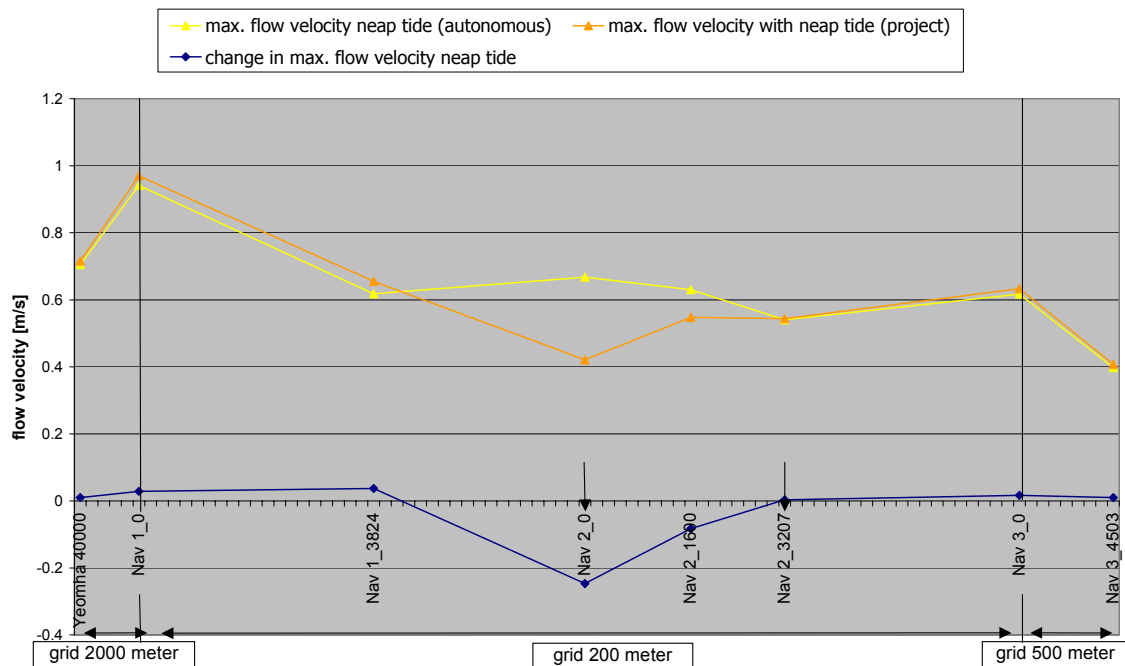
XV-8: Calibration step 5: Varying the friction coefficient of the floodplains

Appendix XVI: 'Far field' results

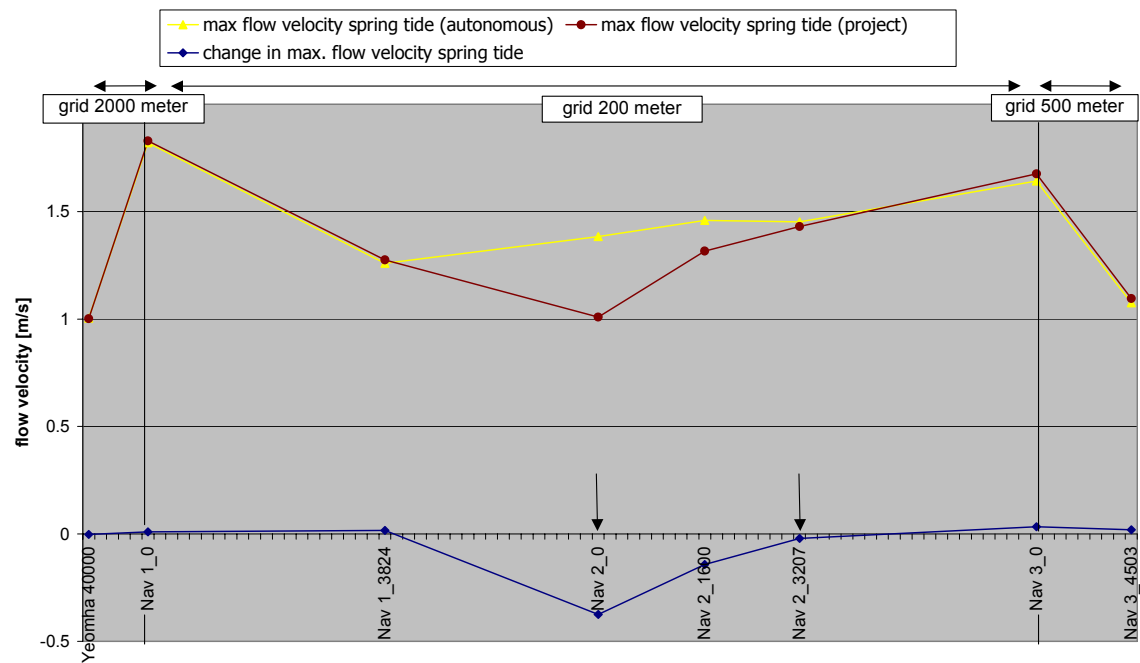
All the figures in this appendix show the 'Autonomous Situation' (old), 'Project Situation' (new) and the absolute differences between both situations.



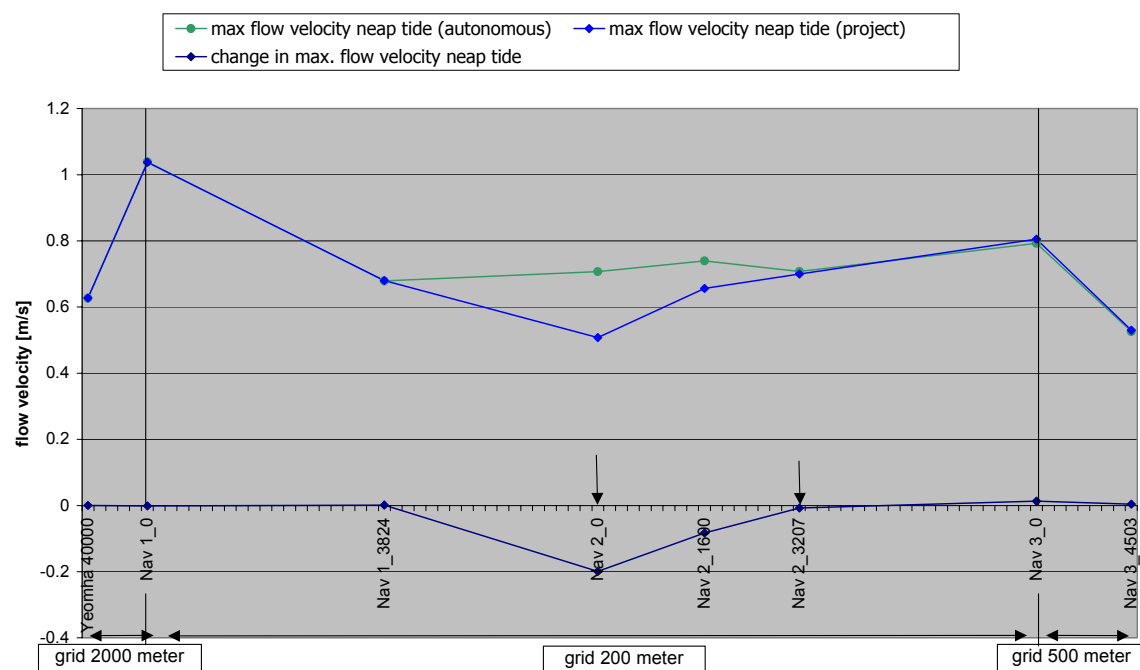
XVI-1: Difference in max. flow velocities with spring tide (ebb tide)



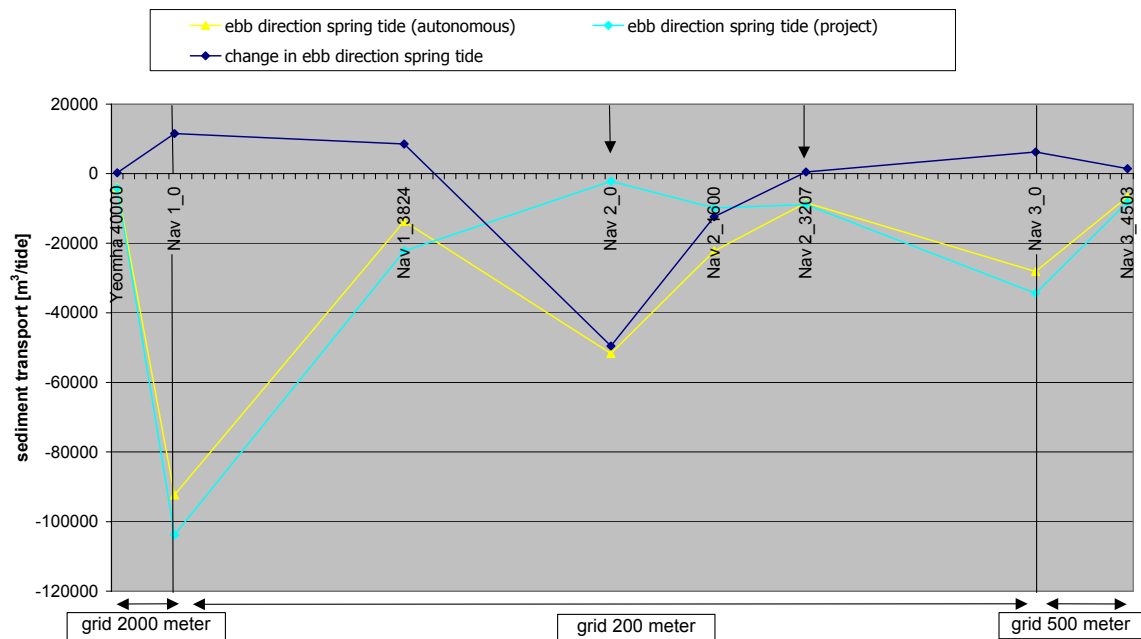
XVI-2: Difference in maximum flow velocities with neap tide (ebb tide)



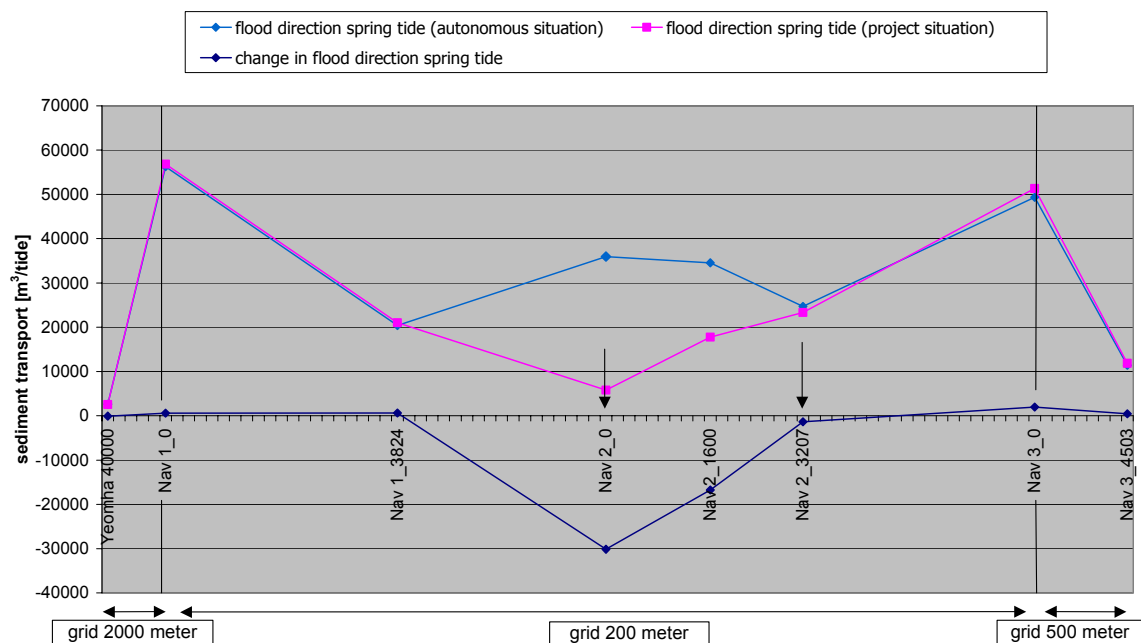
XVI-3: Difference in maximum flow velocities with spring tide (flood tide)



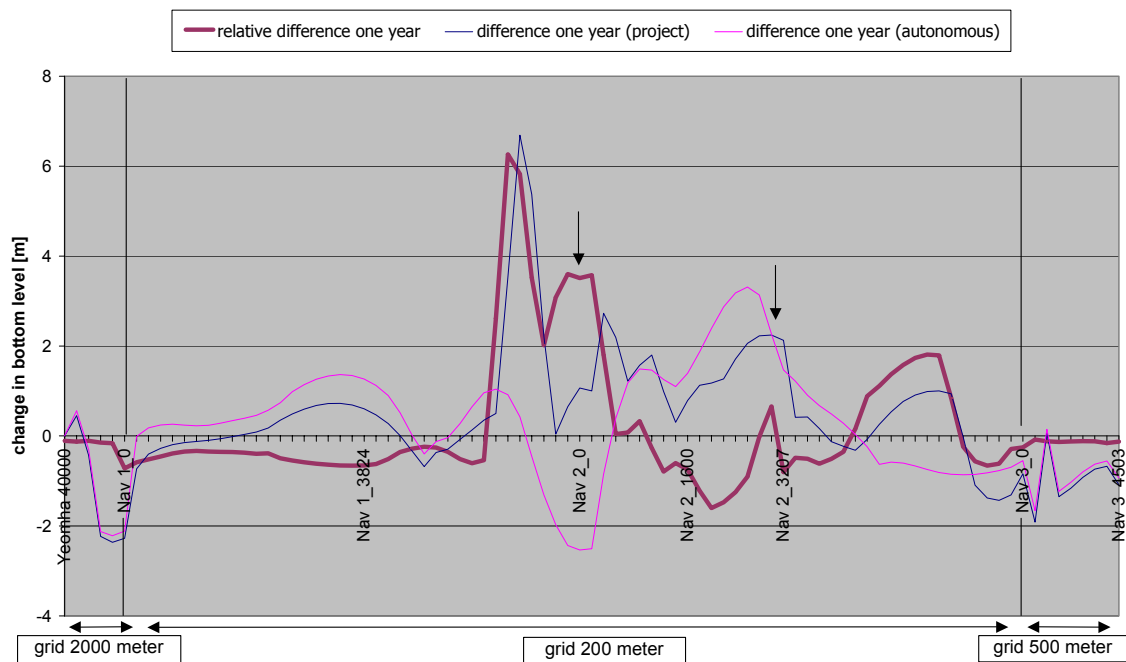
XVI-4: Difference in maximum flow velocities with neap tide (flood tide)



XVI-5: Difference in total sediment transport in ebb direction with spring tide

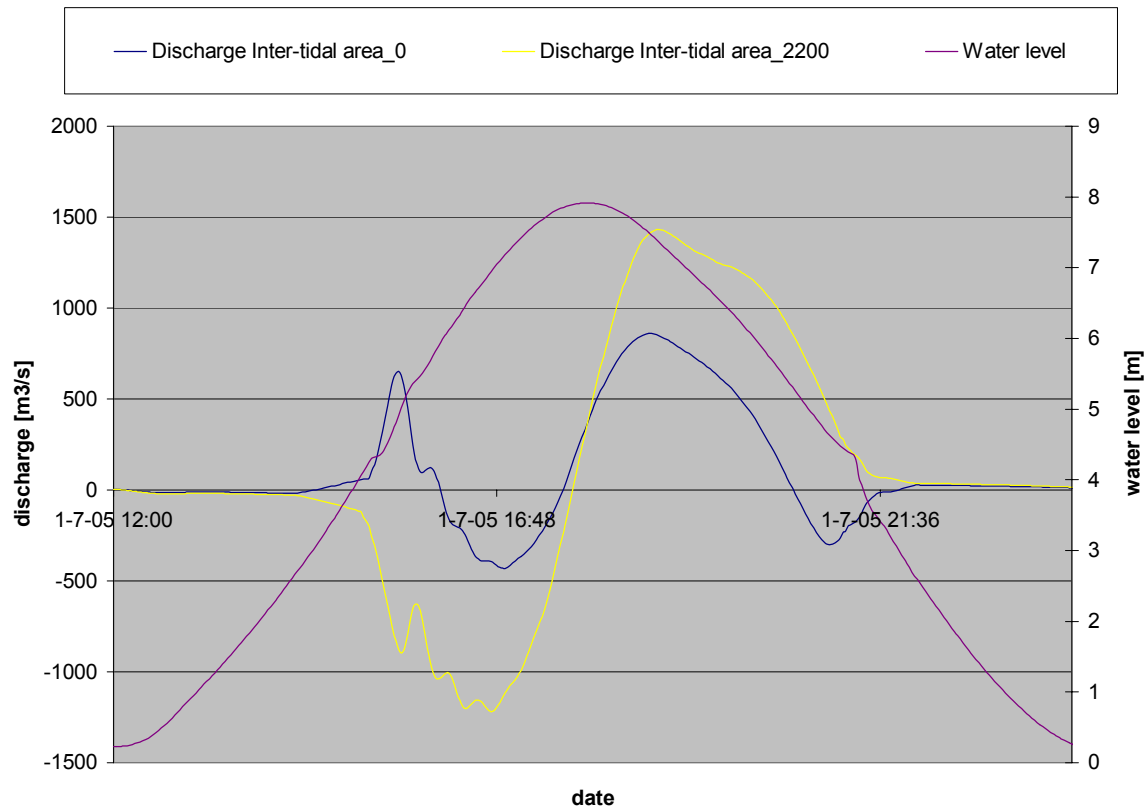


XVI-6: Difference in total sediment transport in flood direction with spring tide



XVI-7: Difference in bottom level in one year

Appendix XVII: 'Near field' results



XVII-1: Discharge across the inter-tidal area with spring tide (no extreme frictions)

Appendix IX: Schematisation of ‘Autonomous Situation’

- Rectangle:

Numbers:

Small text:
- Name of branches

Important nodal points

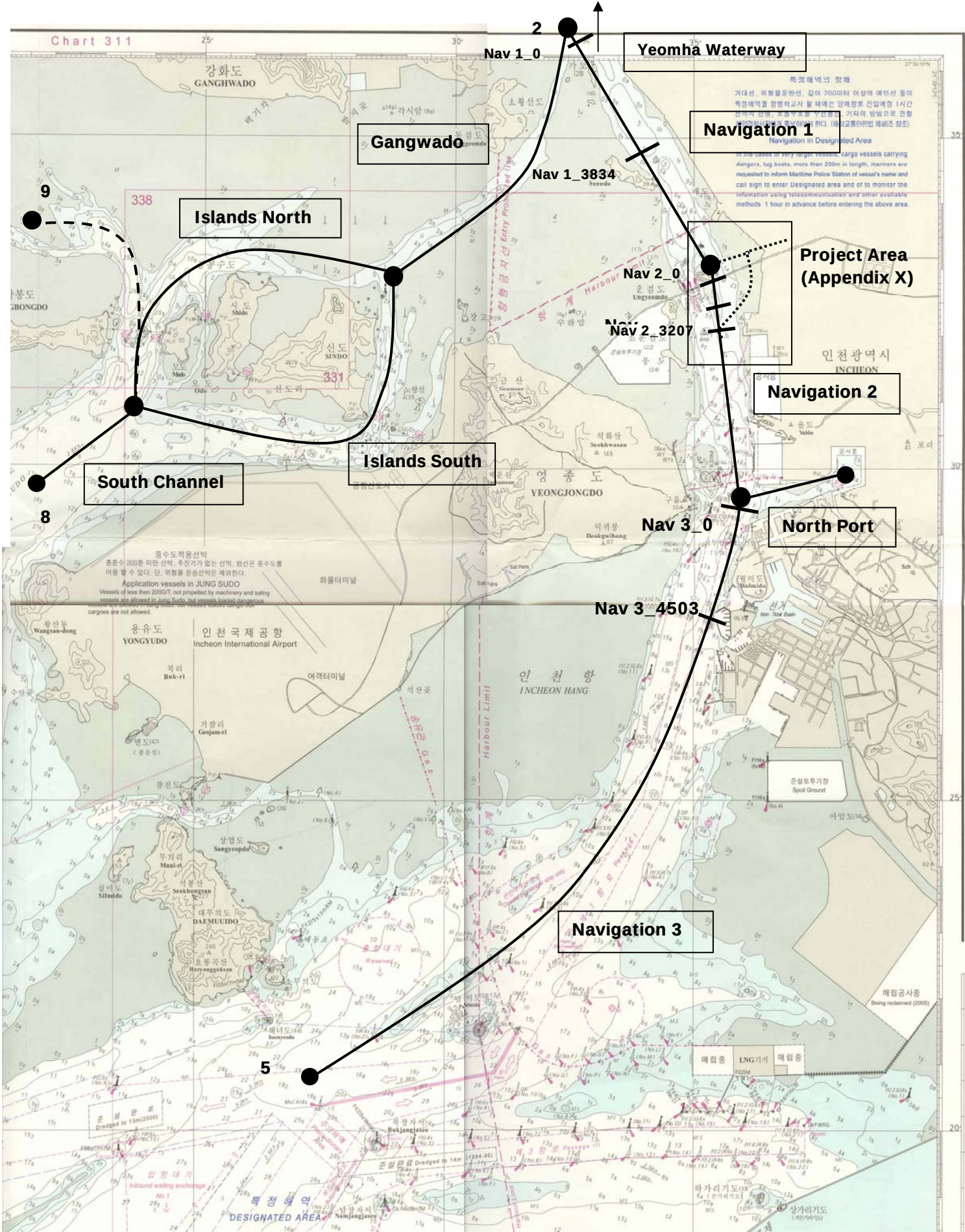
Names of observation points in ‘far field’ analysis
- Note 1:

Note 2:

Note 3:
- North of the chart the mouth of Yeomha Waterway starts

The ‘far field’ area runs from 8 km stream upwards of Yeomha Waterway to Navigation 3_4503 south of Incheon North Port.

For the Project Area, see Appendix X



Appendix X: Schematisation of ‘Project Situation’

- Blue:
- Name of the branch
- Red:
- Important subjects of the Kyung-In Canal project
- Black:
- Important grid points in the schematisation
- Numbers:
- Nodal points

