Morphological behavior of a non-equilibrium coastal profile

The response of the Maasvlakte-2 outer contour to a storm event.

Cláudia França de Abreu

[1550306]

Delft University of Technology

June 2010
The Erasmus Mundus MSc Coastal and Marine Engineering and Management is an integrated programme organized by five European partner institutions, coordinated by Delft University of Technology (TU Delft).

The joint study programme of 120 ECTS credits (two years full-time) has been obtained at three of the five CoMEM partner institutions:

- Norges Teknisk- Naturvitenskapelige Universitet (NTNU) Trondheim, Norway
- Technische Universiteit (TU) Delft, The Netherlands
- City University London, Great Britain
- Universitat Politècnica de Catalunya (UPC), Barcelona, Spain
- University of Southampton, Southampton, Great Britain

The first year consists of the first and second semesters of 30 ECTS each, spent at NTNU, Trondheim and Delft University of Technology respectively. The second year allows for specialization in three subjects and during the third semester courses are taken with a focus on advanced topics in the selected area of specialization:

- Engineering
- Management
- Environment

In the fourth and final semester an MSc project and thesis have to be completed.

The two year CoMEM programme leads to three officially recognized MSc diploma certificates. These will be issued by the three universities which have been attended by the student. The transcripts issued with the MSc Diploma Certificate of each university include grades/marks for each subject. A complete overview of subjects and ECTS credits is included in the Diploma Supplement, as received from the CoMEM coordinating university, Delft University of Technology (TU Delft).

Information regarding the CoMEM programme can be obtained from the programme coordinator and director

Prof. Dr. Ir. Marcel J.F. Stive
Delft University of Technology
Faculty of Civil Engineering and geosciences
P.O. Box 5048
2600 GA Delft
The Netherlands
Morphological behavior of a non-equilibrium coastal profile

The response of the Maasvlakte-2 outer contour to a storm event.

M.Sc. Thesis
Cláudia França de Abreu
June 2010

Graduation Committee:
Prof.dr.ir. M.J.F. Stive
Ir. W.Jacobs
Dr. ir. J.S.M. Van Thiel De Vries
Ir. M.A de Schipper
Ir. K. G. Nipius

TU Delft & CoMEM
Royal Boskalis Westminster
Deltares & TU Delft
TU Delft
Royal Boskalis Westminster
Preface

This report is the result of a study into the morphological response of the outer contour profile of the Maasvlakte-2 to the storm of the 3rd to the 6th of September, 2009. This study has been performed within the framework the Coastal and Marine Engineering and Management master program in the Civil Engineering department of the Delft University of Technology.

The Maasvlakte-2 project is still under execution. Part of the data used in this study is confidential for third parties to protect the contractors until further notice. The confidential data is presented in the Appendix and will be removed when this report is published.

The committee of this MSc thesis consisted of the following persons:

Prof.dr.ir. M.J.F. Stive
Ir. W.Jacobs
Dr. ir. J.S.M. Van Thiel De Vries
Ir. M.A de Schipper
Ir. K. G. Nipius

Cláudia França de Abreu

June, 2010
To my family, Pedro, Aline, Marina and Júlia de Abreu

To my extended family Thiago Ferreira and to the little person who brightens up my days, Marcelinho

And to meu amor that stood by me every day during this Thesis, Arnold van Rooijen
Abstract

The objective of this study is to analyze and simulate the behavior of a non-equilibrium profile in a storm event, in particular, the Maasvlakte-2 (MV2). The MV2 is a large reclamation project at which both soft and hard sea-defenses are applied. Soft sea-defenses exhibit steep initial profiles during construction. Understanding how this sea-defense behaves under storm conditions is important to predict its stability and to optimize its construction scheme. There is little information available on the behavior of non-equilibrium profiles. Therefore the availability of the XBeach model, in combination storm data from the MV2, provides a unique possibility to obtain more insight in the morphological behavior of non-equilibrium profiles. Steep cross-shore profiles tend to be highly dynamic and are not in equilibrium. Most models which predict the behavior of sandy coasts are based on empirical relations derived from data of equilibrium profiles. Storms, however, exhibit a relatively small temporal scale, which implies that these empirical models are generally unsuitable to predict the response of a profile during storm events. With this in mind and in order to approach the objective, a thorough data analysis was done. From the data analysis the main cross-shore and longshore morphological processes were identified and a profile analysis, and mass balance of the soft structure was carried out. The information obtained from this was used to compare with the results of commonly used empirical and semi-empirical engineering tools. And also used as input for the process-based simulation (XBeach), and for the comparison with its results. A net loss in sediment was observed from the outer contour boundaries due to longshore transport but not sediment is lost offshore from the cross-shore profile. The upper profile suffered greatly from the storm, presenting very large erosion volumes in a small-time scale. Due to the assumptions based on pre-storm equilibrium profile conditions made by the semi-empirical, their application yielded results that were difficult to compare to the results of the data analysis. In general, the approaches underestimated the response of the steep non-equilibrium profile. The 1DV simulations of the process-based model however, represented the cross-shore profile response rather well. Its comparison with the post-storm data analysis, demonstrated though that there is a need for a 2DH or 3D simulations, due to the large variability in shoreline orientation, elevation and steepness of the profile alongshore.
Acknowledgments

First of all I would like to thanks the Erasmus Mundus program for giving the opportunity to so many people, from different nationalities, to pursue higher education programs in the best universities of Europe. In particular, I would like to thank them for granting me my scholarship, which made this MSc possible.

I would like to thank the initiators of the Coastal and Marine Engineering and Management program (CoMEM) and the CoMEM board and staff for all their support. So a special thanks to: Professor Eivind, Oivind Arntsen, Marcel Stive, Augustin Sanches, Cesar Mosso, Helena Wasmus, Madelon Burgmeijer, Mariette van Tilburg and all the others involved.

I would like to thank this MSc thesis committee for their patience and attention towards me, especially when reading and re-reading my report, in particular to Walter Jacobs. I would also like to thank Davide Merli for all his help with the data, calculations and comments on this thesis. And I would also like to thank PUMA for providing me the data necessary for this study.

Next, I would like to thank my family. I would like to thank my parents for all their teachings throughout my life. Thank you for giving me so much love, so much knowledge and opportunities... and for supporting me even when I don't deserve it. Thank you to my sisters that have accompanied me along the way. One, for always being there to help me and the other for spending the past 5 months here in the Netherlands, making me company.

I would like to thank all my friends. The new ones that I made these past years, and the ones back home that have via email and messages participated in every aspect of this new venture. Especially, to the CoMEM girls that have made these past two years so spectacular: Anna W., Jimena H., Sarah Jo M., Dañyl D., Nancy H. A big thanks to Elisa de Deus, Natasha Damiani, Gabi Borges and Helen Korobinski for being my unconditional friends for so many years. And thanks to the people which without my whole university experience would have not been the same: Nalu G., Guta R., Laura P., Carol S., Camila M., Aninha Fátima, Beta B., and Carla D’aquino. All these girls are way beyond special.

And last but not least, I would like to thank Arnold van Rooijen for so much support, patience, attention, long nights, thoughts shared, for listening, for being there, in summary, for taking such good care of me!! Thank you meu amor! And I would also like to that the Van Rooijen family for taking me in, and for making me feel at home in the Netherlands.

THANK YOU ALL SO MUCH!
# Table of Contents

*Abstract* .................................................................................................................................................. v

*Table of Contents* .................................................................................................................................. ix

*List of Figures* ......................................................................................................................................... xiii

*List of Tables* .......................................................................................................................................... xix

*List of Symbols* ....................................................................................................................................... xxi

**Chapter 1 - Introduction** ................................................................................................................. 25

**Chapter 2 - Literature review** ........................................................................................................... 29
  2.1. Sandy coasts .................................................................................................................................. 29
  2.2. Hydrodynamic Forcing and Morphological processes ................................................................. 31
    2.2.1. Hydrodynamic Forcing .......................................................................................................... 31
    2.2.2. Morphological processes ...................................................................................................... 37
  2.3. Modeling the behavior of sandy coasts ......................................................................................... 41
    2.3.1. Empirical Models .................................................................................................................. 41
    2.3.2. Semi-Empirical Models ........................................................................................................ 43
    2.3.3. Process-Based Models ........................................................................................................... 45

**Chapter 3 - Maasvlakte 2** ................................................................................................................. 49
  3.1. The outer contour in the constructional phase .............................................................................. 51
  3.2. Data description ............................................................................................................................ 51
    3.2.1. Boundary conditions .............................................................................................................. 51
    3.2.2. Bathymetrical survey data .................................................................................................... 54
    3.2.3. Production and sediment characteristics ............................................................................... 55
Chapter 4 - Data Analysis ................................................................. 57

4.1. Boundary conditions ................................................................. 57

4.2. Overall description of the outer contour ................................. 60

4.3. Profile response to the September 2009 storm ........................... 65

4.3.1. Volume balance methodology .............................................. 66

4.3.1. Overall volume balance analysis ........................................... 67

4.3.2. Longshore profile response .................................................. 73

4.3.3. Cross-shore profile response ................................................ 75

4.4. Summary of data analysis ......................................................... 80

Chapter 5 - Application of (semi-) empirical engineering tools .......... 83

5.1. Bruun rule applied to storms ..................................................... 83

5.1.1. Bruun rule description .......................................................... 83

5.1.2. Application of the Bruun rule ............................................... 84

5.1.3. Discussion ........................................................................... 91

5.2. UNIBEST -LT .......................................................................... 92

5.2.1. Model input .......................................................................... 93

5.2.2. Results ................................................................................. 94

Chapter 6 - Process-based Tool ......................................................... 97

6.1. XBeach model description ....................................................... 97

6.2. Model Formulation .................................................................. 99

6.3. 1DV Model Input ................................................................. 101

6.3.1. Profile selection ................................................................. 101
6.3.2. Boundary conditions ........................................................................................................... 103

6.4. 1DV simulation results ............................................................................................................. 104
  6.4.1. Box 11 simulations ............................................................................................................. 104
  6.4.2. Box 16 simulations ............................................................................................................. 108
  6.4.3. Box 19 simulations ............................................................................................................. 111

6.5. Discussion .................................................................................................................................. 115
  6.5.1. Summary of the XBeach simulations ................................................................................... 118

Chapter 7 - Conclusions and Recommendations ............................................................................. 121
  7.1. Conclusions .......................................................................................................................... 121
  7.2. Recommendations ................................................................................................................ 125

References ....................................................................................................................................... 127

Appendix 1 - Erosion Sedimentation Tables .................................................................................. 127
Appendix 2 - Production Tables ...................................................................................................... 127
Appendix 3 - Maps .......................................................................................................................... 130
Appendix 4 - XBeach Input Parameters .......................................................................................... 140
List of Figures

Figure 1.1 Schematization of thesis approach.......................................................... 26

Figure 2.1 Diagram of the main parts of a sandy coast (Modified from: Dean and Dalrymple, 2002) ....29

Figure 2.2 - Definitions of axis system. X-axis is shore normal, y-axis is shore-parallel and z-axis is water depth..............................................................................................................................30

Figure 2.3 - Wave refraction schematization. Wave propagation increases with depth..................32

Figure 2.4 – Water particle motion in deep, intermediate and shallow water wave (Holthuijsen, 2007) 33

Figure 2.5 - Measured velocities under a propagating wave. Diagram of the undertow current (Modified from: Bosboom and Stive, 2010). ..................................................................................................................34

Figure 2.6 - Influence of the angle of the incident waves on the magnitude of the longshore current. (d’Angremond and Pluim-Van der Velden, 2001) ........................................................................................................36

Figure 2.7 - Results of gradients in the longshore current. a: Increase in transport after breaker zone induced by the increase in tide-driven currents; b: Increase in transport in the breaker zone due to difference in wave height along the coast; c: Increase in transport due increase of the wave incidence angle. Sl is sediment transport. (d’Angremond and Pluim-Van der Velden, 2001) ................................................................................37

Figure 2.8 Empirical Modeling schematization. ........................................................................41

Figure 2.9 - Semi-empirical modeling schematization ..................................................................43

Figure 2.10 Principal of the dune erosion prediction model (Vellinga, 1986). .................................44

Figure 2.11 Standard process-based model schematization (Modified from Roelvink (1993)). ........45

Figure 3.1 Location of the Maasvlakte-2 in The Netherlands. (a): the MV2 project (b) Detail of the outer contour and its soft and hard sea defenses. .........................................................................................50

Figure 3.2 Outer contour as it was constructed until September 2009. (a): Top view of the soft sea-defense. (b): typical cross-section ..................................................................................................................52

Figure 3.3 Map of the wave propagation locations (red cross). The west side of the outer contour soft sea defense is outlined in yellow. The study area is indicated by the dashed rectangle........................................53
Figure 3.4  Wave time series for the nearshore location 15 (see Figure 3.3) and water level measurements. The duration of the storm is indicated between the black lines..................................................54

Figure 3.5 Schematization of the period between pre and post-storm surveys...........................................55

Figure 3.6 Outer contour map with the indicated production locations for the period of 3rd to 7th of September 2009..................................................................................................................56

Figure 4.1 Representative wave height, period and direction per location relative to the nearshore locations in Figure 3.3..................................................................................................................58

Figure 4.2 Longshore component of the radiation stress Sxy for the location of the outer contour. Positive values represent longshore transport in the south-north direction and negative values represent transport in the north-south direction........................................................................................................59

Figure 4.3 (a) Depth contour map of the outer contour structure of the Maasvlakte-2. Dashed lines indicate North, Central and South parts of the structure. (b) Map of the difference in elevation before and after the storm of September 2009. Brown rectangles indicate production areas. In both maps the numbers are refer to the text ........................................................................................................................................61

Figure 4.4 Cross-sectional profiles of the outer contour selected according to the difference in slope and elevation characteristics of each area. (a) Box 21 (b) Box 19 (c) Box 16 (d) Box 11 (e) Box 7. Blue line: mean sea level and Black dashed line: - 3 m depth line..................................................................................................................63

Figure 4.5 Schematization of the cross-shore profile sub-division into B&D (blue), FS (red), SF (green) and shore FND (purple). The cross-shore fluxes are indicated in figures (a) and (b) and the longshore fluxes are indicated in figure (b). ..................................................................................................................64

Figure 4.6 Difference map indicating box dimensions, location, and the number of each box used in the volume balance calculation. (a) Wide boxes: west and east side of the structure combined. (b) Narrow boxes: west side of the structure, directly subject to storm impact..................................................................................................................68

Figure 4.7 Combined wide and narrow box approach, concerning the morphological response of the outer contour profile..................................................................................................................70

Figure 4.8 Definition of the north and south division of the volume balance analysis, according to the shift in direction of the longshore current..........................................................................................71

Figure 4.9 Sedimentation/erosion box volumes for the wide+narrow boxes (refer to Figure 4.7) Negative values represent erosion volume [m3], and positive values represent sedimentation volume [m3]...........72
Figure 4.10 Graph of the net volume change (per m alongshore) derived from the net volumes measured for each box and the absolute radiation stress where both north and south directed currents are represented by positive values. ................................................................. 74

Figure 4.11 Alongshore profile behavior for the different sections (B&D, FS, SF and FND) of the cross-sectional profile of the central part of the outer contour. ......................................................................................... 75

Figure 4.12 Volumes [m$^3$] of the profile sections: B&D, FS, SF and FND in the (a) North, (b) Central and (c) South areas of the outer contour. ........................................................................................................... 77

Figure 4.13 Before and after storm cross-sectional profiles. Blue line: before storm and Red line: after storm. (a) box 21, (b) box 19, (c) box 16 and (de) box 11. Where B&D, FS, SF and FND are the beach and dunes, foreshore, shoreface and shore foundation sections. ......................................................................................... 79

Figure 4.14 Physical conceptual plot of the response of the MV2 outer contour to the September 2009 storm. The sediment movement is indicated by the longshore and cross-shore fluxes. The size of the arrows indicate gradients in transport. ............................................................. 82

Figure 5.1. Erosion profile schematization for Bruun rule applied to storm calculation. R is the beach and dune retreat, h is the maximum elevation of the dune plus the water depth of the depth of closure. L is the length over which sedimentation will occur from the eroded dune foot to the depth of closure.....84

Figure 5.2 Dune retreat calculation and measurement comparison. Red: volumes calculated using the Bruun rule applied to storms, modified using Vellinga’s (1986) approach. Blue: measured retreat data obtained from the bathymetrical data. ............................................................................................................ 86

Figure 5.3 Beach and dune retreat calculation and measurement comparison. Red: volumes calculated using the Bruun rule applied to storms, using Vellinga’s (1986) depth of closure. Blue: measured retreat data. ............................................................................................................ 88

Figure 5.4 Beach and dune retreat calculation and measurement comparison. Red: volumes calculated using the Bruun rule applied to storms, with measured depth of closure and sedimentation lenght. Blue: measured retreat data. ............................................................................................................ 90

Figure 5.5 Input profiles for UNIBEST-LT simulation. Schematized profiles were used for each area of the outer contour. ...................................................................................................................... 94

Figure 5.6 Sediment transport result from the UNIBEST-LT simulations for each box. ......................... 95
Figure 5.7 Comparison between longshore transport results from UNIBEST-LT simulations and net volume change per meter alongshore derived from the net volumes calculated in the data analysis (Chapter 4). The arrows indicate the direction of the longshore current.

Figure 6.1 Representation of the process-based XBeach model input, output and updating scheme.

Figure 6.2 (a) Boxes selected for simulation input. (b) A 3D view of pre-storm selected profiles. (c) Averaged profiles. Blue: pre-storm. Red: post-storm.

Figure 6.3. Storm wave and water level time-series for box 11. The period between the black lines corresponds to the simulated period.

Figure 6.4 XBeach simulation results for box 11. Dashed line: Initial profile. Solid line: simulation result. Red line: measured post-storm profile. In detail are the upper profile and the lower profile results.

Figure 6.5 Morphological evolution in time of each cross-shore section of box 11 for the beach and dunes, foreshore, shoreface and shore foundation (B&D, FS, SF and FND, respectively).

Figure 6.6 Simulated and measured erosion and sedimentation volumes (m$^3$) for each cross-shore section of box 11.

Figure 6.7 XBeach simulation results for box 16. Dashed line: Initial profile. Solid line: simulation result. Red line: measured post-storm profile. In detail are the upper profile and the lower profile results.

Figure 6.8 Morphological evolution in time of each cross-shore section of box 16 for the beach and dunes, foreshore, shoreface and shore foundation (B&D, FS, SF and FND, respectively).

Figure 6.9 Simulated and measured erosion and sedimentation volumes (m$^3$) for each cross-shore section box 16.

Figure 6.10 XBeach simulation results for box 19. Dashed line: Initial profile. Solid line: simulation result. Red line: measured post-storm profile. In detail are the upper profile and the lower profile results.

Figure 6.11 Morphological evolution in time of each cross-shore section of box 19 for the beach and dunes, foreshore, shoreface and shore foundation (B&D, FS, SF and FND, respectively).

Figure 6.12 Simulated and measured erosion and sedimentation volumes (m$^3$) for each cross-shore section box 16.

Figure 6.13 Schematization of the main longshore transport gradients and the cross-shore fluxes for boxes 11 and 16. Blue: erosion area. Yellow: sedimentation area. The size of the arrow indicates the
gradient in longshore transport. B&D, FS, SF and FDN are the beach and dunes, foreshore, shoreface and shore foundations cross-sections, respectively. The size of the arrows indicate the magnitude of transport in either the longshore direction (from left to right, or vice versa) or the cross-shore direction (from top to bottom).

Figure 6.14 Schematization of the longshore transport gradients and the cross-shore fluxes for box 19. Blue: erosion area. Yellow: sedimentation area. The size of the arrow indicates the gradient in longshore transport. B&D, FS, SF and FDN are the beach and dunes, foreshore, shoreface and shore foundations cross-sections, respectively. The size of the arrows indicate the magnitude of transport in either the longshore direction (from left to right, or vice versa) or the cross-shore direction (from top to bottom).
**List of Tables**

Table 5.1 Bruun rule retreat calculations, using Vellinga’s depth of closure and sedimentation/erosion length and measures retreat calculations........................................................................................................85

Table 5.2 The sedimentation/erosion length calculated using Vellinga’s equation measured of the MV2 profiled. ..............................................................................................................................87

Table 5.3 Bruun rule retreat calculations using Vellinga’s depth of closure approach. The sedimentation length was measured from the dune foot to the measured depth of closure....................................................89

Table 6.1 Simulated and measured erosion and deposition volumes for Box 11 (m$^3$)........................................106

Table 6.2 Simulated and measured volumes for box 16 (m$^3$).................................................................................108

Table 6.3 Simulated and measured volumes (m$^3$) for Box 19.....................................................................................113

Table 7.1 Cross-shore sections net erosion and sedimentation volumes [m$^3$], calculated from the narrow boxes..............................................................................................................................¡Error! Marcador no definido.

Table 7.2 “Mixed” box approach, encompassing the east and west side of the structure when both sides are morphologically active..............................................................................................¡Error! Marcador no definido.

Table 7.3 Production volumes per cross-section for the narrow boxes....¡Error! Marcador no definido.

Table 7.4 Production volumes for wide boxes........................................¡Error! Marcador no definido.
# List of Symbols

## ROMAN SYMBOLS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A )</td>
<td></td>
<td>constant non-dimensional shape factor</td>
</tr>
<tr>
<td>( A_w )</td>
<td>W/m( ^2 )</td>
<td>Wave action</td>
</tr>
<tr>
<td>( A_{sb} )</td>
<td></td>
<td>bed load coefficient</td>
</tr>
<tr>
<td>( A_{ss} )</td>
<td></td>
<td>suspended load coefficient</td>
</tr>
<tr>
<td>( C )</td>
<td>g/m( ^3 )</td>
<td>depth-averaged sediment concentration</td>
</tr>
<tr>
<td>( C_{eq} )</td>
<td>g/m( ^3 )</td>
<td>equilibrium sediment concentration</td>
</tr>
<tr>
<td>( D )</td>
<td>mm</td>
<td>diameter</td>
</tr>
<tr>
<td>( Dir )</td>
<td></td>
<td>direction</td>
</tr>
<tr>
<td>( D_r )</td>
<td>W/m( ^2 )</td>
<td>roller energy dissipation,</td>
</tr>
<tr>
<td>( D_w )</td>
<td>W/m( ^2 )</td>
<td>wave energy dissipation due to breaking</td>
</tr>
<tr>
<td>( D_{50} )</td>
<td>Mm</td>
<td>median grain diameter</td>
</tr>
<tr>
<td>( E )</td>
<td>m( ^3 )</td>
<td>erosion volume</td>
</tr>
<tr>
<td>( E_r )</td>
<td>W/m.s</td>
<td>Energy to keep sediment load in suspension</td>
</tr>
<tr>
<td>( E_d )</td>
<td>W/m.s</td>
<td>energy dissipation by sediment transport</td>
</tr>
<tr>
<td>( H )</td>
<td>M</td>
<td>wave height</td>
</tr>
<tr>
<td>( H_{os} )</td>
<td>M</td>
<td>Storm surge level</td>
</tr>
<tr>
<td>( L )</td>
<td>M</td>
<td>length over which erosion and sedimentation takes place</td>
</tr>
<tr>
<td>( L_o )</td>
<td>M</td>
<td>wave length in deep water</td>
</tr>
<tr>
<td>( P )</td>
<td>m( ^3 )</td>
<td>production</td>
</tr>
<tr>
<td>( R )</td>
<td>M</td>
<td>dune retreat</td>
</tr>
<tr>
<td>( S )</td>
<td>m( ^3 )</td>
<td>sedimentation volume</td>
</tr>
<tr>
<td>( S_{ij} )</td>
<td>N/m</td>
<td>short wave contribution to radiation stress</td>
</tr>
<tr>
<td>( S_r )</td>
<td></td>
<td>roller energy balance</td>
</tr>
<tr>
<td>( T )</td>
<td>S</td>
<td>period</td>
</tr>
<tr>
<td>( T_s )</td>
<td>S</td>
<td>adaptation time</td>
</tr>
</tbody>
</table>
SSL  M  maximum storm surge level
T  S  period
U  m/s  flow velocity
c  m³/m³  concentration of sediment
c_{ijθ}  wave action propagation speed
e_s  efficiency coefficient
g  m/s²  acceleration of gravity
h  M  water depth
k  wave number
n  ratio of wave group over wave propagation speed
q̄  m³/m  time averaged cross-shore rate
t  S  time
u  m/s  flow velocity in x-direction
u_E  m/s  eulerian flow velocity in x-direction
u_{bed}  m/s  intra wave near-bed flow velocity
u_{cr}  m/s  critical flow velocity for sediment entrainment
u_{rms}  m/s  short wave orbital velocity
v  m/s  flow velocity in y-direction
v_E  m/s  Eulerian flow velocity in y-direction
x  M  horizontal cross-shore coordinate
y  M  horizontal alongshore coordinate
w  m/s  fall velocity
z  M  vertical coordinate
z_b  M  bed elevation

GREEK SYMBOLS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>α</td>
<td></td>
<td>wave breaking parameter</td>
</tr>
<tr>
<td>Δt</td>
<td>S</td>
<td>time step</td>
</tr>
<tr>
<td>ε</td>
<td></td>
<td>dimensionless surf similarity parameter</td>
</tr>
</tbody>
</table>
\[ \theta \] Degrees wave angle of incidence with respect to the x-axis

\[ \rho \] kg/m\(^3\) density of water

\[ \rho_s \] kg/m\(^3\) specific density of the grain

\[ \mu \] m\(^2\)/s kinematic viscosity coefficient

\[ \sigma \] intrinsic wave frequency

\[ \tau_b \] bed shear stress

### ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>B&amp;D</td>
<td>beach and dunes</td>
</tr>
<tr>
<td>CERC</td>
<td>Concurrent Engineering Research Center</td>
</tr>
<tr>
<td>CS</td>
<td>cross-shore</td>
</tr>
<tr>
<td>ERDC</td>
<td>Engineer Research and Development Center</td>
</tr>
<tr>
<td>FS</td>
<td>foreshore</td>
</tr>
<tr>
<td>FND</td>
<td>shore foundation</td>
</tr>
<tr>
<td>GLM</td>
<td>Generalized Lagrangean Mean</td>
</tr>
<tr>
<td>LS</td>
<td>longshore</td>
</tr>
<tr>
<td>MV2</td>
<td>Maasvlakte 2</td>
</tr>
<tr>
<td>SF</td>
<td>shoreface</td>
</tr>
<tr>
<td>NAP</td>
<td>normaal Amsterdam pile</td>
</tr>
<tr>
<td>USACE</td>
<td>United States Army Corps of Engineers</td>
</tr>
</tbody>
</table>
Chapter 1 - **Introduction**

A significant part of the world’s coastline concerns sandy coasts including offshore sand bars, beaches in the wave breaker and dune at the landward side. When these sandy coasts are subject to high water levels in combination with wave attack during storm conditions they are known to erode due to cross-shore and longshore transport of sand. Eroded sand will settle on the submerged part of the beach profile and may subsequently be transported by longshore currents. Insight on the qualitative and quantitative characteristics of erosion and transport processes during storms is important for the stability of sandy coasts, natural or artificial.

Artificial coasts, e.g. part of land reclamation projects, often exhibit rather steep cross-shore slopes in the construction phase. Steep cross-shore profiles tend to be highly dynamic and are not in equilibrium. An equilibrium profile can be defined as a steady beach profile which shape is achieved under steady hydrodynamic conditions, on a relatively large temporal scale. Most models which predict the behavior of sandy coasts are based on empirical relations derived from data of equilibrium profiles. Storms exhibit however, a relatively small temporal scale, and steep reclamation profiles are not yet in equilibrium with the hydraulic conditions. Implying that these (semi) empirical models are generally unsuitable to predict the response of a profile during storm events.

The UNESCO-IHE Institute for Water Education, Deltares Research Institute, Delft University of Technology and the University of Miami, have recently developed a two-dimensional process-based prediction tool, the XBeach model. This model assesses the response of sandy coasts during time-varying storm and hurricane conditions (Roelvink et al., 2008), which permits its application in the simulation of the behavior of non-equilibrium profiles.

The Maasvlakte 2 (MV2), in the Netherlands, is a large reclamation project at which both soft and hard sea-defenses are applied. The soft sea-defenses exhibit steep initial profiles during construction. Understanding how this sea-defense behaves under storm conditions is important to predict its stability and to optimize its construction scheme.
There is little information available on the behavior of non-equilibrium profiles. Therefore the availability of the new XBeach model, in combination storm data from the MV2, provides a unique possibility to obtain more insight in the morphological behavior of non-equilibrium profiles. The main aim of this MSc study is to therefore simulate the behavior of the MV2 profile with XBeach, during storm events.

In order to approach the objective of this study, a thorough data analysis was done. From the data analysis the main cross-shore and longshore morphological processes were identified and an analysis of the volume balance of the soft structure was carried out. The information obtained from the data analysis was used to compare with the results of commonly used empirical and semi-empirical engineering tools, and also as input for the processed-based simulation, and for the comparison with its results (Figure 1.1)

![Diagram of thesis approach]

Figure 1.1 Schematization of thesis approach.
Morphological behavior of a non-equilibrium profile
The response of the MV2 to a storm event

This report contains a literature review on the main characteristics and governing processes of sandy coasts in Chapter 2. The MV2 project is described in Chapter 3, along with the data used in this project. Chapter 4 consists of the methodology, results and discussion of the data analysis. Chapter 5 is the description and discussion of the application of the (semi) empirical engineering tools. And an overview of the XBeach model along with an analysis of the results obtained from the simulations is presented in Chapter 6. Chapter 7 is then a summary of the results, the conclusions, and recommendations for future studies concerning the non-equilibrium profile of the MV2.
Chapter 2 - **Literature review**

A review of the important definitions and relevant processes and formulations to this thesis, found in the literature, will be described in the following sections.

### 2.1. Sandy coasts

The presence of sandy coasts is both a function of sediment sources and coastal processes, such as the geology of the hinterland and shore, and wave and tidal forcing. A coastal zone can be divided into four sections (Dean and Dalrymple, 2002; Shore Protection Manual, 1984): offshore, nearshore, beach, and coast (Figure 2.1).

![Figure 2.1 Diagram of the main parts of a sandy coast](Modified from: Dean and Dalrymple, 2002)

The offshore section concerns the deep water part of the coast, and is not considered part of the morphologically active zone of the profile. The beach section is formed by the area
between the dunes and the end of the beginning of the surf zone. The part of the profile that is always submerged consists of the shoreface, where the wave breaker zone occurs. Dunes are formed by wind driven transport behind the beach section are only reached by wave attack when the water level is elevated due to storms. The breaker zone is the section where the waves break, and is followed by the surf zone. The wave action extends from the breaker zone to the end of the surf zone, at the shoreline, and varies in length according to the hydraulic conditions (Mangore, 2004).

The axis-system used to represent the coastal zone in the current thesis is shown in Figure 2.2, where the x-axis is shore-normal, the y-axis is shore-parallel and the z-axis is vertically upwards from the bottom.

![Figure 2.2 - Definitions of axis system. X-axis is shore normal, y-axis is shore-parallel and z-axis is water depth.](image)

Considering that sandy coasts are dynamic systems, the beach profile constantly adjusts to efficiently dissipate incoming wave energy (Shore Protection Manual, 1984). If a profile is exposed to certain wave and water level condition for a sufficiently long time, it reaches an equilibrium condition.

If the wave or water level conditions are altered, such as an increase in wave height or period, or a storm surge water level, the existing profile will evolve towards a new equilibrium condition (Dean and Dalrymple, 2002). Besides hydrodynamic characteristics, the equilibrium profile also depends on sediment characteristics.

In reality, steady wave or water levels rarely occur as dynamic conditions generally vary in a small temporal scale (Steetzel, 1993). Consequently, a profile will hardly ever develop a
full equilibrium condition, but will constantly adjust to the varying hydrodynamic conditions. This profile condition is referred to as dynamic equilibrium.

Natural equilibrium profiles present slopes in the order of 1:100 (Dronkers, 2005) which vary according to their sediment diameter. The greater the sediment diameter is the steeper the profile, and the smaller the sediment, the more gentle the profile will be.

On artificial coasts, such as nourishments, landfills, and soft structures, profiles during construction are generally much steeper than natural profiles. These profiles are referred to as non-equilibrium profiles and often undergo more rapid changes compared to natural profiles (Vellinga, 1986).

2.2. Hydrodynamic Forcing and Morphological processes
The coastline responds to various forcing mechanisms that provide the energy and momentum to drive the coastal processes (Dean and Dalrymple, 2002). In this section the main hydrodynamic forcing mechanisms, and the subsequently generated morphological processes will be discussed.

2.2.1. Hydrodynamic Forcing
The water level at the coast can vary due to astronomical interaction between the Sun, Moon and Earth, referred to as tide, and also due to meteorological interaction between the atmosphere and the ocean surface, referred to as surge.

Meteorological conditions, especially storms, can significantly change the height of a particular tide and the time in which it will occur (Brown et. al., 1989). The wind and the atmospheric pressure can change either positively or negatively the water level (Woodroffe, 2002). This effect depends on the duration and intensity of the meteorological process, the effect of the Coriolis phenomena (an apparent force due to Earth’s rotation) and the depth and roughness of the sediment bed.

The wind interaction with the water surface also generates waves. When waves reach shallow water they start to interact with the sediment bed. This interaction will causes waves to shoal and/or refract. Shoaling is the increase in wave height as a result of the decrease of the wave celerity, due to bottom friction (Mangore, 2004). Wave refraction is
a change of direction of waves due to the change in their speed, caused a decreasing water depth (Dronkers, 2005). When the sea bed is irregular waves tend to bend slightly towards the shallower part of the coast, depending on the relation between water depth and wavelength. In the case of waves arriving obliquely to the coast, the contact with the bed makes them tend to align crest-parallel to the coast (Figure 2.3).

![Wave refraction schematization. Wave propagation increases with depth.](image)

**Figure 2.3 - Wave refraction schematization. Wave propagation increases with depth.**

Refraction, coupled with shoaling, determines the wave height at any particular water depth for a given set of incident deepwater wave conditions characterized by wave height, period and the direction of the propagation. Therefore, these processes significantly contribute to the distribution of wave energy along the coast (Shore Protection Manual, 1984).

The manner in which a wave breaks depends on the beach profile slope and shoaling process. The steeper the profile, the closer to the beach waves break. The more gentle the profile, the larger the breaker zone
Morphological behavior of a non-equilibrium profile
The response of the MV2 to a storm event

is, and in this situation, waves break and dissipate their energy further from the beach, which is important for sediment transport (described in section 2.2.2).

When particle velocity exceeds the wave phase speed, the crest of the wave is no longer stable, and breaking occurs (d’Angremond and Pluim-Van der Velden, 2001).

Particle motion under waves is assumed to be orbital. As the waves move into shallow water, this motion ceases to be orbital, and describes a more elliptical path. The particle path grows flatter towards the bottom (Holthuijsen, 2007) (Figure 2.4). The water particles do not described perfectly closed paths. As a result, the water experiences a slight wave-induced residual drift or volumes transport, in the direction of the waves, referred to as Stokes drift. In shallow water waves produce an oscillatory velocity at the sea bed, which acts on the sediment. The net volumes transport generated by the Stokes drift plays, therefore, a role in sediment transport and tends to drive the sediment onshore (Soulsby, 1997) in normal hydraulic conditions.

Nearshore currents in the littoral zone generated by wind, tide, and wave forces are the main agent responsible for transporting sediment in suspension (Bosboom and Stive, 2010). Tidal forcing generates currents which can reach high velocities when tidal range is large or in a constricted coast or basin. Wave-induced currents are the main drivers of sediment transport in the current study; therefore, neither wind nor tidal generated currents will be described in this section.

As waves propagate into the surf zone, the momentum flux is equal to its value at the breaker line. In the case of a closed boundary (like a coastline) the momentum flux is zero.
at the limit of the uprush (no more volumes motion) (Bosboom and Stive, 2010). The gradient in the momentum flux is thus balanced by a slope in the water level, which generates a wave set-up against the coast.

Since the horizontal particle velocity is smaller close to the bottom than at the surface, particles moves faster in the wave direction when they are located under the wave crest. This generates a momentum flux gradient above trough level. To compensate for this gradient a net a return current occurs below wave trough level, undertow (Figure 2.5).

Figure 2.5 - Measured velocities under a propagating wave. Diagram of the undertow current (Modified from: Bosboom and Stive, 2010).

Undertow currents often exhibit relatively large offshore-directed velocity in the lower and middle part of the water column, which is the zone that contains the highest sediment concentrations (Bosboom and Stive, 2010). It is therefore, an important contribution for seaward sediment transport, especially during storm events, when volumes-transport
Morphological behavior of a non-equilibrium profile
The response of the MV2 to a storm event
towards the coast is larger (larger volumes-transport for higher waves), and consequently
the undertow is stronger.

The transport of wave induced-momentum is equivalent to the radiation stress
(Holthuijsen, 2007). It is necessary to describe the radiation stress in order to explain the
generation of the alongshore currents. The momentum flux has two main contributions:
one due to wave-induced velocities of the water particle and another due to pressure
(Fredsoe and Deigaard, 1993).

When waves approach normal to the coast, there is no wave generated momentum flux in
the y-direction, since there is no wave velocity in this direction. In this situation the only
contribution to the momentum flux in the y-direction is pressure ($S_{yy}$ [N/m]) in the case
of obliquely incident waves both wave-induced and pressure induced components apply
for the x and y-directions (note that depending on the wave angle, they will have different
contribution in each direction).

Every stress has a perpendicular shear stress component, which is the transport of x-
momentum in the y-direction, and vice-versa. It consists partly of advection by the
horizontal orbital velocity. To balance the gradients of the radiation stress, mean
alongshore currents develop at the sea bed. Horizontal variations in the radiation stresses
give rise to a net wave-induced force in a particular direction. The corresponding wave-
induced radiation force [N/m] per unit horizontal surface area in the x-direction is
(Holthuijsen, 2007):

$$F_x = -\frac{\partial S_{xx}}{\partial x} - \frac{\partial S_{xy}}{\partial y}$$

Eq. 2.1

where the first term $-\partial S_{xx}/\partial x$ represents the variations in the x-directed radiation normal
stress and second term $-\partial S_{xy}/\partial y$ is the variation of the shear stress in the x-direction.

The wave heights in the surf zone generally decrease towards the shore, correspondingly,
the radiation stress also decreases. This reduction results in a force on the water body
directed towards the shore, which is indicated in Eq. 2.2 by the minus sign in front of the terms.

Similarly in the y-direction:

\[
F_y = -\frac{\partial S_{yy}}{\partial y} + \frac{\partial S_{yx}}{\partial x}
\]

In the shoaling region the wave height and hence the wave energy increase until it reaches the surf zone. In the surf zone the wave height and energy decrease again (Bosboom and Stive, 2010) due to wave breaking. The increase and decrease in energy result in a positive gradient in the shoaling region and a negative gradient in the surf zone, which causes a set-up in the breaker zone.

When the incident wave angle is greater than zero (offshore wave angle is \(\alpha = 0^\circ\); coast-normal), due to the wave setup in the breaker zone, longshore currents are generated in this zone (d’Angremond and Pluim-Van der Velden, 2001; Van Rijn, 2009) (Figure 2.6).

![Figure 2.6 - Influence of the angle of the incident waves on the magnitude of the longshore current. (d’Angremond and Pluim-Van der Velden, 2001)](image)

The variations in radiation stress as function of wave breaking and wave incidence angle may also vary along the coast. The variations in radiation stress determine the magnitude of the longshore current (Figure 2.7), which in turn drives the amount of sediment...
transport. The variation of the magnitude of the longshore current, from one section of the coast to another, generates a gradient. A positive gradient between two sections of the coast generates an increase in transport; a negative gradient generates a decrease in transport.

Figure 2.7 - Results of gradients in the longshore current. a: Increase in transport after breaker zone induced by the increase in tide-driven currents; b: Increase in transport in the breaker zone due to difference in wave height along the coast; c: Increase in transport due increase of the wave incidence angle. SI is sediment transport. (d’Angremond and Pluim-Van der Velden, 2001)

2.2.2. Morphological processes

Cross-shore sediment transport occurs as a direct response to wave action on a beach profile. There are two general types of dynamic beach response to wave motion: response
to normal conditions and response to storm conditions (Shore Protection Manual, 1984), also known as winter and summer conditions, in a yearly time scale.

Normal hydraulic conditions are the conditions that dominate most of the time. The wave energy is then easily dissipated by the natural defense mechanism of the profile in case the profile is in equilibrium. During storm events the beach responds to the extreme hydraulic conditions by modifying its profile to adapt to the new condition. Sediment is eroded from the berm and in case of large storms also from the dunes, and is deposited on the shoreface, mainly by the undertow current. The sediment transported offshore forms a bar further offshore than the bar generated in normal conditions. This process generates a milder profile slope; a storm profile (Van de Graaff, 2009).

The new bar causes the waves to break further from the beach, dissipating more energy before it reaches the beach. Consequently, the erosion of the berm and dunes will decrease. The erosions-deposition process during new hydraulic conditions would continue until a new equilibrium profile is achieved, corresponding to the storm surge level. However, beach profile changes are slower than the changes in hydraulic and meteorological conditions and such equilibrium is not usually reached during a single storm (Vellinga, 1986).

In this situation there is no net sediment loss. The sediment transported to the shoreface during a storm usually returns to the beach (Steetzel, 1993) during normal wave conditions (Van Rijn, 2009), by the Stokes drift. However, in the presence of longshore currents the sediment placed in the shoreface may be carried by the current and lost from the cross-shore profile. Longshore currents transport sediment in the alongshore direction, and only cause erosion or accretion if there is a gradient in transport along the coast.

The net longshore transport scales are typically larger than the cross-shore transport scales. However, longshore transport occurs in the spatial scale of kilometers and temporal scale in the order of years, whereas cross-shore transport occurs in the order of meters and the time scale varies in the order of minutes to days (Stive et. al, 1992; Steetzel, 1993).

On a smaller scale sediment transport processes involve, sediment entrainment, transport characteristics and sedimentation. Transport initiates with the entrainment of sand from
Morphological behavior of a non-equilibrium profile
The response of the MV2 to a storm event

The seabed, subject to wave or current action. The entrainment of sediment and its subsequent transport are determined by water movement and sediment characteristics e.g. flow velocity, turbulence, bed roughness, and sediment properties such as diameter ($D$ [mm]) and specific density ($\rho_s$ [kg/m$^3$]).

The entrainment of sediment is dependent on a minimum current velocity capable of picking the sediment up from the bed and putting into transport, denominated critical velocity ($u_{cr}$). It can be represented, in terms of bed shear stress by the Shields parameter for initiation of motion (cf. Soulsby, 1997).

Sediment transport can be described as the product of the concentration of sediment in movement ($c$ [m$^3$/m$^3$]) and the flow velocity ($u$ [m/s]), integrated over the water depth, where currents are the only drivers. However, sediment transport in the coastal zone is more complex due to the interaction of waves and currents as a result transport is a function of space (depth) and time (concerning the wave period).

Sediment transport can be divided in bedload transport and suspended load transport. Bedload transport concerns rolling or jumping (saltation) of sediment, and occurs within a thin layer above the seabed. The thickness of this layer is equal to the bed roughness (height of ripples) (Bijker 1971).

Suspended load transport occurs for sediment that is put in suspension in the water column above the bed load layer. The transport rate is found by integrating the product of the particle velocity and the sediment concentration over the water depth (measured above the bed layer) (Van der Velden, 2000).

When the transport capacity of the current decreases below critical level the level of turbulence decreases and the sediment settles, resulting in deposition. Settling is a function of the fall velocity ($w$) which is defined as the terminal velocity attained when the grain is settling in an extended fluid under the action of gravity (Fredsoe and Deigaard, 1992). The settling of suspended load is thus related to the drag coefficient for spheres, obtained by Stokes (1851). Stokes derived the fall velocity to be
Eq. 2.3

\[ w = \frac{(\rho_s - \rho)gd^2}{18\mu} \]

where, \( w \) [m/s] is the fall velocity, \( \rho_s \) [kg/m\(^3\)] is the density of the grain, \( \rho \) [kg/m\(^3\)] is the density of water, \( g \) [m/s\(^2\)] is the acceleration of gravity and \( \mu \) [m\(^2\)/s] is kinematic viscosity coefficient. This relation shows that the fall velocity increases with the density of the grain and its size.

Bedload is assumed to follow the physical changes of the transporting agent directly (Bijker, 1980), its movement being mainly limited by the effect of gravity (Van de Graaff, 2009). Consequently, bedload settles when the flow is reduced below transporting capacity (\( w \) is constant).

Bagnold (1962, 1996) derived the equilibrium sediment concentration (\( C_{eq} \) [g/m\(^3\)]) by considering the wave energy required to keep the sediment load in suspension (\( E_r \)) and the energy dissipation by sediment transport (\( E_d \)). The energy per unit time to keep the suspended load in suspension is

\[ E_r = (\rho_s - \rho)gh(c_{eq}/\rho_s)w_s \]  
Eq. 2.4

where, \( w_s \) is the effective fall velocity, that accounts not only for each individuals particles drag force, but also for the hindered settling effect of a fluid-sediment mixture. The energy required to keep sediment in suspension is assumed uniform over the depth \( h \) [m] and the energy dissipated by the flow in transporting sediments is

\[ E_d = e_s(\tau_bu) \]  
Eq. 2.5

where, \( e_s \) is the efficiency coefficient, \( \tau_b \) is the bed shear stress and \( u \) [m/s] is the depth-averaged velocity. Assuming \( E_r = E_d \) the equilibrium sediment concentration can be found (cf. Van Rijn, 2007)

\[ c_{eq} = K\rho_s[(1 + ac_{eq})][(u^3/ghw_s)] \]  
Eq. 2.6
where, \( K = \left( \frac{e_s g}{(s-1)c^2} \right) \) and \( s = \frac{\rho_s}{\rho_w} = \) relative density, and \( a = \frac{s-1}{\rho_s} \). The sediment transport equations used in XBeach follow from the equilibrium sediment concentration concept.

2.3. Modeling the behavior of sandy coasts

In this section, three types of models simulating the behavior of sandy coasts are distinguished: empirical models (section 2.3.1), semi-empirical models (section 2.3.2) and process-based models (section 2.3.3),

2.3.1. Empirical Models

Empirical models are descriptive models that have been developed through the observations of beaches in different environments and times scales (Roelvink et. al, 1993).

\[
h = Ax^m
\]

Eq. 2.7

Bruun (1954) was the first to empirically develop a predictive equation for natural equilibrium beach profile. By observing beaches along the Danish North Sea coast and the US west coast. His theory is supported by considering that the beach profile is formed by the onshore component of the shear stress due to wave action. A simple power law was proposed to relate the water depth \( h \) [m] to the offshore distance \( x \) [m]:

\[
h = Ax^m
\]
where, \( m=2/3 \); \( x \) is the offshore distance related to the morphological closure depth beyond where significant long shore or cross shores process take place, and; \( A \) is the constant non-dimensional shape factor, depending on the stability of the bed material.

Dean (1977) supported the Bruun power law by reasoning that nature aims at a uniform energy dissipation per unit volume of water across the surf zone (Steetzel, 1993; Van de Graaff, 2002). For monochromatic waves and constant breaker index, \( \gamma = H/h \), the magnitude of the exponent \( m \) of \( h = A x^m \) can be derived and the \( \frac{2}{3} \)-power curve is found:

\[
A = \left( \frac{24}{5} \frac{D_{eq}}{\rho g \sqrt{g \gamma^2}} \right)^{2/3}
\]  
Eq. 2.8

where, \( H [m] \) is wave height and \( h [m] \) is water depth. The shape parameter \( A \) was later related to the median grain size by Moore (1982). Dean (1987) transformed Moore’s relation to a relation using the fall velocity

\[
A = 0.067 w^{0.44}
\]  
Eq. 2.9

Both relations show that the coarser the grain size, the larger the value for \( A \), yielding a steeper profile, agreeing with the results of the studies of Hughes and Chiu (1978).

Dean and Dalrymple (2002) state a few of the known empirical relationships between equilibrium profile shape and sediment size, wave height and period, and water level characteristics, where: coarse sediments (0.5 – 1mm) are said to be associated with relatively steep equilibrium profiles, increasing wave heights generate milder slopes, increasing waves periods transport sediment onshore and increasing tide or water level cause sediments to be transported seaward, resulting in shoreline recession.

It is important to note that empirical models should not be extended beyond their capacity (Bruun, 1954). They are based on regular waves and equilibrium profiles and generate a vertical slope of the beach profile at the water line, which is far from realistic (Vellinga, 1986; Steetzel, 1993; Van de Graaff, 2002).
Empirical descriptive models are very useful to describe typical beach topography and its transitions in natural beaches. However, they are limited, however, in describing the processes in artificial and/or non-equilibrium profiles, and also in quantifying these processes (Vellinga, 1986; Roelvink et. al, 1993).

2.3.2. Semi-Empirical Models

The semi-empirical modeling approach also forces an equilibrium condition. Sediment transport modes are based on equilibrium profile concepts and assume that a profile will eventually achieve equilibrium (Zheng and Dean, 1997). Figure 2.9 shows the semi-empirical modeling schematization.

![Figure 2.9 - Semi-empirical modeling schematization.](image)

Edelman (1968; 1972) presented a method to predict dune erosion during severe storms, where it was considered that even though a storm profile is not identical to an equilibrium profile the same basic principals are applied.

The method was improved through scale experiments by Van de Graaff (1977) based on field observations. It was assumed mainly that the level of erosion profile is determined by the storm surge level, and that the shape of the erosion profile was not affected by grain size, or by wave height and period.

Vellinga (1986) extended the work of Van de Graaff (1977). Where the storm erosion profile was represented as a function of storm surge level, wave height and sediment size.
Now a typical storm profile develops as a response to the extreme hydraulic conditions, which extends to a depth of approximately 0.75 $H_{os}$ below storm surge level.

From physical model tests an equation to estimate the erosion profile (Eq. 18) and its seaward limits was developed:

\[
\left( \frac{7.6}{H_{os}} \right)^y = \left[ \frac{7.6}{H_{os}} \right]^{1.28} \left( \frac{w}{0.0268} \right)^{0.56} x + 18 \] 
\[ - 2.0 \]  
\[ x = 250 \left( \frac{H_{os}}{7.6} \right)^{1.28} \left( \frac{0.0268}{w} \right)^{0.56} \]  
\[ y = 5.72 \left( \frac{H_{os}}{7.6} \right) \]

which led to the conclusion that the erosion profiles shifts towards a more landward position than the initial profile, during storms (Figure 2.10).

\[ x \in [0, 250] \quad y \in [0, 5.72] \quad H_{os} \text{ in m; } w \text{ in m/s} \]

Figure 2.10 Principal of the dune erosion prediction model (Vellinga, 1986).

Vellinga also assumed that the shape of the post-storm profile was not related to the shape of the pre-storm profile which was later denied by Steetzel (1993).
Stive and Battjes (1984) describe the sediment transport as a product of the time-averaged velocity field and the time averaged sediment concentration in the surf-zone, in a first-order approach by the return flow, which makes this concept useful to predict the initial erosion during storm surges and has proved to be successful (Roelvink et al., 1993). However, the stage in which the storm starts do subside and the profile starts to recover cannot be represented.

Various semi-empirical models based on the pre-storm equilibrium profile concept, where developed, e.g. DUNERULE-model (Van Rijn, 2009), EDUNE (Kriebel, 1982; Kriebel and Dean, 1985; Kriebel, 1986), Sbeach (Larson and Kraus, 1989), and DUROSTA (Steetzel, 1993) which simulate the cross-shore profile response to storm events (Roelvink et al., 2009). Semi-empirical models that simulate longshore and cross-shore processes were also developed, e.g. the UNIBEST package, developed by former WL|DELFTHYDRAULICS (Deltares). The longshore module of UNIBEST will be described in Chapter 5.

2.3.3. Process-Based Models

Process-based models describe the elementary process of flow and sediment response for medium and short-term time scales (Stive et. al, 2001), and are not based on a prior equilibrium condition. Therefore, the changes in coastal morphology are derived from the balance of forces. Figure 2.11 shows the process-based model schematization.
An important characteristic of process-based model is that there is a morphological feedback at each time step. They differ in the type of governing equations and the main processes that are to be modeled. A basic approach to process-based models was presented by Roelvink et al. (1993) and is briefly described below.

The sediment transport distribution over the profile, in a process-based model, is computed as a function of the cross-shore profile, sediment properties and seaward boundary conditions, such as wave height and period. From the continuity equation for the sediment volume

\[
(1-n) \frac{\partial c_b}{\partial t} + \frac{\partial \bar{q}}{\partial x} = 0 \tag{Eq. 2.13}
\]

where, \( \bar{q} \) is the time-averaged cross-shore rate of volume transport \([m^3/m]\), \( z_b [m] \) is the bed elevation and \( n \) the pore content of the bed material. The rate of change of the bottom level is computed. After a time step \( \Delta t \) is estimated, the procedure is repeated.

It is usually assumed that the sea state and boundary conditions are stationary over the duration of a time step, that the motion of the bed does not affect the hydrodynamics and that the porosity of the bed material is constant.

It is usually assumed that the sea state and boundary conditions are stationary over the duration of a time step, that the motion of the bed does not affect the hydrodynamics and that the porosity of the bed material is constant. A common schematization of these models is the separation of time scales, where the time-averaged transport equation can be written as

\[
\bar{q}(x) = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} \left( \bar{u} \bar{c} + u_{lo} c_{lo} + u_{hi} c_{hi} + u c \right) dz dt \tag{Eq. 2.14}
\]

where, \( u [m/s] \) is the horizontal velocity and \( c [m^3/m^3] \) the volume concentration of sediment. The first term is related to the time-averaged current and concentration and is usually the dominant process in case of severe erosion. The second term is related to
wave groups, and the third term is related to wave asymmetry and time lag effects within the wave period. The effect of turbulent fluctuations of the horizontal velocity is generally very small, compared to other terms, and is usually neglected.

Process-based modeling can be done in 1, 2 or 3-Dimensions, depending on the process to be simulated and the available information and computational capacity.
Chapter 3- **Maasvlakte 2**

The Maasvlakte-2 (MV2) project is the seaward extension of the port of Rotterdam in The Netherlands, and will be situated directly adjacent to the existing Maasvlakte 1 (Figure 3.1). The project is executed by PUMA, which is a consortium of the Dutch dredging contractors Royal Boskalis Westminster and Van Oord. The total area of the MV2 will measure approximately 2000 hectares after its completion\(^1\).

The construction of MV2 started in 2008 with the outer contour sea-defense, which concerns soft and hard structures. The sea defenses will occupy an area above sea level of approximately 165 ha, with the soft sea defense extending to 8.4 km in length, which will be formed of dandy beaches and dunes.

In the first phase of construction (2008 until 2013) 240 Mm\(^3\) of sand is required for the soft sea defense and also for infrastructure within the outer contour. For the full completion of the MV2 project, approximately 365 Mm\(^3\) of sand is required.

Most of the sand required for the construction of the MV2 (75%) will be extracted at offshore borrow areas and transported to the construction site by Trailing Suction Hopper Dredgers (TSHD’s). Sand will be discharged by three different (production) methods: bottom door dumping, rainbowing and discharge by pipeline, which are chosen according to the local depth. The rest of the sand will be reused from changes made in the existing Maasvlakte 1 sea defense and from dredging of the new port basin.

\(^1\) www.maasvlakte2.com
Figure 3.1 Location of the Maasvlakte-2 in The Netherlands. (a): the MV2 project (b) Detail of the outer contour and its soft and hard sea defenses.
3.1. The outer contour in the constructional phase

The construction of MV2 began by creating a sandy banana-shaped island about 3 km west of the present coastline, forming the first part of the outer contour. This study is an analysis of the response of the constructed profile of the outer contour to a storm that occurred in September 2009. In that period, the outer contour exhibited a north-south length of approximately 5 km. However, out of these 5 km, only 3.2 km were constructed above water level, reaching a maximum elevation of 6 m NAP (Figure 3.2).

The cross-shore profile of the outer contour exhibits rather steep slopes during its construction phase. The profile can be divided into two main sections based on its slope; one above -3 m NAP and one below. The typical construction slope is 1:20 to 1:25 on the upper section of the profile (above -3 m), and 1:10 to 1:15 on the lower section (below -3 m) (see Figure 3.2).

3.2. Data description

The current study focuses on the morphological behavior at the seaward side of the outer contour during the autumn storm that occurred from the 3rd to the 5th of September, 2009. All data used in this project was received in a personal communication with PUMA (Loman, 2009). The data includes pre and post-storm profile elevation data, hydraulic storm conditions, production information for the duration of the storm period, and sediment size distribution data.

3.2.1. Boundary conditions

The September 2009 storm was considered to be a mild storm when compared to the average storm for the past 30 years. The storm data concerns time-series of spectral wave height and wave period, wave direction and water level, averaged every three hours.

The original hydraulic information was obtained from the Europlatform. The Europlatform buoy is located approximately 60 km offshore Hoek van Holland (i.e. the entrance of the Rotterdam harbor channel) at 32 m water depth. The wave transformation from offshore to nearshore (800 m offshore of the MV2 outer contour) was computed with the SWAN model\(^2\) for different locations along the outer contour (Figure 3.3).

\(^2\)www.swan.tudelft.nl
Figure 3.2 Outer contour as it was constructed until September 2009. (a): Top view of the soft sea-defense. (b): typical cross-section.
The morphological behavior of a non-equilibrium profile
The response of the MV2 to a storm event

Figure 3.3 Map of the wave propagation locations (red cross). The west side of the outer contour soft sea defense is outlined in yellow. The study area is indicated by the dashed rectangle.

The wave and water level time-series are shown in Figure 3.4. The duration of the storm followed from the period for which wave heights exceeded 2 m (nearshore wave data), lasting for about 2 days. The maximum wave height recorded was 3 m with a corresponding period of 6.8 s. The water level time-series is composed of astronomical tidal recording and meteorological variations. The maximum water level during the storm period was +1.43 m NAP. This storm is considered to be a mild storm for Dutch conditions.
Figure 3.4 Wave time series for the nearshore location 15 (see Figure 3.3) and water level measurements. The duration of the storm is indicated between the black lines.

The area of the MV2 is located on an open coast with small tidal range (not exceeding 2 m). Tidal driven flow velocities may play a role in the morphological behavior of the outer contour, however during extreme conditions they are less relevant and are therefore not considered in this study. Therefore, only wave and surge level conditions will be described in this chapter and used in the analysis.

3.2.2. Bathymetrical survey data

The profile elevation data is a compilation of daily surveys, obtained by a land-based platform and by acoustic soundings measured from a vessel. During the storm period, no bathymetrical data was obtained, due to the impossibility of surveying during rough sea conditions (Figure 3.5). The bathymetry information includes the effect of ongoing production, concerning the disposal of sand during the storm, or in between surveys periods, by the TSHD’s. The resolution of the bathymetrical data is 10x10 m.
3.2.3. Production and sediment characteristics

During the storm period production occurred in the inner east side of the outer contour structure, and in other areas protected from the direct storm effect. The production locations are shown in Figure 3.6.

The discharged volumes were obtained through measurements on board of the hopper (m$^3$-situ). When the hopper content is discharged a percentage of sediment is lost due to washout of the fine sediments, erosion by tidal and wave action, and also consolidation of the sediment. Accordingly, this percentage is accounted for in the production volumes used in the volume balance calculations (Chapter 4).

The mean sediment size ($d_{50}$) was determined for each hopper load brought to the construction locations. This enables the determination of the $d_{50}$ for each part of the outer contour, which was found to be of medium grain size for the whole outer contour.
Figure 3.6 Outer contour map with the indicated production locations for the period of 3\textsuperscript{rd} to 7\textsuperscript{th} of September 2009.
Chapter 4 - Data Analysis

The outer contour structure has a strong longshore variability concerning its shoreline orientation and profile elevation (Figure 4.1). Accordingly, the effect if the incoming waves on the profile will also vary along the structure.

4.1. Boundary conditions

The hydraulic data is utilized to analyze the bathymetrical survey data, and also as input for the semi-empirical and process-based model simulations. A schematization of the hydraulic storm conditions was found necessary, except for the process-based modeling where the time-series is directly inputted.

The representative wave condition was calculated in a way that it would be proportional to sediment transport. Therefore the calculation was based on the CERC (longshore transport) formula. The time series were simplified into one representative value through a weighted average of the wave heights, periods and directions, using the wave incidence angle as the weight.

\[
H_{s,rep} = \left( \frac{\sum((\sin \theta \times \cos \theta) \times H_s^{2.5})}{\sum(\sin \theta \times \cos \theta)} \right)^{1/2.5} \quad \text{Eq. 4.1}
\]

In this way representative wave heights, period and direction were obtained for the storm wave condition (period in between black lines in Figure 3.5) using Eq. 4.1. The representative wave condition is presented in Figure 4.1 relative to the nearshore locations shown in Figure 3.3.
Figure 4.1 Representative wave height, period and direction per location relative to the nearshore locations in Figure 3.3.

To estimate the variation of the longshore component of the wave force along the outer contour the $S_{xy}$ component of the radiation stress was calculated using Dronker’s (2005) approach for every location, using the representative wave conditions (Figure 4.1)

$$S_{xy} = (n(1 + \sin^2 \theta) - \frac{1}{2})E$$ 

Eq. 4.2

where,

$$E = \frac{1}{2} \rho ga^2$$ 

Eq. 4.3

and $n$ is the ratio of wave group over wave propagation speed
Morphological behavior of a non-equilibrium profile
The response of the MV2 to a storm event

\[ n = \frac{1}{2} + \frac{kh}{\sin(2kh)} \]  
Eq. 4.4

where, \( k \) is the wave number and \( h \) [m] is the water depth, and \( a \) is the wave amplitude [m].

The results of the radiation stress calculation are presented in Figure 4.2, where positive values represent longshore transport in the south-north direction and negative values represent flow and transport in the north-south direction.

According to the Figure (Figure 4.2) between locations 16 and 17 the dominant wave angle is coast-normal (\( \theta = 0^\circ \)), and no longshore current occurs there. From location 17 to 24 the longshore current is directed to the north and from location 16 to 2 it is directed to the south. Strong longshore gradients are estimated between locations 9 to 21, with smaller gradients shown in the southern boxes (1 to 9).

For simplicity the wave height (\( H \)), period (\( T \)) and direction (\( Dir \)) will be represented by one value for the whole outer contour; \( H = 2 \) m, \( T = 6 \) s and \( Dir = 290^\circ \).

![Figure 4.2 Longshore component of the radiation stress \( S_{xy} \) for the location of the outer contour. Positive values represent longshore transport in the south-north direction and negative values represent transport in the north-south direction.](image)

In this chapter an analysis of the morphological response of the outer contour profile to the September 2009 storm is carried out through a volume balance analysis and through
identification of the longshore and cross-shore sediment fluxes. However, first a
description of the outer contour concerning its construction phase and profile
characteristics is presented in the following section.

4.2. Overall description of the outer contour

From the variations in elevation of the outer contour map (Figure 4.3a), the construction
phases along the structure can be derived. According to the construction phases the outer
contour was divided into three different areas: North, Center and South.

The central area of the outer contour is in its final construction phase. The profile is
constructed with an elevation of approximately 6 m NAP (see (1) Figure 4.3a). As
presented in Chapter 3, the profile steepness is 1:20 to 1:25 for the area above -3 m NAP
and 1:10 to 1:15 for the area below -3 m NAP (see Figure 3.2b). The north area of the
outer contour is not fully constructed. The profile here reaches elevations of 1 to 2 m NAP
(see (2) Figure 4.3a), which may be submerged during extreme conditions. The south
area of the structure is constructed as a large plateau with an average depth of -8 m NAP
(see (3) Figure 4.3a). An island has been constructed in the south area (see (4) Figure
4.3a), with a length of 400 m, a width of 200 m, and a maximum elevation of 1 m NAP.
However this island is not of too much interest for this study and will not be discussed
further. The north and central areas present large shallow plateaus with a depth of 0 to -5
m (see (5) and (6) Figure 4.3a); features which may affect the profile’s response.

Different cross-sections were chosen to represent the characteristics of certain parts of the
outer contour (Figure 4.4). Each profile was selected due to its steepness, maximum
elevation, and/or certain features present that might affect the morphological response.
The boxes selected are boxes 21, 19, 16, 11 and 7, (letters (a), (b), (c), (d) and (e),
respectively in Figure 4.4).
Figure 4.3 (a) Depth contour map of the outer contour structure of the Maasvlakte-2. Dashed lines indicate North, Central and South parts of the structure. (b) Map of the difference in elevation before and after the storm of September 2009. Brown rectangles indicate production areas. In both maps the numbers are refer to the text.
Box 21 was selected to represent a characteristic profile form the north area, where the maximum profile elevation was maximum 2 m NAP. It was specifically chosen because it exhibits a large foreshore, forming a nearshore bar-like feature. Box 19, although from the same area was selected because it is the location where overwash occurred and it is interesting to observe the profile's response to this event. Boxes 16 and 11 are part of the center area. They are both constructed to a maximum elevation of 6 m NAP they and were selected due to their position in the outer contour. Box 16 faces west and box 11 faces southwest. Box 7 was chosen to demonstrate the construction phase of the south area. The profile's maximum elevation is -5 m NAP, and is irregularly built.

Boxes 16 and 11 are part of the center area. They are both constructed to a maximum elevation of 6 m NAP they and were selected due to their position in the outer contour. Box 16 faces west and box 11 faces southwest. Box 7 was chosen to demonstrate the construction phase of the south area. The profile’s maximum elevation is -5 m NAP, and is irregularly built.

The steepness of the profile varies along the outer contour. The profile with the steepest slope is box 16 (Figure 4.4c) which represents the typical construction profile: 1:20 to 1:25 on the upper section of the profile (above -3 m NAP), and 1:10 to 1:15 on the lower section (below -3 m NAP). The boxes of the north area are less steep, with slopes between 1:40 to 1:45 above -3 m NAP and 1:15 to 1:18 below -3 m NAP. Box 7 presents a slope below -5 m NAP of 1:42.

The cross-shore profiles have been divided into sections, according to is response to the storm. The definition of each section follows the definitions made by PUMA and are used in this thesis in order to facilitate comparisons. For a more detailed analysis of the cross-shore fluxes, the boxes were subdivided into four sections (Figure 4.5):

- Beach and dunes: bed elevation above +1 m NAP
- Foreshore: bed elevation between 1 and -4 m NAP
- Shoreface: bed elevation between -4 and -8 m NAP
- Shore foundation bed elevation below -8 m NAP

The profile sections from here on will be referred to as B&D, FS, SF and FND, respectively.
Figure 4.4 Cross-sectional profiles of the outer contour selected according to the difference in slope and elevation characteristics of each area. (a) Box 21 (b) Box 19 (c) Box 16 (d) Box 11 (e) Box 7. Blue line: mean sea level and Black dashed line: -3 m depth line.
Figure 4.5 Schematization of the cross-shore profile sub-division into B&D (blue), FS (red), SF (green) and shore FND (purple). The cross-shore fluxes are indicated in figures (a) and (b) and the longshore fluxes are indicated in figure (b).
4.3. Profile response to the September 2009 storm

A map of the difference in elevation of the bed profile before and after the storm was generated in order to evaluate the morphological processes that occurred on the outer contour during the storm period (Figure 4.3b). Negative differences (cold colors) represent erosion and the positive differences (hot colors) represent sedimentation. The production that occurred during the storm has to be taken into account to accurately analyze natural morphological processes. Therefore the production that occurred during the observed period occurred within the brown boxes (Figure 4.3b).

In the central area of the outer contour erosion occurred at the B&D and FS sections of the profile and sedimentation occurred in the deeper section of the profile; SF and FND (see (1) Figure 4.3b). This erosion/sedimentation pattern is the general trend for the outer contour.

In the north area erosion also occurred in the upper part of the profile (see (2) Figure 4.3b) and apparently less sedimentation occurs on the lower part, when compared to the center area. Part of the sediment that was not deposited on the lower profile was deposited on the eastern side of the structure due to overwash (see (3) Figure 4.3b). A large deposition area occurred at the northern end of the structure (see (4) Figure 4.3b). A smaller, yet relevant, deposition area occurred in the northern-eastern end of the structure (see (5) Figure 4.3b).

At the southern end of the central area, a very large deposition area is seen from 1 m to -8 m NAP (see (6) in Figure 4.3b), where a large production area also occurs. To the west of this area (see (7) in Figure 4.3b), significant erosion occurred between the depths of -2 to -8 m NAP, discontinuing the sedimentation pattern that occurred along the central area of the outer contour. Other sedimentation areas occurred on the eastern and western sides of the structure (see (8) and (9), respectively, in Figure 4.3b), at depths below -8 m NAP. At these locations production also occurred, which makes it difficult to define if natural deposition occurred in these areas or not.

A large patch of erosion is seen at the east side of the outer contour (see (11) in Figure 4.3b), at depths of approximately -15 m (see Figure 4.3a). This erosion can possibly be attributed to circulation east of the outer contour area and is not part of the morphological
active zone of the outer contour structure. It will therefore not be discussed further in this thesis.

4.3.1. Volume balance methodology

Through a volume balance analysis, the behavior of a profile can be determined with respect to its forcing. By accounting for material entering and leaving a system, volume flows can be identified. Therefore, a volume balance analysis was carried out to identify the morphological processes that occurred on the outer contour during the storm in both a qualitative and a quantitative way. The sediment density is assumed to be constant throughout the analysis.

The outer contour was divided into 25 boxes of 200 m in the alongshore direction and 880 m in the cross-shore direction (Figure 4.6a). The configuration of the boxes was defined to encompass the active morphological zone of the outer contour, including both the west and east sides of the structure. These boxes are referred to as wide boxes in this report. As a result, the north part of the outer contour contains boxes 18 to 25, the central part contains boxes 9 to 17, and the south part contains boxes 1 to 8 (Figure 4.6a).

The eroded or deposited volumes of sand were derived for each box from the difference in elevation of the profile before and after the storm. These volumes were summed in each box and then corrected for the correspondent production volume. To check the overall volume balance of the outer contour, the net erosion and sedimentation volume were summed.

\[
Volume\ balance = \sum ((E + S) - P)
\]  \hspace{1cm} Eq. 4.5

where \(E\) [m\(^3\)] is erosion volume, \(S\) [m\(^3\)] is sedimentation volume, and \(P\) [m\(^3\)] is production.

To evaluate smaller scale cross-shore processes narrower boxes were defined (Figure 4.6b), compared to the wide boxes used to study the larger-scale morphological processes. The configuration of these narrow boxes was defined in such a way that only the processes on the western side of the structure are accounted for, which is the side
directly impacted by the storm. The dimension of these boxes is 200 m length alongshore and 520 m width cross-shore.

The eastern position of the narrow boxes coincides with the highest elevation point of the profile (Figure 4.6b). Erosion and sedimentation volumes were calculated for each of these boxes in order to check for volumes conservation in both the cross-shore and alongshore direction.

The production data was obtained for the exact locations of discharge. However, during the storm the sediment was spread along the profile by the waves and tidal currents. Estimating the exact location of the production volume for the time at the end of the storm period, in order to correct the measured volumes, generates a source of uncertainty in the volume calculation.

4.3.1. Overall volume balance analysis

From the description of the morphological response of the profile to the storm it was decided that the best approach to analyze the longshore and cross-shore response of the outer contour is to combine the wide and the narrow boxes (Figure 4.7). In the locations where the west and east sides of the outer contour are morphologically active, the wide boxes are used. In the locations where only the west side is active, narrow boxes are used.

In general, the narrow boxes are used in the center area, where the profile elevation is above 2 to 6 m NAP. The wide boxes were used at the locations were the profile was not constructed above water level, or at the ends of the structure, as well as where overwash occurred.

The measured net erosion and sedimentation volumes, the production volumes for the boxes used in the approach and the corrected net volumes are presented in Figure 4.9b (see also Appendix 1). From the volume balance calculation it follows that out of approximately 900,000 m$^3$ of sediment moved during the storm, 246,300 m$^3$ was lost from the outer contour boundaries, which corresponds to 27%. This means that 49 m$^3$/m alongshore of sediment was lost from the outer contour.
Figure 4.6 Difference map indicating box dimensions, location, and the number of each box used in the volume balance calculation. (a) Wide boxes: west and east side of the structure combined. (b) Narrow boxes: west side of the structure, directly subject to storm impact.
The outer contour was divided into two parts concerning the change in direction of the longshore current, estimated by the radiation stress calculation (and taking into account the shift in position between the nearshore locations and box definition), into: north and south (Figure 4.8). Volume balance was calculated for each area. In the north part a net erosion volume of 79,300 m$^3$ or 57 m$^3$/m alongshore, was found (9% of the total sediment moved – 900,000 m$^3$). In the south part a net erosion volume of 167,000 m$^3$ or 52 m$^3$/m alongshore was found (18% of the total sediment moved).

Relatively much more sediment is lost in the (smaller) north part (1.8 km length) than in the south part (3.8 km in length). It is seen that the total volume of sand eroded in the north and south parts is not fully deposited within the boundaries of the outer contour, which occurs due to the small gradients in the longshore transport at the northern and southern ends of the part of the structure constructed above water level (boxes 23 to 25 and 9 to 1, respectively; Figure 4.2 ).
Figure 4.7 Combined wide and narrow box approach, concerning the morphological response of the outer contour profile.
Figure 4.8 Definition of the north and south division of the volume balance analysis, according to the shift in direction of the longshore current.
Figure 4.9 Sedimentation/erosion box volumes for the wide+narrow boxes (refer to Figure 4.7) Negative values represent erosion volume [m³], and positive values represent sedimentation volume [m³].
4.3.2. Longshore profile response

The increase in erosion volume from boxes 19 to 17 (Figure 4.9) follows from the increase in the longshore radiation stress observed in Figure 4.10. Box 19 is the location where the incident wave angle is coast-normal and the longshore current direction shifts from north to south. From box 17 to 16 there is a slight decrease in radiation stress and consequently the net erosion volume decreases as well. From box 16 to 15, there is an increase in radiation stress, the transport increases, generating a positive gradient, and therefore the net erosion volume also increases.

The longshore transport decreases towards box 11, where net sedimentation occurs. Part of the sediment transported from the North is deposited in this box. The net deposition that occurred here, of 10 000 m$^3$ corresponds to 6% of the total net erosion of boxes 14 to 18.

An increase in net erosion volume occurs from box 19 to box 21, decreasing in 22 and increasing again in 23 (Figure 4.9). When compared to the radiation stress curve (Figure 4.10), it is as if there is a shift in position from the radiation stress, to the longshore transport. This shift may be due to the shift in location between the nearshore wave locations (Figure 3.3), and the box locations. In box 25 (Figure 4.9) it is seen that there is a large net sedimentation volume, approximately 42,100 m$^3$ which corresponds to 53% of the total net erosion volume of the north area (from box 19 northwards).

Boxes 10 and 23 correspond to the ends of the part of the outer contour constructed above water level. In these boxes the net erosion volume does not follow from gradients in longshore transport, as seen in Figure 4.10. In this figure the radiation stress is plotted in absolute values, different then in Figure 4.2, where negative values represented a north-south direction of the resultant current and positive values represented a south-north. The net volumes change was calculated dividing the net erosion or sedimentation volume per alongshore length of each box (200 m).

The large increase in erosion volumes (Figure 4.9) in these boxes is most likely due to vortex formation of the longshore current, or possibly even tidal currents caused by a change of the pressure gradient at the ends of the structure. In box 10 the net erosion
volume is increased due to a large erosion patch (see (7) Figure 4.3b), due to a bar-like feature, in the foreshore and shoreface that was intensively eroded during the storm.

The gradients in the longshore current from box 9 towards the south are small when compared to the gradients that occur in the rest of the outer contour (Figure 4.10). Net sedimentation occurs in the boxes and it is difficult of the longshore current since the south area is in average -8 m deep. Nevertheless, the sedimentation volumes decrease slightly towards box one, with the exception of boxes 3 and 4, which is where the island is located, following the general trend of the radiation stress curve (Figure 4.10). The total sedimentation volume is in the south area is of 46,250 m³, which corresponds to only 23% of the net erosion volumes transported to the south from the center area.

![Graph of the net volume change (per m alongshore) derived from the net volumes measured for each box and the absolute radiation stress where both north and south directed currents are represented by positive values.](image)

Even though it has been estimated that in between box 19 and 18 there would be no longshore transport due to the coast-normal incident angle of the wave, both boxes present a net erosion volume, demonstrating the effect of a gradient in the longshore current. This occurs because the shoreline orientation varies within each box, and a mean shoreline was used to make the calculations. Hence, in reality, the longshore component of the radiation stress exists in these boxes and does affect the profile, by transporting the sediment put into suspension.
Morphological behavior of a non-equilibrium coastal profile
The response of the MV2 outer contour to a storm event

The central area was the only area of the outer contour that had been fully constructed to the maximum profile height (6 m NAP) and with the design slopes. It interesting then to analyze the alongshore profile behavior of this area as whole. Form Figure 4.11 it is seen that erosion mainly occurs on the upper sections of the profile (B&D, and FS), and sedimentation occurs on the lower sections of the profile (SF and FND). By subtracting the erosion volumes of approximately 241,000 m³ from the sedimentation volumes of approximately 75,700 m³, it follows that there is a total net erosion of approximately 165,300 m³, which corresponds to 68% of the eroded volume. In other words, 68% of the eroded sediment from the upper profile is being transported out of the box.

**Figure 4.11** Alongshore profile behavior for the different sections (B&D, FS, SF and FND) of the cross-sectional profile of the central part of the outer contour.

4.3.3. Cross-shore profile response

In the cross-shore profile analysis, only the west side of the outer contour is of interest, since it is the side directly affected by the storm impact. For that reason only the narrow boxes will be used in this analysis (Figure 4.6b). As a result, the south area boxes will present net erosion, different from what is seen in Figure 4.9, showing that the sedimentation that occurs is in the east side of the south area.
From Figure 4.12 the general trend of the sand movement can be derived. In the center area (Figure 4.12b), erosion and sedimentation occur in the B&D and FS sections and deposition occurs in the SF and FND. The erosion volumes decrease towards the south and the sedimentation volumes increase towards the south, clearly demonstrating the decrease of the longshore current intensity. With the exception of box 10, explained in the section above.

In the North area (Figure 4.12a), looking at figure from bottom to top (south to north), the general trend observed in the center area (Figure 4.12b), is continued. Sediment is eroded from the upper profile and deposited in the lower profile. The difference however, is that now due to the shift in longshore current direction (now to the north) the erosion volumes increase to the north, until box 22, and the net sedimentation values increase, in general. It can be seen though that in boxes 22 and 21, the sedimentation in the SF and FND is much smaller than the erosion in the B&D and FS. Only 14% of the erosion volumes were deposited. In these locations, a large foreshore area occurs, which dissipates the energy of the waves before it reaches the B&D section. There foreshore is thus intensively eroded, as seen in Figure 4.11a and (2) in Figure 4.3b.

In the south area (Figure 4.12c), the boxes do not exhibit B&D and FS sections, with the exception of the locations where the island is present (boxes 4, 5 and 6). The general trend, excluding the island is erosion of the SF and deposition in the FND. In boxes 1 and 2, only net sedimentation occurs, however of rather small volumes (1000 and 68 m$^3$, respectively).

In Figure 4.13 the process described here can be observed in more detail in the characteristics profiles. The erosion and deposition trend observed in the center area is seen in boxes 11 and 16 (Figure 4.13b and c), where even though they present very similar slopes and maximum profile elevations, they suffer differently from the wave action. This basically occurs due to the longshore current action. Where the longshore current is stronger, more sediment put in to suspension will be transported away from the cross-shore profile, and the slower the shoreface will develop. Preventing the shore face from developing, it enables the wave attack to continue affecting the B&D and FS sections. And consequently, more erosion occurs on the upper profile of box 16.
Figure 4.12 Volumes \([m^3]\) of the profile sections: B&D, FS, SF and FND in the (a) North, (b) Central and (c) South areas of the outer contour.
The influence of the longshore current is reduced in box 11 and there is a negative gradient. By reducing the current, less sediment put into erosion is transported, which allows the shoreface to develop, reducing the effect of the wave attack on the B&D and FS. This can be seen by the smaller erosion volume between box 16 and 11 (Figure 4.12b).

The negative gradient causes sediment incoming from other boxes to deposit here. This can be seen by the shape of the post-storm profile, where the erosion area is smaller than the deposition area.

The erosion of the foreshore area of box 21 and 22 is seen in Figure 4.13a (represented by the cross-section of box 21). Where the foreshore is so elevated it functions as a bar, dissipating the wave energy before it reaches the shoreline. After the storm, the “bar” is completely eroded, and the profile is smoothened out.

Where overwash occurred (Figure 4.13b), the cross-shore development is smaller than in other profiles. What is clearly observed is the shift in the profile towards land and a decrease in profile elevation from 1 m NAP to 0 m NAP, approximately. The deposition observed in the back barrier, in the post-storm profile is mostly due to production, making it hard to compare with the initial profile.

Although in boxes 16 and 11 (Figure 4.13c and d) the longshore transport affected the amount of sedimentation on the lower profile, the shift seen in the profile shape from before to after storm, follows from the change in profile shape of an equilibrium profile. Where the profile that was adapted to the normal hydraulic condition adjusts to the storm hydraulic conditions. In boxes 21 and 19, the presence of the large bar-like feature in the foreshore and the overwash process, prevented the development of the cross-shore profile.

From the difference in elevations of Figure 4.3b and the profile comparison, pre and post-storm, of Figure 4.13, it is seen that there is no substantial transport of sediment beyond the depth of -12 m NAP. Two conclusions can be taken from this observation: the extension of the erosion zone in the lower profile can be defined by a morphological depth of closure of in average -10 m for boxes 9 to 24, and there is no significant sediment loss from the cross-shore profile. Boxes 1 to 8 and 25 exhibit very deep maximum elevations and cannot be described in the same way.
Figure 4.13 Before and after storm cross-sectional profiles. Blue line: before storm and Red line: after storm. (a) box 21, (b) box 19, (c) box 16 and (de) box 11. Where B&D, FS, SF and FND are the beach and dunes, foreshore, shoreface and shore foundation sections.
4.4. Summary of data analysis

From the data analysis it can be concluded that steep non-equilibrium profiles exhibit large upper profile erosion, even during a mild storm, such as the September 2009 storm, analyzed in this thesis. The center area of the outer contour exhibited a maximum B&D erosion of 33,000 m$^3$ (Appendix 1), which added to the erosion of the FS of 11,000 m$^3$, yields in a total erosion of the upper profile of 44,000 m$^3$ (box 15).

Due to the occurrence of gradients in the longshore transport current, most of the eroded volumes were transported away from their profile to be partly deposited within the outer contour. A volume of 246,300 m$^3$ was lost from the outer contour, which corresponds to 27% of the total sand moved (in total 900,000 m$^3$). The sediment loss was mostly to the south boundary of the outer contour.

The cross-shore profile responded to the storm by transporting the eroded sand to the surf zone, by the return flows, depositing it on the SF and FND. The time-scale of the profile evolution is difficult to evaluate since there is no bathymetrical data for the duration of the storm period and only the final profile response was analyzed.

It is seen, that the response of the profiles varied substantially according to their steepness. The B&D erosion volumes were larger in the steeper profiles (center area), especially concerning steepness of the profile above -3 m NAP. It is difficult to make this affirmation however, since the steep and less steep profiles suffered differently from the wave attack and longshore current due to the curvature of the outer contour, since the longshore and cross-shore processes occur simultaneously. Where the profile’s exhibit a more gradual slope, the gradients in the longshore current were smaller, and the steeper profiles are located in the maximum curvature point of the outer contour (boxes 13 to 17).

Concerning cross-shore profile development it is observed from the comparison between pre and post-storm profiles (Figure 4.13), that after the storm the profile tends to a gentler slope, with an s-shape development, which characterizes an equilibrium profile. It is also seen that no sediment is lost offshore form the cross-shore profile, and that the morphological depth of closure is in average -10 m (NAP), along the outer contour (for the areas where the profile elevation reaches above water level (NAP).
Morphological behavior of a non-equilibrium coastal profile
The response of the MV2 outer contour to a storm event

Figure 4.14 shows a conceptual plot of the morphological response of the MV2 profile to the September 2009 storm. The plot characterizes the gradients in longshore and cross-shore transport, which indicate the erosion and sedimentation areas.
Figure 4.14 Physical conceptual plot of the response of the MV2 outer contour to the September 2009 storm. The sediment movement is indicated by the longshore and cross-shore fluxes. The size of the arrows indicate gradients in transport.
Chapter 5- **Application of (semi-) empirical engineering tools**

Most (semi-) empirical engineering tools that predict the response of a profile as a function of hydrodynamic forcing are calibrated for equilibrium coasts. Due to the availability and facility to use these engineering tools, and on the other hand, the lack of simple tools to predict steep profiles response to storms, two models will be investigated. First the Bruun rule’s dune retreat, concerning cross-shore response, and second the UNIBEST-LT model, which estimates longshore transport.

Even though it is expected of these two models to yield results rather far from the measured values, the analysis may be useful to help make engineering assumptions: in modeling steep profiles subject to storms and in the design of structures subjected to similar hydrodynamics conditions.

The representative wave conditions shown in Chapter 4 will be used as input in the Bruun Rule and UNIBEST-LT calculations. The beach and dunes, foreshore, shoreface and shore foundations sections abbreviations will also be used in this chapter: B&D, FS, SF and FND, respectively.

5.1. **Bruun rule applied to storms**

5.1.1. **Bruun rule description**

The Bruun rule determines the retreat of the dune \((R [\text{m}])\) by approximating that the shape of the post-storm profile is similar to the pre-storm equilibrium profile, but at the elevation of the storm surge level, instead of the mean sea level (Figure 5.1).

\[
R = SSL \left( \frac{1}{h} \right)
\]

\textbf{Eq. 5.1}

where, \(SSL [\text{m}]\) is the maximum storm surge level, \(L [\text{m}]\) is the length over which erosion and sedimentation takes place and \(h [\text{m}]\) is the corresponding depth.

In general, the results of the Bruun rule applied to simulate the effect of storms on dune retreat usually yield somewhat lower results than other calculation models applied for the Dutch coast (Bosboom and Stive, 2010). Most likely because erosion profiles tend to be flatter than the pre-storm profile actually is. However, by using Vellinga’s (1986) approach for the extent of the sedimentation/erosion zone (Eq. 2.11,
Eq. 2.12; Figure 2.1) the results are expected to be closer to what is observed at the Dutch coast, where the profiles are relatively steep. To verify this, three cases were calculated.

Figure 5.1. Erosion profile schematization for Bruun rule applied to storm calculation. R is the beach and dune retreat, h is the maximum elevation of the dune plus the water depth of the depth of closure. L is the length over which sedimentation will occur from the eroded dune foot to the depth of closure.

5.1.2. Application of the Bruun rule

The Bruun rule is a simple method to make quick estimations of beach and dune erosion in storm conditions. Three different attempts to use the Bruun rule are presented in this section with the objective of evaluating its applicability for steep non-equilibrium profiles. In all three attempts (cases) the Bruun rule was tested for the steep profile of the MV2, that exhibit a B&D section and on which no production took place (boxes 11 to 21) (data analysis methodology, Chapter 4):

- In the first case, Vellinga’s approach was applied to calculate both: the depth of closure and the length of erosion/sedimentation zone. The results are presented in Table 5.1 and Figure 5.2.
In the second case Vellinga’s approach was used only to calculate the depth of closure. The length of the erosion/sedimentation zone was measured on the profile from the dune foot to Vellinga’s depth of closure. The results are shown in Table 5.3 and Figure 5.3.

In the last case, the depth of closure found in Chapter 4 is used, and the length of sedimentation/erosion zone was again measured from the profile’s dune foot to the depth of closure. The results are presented in Table 5.1 and Figure 5.2.

**Case 1** - The Bruun rule using Vellinga’s approach was applied to calculate both: the depth of closure and length of sedimentation/erosion zone. The results are presented in Table 5.1 and Figure 5.2. The measured retreat is obtained from the bathymetrical data.

**Table 5.1 Bruun rule retreat calculations, using vellinga’s depth of closure and sedimentation/erosion length and measures retreat calculations.**

<table>
<thead>
<tr>
<th>Box</th>
<th>H</th>
<th>Depth of Closure</th>
<th>Max elevation</th>
<th>h</th>
<th>SSL</th>
<th>L</th>
<th>Dune Retreat (m)</th>
<th>Measured retreat [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>21</td>
<td>2.51</td>
<td>1.88</td>
<td>2.96</td>
<td>4.84</td>
<td>1.43</td>
<td>31</td>
<td>9</td>
<td>60</td>
</tr>
<tr>
<td>20</td>
<td>2.51</td>
<td>1.88</td>
<td>1.81</td>
<td>3.69</td>
<td>1.43</td>
<td>31</td>
<td>12</td>
<td>30</td>
</tr>
<tr>
<td>19</td>
<td>2.57</td>
<td>1.93</td>
<td>2.29</td>
<td>4.21</td>
<td>1.43</td>
<td>32</td>
<td>11</td>
<td>10</td>
</tr>
<tr>
<td>18</td>
<td>2.55</td>
<td>1.92</td>
<td>2.91</td>
<td>4.83</td>
<td>1.43</td>
<td>32</td>
<td>9</td>
<td>50</td>
</tr>
<tr>
<td>17</td>
<td>2.52</td>
<td>1.89</td>
<td>6.21</td>
<td>8.10</td>
<td>1.43</td>
<td>31</td>
<td>6</td>
<td>40</td>
</tr>
<tr>
<td>16</td>
<td>2.50</td>
<td>1.88</td>
<td>6.34</td>
<td>8.21</td>
<td>1.43</td>
<td>31</td>
<td>5</td>
<td>40</td>
</tr>
<tr>
<td>15</td>
<td>2.47</td>
<td>1.85</td>
<td>6.41</td>
<td>8.26</td>
<td>1.43</td>
<td>30</td>
<td>5</td>
<td>40</td>
</tr>
<tr>
<td>14</td>
<td>2.46</td>
<td>1.84</td>
<td>6.43</td>
<td>8.27</td>
<td>1.43</td>
<td>30</td>
<td>5</td>
<td>40</td>
</tr>
<tr>
<td>13</td>
<td>2.45</td>
<td>1.84</td>
<td>6.54</td>
<td>8.37</td>
<td>1.43</td>
<td>30</td>
<td>5</td>
<td>40</td>
</tr>
<tr>
<td>12</td>
<td>2.56</td>
<td>1.92</td>
<td>6.55</td>
<td>8.47</td>
<td>1.43</td>
<td>32</td>
<td>5</td>
<td>30</td>
</tr>
<tr>
<td>11</td>
<td>2.60</td>
<td>1.95</td>
<td>6.34</td>
<td>8.28</td>
<td>1.43</td>
<td>33</td>
<td>6</td>
<td>30</td>
</tr>
</tbody>
</table>
The results of the Bruun rule highly underestimate the measurements, with a factor varying between 5 and 7. The only exception was box 19. In that location, however, overwash occurred and thus, a shift in profile position was observed (Figure 4.13b) rather than a large erosion at the dune front and beach, as was the case for most of the B&D sections (Data analysis Chapter 4).

It was observed that the length of the erosion/sedimentation calculated using Vellinga's equation (Table 5.1) underestimated the actual length measured of the MV2's profile by a factor of about 3 to 7 (Table 5.2). In order to get a better approximation for the results of the Bruun rule the measured length instead of the calculated length is used next.

**Case 2** - The Bruun rule using Vellinga’s approach was used to calculate the depth of closure and the length of the erosion/sedimentation zone was obtained by measurements of the bathymetrical data. This approach yielded the retreats presented in the Table 5.3 and Figure 5.3.
Morphological behavior of a non-equilibrium coastal profile
The response of the MV2 outer contour to a storm event

Table 5.2 The sedimentation/erosion length calculated using Vellinga’s equation measured of the MV2 profiled.

<table>
<thead>
<tr>
<th>Box</th>
<th>Vellinga</th>
<th>Estimated</th>
</tr>
</thead>
<tbody>
<tr>
<td>21</td>
<td>31</td>
<td>220</td>
</tr>
<tr>
<td>20</td>
<td>31</td>
<td>220</td>
</tr>
<tr>
<td>19</td>
<td>32</td>
<td>210</td>
</tr>
<tr>
<td>18</td>
<td>32</td>
<td>220</td>
</tr>
<tr>
<td>17</td>
<td>31</td>
<td>110</td>
</tr>
<tr>
<td>16</td>
<td>31</td>
<td>90</td>
</tr>
<tr>
<td>15</td>
<td>30</td>
<td>110</td>
</tr>
<tr>
<td>14</td>
<td>30</td>
<td>130</td>
</tr>
<tr>
<td>13</td>
<td>30</td>
<td>150</td>
</tr>
<tr>
<td>12</td>
<td>32</td>
<td>190</td>
</tr>
<tr>
<td>11</td>
<td>33</td>
<td>190</td>
</tr>
</tbody>
</table>

Before analyzing the results of one should be aware that the measured retreat may present an inaccuracy of ±5 m, since the bathymetry data used has a 10 by 10 m resolution.

Table 5.3 Bruun rule retreat calculations using Vellinga’s depth of closure approach. The sedimentation/erosion length was measured from the dune foot to the depth of closure calculated.

<table>
<thead>
<tr>
<th>Box</th>
<th>H</th>
<th>Depth of Closure</th>
<th>Max elevation</th>
<th>h</th>
<th>SSL</th>
<th>L</th>
<th>Dune Retreat (m)</th>
<th>Measured retreat [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>21</td>
<td>2.51</td>
<td>1.88</td>
<td>2.957</td>
<td>4.84</td>
<td>1.43</td>
<td>220</td>
<td>65</td>
<td>60</td>
</tr>
<tr>
<td>20</td>
<td>2.51</td>
<td>1.88</td>
<td>1.81</td>
<td>3.69</td>
<td>1.43</td>
<td>220</td>
<td>85</td>
<td>30</td>
</tr>
<tr>
<td>19</td>
<td>2.57</td>
<td>1.93</td>
<td>2.285</td>
<td>4.21</td>
<td>1.43</td>
<td>210</td>
<td>71</td>
<td>10</td>
</tr>
<tr>
<td>18</td>
<td>2.55</td>
<td>1.92</td>
<td>2.91</td>
<td>4.83</td>
<td>1.43</td>
<td>220</td>
<td>65</td>
<td>50</td>
</tr>
<tr>
<td>17</td>
<td>2.52</td>
<td>1.89</td>
<td>6.213</td>
<td>8.10</td>
<td>1.43</td>
<td>110</td>
<td>19</td>
<td>40</td>
</tr>
<tr>
<td>16</td>
<td>2.5</td>
<td>1.88</td>
<td>6.338</td>
<td>8.21</td>
<td>1.43</td>
<td>90</td>
<td>16</td>
<td>40</td>
</tr>
<tr>
<td>15</td>
<td>2.47</td>
<td>1.85</td>
<td>6.412</td>
<td>8.26</td>
<td>1.43</td>
<td>110</td>
<td>19</td>
<td>40</td>
</tr>
<tr>
<td>14</td>
<td>2.46</td>
<td>1.84</td>
<td>6.427</td>
<td>8.27</td>
<td>1.43</td>
<td>130</td>
<td>23</td>
<td>40</td>
</tr>
<tr>
<td>13</td>
<td>2.45</td>
<td>1.84</td>
<td>6.538</td>
<td>8.37</td>
<td>1.43</td>
<td>150</td>
<td>26</td>
<td>40</td>
</tr>
<tr>
<td>12</td>
<td>2.56</td>
<td>1.92</td>
<td>6.554</td>
<td>8.47</td>
<td>1.43</td>
<td>190</td>
<td>32</td>
<td>30</td>
</tr>
<tr>
<td>11</td>
<td>2.6</td>
<td>1.95</td>
<td>6.336</td>
<td>8.28</td>
<td>1.43</td>
<td>190</td>
<td>33</td>
<td>30</td>
</tr>
</tbody>
</table>
Figure 5.3 Beach and dune retreat calculation and measurement comparison. Red: volumes calculated using the Bruun rule applied to storms, using Vellinga’s (1986) depth of closure. Blue: measured retreat data.

The calculated retreat shows different results for the different parts of the outer contour. The retreats of boxes 18, 19 and 20 are largely overestimated compared to the actual retreats, which can be associated to overwash that occurred in reality (Figure 4.3b). In this way the dune was breached and the wave “passes over” the barrier, not colliding directly with the beach and dune front, as would be the case during storms. Hence, there is not as much retreat of the B&D section as expected, explaining the great overestimation of the model in these boxes.

Box 11 and 12 and 21 are not affected by overwash and their retreat was estimated rather well by the dune rule, differently then what occurs in boxes 13 to 17, where the retreat was underestimated by a factor of 2, approximately. The main difference between the profile of these boxes (boxes 11, 12 and 21, and boxes 13 to 17) is the steepness of their profile (Figure 4.4). The retreat was better estimated for the profiles that are less steep (boxes 11, 12 and 21). This result indicates that the Bruun rule apparently simulates better the retreat of less steep profiles. However, there is a strong influence of the longshore transport component in these profiles. Between boxes 13 to 17 strong positive gradients are observed whereas in boxes 11, 12 and 13 there is a decrease in the longshore current, generating negative gradients.

These gradients affect the development of the cross-shore profile. They slow down the formation of a milder slope on the shoreface, by transporting the sediment eroded on the B&D away from the profile, which in turn, enables the wave attack to continue on the eroding the B&D. Accordingly, in the boxes where there is more effect of the longshore transport, the B&D retreat is larger, and where the longshore current has
less effect, the retreat is smaller. The Bruun rule only takes in account cross-shore processes and cannot account for the longshore effect on the profile, which can also be an explanation for why the Bruun rule estimates well the retreat in boxes 11, 12 and 21, but not in boxes 13 to 17.

The variations in underestimation of the retreat between boxes 13 to 17 (Figure 5.3) is also, most likely related to longshore variability of the coast and the effect of the longshore transport on the profile erosion (see Figure 4.2).

**Case 3** – In the calculation of Bruun rule the depth of closure was estimated from observations, and the length of sedimentation/erosion zone was measured from the profile.

The estimated depth of closure from the measured profiles was found to be ±10 m for the part of the outer contour constructed above water level (Figure 4.3a). The sedimentation length used in the calculations was measured from the dune foot to the observed closure depth. The measured lengths and retreats are presented in the table below, along with the results of the calculations (Table 5.3; Figure 5.4). This attempt was done in order to evaluate the applicability of Vellinga’s depth of closure applied in case 2.

**Table 5.3 Bruun rule retreat calculations using Vellinga’s depth of closure approach. The sedimentation length was measured from the dune foot to the measured depth of closure.**

<table>
<thead>
<tr>
<th>Box</th>
<th>H</th>
<th>Depth of Closure</th>
<th>Max elevation n</th>
<th>h</th>
<th>SSL</th>
<th>L</th>
<th>Dune Retreat (m)</th>
<th>Measured retreat [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>21</td>
<td>2.51</td>
<td>10.00</td>
<td>2.957</td>
<td>12.96</td>
<td>1.43</td>
<td>350</td>
<td>39</td>
<td>60</td>
</tr>
<tr>
<td>20</td>
<td>2.51</td>
<td>10.00</td>
<td>1.81</td>
<td>11.81</td>
<td>1.43</td>
<td>360</td>
<td>44</td>
<td>30</td>
</tr>
<tr>
<td>19</td>
<td>2.57</td>
<td>10.00</td>
<td>2.285</td>
<td>12.29</td>
<td>1.43</td>
<td>350</td>
<td>41</td>
<td>10</td>
</tr>
<tr>
<td>18</td>
<td>2.55</td>
<td>10.00</td>
<td>2.91</td>
<td>12.91</td>
<td>1.43</td>
<td>320</td>
<td>35</td>
<td>50</td>
</tr>
<tr>
<td>17</td>
<td>2.52</td>
<td>10.00</td>
<td>6.213</td>
<td>16.21</td>
<td>1.43</td>
<td>220</td>
<td>19</td>
<td>40</td>
</tr>
<tr>
<td>16</td>
<td>2.5</td>
<td>10.00</td>
<td>6.338</td>
<td>16.34</td>
<td>1.43</td>
<td>200</td>
<td>18</td>
<td>40</td>
</tr>
<tr>
<td>15</td>
<td>2.47</td>
<td>10.00</td>
<td>6.412</td>
<td>16.41</td>
<td>1.43</td>
<td>200</td>
<td>17</td>
<td>40</td>
</tr>
<tr>
<td>14</td>
<td>2.46</td>
<td>10.00</td>
<td>6.427</td>
<td>16.43</td>
<td>1.43</td>
<td>220</td>
<td>19</td>
<td>40</td>
</tr>
<tr>
<td>13</td>
<td>2.45</td>
<td>10.00</td>
<td>6.538</td>
<td>16.54</td>
<td>1.43</td>
<td>230</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>12</td>
<td>2.56</td>
<td>10.00</td>
<td>6.554</td>
<td>16.55</td>
<td>1.43</td>
<td>280</td>
<td>24</td>
<td>30</td>
</tr>
<tr>
<td>11</td>
<td>2.6</td>
<td>10.00</td>
<td>6.336</td>
<td>16.34</td>
<td>1.43</td>
<td>290</td>
<td>25</td>
<td>30</td>
</tr>
</tbody>
</table>
Figure 5.4 Beach and dune retreat calculation and measurement comparison. Red: volumes calculated using the Bruun rule applied to storms, with measured depth of closure and sedimentation length. Blue: measured retreat data.

Using the observed depth of closure and its respective erosion/sedimentation length, the Bruun rule underestimated the measured retreat by a factor of about 2 in the boxes 13 to 18 and 21. The retreats of boxes 19 and 20 where overestimated most likely due to the effect of the overwash on the erosion of the profile. Boxes 11 and 12 were well estimated by the Bruun rule once more.

The best results seemed to be presented in case 2 (
Table 5.2 and Figure 5.3), which demonstrates that by using Vellinga’s depth of closure the Bruun rule yields the best retreat results.

5.1.3. Discussion
Throughout the attempts to calculate the Bruun rule retreat, boxes 11 and 12 presented rather good results, and the retreat of boxes 13 to 17 was always underestimated. The results of boxes 18 to 21 varied in the different attempts and is hard to assess due to the fact that this area suffered from overwash and that it exhibits a large foreshore area, as bar-like feature (Figure 4.3b and Figure 4.4a), which makes difficult to simulate the retreat of the B&D section (Steetzel, 1993).

The part of the outer contour from boxes 13 to 17 exhibits the steepest profile slopes and elevation of about 6 m NAP, with steep dune/beach face slopes. The Bruun rule was initially derived for natural beaches, with equilibrium profiles. The fact that these boxes exhibit steep non-equilibrium profiles differs from his assumptions of bed stability and profile shape.

The longshore variability in the curvature of the outer contour and also in profile steepness makes it difficult to make ascertained conclusions from the results of the three cases presented here. The Bruun rule could be underestimating the B&D retreat of boxes 13 to 17 but simulating well the retreats of boxes 11 and 12, due to both longshore transport gradient differences and difference in profile steepness between the two areas.

The difference in result from case 1 to case 2 indicate that Vellinga’s equation to calculation the erosion and sedimentation zone may not be a good approach when using the Bruun rule to simulate the retreat of steep non-equilibrium profiles. Vellinga (1986) considers that the initial profile has no affect on the development of the storm profile. He also derived his equation (Eq. 2.12) for the length of the sedimentation and erosion zone based on experiments done using a characteristic Dutch coastal profile (which is less steep then the MV2 profiles) (cf. Vellinga, 1986; Steetzel, 1993).

Two hypotheses have been formulated to explain why Vellinga’s erosion/sedimentation length equation may not be applicable to steep non-equilibrium profiles, taking in consideration Vellinga’s assumptions:
1) Due to the steepness of the profile of the MV2, the eroded sediment is transported further (deeper) on the lower profile, then what is accounted for in Vellinga’s approach. His equation yields a smaller erosion/sedimentation zone that what is observed in reality.

2) The shape of the profile used by Vellinga to derive or test his equation is different than the initial profile of the MV2, in particular from boxes 13 to 17. Therefore, in this case the initial profile does affect the development of the storm profile, and can be responsible of the underestimations of the retreat in all the cases for these boxes.

From the three different attempts to apply the Bruun rule to steep non-equilibrium profiles, it is concluded here that the underestimation of the retreats from boxes 13 to 17 and the good simulation of the retreats of boxes 11 and 12, is most likely due to a combination of the longshore effect, the length of the sedimentation zone, and the influence of the shape and steepness of the initial profile.

Further assessment of the applicability of the Bruun rule to storms needs is recommended. It is suggested that the Bruun be tested for steep profiles, such as the profiles from the central part of the outer contour, but with less influence (or no influence) of longshore transport. It is also suggested that the Vellinga’s equations should be calibrated for steep non-equilibrium profiles. With the purpose of developing a simple tool to predict the erosion of the B&D sections for steep non-equilibrium profiles.

5.2. **UNIBEST – LT**

UNIBEST-CL+ is a software package that is developed to calculate longshore transports and the effect of transport gradients on a coastline. UNIBEST is an acronym for UNIform BEach Sediment Transport and consists of two separate modules: the Longshore Transport-module (LT) and the Coastline Evolution-module (CL). The LT-module is designed to calculate tide- and wave-induced longshore sediment transports along a coast while the effect of longshore transport gradients can be investigated in the CL-module.

For the LT-module the following data is required: wave/current scenario, cross shore profile, wave parameters, transport parameters and a coastline orientation angle. The wave/current scenario describes the wave climate and the tide information that is used
for the computation. Different cross shore profiles can be defined to account for the effect of the profile on the longshore current generation. A number of wave parameters (i.e. coefficients for wave breaking, bottom friction and bottom roughness) can be defined. However, for most cases default values can be used. The following transport formulae can be applied in the UNIBEST LT-module: Bijker (sand), Van Rijn (sand), CERC (sand), Van der Meer/Pilarczyk (gravel).

From the coastline input, the model defined rays, based on the $S$-$\phi$ curve (sediment transport as a function of the coastline orientation). The simulation will result in a transport, estimated over a year, within the rays.

5.2.1. Model input

The schematized storm conditions were used as input for the boundary conditions of simulation: wave height of 2.5 m, period of 6 s and incoming direction of $290^\circ$ and maximum water level of 1.43 m. The storm duration was set as 6 days. The wave parameters, porosity, bottom friction and roughness, fall velocity and current parameters were set as default values. The sediment transport formula chosen was Van Rijn (1992). A $d_{50}$ of 320 $\mu$m was chosen to represent the outer contour sediment size and a $d_{90}$ of 370 $\mu$m, was used.

The coastline was defined by providing the model with the coast normal angles of different points of the coast. These points correspond to an average coastline of each box (from the data analysis, Chapter 4). Rays were defined for each point of the coastline in which the sediment transport gradients were calculated. Different cross-shore profiles were defined for the north, center and south areas. The profiles used are schematization of the typical profile of each area (Figure 5.5).
Figure 5.5 Input profiles for UNIBEST-LT simulation. Schematized profiles were used for each area of the outer contour.

5.2.2. Results

The transport resulting from the UNIBEST-LT simulation is shown in Figure 5.6. It can be seen that the general transport trend is represented rather well. The shift in direction of the longshore current occurs in ray 18, and the longshore current increase to the south, until ray 11, and increases to the north until box 24, generating positive gradients. Similar to what occurred in reality, seen in the data analysis. From ray 10 to 9 there is a decrease in the longshore current, and it from ray 9 to 1 no longshore current is generated according to the model.
Figure 5.6 Sediment transport result from the UNIBEST-LT simulations for each box.

The main difference between the model results and the measured values is the order of magnitude of the transport, which is seen in Figure 5.7. Here the balance (what comes in minus what comes out of each ray) is calculated for the simulated transport. The UNIBST-LT results generated balance volumes of one order of magnitude greater than the measured volumes in the data analysis (Chapter 4).

It is also seen that highest erosion volumes and large deposition volumes do not occur in the same location (Figure 5.7). However, the coast orientation was defined by average values and therefore the variability of the coastline within each ray is not taken in account. Another process that is not accounted for is the erosion that occurs at the ends of the center and north outer contour, where the profile constructed above NAP is becomes submerged. In these locations the current increases due to vortex formation and the net erosion volumes increase significantly. This difference is show in Figure 5.7, when comparing the UNIBEST-LT with the measured values in box 10. UNIBEST predicts a large sedimentation volume and in reality erosion occurs.
Figure 5.7 Comparison between longshore transport results from UNIBEST-LT simulations and net volume change per meter alongshore derived from the net volumes calculated in the data analysis (Chapter 4). The arrows indicate the direction of the longshore current.

The main finding from the UNIBEST-LT simulations is that when the balance volumes are summed, the net erosion volume found is only 6% smaller than the net erosion calculated in the volume balance (230,600 m$^3$ and 246,100 m$^3$, respectively). Taking into account the inaccuracies of the data analysis calculation (mainly accounting for production) and the inaccuracies of the UNIBEST-LT simulations (mainly average coast orientation), the result is comparable.

The simulation done here was very simple, in particular concerning the storm schematization, where only one set of wave condition was used. Even so, it demonstrated that UNIBEST has some potential in estimating rough net volume balance volumes, and the general erosion and sedimentation trends.

Further analysis and simulations would have to be carried out, in order to accurately evaluate the model’s capacity. It is thought nevertheless, that a first assessment of the longshore response of a profile to a storm event can be done with this model.
Chapter 6- Process-based Tool

Previous chapters show that the response of a steep non-equilibrium profile is hard to successfully simulate using existing (semi-) empirical tools. It behaves differently mostly concerning the extent of the erosion and retreat of the coastline. Steep non-equilibrium profiles respond faster to changes then in hydraulic condition with rather large volumes transported in both cross-shore and longshore direction.

The (semi-) empirical models applied in Chapter 5 were not completely successful in predicting the morphological response, of the profile in either the cross or longshore direction and gave only rough estimates, and over and underestimating the profile response. Furthermore, Chapter 4 indicates that cross-shore and longshore processes occur simultaneously, which makes it difficult to identify which processes occurred due to longshore or cross-shore forcing.

The process-based XBeach model is therefore, applied in 1D vertical (1DV) to represent the morphological behavior of the MV2 outer contour, concerning the development of the cross-profile. First the model will be shortly described and results of the simulations will be presented and discussed next.

6.1. XBeach model description

XBeach is a process-based model that simulates coastal profile response in particular to extreme events. It is an open source program, developed as part of the Morphos-3D project that was initiated by the Engineer Research Development Center of the United State corps of Engineers (USACE-ERDC). The model includes wave breaking, surf and swash zone processes, dune erosion, overwash and breaching (Roelvink et. al, 2009). A detailed description of the model can be found in Roelvink et al., 2009.
This model is a process-based model, in which the boundary conditions input are updated from the morphological output (Figure 6.1).

![Diagram showing the process-based XBeach model input, output and updating scheme]

**Figure 6.1 Representation of the process-based XBeach model input, output and updating scheme**

The model solves coupled 2D horizontal equations for wave propagation, flow, sediment transport, and bottom changes, for varying wave and flow conditions. It also solves long wave motions. The cross-shore erosion processes are modeled in four different regimes: swash, collision, overwash and inundation (cf. Sallenger, 2000).

The numerical implementation is an upwind scheme (Stelling and Duinmeijer, 2003) with first order accuracy. With this schematization a proper calculation of the spatial and temporal gradients is ensured, in the nearshore and the swash zone, which combined with a rectilinear non-equidistant staggered grid makes this a robust model (Roelvink et al., 2009).

Bed levels, water levels, water depths and concentrations are defined at the center of the computational cells and velocities and sediment transports at the cell interfaces. The wave energy balance, the roller energy and the radiation stress are also calculated at the center of the cells. Radiation stress gradients are calculated at the cell interfaces.
The model is forced by a time-dependent wave action balance solver, which calculates wave refraction. It takes in account directional spreading, simulates short wave propagation and calculates energy dissipation of wave groups. In addition, wave-current interaction is included. The Generalized Lagrangean Mean (GLM) approach is used to couple depth-averaged flow velocities which are translated into Eulerian flows to take into account undertow effects. The Eulerian flow velocity is used in the formulation of bed shear stresses and sediment transport (Roelvink et al., 2009).

XBeach makes use of two different equilibrium sediment concentration formulations which compute the source to a sediment advection-diffusion equation, producing transport vectors. The transport vectors are used for morphological updating. The sediment concentration equations are the Soulsby-Van Rijn (1997) equation and the adapted Van Rijn (2007) equation (Van Thiel de Vries, 2009). In the Soulsby-van Rijn equation sediment is stirred up by the Eulerian mean and infragravity velocity in combinations with the near bed short-wave orbital velocity, obtained from the wave-group varying wave energy using linear wave theory. A bed-slope correction factor has been introduced in the bed-update approximation to account for bed-slope effects.

For the simulations discussed in this thesis the adapted Van Rijn formulation is applied, in which the effect of wave breaking induced turbulence is included. An avalanching algorithm is introduced to update bed evolution during storm-induced dune erosion. Separate critical slopes are applied for dry and wet points. A morphological factor has been introduced in bed-update approximations to speed up bed evolution calculations.

### 6.2. Model Formulation

Wave forcing is obtained from a time-dependent wave action balance equation. Similar to the HISWA model (Holthuijsen, et al., 1989). Directional wave distribution is taken into account, whereas the frequency spectrum is represented by a mean frequency.

\[
\frac{\partial A_w}{\partial t} + \frac{\partial c_x A_w}{\partial x} + \frac{\partial c_y A_w}{\partial y} + \frac{\partial c_\theta A_w}{\partial \theta} = \frac{-D_w}{\sigma} \tag{6.1}
\]

- \(D_w \ [W/m^2]\) is the wave energy dissipation due to breaking, \(A_w \ [W/m^2]\) is the wave action, \(\sigma\) is the intrinsic wave frequency, \(c \ [m/s]\) is the wave action propagation speed and \(\theta \ [\circ]\) is the angle of incidence with respect to the x-axis.
The roller energy balance \((S_r)\) is coupled to wave action/energy balance, where the dissipation of the wave energy serves as a source term. Directional distribution is also taken into account and the frequency spectrum is represented here also by a mean frequency.

\[
\frac{\partial S_r}{\partial t} + \frac{\partial c_x S_r}{\partial x} + \frac{\partial c_y S_r}{\partial y} + \frac{\partial c_\theta S_r}{\partial \theta} = -D_r + D_w \tag{Eq. 6.2}
\]

where, \(D_r \text{ [W/m}^2\) is the roller energy dissipation, \(D_w \text{ [W/m}^2\) is the wave energy dissipation. The total wave dissipation is distributed proportionally over the wave directions. Since the roller energy also affects the wave forcing it has been included in the radiations stress calculation terms.

The wave-group varying short wave energy and direction are obtained from the wave-action balance result in the GLM-momentum equations are given by:

\[
\begin{align*}
\frac{\partial v^L}{\partial t} + u^L \frac{\partial v^L}{\partial x} + v^L \frac{\partial v^L}{\partial y} &= -\frac{\tau_{bx}^E}{\rho h} - g \frac{\partial \eta}{\partial x} + \frac{F_x}{\rho h} \\
\frac{\partial u^L}{\partial t} + u^L \frac{\partial u^L}{\partial x} + v^L \frac{\partial u^L}{\partial y} &= -\frac{\tau_{by}^E}{\rho h} - g \frac{\partial \eta}{\partial y} + \frac{F_y}{\rho h}
\end{align*} \tag{Eq. 6.3}
\]

For the x- and y-direction respectively.

Sediment transport is modeled with a depth averaged advection diffusion equation following Gallapatti (1983).

\[
\frac{\partial hC}{\partial t} + \frac{\partial hCU^E}{\partial x} + \frac{\partial hCU^E}{\partial y} + \frac{\partial}{\partial x} \left[ D_h \frac{\partial C}{\partial x} \right] + \frac{\partial}{\partial y} \left[ D_h \frac{\partial C}{\partial y} \right] = \frac{hC_{eq} - hC}{T_s} \tag{Eq. 6.4}
\]

where, \(C\) is the depth-averaged sediment concentration, which varies with infragravity time-scale, \(T_s\) is the adaptation time used to represent entrainment (a small \(T_s\) corresponds to a nearly instantaneous response) and \(C_{eq}\) is the equilibrium sediment concentration.

The bed change within one time step is given by:
\[ \Delta z_b = \min \left( \left( \frac{\partial z_b}{\partial x} - m_x \right) \Delta x, \ 0.05\Delta t \right), \frac{\partial z_b}{\partial x} > 0 \]

\[ \Delta z_b = \max \left( -\left( \frac{\partial z_b}{\partial x} - m_x \right) \Delta x, -0.05\Delta t \right), \frac{\partial z_b}{\partial x} < 0 \]

Where the estimated bed slope is given by:

\[ \frac{\partial z_b}{\partial x} = \frac{z_{b,j+1,j} - z_{b,j,j}}{\Delta x} \]

Eq. 6.5

Eq. 6.6

6.3. 1DV Model Input

6.3.1. Profile selection

Following from the data analysis (Chapter 4) three different cross-shore profiles are individually analyzed. The areas are indicated in Figure 6.2a by the red rectangles and represent boxes 11, 16 and 19 (see Figure 4.13). Boxes 11 and 16 were selected based on their shoreline orientation with respect to the angle of incidence (290°). The coastline in box 11 is southwest orientated and in box 16 it’s orientated to the west. Due to their orientation and profile characteristics the boxes exhibit different erosion and sedimentation patterns. Box 11 exhibits net sedimentation and box 16 exhibits a net erosion. In box 19 overwash occurred.

A mean cross-shore profile was generated for each location (Figure 6.2b) for both pre and post-storm profiles, the longshore morphological variability was small. The longshore averaged profiles were gridded using a varying cross-shore grid size and a constant longshore grid size. The cross-shore grid size varied from 21 m offshore to 5 m onshore, and the longshore grid size was 10 m.
Figure 6.2 (a) Boxes selected for simulation input. (b) A 3D view of pre-storm selected profiles. (c) Averaged profiles. Blue: pre-storm. Red: post-storm.
6.3.2. Boundary conditions

Wave and water level boundary conditions were input as a three hour averaged measured time series, and are described in Chapter 3. The wave input was composed of spectral wave height ($H_{m0}$), wave periods ($T_{m1}$) and wave direction ($\theta$). The simulation period was in total 90 h initiating half a day before the 2 m wave heights occurred and a day after the wave conditions subsided. Approximately from the 3rd to the 6th of September (Figure 6.3). The 1DV simulations presented in this Thesis do not take in account directional spreading, therefore the wave direction was assumed to be normal to the shoreline.

A water level time-series composed of water level variation was used as input (Figure 6.3). The maximum water level recorded was of 1.43m.

![Figure 6.3. Storm wave and water level time-series for box 11. The period between the black lines corresponds to the simulated period.](image)

Sediment characteristics were included in the model only concerning $d_{50}$. For each simulated profile a different $d_{50}$ was chosen according to the production information for that particular location. The $D_{50}$ for boxes 11 and 16 was of 300 $\mu$m, and for box 19 it was of 370 $\mu$m.
Some empirical constants have to be defined in the XBeach model to parameterize physical processes like short wave hydrodynamics, flow, sediment transport, and bed update. Since no measurements are available to calibrate the hydrodynamics of the model, default values are used for this version of XBeach concerning short wave hydrodynamics and flow characterization based on Van Thiel de Vries (2009) (see Appendix 4).

6.4. 1DV simulation results

The results of the XBeach model simulations will be discussed and compared to the results obtained from the data analysis (Chapter 4) concerning profile shape and erosion and sedimentation volumes. Correspondingly, the simulated profile was also divided in four sections according to the section division of Chapter 4: beach and dunes, foreshore, shoreface and shore foundation (B&D, FS, SF and FND, respectively).

The simulation results are presented and discussed below.

6.4.1. Box 11 simulations

The bed level of the pre-storm profile to the post-storm profile is shown in Figure 6.4. Analyzing the cross-shore profile development of the simulated post-storm profile indicates that a milder slope is formed during the storm. Sediment is eroded from the beach and dune front and is transported to the shore face and foundation sections where it deposits. The transition point between erosion and sedimentation areas occurs at approximately -2 m NAP.

The morphological evolution of the four sections of the cross-shore profile during the storm is presented in Figure 6.5. The change in volume (m$^3$) is shown for every 15 hours (h). The evolution of the FS, SF and FND sections reaches equilibrium in volume change around hour 45 h (approximately 05-Sept, Figure 6.3). The change in volume of the B&D continues to increase in time.
Figure 6.4 XBeach simulation results for box 11. Dashed line: Initial profile. Solid line: simulation result. Red line: measured post-storm profile. In detail are the upper profile and the lower profile results.
Table 6.1 Simulated and measured erosion and deposition volumes for Box 11 (m$^3$)

<table>
<thead>
<tr>
<th>Volume [m$^3$]</th>
<th>B&amp;D</th>
<th>FS</th>
<th>SF</th>
<th>FND</th>
<th>Volume Transported</th>
<th>Sediment loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulated</td>
<td>-3,400</td>
<td>-2,200</td>
<td>4,400</td>
<td>1,300</td>
<td>11,300</td>
<td>-4</td>
</tr>
<tr>
<td>Measured</td>
<td>-13,600</td>
<td>1,100</td>
<td>15,450</td>
<td>7,100</td>
<td>37,300</td>
<td>10,100</td>
</tr>
<tr>
<td>Difference%</td>
<td>75</td>
<td>296</td>
<td>72</td>
<td>82</td>
<td>70</td>
<td>100</td>
</tr>
</tbody>
</table>

% = (V$_{measured}$ – V$_{simulated}$)/V$_{measured}$

Comparing the simulation results with the measured post-storm profile (Figure 6.6 and Table 6.1), indicates that the eroded volume for the B&D section was underestimated with 75%. The FS sedimentation volume was underestimated in the order of 296%. The latter value can be explained by the fact that in reality a net sedimentation occurred on the FS (Figure 6.4). The sedimentation volumes of the SF and FND were also underestimated (72 and 82%, respectively). Table 6.1 shows that the simulated results indicate a net volume of approximately 0 m$^3$. This implies that there is volume conservation for the XBeach simulation.

![Figure 6.5 Morphological evolution in time of each cross-shore section of box 11 for the beach and dunes, foreshore, shoreface and shore foundation (B&D, FS, SF and FND, respectively).](image)
Morphological behavior of a non-equilibrium coastal profile
The response of the MV2 outer contour to a storm event

Figure 6.6 Simulated and measured erosion and sedimentation volumes (m³) for each cross-shore section of box 11
6.4.2. Box 16 simulations

The simulation of box 16 demonstrated a similar cross-shore trend as for box 11 (Figure 6.9 and Figure 6.7). Although there is more erosion, which agrees with the data presented in Chapter 4. Sand was eroded from the B&D section and supplied to the swash and surf zone by the return flows. Erosion occurred until approximately -2 m of depth, which is the transition point between erosion and sedimentation.

The morphological evolution of the cross-shore profile of box 16 during the storm is presented in Figure 6.8. The SF and FND sections reach equilibrium in about 75 h (approximately 06-Sept, Figure 6.3). The change in volume in the FS section apparently begins to decrease after 60 h. The B&D volume curve does not stabilize within the 90 h.

The comparison of the simulation results with the measured post storm profile (Figure 6.7) it occurs that the erosion volumes of the B&D and FS was underestimated in the order of 63% and 65%, respectively (Figure 6.9). The sedimentation volume in SF was underestimated by 2% and the sedimentation of the FNDs is overestimated by 323%. Subtracting the erosion from the sedimentation volume, indicates volume continuity.

Table 6.2 Simulated and measured volumes for box 16 (m$^3$)

<table>
<thead>
<tr>
<th>Volume [m$^3$]</th>
<th>B&amp;D</th>
<th>FS</th>
<th>SF</th>
<th>FND</th>
<th>Volume Transformed</th>
<th>Sediment loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculated</td>
<td>-9,900</td>
<td>-4,200</td>
<td>10,000</td>
<td>4,100</td>
<td>28,100</td>
<td>-2</td>
</tr>
<tr>
<td>Measured</td>
<td>-26,700</td>
<td>-12,000</td>
<td>10,150</td>
<td>1000</td>
<td>49,800</td>
<td>-27,500</td>
</tr>
<tr>
<td>%</td>
<td>63</td>
<td>65</td>
<td>2</td>
<td>-323</td>
<td>43</td>
<td>100</td>
</tr>
</tbody>
</table>

$\% = \frac{(V_{measured} - V_{simulated})}{V_{measured}}$
Figure 6.7 XBeach simulation results for box 16. Dashed line: Initial profile. Solid line: simulation result. Red line: measured post-storm profile. In detail are the upper profile and the lower profile results.
Figure 6.8 Morphological evolution in time of each cross-shore section of box 16 for the beach and dunes, foreshore, shoreface and shore foundation (B&D, FS, SF and FND, respectively).

Figure 6.9 Simulated and measured erosion and sedimentation volumes (m$^3$) for each cross-shore section box 16.
6.4.3. Box 19 simulations

Due to the lower elevation of the cross-shore profile of box 19 overwash was simulated as also observed in the data (Chapter 4) (Figure 6.10). The simulation overestimated the erosion on the top of the profile (B&D section), whereas erosion was underestimated on the FS section (Figures 6.9 and Figures 6.11). The underestimation of the deposition on the back of the barrier (east side of the structure) is only apparent. Production occurred at that location, and therefore it is difficult to quantify what is production (from the pre-storm profile) and what is deposition volume. For that reason there is a net loss of 10,800 m$^3$ shown on Table 6.3 Simulated and measured volumes (m$^3$) for Box 19.

The dune height reduced significantly due to overwash and an eastward shift of the profile is observed in the simulation results, as well as in the data. The transition between erosion and sedimentation areas on the sea-side of the cross-shore profile (west) is observed here below around -5 m, differently then what was observed in boxes 11 and 16.

There was less FS erosion in the simulation then on the post-storm profile (Figure 6.10 and Figure 6.11). On the XBeach simulation the dune is breached faster than in reality since the incidence angle was defined to be coast-normal. After the dune is breached there is no more wave attack on the beach front and therefore less erosion.

The morphological evolution of the profile sections during the storm is presented in Figure 6.11. The volume change of the FS, SF and FND sections reach equilibrium in around hour 45 h (approximately 05-Sept, Figure 6.3). The change in volume of the B&D continues to increase significantly in time, most likely due to the overwash process.

In table 6.3 it can be seen that from the eroded 13,900 m$^3$ only 3,100 m$^3$ was deposited in the SF and FND section (in order of 22%). Therefore, volume conservation cannot be observed in this profile due to the transport of sediment to the back of the dune. Less deposition occurred in the FND, in the simulation, than in the measured post-storm profile (in order of 79%), as well as, 19% and 79% less erosion occurred in the B&D an FS sections respectively. A smaller difference in sedimentation volume is seen in SF section where the simulated profile underestimated in 12%. 
Figure 6.10XBeach simulation results for box 19. Dashed line: Initial profile. Solid line: simulation result. Red line: measured post-storm profile. In detail are the upper profile and the lower profile results.
Morphological behavior of a non-equilibrium coastal profile
The response of the MV2 outer contour to a storm event

Table 6.3 Simulated and measured volumes (m$^3$) for Box 19

<table>
<thead>
<tr>
<th>Volume [m$^3$]</th>
<th>B&amp;D</th>
<th>FS</th>
<th>SF</th>
<th>FND</th>
<th>Volume Transported</th>
<th>Sediment loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculated</td>
<td>-12,200</td>
<td>-1,700</td>
<td>2,200</td>
<td>900</td>
<td>17,000</td>
<td>-10,800</td>
</tr>
<tr>
<td>Measured</td>
<td>-15,100</td>
<td>-16,000</td>
<td>2,500</td>
<td>4,300</td>
<td>37,900</td>
<td>-24,200</td>
</tr>
<tr>
<td>%</td>
<td>19</td>
<td>90</td>
<td>12</td>
<td>79</td>
<td>55</td>
<td>55</td>
</tr>
</tbody>
</table>

$\% = (V_{\text{measured}} - V_{\text{simulated}})/V_{\text{measured}}$

Figure 6.11 Morphological evolution in time of each cross-shore section of box 19 for the beach and dunes, foreshore, shoreface and shore foundation (B&D, FS, SF and FND, respectively).
Figure 6.12 Simulated and measured erosion and sedimentation volumes (m$^3$) for each cross-shore section box 16.
6.5. Discussion

The XBeach model simulated the cross shore response for each profile rather well. The erosion volumes, in particular on the B&D section were in general underestimated. And the sedimentation volumes varied from profile to profile. Box 19 was the profile where the results varied the most, due to the overwash process that occurred at that location.

The XBeach simulation results, with the exception of the box where overwash occurred (box 19), volume conservation is observed. Approximately the same volume eroded on the upper profile is deposited on the lower profile. This is expected since in 1DV simulations longshore processes are not included. In overwash that was not observed since we are taking in consideration only the sea-side (west) of the structure. It is difficult to quantify the discharge of the overwash over the barrier with accuracy, in reality, since production occurred simultaneously in that area.

When the volumes are compared to the measured post-storm profile volumes, generally, an underestimation of the erosion volumes of the B&D section occurs. The underestimation of erosion is larger in box 16 than in 11. The total net sedimentation on the lower part of the profile (SF and FND) is underestimated in box 11 (O 75%) and slightly overestimated in box 16 (O 26%). Box 19 will be discussed separately.

The under and overestimations of the erosion and sedimentation volumes, in boxes 11 and 16, relate to the shoreline orientation in relation to incident wave angle. Therefore, the 1DV simulation does not take into account the longshore component of the radiation stress. And consequently, does not consider the effect of the longshore current on the profile. It was suggested in the data analysis (Chapter 4) that the longshore current transports substantial amounts of sand away from the cross-shore profiles, and that there are sharp gradients in transport due to the MV2’s curvature. Thus, the post-storm simulated profile cannot be directly compared with the measured post-storm profile.

Thereupon, the differences in erosion and sedimentation volumes as observed for the simulated and measured post-storm profiles can be attributed to the gradients present in the longshore current and associated sediment transport. Figure 6.13 shows
schematizations of the longshore transport gradients and the cross-shore fluxes for boxes 11 and 16.

The position of box 16 is in the center part of the structure (Figure 6.2a), where there is a strong longshore transport gradient (Chapter 4). In this location the transport capacity increases and therefore, a percentage of the sediment eroded from the B&D and FS sections is transported towards the south, and not deposited on the SF and FND sections. This transport prevents the formation of a new equilibrium profile in the FS section, and hence enables the wave attack to continue to erode the B&D with the same intensity, differently then what occurs in reality, which explains the underestimation of the B&D erosion volume.

During the XBeach simulations sediment eroded from the B&D and FS settles on the SF and FND forming a less steep profile, which dissipates the wave energy further from the beach.

The same reasoning explains the slightly overestimation of the sedimentation volume in box 16. It is expected that the volume eroded from the B&D section deposits on the lower profile, due to the return flow. However, since the sediment eroded is being transported out of the cross-section and the sedimentation volume is smaller than the eroded volume, the simulation presented less erosion on the upper profile and more deposition on the lower part of the profile, than compared to the data.
Figure 6.13 Schematization of the main longshore transport gradients and the cross-shore fluxes for boxes 11 and 16. Blue: erosion area. Yellow: sedimentation area. The size of the arrow indicates the gradient in longshore transport. B&D, FS, SF and FDN are the beach and dunes, foreshore, shoreface and shore foundations cross-sections, respectively. The size of the arrows indicate the magnitude of transport in either the longshore direction (from left to right, or vice versa) or the cross-shore direction (from top to bottom).

Basically the same process occurs in box 11. Except the gradient in the longshore transport is negative (Figure 6.13) and instead of transporting sediment out of the profile, sediment incoming from other profiles will be deposited here. The sediment deposited coming from other profiles in addition to the cross-shore eroded volume generates the difference in sedimentation volumes from simulated to measured results.

The time-scales between longshore transport deposition and cross-shore development are different (Stive et al., 1992; Steetzel, 1993). Deposited sand incoming from other profiles takes longer to arrive at the profile, then the eroded sand from the beach and dune takes to arrive at the lower part of the profile.

Therefore, speaking only in terms of cross-shore development, the underestimation of the dune erosion occurs in the same way as it does for box 16. The longshore current transports sediment put into suspension from the beach and dune erosion away from the profile, preventing an adjustment of the profile to the storm conditions by enabling the wave attack.
Overestimation of the erosion of the dune top in box 19 occurs and is explained as follows. The flow velocities generated by overwash on the top of the dunes increase into sheet flow conditions. In this conditions there is a linear relationship between flow velocity and sediment transport. Different than the exponential relation for lower flow conditions, as observed in coastal processes in general. XBeach makes use of sediment transport equations developed to represent these coastal processes and therefore, does not represent well transport by overwash. To better represent the measured results a coefficient would need to be introduced (parameter smax) to account for the effect of the sheet flow velocities on the sediment transport (McCall, 2010).

![Diagram](https://via.placeholder.com/150)

**Figure 6.14 Schematization of the longshore transport gradients and the cross-shore fluxes for box 19. Blue: erosion area. Yellow: sedimentation area. The size of the arrow indicates the gradient in longshore transport. B&D, FS, SF and FDN are the beach and dunes, foreshore, shoreface and shore foundations cross-sections, respectively. The size of the arrows indicate the magnitude of transport in either the longshore direction (from left to right, or vice versa) or the cross-shore direction (from top to bottom).**

**6.5.1. Summary of the XBeach simulations**

By comparing the final simulation profile with the post-storm measured profile the effect of the longshore transport on the outer contour is made clear. Where erosion occurs due to a positive gradient in transport, sedimentation is overestimated by the model (box 16). Where sedimentation occurs due to a negative gradient in longshore transport, sedimentation is underestimated (box 11).
The XBeach simulations also demonstrate the temporal scale of the cross-shore development, made possible by the morphological feedback at each time step, and also the exact length of the erosion and sedimentation zones, with a morphological depth of closure of approximately -10 m for all boxes, as was also observed in the data (Chapter 4). In all simulations the development of the FS, SF and FND, stabilizes at 45 h, while the B&D section stabilizes only from 45h to 60h following the peaks and troughs of the storm.

The XBeach model also simulated overwash rather well, taking in account that the proper parameters to account for the increase in flow velocities on the top of the barrier were not used.
Chapter 7 - Conclusions and Recommendations

7.1. Conclusions

The data analysis clearly demonstrated that a non-equilibrium profile suffers greatly from the effects of hydraulic storm conditions exhibiting large erosion volumes in a small-temporal scale. The semi-empirical tools used to try to hindcast the results of the data analysis, in general underestimated the response of the profile. However, they were very insightful in understanding the profile response in reality. The XBeach model simulations yielded interesting results, simulating the cross-shore profile response quite well. These results should be further analyzed and improved to try to obtain a simple tool to predict the response of a non-equilibrium profile, and also to analyze the profile response time-scale, and the characteristics of the development of each profile section (beach, foreshore and shoreface). In a 1DV simulation however, the longshore processes are not accounted for, and thus, it is difficult to compare the simulations with the data analysis results. In order account for both longshore and cross-shore processes a 2DH/3D model needs to be implemented.

The main conclusions per chapter are presented below.

Data analysis

- Steep non-equilibrium profiles exhibit large upper profile erosion, even during a mild storm. Due to the occurrence of gradients in the longshore transport most of the eroded volumes were transported away from their profile to be partly deposited within the outer areas of the contour. The main findings are:
  - No volume balance was found within the active morphological zone of the outer contour. A net erosion volume of 246,300 m³ was lost from the outer contour, representing 27% of the total sand moved. 18% of this volume was lost to border and 18% was lost to the north.
- The cross-shore profile responded to the storm by transporting the eroded sand to the surf zone, by the return flows, depositing what was not transported away by the longshore current to the shoreface and shore foundation sections.
The beach and dunes erosion volumes were larger where the profiles were steeper (center area), especially concerning the slope of the profile above -3 m NAP. The steep and less steep profiles suffered differently from the wave attack and longshore current due to the curvature of the structure. Where the profile’s exhibit a more gradual slope, the gradients in the longshore current were smaller, and the steeper profiles are located in the maximum curvature point of the outer contour.

Concerning cross-shore profile development it is observed from the comparison between pre and post-storm profiles, that after the storm the profile tends to a gentler slope, with an s-shape development, which characterizes an equilibrium profile. It is also seen that no sediment is lost offshore form the cross-shore profile, and that the morphological depth of closure is in average -10 m (NAP), along the outer contour (for the areas where the profile elevation reaches above water level (NAP).

(Semi-) empirical models

**Bruun rule applied to steep profiles subject to storm**

The results of the Bruun rule using Vellinga’s approach highly underestimate the retreat, with a factor varying between 5 and 7. The only exception was in the area were overwash occurred were and with a difference in $O10\%$.

Using the length of erosion/sedimentation zone measured from the profile bathymetries instead of using Vellinga’s equation different results were found for different parts of the outer contour. In the part where the profiles exhibit the steepest slopes the retreats calculated were underestimated by a factor of approximately 2. Where the profile profiles represent a milder steep slope the difference of the dune retreat was in $O7\%$ to $O10\%$.

When the depth of closure and the length of sedimentation/erosion zone were estimated from profile observation a similar results were found. The area that exhibits a large foreshore section similar to a nearshore bank the simulation a better agreement was found. The retreat was overestimated in overwash section by a factor ranging from 1.5 to 3 and underestimated in other sections by a factor of 1.5. Where the profile profiles represent a milder steep slope underestimated by a factor ranging from 2 to 1.2.
Two hypotheses were formulated to explain why Vellinga’s erosion/sedimentation length equation may not be applicable to steep non-equilibrium profiles, taking in consideration Vellinga’s assumptions:

1) Due to the steepness of the profile of the MV2, the eroded sediment is transported further (deeper) on the lower profile, then what is accounted for in Vellinga’s approach. His equation yields a smaller erosion/sedimentation zone that what is observed in reality.

2) The shape of the profile used by Vellinga to derive or test his equation is different than the initial profile of the MV2, in particular from boxes 13 to 17. Therefore, in this case the initial profile does affect the development of the storm profile, and can be responsible of the underestimations of the retreat in all the cases for these boxes.

From the three different attempts to apply the Bruun rule to steep non-equilibrium profiles, it is concluded here that the underestimation of the retreats from boxes 13 to 17 and the good simulation of the retreats of boxes 11 and 12, is most likely due to a combination of the longshore effect, the length of the sedimentation zone, and the influence of the shape and steepness of the initial profile.

The application of Bruun rule needs further assessment to better evaluate under steep profiles subjected to storms conditions. It is suggested that the Bruun rule behaves differently for steep profiles exhibit: (1) a large foreshore section similar to a nearshore bank were the results are overestimated; (2) the steepest slopes where the retreats calculated were underestimated; (3) a milder steep slope where the difference of the dune retreat was well simulated and; (4) in the overwash zone where the results were inconclusive.

**UNIBEST –LT**

The UNIBST-LT results generated balance volumes of one order of magnitude greater than the measured volumes in the data analysis. In the sections where the profile was constructed above NAP (submerged) were erosion volumes increase significantly UNIBEST predicts a large sedimentation volume. But in the overall volume balance is done the
calculated erosion volume is only 6% smaller than measured (230,600 m$^3$ and 246,100 m$^3$, respectively). Taking in account the inaccuracies of the data analysis calculation (mainly accounting for production) and the inaccuracies of the UNIBEST-LT simulations (mainly average coast orientation) the result are in good agreement.

Even though, the simulation done in this study was very simple, in particular concerning the storm schematization, where only one set of wave condition was used, there is indication that UNIBEST has potential in estimating rough net volume balance volumes, and the general erosion and sedimentation trends. Further analysis and simulations would have to be carried out, in order to accurately evaluate the model’s capacity. It is thought nevertheless, that a first assessment of the longshore response of a profile to a storm event can be done with this model.

**Process-based Models**

From the XBeach simulations, with the exception of the box where overwash occurred (box 19), volumes conservations is observed. Approximately the same volume eroded on the upper profile is deposited on the lower profile, which means that conclusions could be made in relation to the cross-section profile.

When the volumes are compared to the measured post-storm profile volumes, in general, an underestimation of the erosion volumes of the B&D section occurs. The total net sedimentation on the lower part of the profile (SF and FND) is underestimated in box 11 ($O75\%$) and slightly overestimated in box 16 ($O26\%$). The under and overestimations of the erosion and sedimentation volumes, in boxes 11 and 16, are both due to the longshore variability of the MV2 profile, in particular in relation to the shoreline orientation in relation to incident wave angle. The 1DV simulations do not take into account longshore component of the radiation stress. And therefore, do not consider the effect of the longshore current on the profile. The longshore current transports significant amounts of sand away from the cross-shore profiles, and that there are sharp gradients in transport due to the MV2’s curvature. Thus, the post-storm simulated profile cannot be directly compared with the measured post-storm profile.
Morphological behavior of a non-equilibrium coastal profile
The response of the MV2 outer contour to a storm event

By comparing the final simulation profile with the post-storm measured profile the effect of the longshore transport on the outer contour is made clear. Where erosion occurs due to a positive gradient in transport, sedimentation is overestimated by the model (box 16). Where sedimentation occurs due to a negative gradient in longshore transport, sedimentation is underestimated (box 11).

The XBeach simulations also demonstrate the temporal scale of the cross-shore development, made possible by the morphological feedback at each time step, and also the exact length of the erosion and sedimentation zones, with a morphological depth of closure of approximately -10 m for all boxes, as was also observed in the data (Chapter 4). In all simulations the development of the FS, SF and FND, stabilizes at 45 h, while the B&D section stabilizes only from 45h to 60h following the peaks and troughs of the storm.

The XBeach model also simulated overwash rather well, taking in account that the proper parameters to account for the increase in flow velocities on the top of the barrier were not used.

7.2. Recommendations

- Analyze the existent data for other storms to identify the similarities and disparities in longshore and cross-shore response. In order to better understand the behavior of non-equilibrium profiles in response to a storm.
- Determine the relation between profile steepness and erosion volumes, through a correlation analysis.
- Analyze the response of the outer contour in a longer timescale to normal hydraulic conditions. To assess what is the effect of wave asymmetry and other processes that dominate in normal conditions.
- Analyze the effect of the tidal currents on the morphological response of the profile during a storm and in normal conditions.
- Test Bruun rule applied to storm in a steep non-equilibrium profile where there is a smaller or no effect of the longshore component and also test it for more steep profiles (typical profile of the center of the outer contour). In order to confirm factor 2 for the underestimation. If the factor is confirmed, a simple rule of thumb can be derived for the B&D retreat in storm events.
Further analysis and simulations with UNIBEST should be carried out, in order to accurately evaluate the model’s capacity of the model to represent the morphological process, due to the simplicity of the simulation done in this thesis.

Improve 1D XBeach simulation to also take into account the LS processes, by e.g. inserting a coefficient for sedimentation time that corresponds to the longshore transport effect. Or run model half of the simulation time then take out deposition and run model again. In this way preventing the development of the shoreface (bar formation) enabling wave attack on the beach and dunes.

Calibrate the XBeach model further for a better understanding of the time scales and the effect of the each forcing on the cross-shore response to the storm.

Carry out a 2DH simulation with XBeach to evaluate how well the model represents a non-equilibrium profile response to the storm and to for a better understanding of the effects of the different forcing.

The lines in the volume change figure per time reflect an exponential function \( V = A(1 - \exp(-B*t)) \). Where \( A \) (\( m^3 \)) and \( B \) (1/h) are empirical constants (XBeach simulation results). \( 1/B \) is the e-folding time scale for which the volume anomaly decreases to 1/e of its previous value. It discriminates between a non-equilibrium and an equilibrium condition. Thus, by fitting this exponential function to the curves of each section it is possible to obtain the typical adaptation time scale of the cross-shore development. By obtaining the adaptation time-scale of steep non-equilibrium profiles to reach an equilibrium condition, this time-scale can be compared to known adaptation time-scales of natural profiles (gentler slopes), and a relation between them can be derived. In this manner, the analysis described above is suggested as an important follow up to the study done in this thesis.
Morphological behavior of a non-equilibrium coastal profile

The response of the MV2 outer contour to a storm event

References


Galapatti, R., 1983. A depth integrated model for suspended transport. Report 83-7, Communications on Hydraulics, Department of Civil Engineering, Delft University of Technology

Loman, G. 2009. Personal Communication concerning survey, storm and production data from the Maasvlakte2. PUMA.


Morphological behavior of a non-equilibrium coastal profile
The response of the MV2 outer contour to a storm event


Figure 4.3 (a) Depth contour map of the outer contour structure of the Maasvlakte-2. Dashed lines indicate North, Central and South parts of the structure. (b) Map of the difference in elevation before and after the storm of September 2009. Brown rectangles indicate production areas. In both maps the numbers refer to the text.
Morphological behavior of a non-equilibrium profile
The response of the MV2 outer contour to a storm event
Figure 4.6 Difference map indicating box dimensions, location, and the number of each box used in the volume balance calculation. (a) Wide boxes: west and east side of the structure combined. (b) Narrow boxes: west side of the structure, directly subject to storm impact.
Figure 4.14 Physical conceptual plot of the response of the MV2 outer contour to the September 2009 storm. The sediment movement is indicated by the longshore and cross-shore fluxes.
## Appendix 4 - XBeach Input Parameters

### Wave input

<table>
<thead>
<tr>
<th>Variables</th>
<th>Variable Description</th>
<th>Units</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>break</td>
<td>option breaker model</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>hmin</td>
<td>threshold water depth for undertow</td>
<td>[m]</td>
<td>0.2</td>
</tr>
<tr>
<td>gamma</td>
<td>wave breaking dissipation coefficient</td>
<td></td>
<td>0.50</td>
</tr>
<tr>
<td>alpha</td>
<td>wave breaking dissipation coefficient</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>delta</td>
<td>wave breaking dissipation coefficient</td>
<td></td>
<td>0.0</td>
</tr>
<tr>
<td>n</td>
<td>rho = 1000 [kg/m3] volumes density of water</td>
<td></td>
<td>1000</td>
</tr>
<tr>
<td>rho</td>
<td>gravitational acceleration</td>
<td>[m/s²]</td>
<td>9.81</td>
</tr>
<tr>
<td>thetamin</td>
<td>lower directional limit (angle with respect to computational x-axis)</td>
<td>[°]</td>
<td>-180</td>
</tr>
<tr>
<td>thetamax</td>
<td>upper directional limit (angle with respect to computational x-axis)</td>
<td>[°]</td>
<td>180</td>
</tr>
<tr>
<td>dtheta</td>
<td>directional resolution</td>
<td>[°]</td>
<td>360</td>
</tr>
<tr>
<td>wci</td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>instat</td>
<td>option time-varying wave boundary condition</td>
<td></td>
<td>41</td>
</tr>
<tr>
<td>bcfile</td>
<td>Boundary conditions file</td>
<td></td>
<td>waves163dhalf.lst</td>
</tr>
<tr>
<td>smag</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>nuh</td>
<td>horizontal background viscosity</td>
<td>[m²/s]</td>
<td>0.1</td>
</tr>
<tr>
<td>nuhfac</td>
<td>coefficient for roller induced horizontal viscosity</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>roller</td>
<td>roller model, 0 = off, 1 = on</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>beta</td>
<td>coefficient in roller dissipation model related to the wave surface slope (beta = sin(β))</td>
<td></td>
<td>0.1</td>
</tr>
<tr>
<td>swtable</td>
<td>table with stream function theory amplitudes to describe non-linear waves</td>
<td></td>
<td>RF_table.txt</td>
</tr>
<tr>
<td>rfb</td>
<td>beta is computed from parameterized wave shape, 0 = rfb is equal to beta defined above</td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>
### General input

<table>
<thead>
<tr>
<th>Variables</th>
<th>Variable Description</th>
<th>Units</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>nx</td>
<td>number of grid cells in (x)-direction</td>
<td></td>
<td>140</td>
</tr>
<tr>
<td>ny</td>
<td>number of grid cells in (y)-direction</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>vardx</td>
<td>0 = equidistant grid; 1 = non-equidistant grid</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>depfile</td>
<td>file that contains bathymetry</td>
<td></td>
<td>z_16.grd</td>
</tr>
<tr>
<td>xfile</td>
<td>variable gridsize file (x)</td>
<td></td>
<td>x_16.grd</td>
</tr>
<tr>
<td>yfile</td>
<td>variable gridsize file (y)</td>
<td></td>
<td>y_16.grd</td>
</tr>
<tr>
<td>xori</td>
<td>(x)-coordinate of computational grid origin in relation to the world ([m])</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>yori</td>
<td>(y)-coordinate of computational grid origin in relation to the world ([m])</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>alfa</td>
<td>grid orientation in relation to the world (\circ) ([\circ])</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>posdwn</td>
<td>vertical elevations defined positive downwards(= 1) or upwards (= -1)</td>
<td></td>
<td>-1</td>
</tr>
<tr>
<td>scheme</td>
<td>Numerical scheme for wave and roller energy: 1 = upwind, 2 = Lax-Wendroff</td>
<td></td>
<td>2</td>
</tr>
</tbody>
</table>

### Flow input

<table>
<thead>
<tr>
<th>Variables</th>
<th>Variable Description</th>
<th>Units</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>zs0file</td>
<td>initial water level file</td>
<td>([m])</td>
<td>waterlevels3dhalf.lst</td>
</tr>
<tr>
<td>tideloc</td>
<td>number of model corners where tidal or surge input time series are defined</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>C</td>
<td>Chezy value</td>
<td>([m^{1/2}/s])</td>
<td>65</td>
</tr>
<tr>
<td>eps</td>
<td>threshold depth</td>
<td>([m])</td>
<td>0.01</td>
</tr>
<tr>
<td>umin</td>
<td>threshold velocity upwind scheme</td>
<td>([m/s])</td>
<td>0.</td>
</tr>
<tr>
<td>tstart</td>
<td>start time of simulation output</td>
<td>([s])</td>
<td>0</td>
</tr>
<tr>
<td>tint</td>
<td>time interval output</td>
<td>([s])</td>
<td>100</td>
</tr>
<tr>
<td>tstop</td>
<td>stop time simulation (is duration simulation)</td>
<td>([s])</td>
<td>324000</td>
</tr>
<tr>
<td>CFL</td>
<td>maximum courant number</td>
<td></td>
<td>0.9</td>
</tr>
</tbody>
</table>
Morphological behavior of a non-equilibrium profile
The response of the MV2 outer contour to a storm event

### Sediment input

<table>
<thead>
<tr>
<th>Variables</th>
<th>Variable Description</th>
<th>Units</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>D50</td>
<td>D50 grain diameter</td>
<td>[m]</td>
<td>0.000304</td>
</tr>
<tr>
<td>#D90</td>
<td>D90 grain diameter</td>
<td>[m]</td>
<td>0.000375</td>
</tr>
<tr>
<td>rhos</td>
<td>volumes density of sand</td>
<td>[kg/m³]</td>
<td>2650</td>
</tr>
<tr>
<td>morfac</td>
<td>morphological acceleration factor</td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>morstart</td>
<td>start time morphology</td>
<td>[s]</td>
<td>0</td>
</tr>
<tr>
<td>por</td>
<td></td>
<td></td>
<td>0.4</td>
</tr>
<tr>
<td>dryslp</td>
<td>critical dry bed slope</td>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>wetslp</td>
<td>critical wet bed slope</td>
<td></td>
<td>0.10</td>
</tr>
<tr>
<td>hswitch</td>
<td>water depth at which is switched from a critical wet slope to a critical dry bed slope</td>
<td>[m]</td>
<td>0.1</td>
</tr>
<tr>
<td>dico</td>
<td></td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>form</td>
<td>option for equilibrium sediment concentration formulation</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>facua</td>
<td>coefficient for time averaged flow due to wave asymmetry, which is related to the phase shift between intra wave sediment suspension and flow</td>
<td></td>
<td>0.10</td>
</tr>
<tr>
<td>dzmax</td>
<td>maximum dune face erosion rate</td>
<td>[m³/ms]</td>
<td>0.17</td>
</tr>
<tr>
<td>turb</td>
<td>contribution wave breaking induced turbulence on equilibrium sediment concentration. 0 = no turbulence, 1 = wave averaged turbulence, 2 = bore averaged turbulence</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Tsmin</td>
<td>Minimum adaptation time scale for the sediment suspension</td>
<td>[s]</td>
<td>1</td>
</tr>
</tbody>
</table>

### Sediment output

<table>
<thead>
<tr>
<th>Variables</th>
<th>Variable Description</th>
<th>Units</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>nglobalvar</td>
<td></td>
<td></td>
<td>4</td>
</tr>
</tbody>
</table>