ERASMUS MUNDUS MSC PROGRAMME

COASTAL AND MARINE ENGINEERING AND MANAGEMENT
COMEM

FEASIBILITY STUDY OF A COUPLED NUMERICAL MODEL FOR LONGSHORE SEDIMENT TRANSPORT AND BEACH RESPONSE

University of Southampton
June, 2011

Zeng Zhou
24472492

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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

UNIVERSITY OF SOUTHAMPTON

FACULTY OF ENGINEERING, SCIENCE AND MATHEMATICS
SCHOOL OF CIVIL ENGINEERING AND THE ENVIRONMENT

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Zeng Zhou

A dissertation submitted in partial fulfilment of the degree of
MSc in Coastal & Marine Engineering & Management
(June 2011)

ABSTRACT

As a good rule of thumb, one-line models have been in use for a wide range of coastal projects for the past 30 years to predict the beach morphological change and make the appropriate shoreline management plans. Though applied to many coastal sites with certain success, these models are still under further development so as to achieve better predictions. Hence, this research aims to extend a state-of-the-art one-line model (BEACHPLAN) in terms of longshore sediment transport rate by linking with a cross-shore profile model (COSMOS) through the OpenMI-based Pipistrelle platform.

To couple these two existing models, three additional modules (i.e. Drift Interpolation module, Vector-To-Scalar module and Orientation Updating module) are developed. The existing two models and the three new modules work together as a whole composition (i.e. the coupled model) which aims to improve the one-line model in terms of longshore sediment transport and morphological response predictability. This coupled model calculates the longshore sediment transport rate based on both the modified CERC-formula and the Energetics approach. It is tested at an idealized straight coast and at Poole Bay, UK. This demonstrates that the model is numerically stable, effective in computing and able to give reasonable predictions of the shoreline morphological change. Hence, this dissertation shows that linking the existing models rather than developing completely new models is a potentially interesting research direction that is both economical and feasible to achieve. Some further developments of the model are also suggested.

However, it is currently too early to reach the conclusion that the coupled model is better than the original one-line model since few validations have been made due to the limitations of field data and research time. Meanwhile, the working principle behind the coupled model needs further exploration and re-examination before a sound conclusion can be made. Therefore, the outcome of this research at this stage can be more precisely recognized as a proof of concept which demonstrates that it is theoretically reasonable and technically feasible to couple the one-line model and cross-shore profile model so as to realize practitioners' certain requirements.

ACKNOWLEDGMENTS

This MSc research is carried out at Coasts and Estuaries Group of HR Wallingford with the financial support from CEM-Stage3 Research Project. Many thanks go to Tim Chesher (Group Manager) for offering me such a great opportunity to work with so many world-renowned experts at HR Wallingford where I benefit a lot both academically and socially.

During the course of my research, I feel very lucky to be supervised by two great scholars: Prof. Robert Nicholls and Dr. Belen Blanco. I would like to gratefully thank my university supervisor Robert for arranging this placement with HR Wallingford for me and also continuously giving me valuable suggestions on both the writing-up of my Master dissertation and the preparation of the conference paper. I would like to express my deep gratitude to my industry supervisor Belen for being so responsible and helpful during my entire placement at Wallingford. Without her invaluable support and continuous encouragement, this research could not have been so enriching. The effort she made regarding my further development is highly appreciated.

I also would like to thank my colleagues for their technical support, particularly Dr. Michiel Knaapen, Dr.Yohama Gunawardena, Dr. Isabel García-Hermosa, Jonathan Kemp and Katie Firman from Coasts and Estuaries Group, John Barnes and Adrian Harper from Innovyze and Gordon Glasgow from Flood Management Group. The valuable advice and discussions from Dr. Alan Brampton, Prof. Richard Whitehouse, Dr. John Harris, David Finch and Dr. David Kelly are highly acknowledged.

I am also grateful to all the teachers for Erasmus Mundus-CoMEM programme, particularly Prof. Marcel Stive (TU Delft, Netherlands) and Associate Prof. Oivind Arntsen (NTNU, Norway). Meanwhile, I would like to say “thank you” to all my CoMEM fellow classmates for being so great and wonderful guys with whom I have an unforgettable 2-year European journey.

Last but not least, I am thankful to my family and my Chinese supervisor Prof. Changkuan Zhang, who always believe and encourage me during my entire Master period.

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LIST OF ACRONYMS AND ABBREVIATIONS

BMP	Beach Management Plan
CCSD	Cumulative Cross-shore Distribution Curves
CEDAS	Coastal Engineering Design & Analysis System, software suite from US Army Corps of Engineers
CEM	Coastal Evolution Model
CERC	Coastal Engineering Research Centre, USA
CIRIA	Construction Industry Research and Information Association, UK
DHI	Danish Hydraulic Institute, Denmark
EIA	Environment Impact Assessment
GENESIS	Generalized Model for Simulating Shoreline Change, software package in CEDAS
GIS	Geographic Information System
GPS	Global Positioning System
ICZM	Integrated Coastal Zone Management
MHW	Mean High Water Level
MSL	Mean Sea Level
ODN	Ordnance Datum Newlyn, UK
OpenMI	Open Modelling Interface
SBEACH	Stormed Induced Beach Change, software package in CEDAS
SMP	Shoreline Management Plan
WFD	Water Framework Directive

LIST OF SYMBOLS

b	denotes breaking conditions, subscript
c	wave phase velocity, m/s
c_f	friction coefficient;
C_{ga}	absolute group velocity, m/s;
d	diameter of sediment grains, m
d_{50}	median grain size, m;
D	depth between swash limit to closure limit, m;
D_b	wave-energy dissipation due to wave breaking;
D_f	wave-energy dissipation due to seabed friction;
D_B	landward limit, berm or swash height, m
E	wave energy density, $J \cdot m^{-2}$;
g	gravity acceleration, $m \cdot s^{-2}$
h	water depth, m.
H	significant wave height, m;
H_o	wave height at one grid point, m;
H_i	wave height at the next grid point, m;
I	immersed weight transport rate, $kg/m/s$;
k	wave number
K_s	shoaling coefficient;
K_r	refraction coefficient;
K_d	Doppler coefficient;
K'	coefficient in CERC formulation
K_1, K_2	non-dimensional coefficients
n	ratio between group and phase velocity, dimensionless
p	porosity of bed material
q	volume of material brought onshore by wave action, or beach nourishment, or sand mining, $m^3/s/m$.
Q	longshore sediment transport rate, m^3/s
s	relative density of the sediment ρ_s/ρ, dimensionless
S	volumetric transport rates of deposited material, $m^3/m/s$
t	time, s

u	near-bed fluid velocity, m/s
$\overline{u}$	time-averaged velocity, m/s
U	longshore current velocity, m/s;
u_{lo}	low-frequency variation velocity, m/s
u_{hi}	wind-wave frequency velocity, m/s
u'	turbulent variation velocity, m/s
$\tilde{u}$	time-varying component of the horizontal velocity, m/s
u_*	shear velocity, m/s
u_m	peak bed orbital velocity, m/s
w_s	sediment falling velocity, m/s
x	distance alongshore, m;
y	distance offshore, m;
z_b	bed level, m
z_s	surface level, m
α	angle between wave crests and the local depth contours, degree;
β	mean slope of the beach face, degree;
γ_s	the submerged weight of beach material in place;
τ_b	bed shear stress, $N \cdot m^{-2}$
θ_{cr}	critical Shields parameter, dimensionless
ρ_s	density of sediment grains, $Kg \cdot m^{-3}$
$\tau_{b,cr}$	critical shear stress, $N \cdot m^{-2}$
υ	kinematic viscosity coefficient, m^2/s.
ρ	density of water, $Kg \cdot m^{-3}$;
ρ_s	sediment density, kg/m^3;
ω_a	absolute wave angular frequency, rad/s;
δ	current's direction, degree;
ω_r	relative wave angular frequency, rad/s;
μ	direction of absolute wave group velocity, refer to Figure 3-4;
ε_b	prescribed bed load efficiency;
ε_s	prescribed suspended load efficiency;
φ	angle of internal friction;

1 GENERAL INTRODUCTION

This chapter acts as a general introduction to this whole dissertation. To begin with, the background information for this research is provided to explain why this topic is worth studying. Then, the potential problems are generally described. After that, the aim and the objectives of the project are introduced considering the possible problems. To make the dissertation more readable and coherent, the last section of this chapter describes the structure of this dissertation.

1.1 Background

Quantitative methods are becoming more and more widely adopted for coastal management due to their predictive capability. Various numerical models have been developed in different research institutes or companies worldwide to predict the coastal evolution at both short and long term. To develop or apply a numerical model, temporal and spatial scales of coastal processes and human activities should always be taken into account (Stive et al, 2002). For example, the time scale of cross-shore profile change is typically hours to seasons while the time scale of years to decades for shoreline evolution. Unfortunately, there are no models that can fully and accurately simulate the coupled cross-shore and longshore transport processes at present. Therefore, more studies are being carried out based on the existing models to develop more comprehensive and robust models.

To predict the shoreline evolutions, one-line models such as BEACHPLAN, GENESIS, UNIBEST-CL have been in use for a wide range of coastal projects for the past 30 years or so. Some typical applications include the morphological predictions and analyses at medium or long term of a stretch of coast so as to assess the impacts of the planning or existing projects, such as beach nourishment and groynes arrangement. One-line models usually predict longshore transport at each grid point based on a modified CERC (short for Coastal Engineering Research Centre, USA) formulation (Komar and Inman, 1970). This longshore transport predictor gives a bulk figure per grid point and then, a cross-shore distribution of the longshore transport can be inferred based on experimental or other pre-defined methods.

However, there are also some cross-shore profile models that can predict the cross-shore distribution of the longshore transport in a more detailed manner, like COSMOS which is for modelling nearshore hydrodynamics, sediment transport and morphodynamics. Based on

different theories of sediment transport, this model produces different longshore sediment transport rate which considers more detailed hydrodynamic conditions (e.g. more detailed wave transformation routine) compared to the one-line model. Meanwhile, the detailed cross-shore distribution of longshore transport calculated by such models can be very useful under the conditions that the coastal structures are involved when sediment by-passing is to be considered.

To develop a completely new model that meet people's needs is always an alternative, however, it is going to be resource-consuming and expensive, even unnecessary sometimes. Therefore, to link the one-line model and the profile model is thought to be another potential way to give better predictions of the longshore sediment transport and beach response, which is the initiative of this research. Thus, the accuracy and predictability of the one-line models are expected to be improved.

Moreover, this research also provides a good opportunity to study the feasibility of the current linking concepts. As is known, to couple two different models through a platform is still on the experimental stage around the world. Thus, it will be interesting and also meaningful to test the linking methods and platform from the numerical point of view.

Both the one-line model (BEACHPLAN) and the profile model (COSMOS) discussed in this research are products of HR Wallingford Limited. Brief introduction to this company is given in Appendix A1. These two models have been in continuous development and applied in different projects worldwide, so they are good representations of the state of the art. To make the models more user-friendly and advanced, an integrated software package called CEM (Coastal Evolution Model) is currently under development. Therefore, this research is ensured to be based on the latest version of the software packages. Introductions to these models are presented in the following chapters.

1.2 Problem Description

To seamlessly link two numerical models is never an easy task, which requires numerous trial-and-error experiments and analyses. In this research, a one-line model and a profile model are to be linked through a platform called OpenMI which will be introduced later. It is envisaged that the following potential problems may be expected.

Firstly, these two kinds of models are based on different formulae, thus the calculated bulk drifts are different. To make better prediction of shoreline evolution, the drifts calculated by COSMOS are to be applied for further calculations in BEACHPLAN. However, BEACHPLAN requires

drift value for each grid point while it's not reasonable to run COSMOS in each grid point since it is going to be time-consuming. Thus, a method needs to be generated to input appropriate drift values to BEACHPLAN model.

Secondly, to couple these two models means all the input data for the two models should be coupled as well. For example, the wave data should be the same for the two models. However, the formats of the input wave data are actually not the same for the two models. Thus, some conversion methods should be generated to tackle this kind of problems.

Thirdly, the one-line and the profile models are developed based on different assumptions, thus some conflicts are unavoidable. For example, the shoreline is assumed to be straight to run COSMOS while it isn't the case in BEACHPLAN, which leads to the difficulty of coupling these two models in terms of coordinate system. These kinds of problems need to be solved.

Moreover, a linking platform OpenMI, which will be introduced later, is needed to combine these two models during runtime. Problems may occur during this stage so the technical support from software-developing group is essential to this research.

In summary, different problems are expected at different stages when proper counter-measures need to be generated accordingly.

1.3 Aim and Objectives

This dissertation aims to develop a coupled model which improves the existing model BEACHPLAN in terms of wave transformation and therefore longshore sediment transport rate. The coupled model will simulate the nearshore processes and beach responses in a more detailed manner.

To achieve the aim, several objectives are raised according to the potential problems:

(1) Generate a proper mathematical method to achieve the reasonable drift values based on both COSMOS and BEACHPLAN models;
(2) Develop a module to pass the bulk drift values from COSMOS to BEACHPLAN;
(3) Develop a module to deal with the potential problems caused by the differences of formats between these two models;
(4) Develop a module to update the COSMOS profile orientation at each time step;
(5) Test the coupled model using simple input conditions;
(6) Validate the model against field data.

1.4 Structure of this Dissertation

The general structure of this dissertation is presented as follows:

Chapter 1 General Introduction gives an introduction to the background information, the objectives and the potential problems of this research.

Chapter 2 Literature Review presents the relevant theoretical basis for this research in order to put it into context.

Chapter 3 Model Components introduces the three components that will be used to form the coupled model. Detailed introductions for BEACHPLAN, COSMOS and OpenMI standard are given in this chapter.

Chapter 4 Methodologies and Model Coupling presents how the coupled model is reached. Three additional modules are discussed and tested. This chapter also shows how the coupled model looks like.

Chapter 5 Model Tests and Discussions aims to test the models in terms of feasibility, accuracy, stability and efficiency. The model is applied to both an idealized coast and a real coast.

Chapter 6 Conclusions and Further Research summarizes the main conclusion achieved and recommends some possible research directions for the future.

Relevant references and some appendixes are listed at the end.

2 LITERATURE REVIEW

This chapter aims to provide relevant theoretical basis for this research so as to lay a foundation for the consequent discussion. To begin with, a general introduction to coastal engineering is given, including some research-related important concepts such as coastal morphodynamics, temporal and spatial scales and shoreline management. Then, the theoretical background of sediment transport which will be discussed throughout this dissertation is briefly presented, in both alongshore and cross-shore directions.

2.1 Coastal Environment

The coastal zone has been extensively explored by human-beings for various purposes, such as transportation, fishing, tourism, agriculture and etc. According to surveys in 2008 (People & Planet), approximately 3.2 billion people- more or less half world's population – live within 200km of the coastline. This figure is expected to increase in the near future. Thus, coastal engineering and management are essential to achieve a sustainable and balanced way to utilize the coastal area.

As a multi-purposed area, the coastal zone is affected by all kinds of components including both natural processes and human activities. Natural processes, such as geologic activities, wind, wave, tide and storm surge, are the initial forces that determine the characteristics of a coast. However, human activities such as coastal sand mining, land reclamation, dredging and building coastal structures along the shoreline, on the other hand, play a more and more important role in shaping the coast area. More importantly, the natural processes and human interventions are always interactional and cause the morphological variations to the coastal zone; meanwhile, the morphological changes also react on the natural and human-induced processes. Therefore, it is important to treat coastal problems in an integrated way considering both technical and social/economic issues, which gives birth to the idea of Integrated Coastal Zone Management (ICZM) these years (Bosbom & Stive, 2009).

Considering the limitations of the models, this research will only focus on the coastal area of sandy beaches. Some relevant terminologies are defined in Figure 2-1 below.

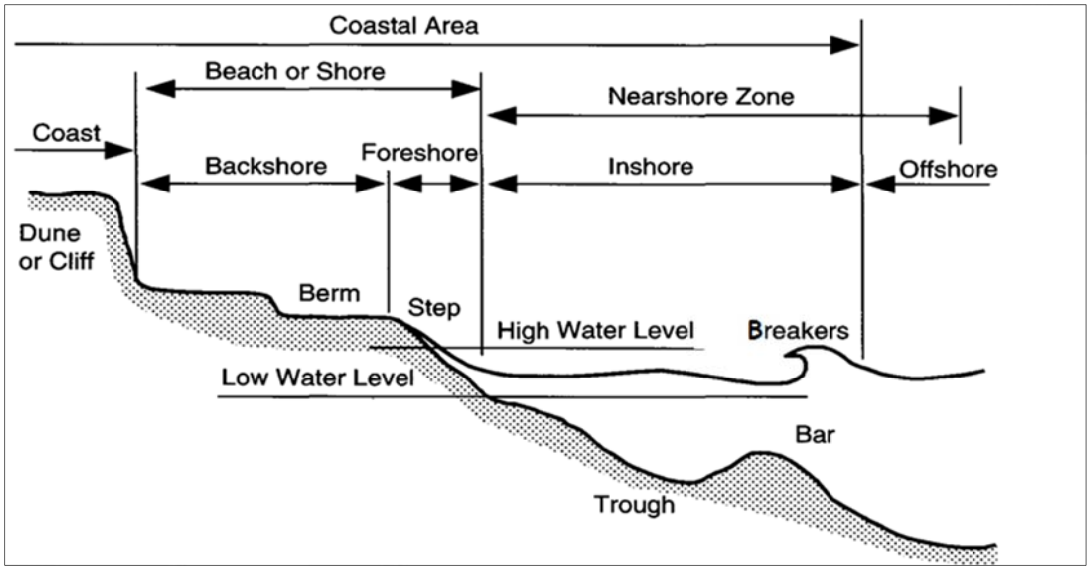


Figure 2 - 1 Terminologies Definition of a Beach (from Schwartz, 2005)

Some terms and concepts that are not included in the figure above but important for the proposed research are introduced as follows:

- Depth of Closure: Seaward of some point along a beach profile in the offshore direction where sand transport is insignificant for a given wave condition (Nicholls et al, 1996).
- Swash Zone: The zone of wave action on the beach, which moves as water levels vary, extending from the limit of run-down to the limit of run-up (CIRIA, 2010).
- Swash Limit: The wave run-up limit of Swash Zone.

Typically, the longshore sediment transport is assumed to occur within the zone bounded by Depth of Closure and Swash Limit. However, it is worthwhile to mention that the depth of closure is timescale-dependent according to Hinton and Nicholls (2007). There is a re-opening phenomenon of closure depth on middle/low shoreface in longer term. In this research, the re-opening situation is not taken into account.

2.2 Temporal and Spatial Scales

Coastal evolutions both due to natural and human-induced factors are variable over a variety of temporal and spatial scales. The spatial scale is generally determined by the dimensions of the morphological elements. For example, a tidal inlet system may have a scale of tens or hundreds of kilometers while the spatial scale of a seabed ripple is only meters or less.

On the other hand, the temporal scales are closely coupled with the spatial scales: the larger the spatial scale of a certain morphological element, the longer the temporal scale, which can be clearly reflected by the figure below:

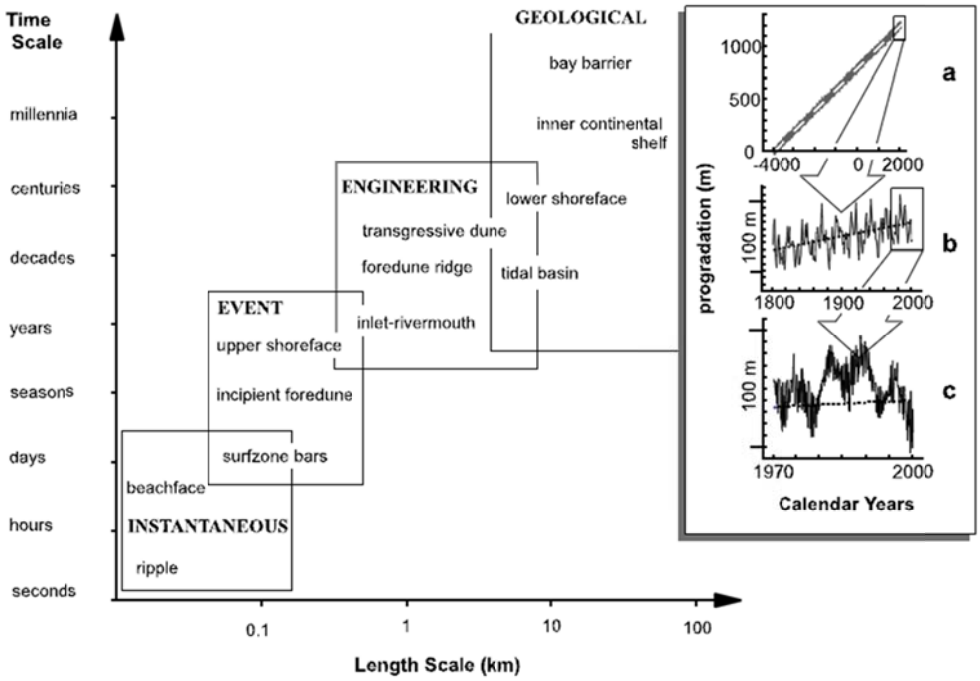


Figure 2 - 2 Scales of coastal evolutions and typical time series (from Stive et al, 2009)

Some short-term variations such as wave or storm events are just "noise" if a large time scale is considered, say the gradual sea-level-rises or tectonic activities, which can also be noticed by the three smaller sketches in Figure 2-2. Since the morphological changes have their specific space and time scales, the relevant models should also take scales into account so that reasonable predictions can be achieved.

As for beach change models, two kinds of models have been widely developed and applied based on the consideration of either alongshore or cross-shore direction. Typically, one-line models such as GENESIS and BEACHPLAN are good representations for modelling alongshore directional changes (i.e. shoreline evolutions). They are normally at the time scale from seasons to decades and the space scale from 1 km to 100km. On the other hand, cross-shore profile models such as SBEACH and COSMOS usually work at the time scale from hours to seasons and the space scale from meters to several hundred meters. The differences of beach change models are quantitatively compared in the figure below by Hanson and Kraus (1989).

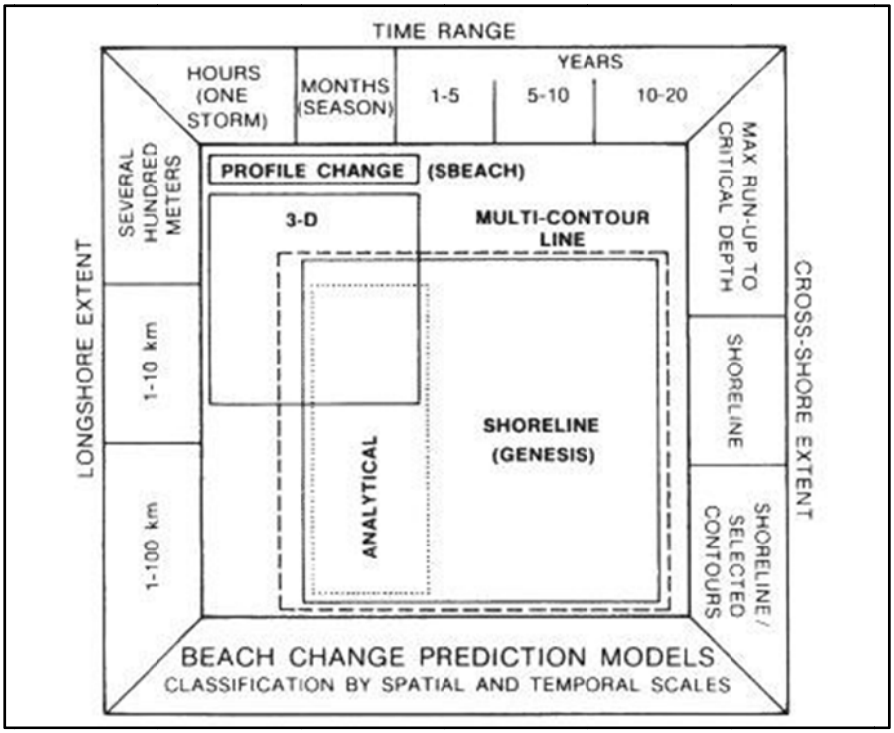


Figure 2 - 3 Comparison of beach change models (from Hanson and Kraus, 1989)

As the main model components in this research, both the one-line models and cross-shore profile models are discussed into more detail in Chapter 3.

2.3 Shoreline Management

In order to make appropriate shoreline management plans, it is essential to have a good knowledge of coastal morphodynamics which can be defined as the mutual adjustment of coastal morphology and hydrodynamic processes involving sediment transport. This is a very important research field in coastal engineering. Knowledge from many fields such as meteorology, geology, hydrology, physics, mathematics, oceanography and structural dynamics is usually required.

Understanding coastal morphodynamics helps people to choose the most suitable strategies to protect the coasts and the hinterlands, as well as to choose the most proper coastal development plans. Various kinds of hard and soft measures have been in use over the years. Hard measures refer to construction of coastal structures while soft measures usually involve the transport and stabilization of sand and other coastal sediments. Both hard and soft measures have their advantages and disadvantages. It is the task of coastal engineers to choose either to use hard or soft measures, and sometimes both. Considering the different situations of the different shoreline passages, various shoreline management plans may be made accordingly to achieve the best effects of shoreline protection and development.

According to DEFRA (2006), Shoreline Management Plan (SMP) aims to provide a large-scale assessment of the risks associated with coastal processes and present a policy framework to reduce these risks to people and the developed, historic and natural environment in a sustainable manner. In order to manage the shoreline, some cells and sub-cells need be defined along the coastline. A coastal cell is a self-contained unit and sediment condition variations in one cell should not affect its neighbouring cell. One coastal cell can be sub-divided into several sub-cells in which different shoreline management plans may apply. The figure below presents the cells defined along the UK coastline.

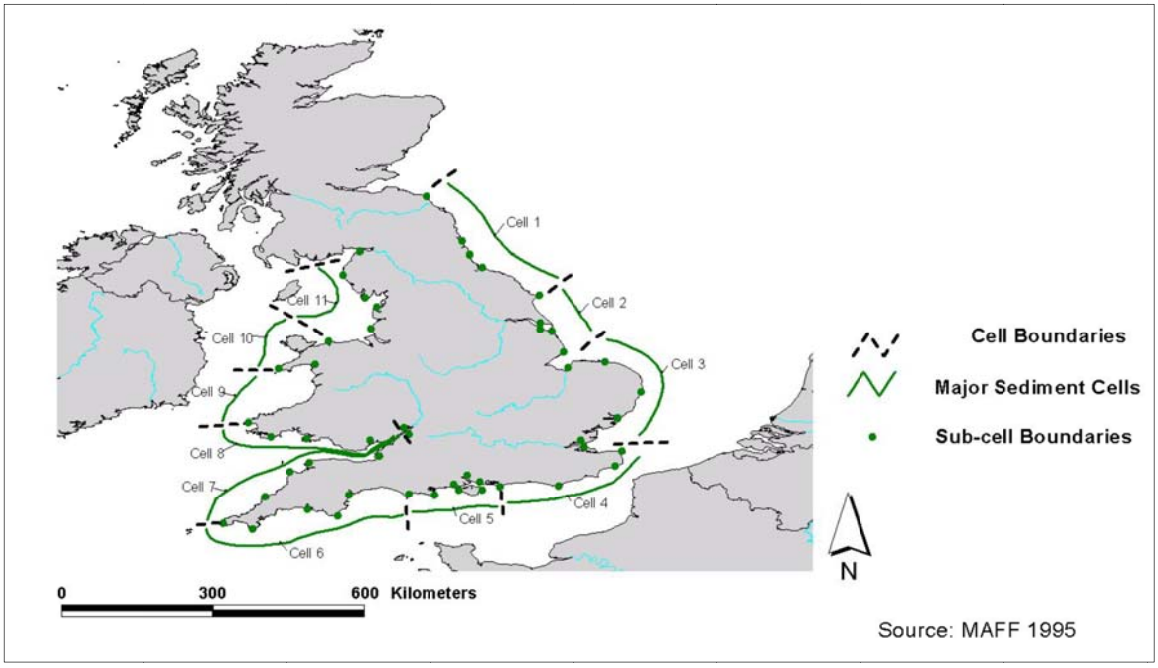


Figure 2 - 4 Coastal cells along British coastline (from MAFF et al, 1995)

Some strategic SMP responses have been raised since 1995 and under continuous improvement ever since. However, the main four strategies are kept as follows: (1) do nothing, (2) hold the line, (3) retreat the line, (4) advance the line.

2.4 Sediment Transport for Sandy Beaches

Coastal morphological changes are usually the consequence of spatial gradients in net sediment transport rates, which should be paid special attention to. Sediment transport can be defined as the movement of sediment particles through a certain plane over a period of time. There are many factors that influence the movement of sediment particles, among which, characteristics of the particles play an important role. For example, the sediment transport processes for a sandy and a muddy beach are quite different. In this research, the sediment transport is only studied for sandy

beaches. According to Wentworth Scale of Sediment Size Classification in the table below, grain diameters of sands range from 0.0625 to 2.0mm.

Table 2 - 1 Wentworth Scale of Sediment Size Classification (from Dean, 2004)

Wentworth Scale Size Description		Phi Units (ϕ)	Grain Diameter d(mm)	U.S. Standard Sieve Size	Unified Soil Classification (USC)	
Boulder		−8	256		Cobble	
Cobble			76.2	3 in		
		−6	64.0		Coarse	Gravel
			19.0	3/4 in		
Pebble		−2.25	4.76	No. 4	Fine	
		−2	4.0		Coarse	Sand
Granular		−1	2.0	No. 10		
Sand	Very coarse	0	1.0	2.0	Medium	
	Coarse	1	0.5			
	Medium	1.25	0.42	No. 40		
		2	0.25			
	Fine	2.32	0.20	No. 100		
		3	0.125	No. 140	Fine	
	Very Fine	3.76	0.074	No. 200		
		4	0.0625			
Silt		8	0.00391		Silt or Clay	
Clay		12	0.00024			
Colloid						

Sediment transport is always an open-end topic in coastal engineering because of its complicacy and unpredictability. For further discussions, it is convenient to start with introducing some basic concepts related to sediment transport such as Initiation threshold of motion, transport modes and etc. Also, some modelling techniques of studying sediment transport are presented at the end.

2.4.1 Basic Concepts

(1) Initiation of motion

To initiate the motion of sediment particles, the shear stress due to the water movement should be large enough to overcome the inertia of the particles and this shear stress is the so-called critical shear stress, denoted by $\tau_{b,cr}$. For a single particle, factors such as grain size and geometry can be important to initiate the motion, so the threshold shear stresses may vary for different grains. It is easy to understand that pebbles or shingles are more difficult to be moved than fines.

The bed shear stress, which is the friction exerted on the seabed by the hydrodynamic agents such as waves and currents, can be related to shear velocity using the following relationship:

$$\tau_b = \rho u_* | u_* | \quad (2 - 1)$$

Where, τ_b bed shear stress, $N \cdot m^{-2}$;

ρ density of water, $Kg \cdot m^{-3}$;

u_* shear velocity, m/s.

For the initiation of a single grain, three forces need to be taken into account: drag force, lift force and gravity. The so-called critical Shields parameter can be deduced after the analysis of each force (e.g. Bosbom & Stive, 2009):

$$\theta_{cr} = \frac{\tau_{b,cr}}{(\rho_s - \rho) g d} \quad (2 - 2)$$

Where, θ_{cr} critical Shields parameter, dimensionless;

ρ_s density of sediment grains, $Kg \cdot m^{-3}$;

g gravity acceleration, $m \cdot s^{-2}$;

d diameter of sediment grains, m;

$\tau_{b,cr}$. critical shear stress, $N \cdot m^{-2}$.

Based on numerous experiments on a flat bed, Shields found the critical shear stress was a function of the grain Reynolds number, defined as:

$$\mathrm{Re}_* = \frac{u_* d}{\nu} \quad (2 - 3)$$

Where, d diameter of sediment grains, m;

u_* shear velocity, m/s.

υ kinematic viscosity coefficient, m^2/s.

A so-called Shields curve can be adopted to show this dependency, see the figure below (note: some notations used in the figure may be different with the ones introduced before, x-axis and y-axis represent grain Reynolds number and Shields parameter respectively.). It is noticeable that the critical Shields parameter is around a constant 0.05. However, this is not always the case in reality since the Shields curve is only valid for uniform flow on a flat bed. Moreover, the sorting of grains, bed armouring effect and cohesive forces between the grains are not taken into account. Though these simplifications, Shields curve is still widely used to define the initiation of motion in practice.

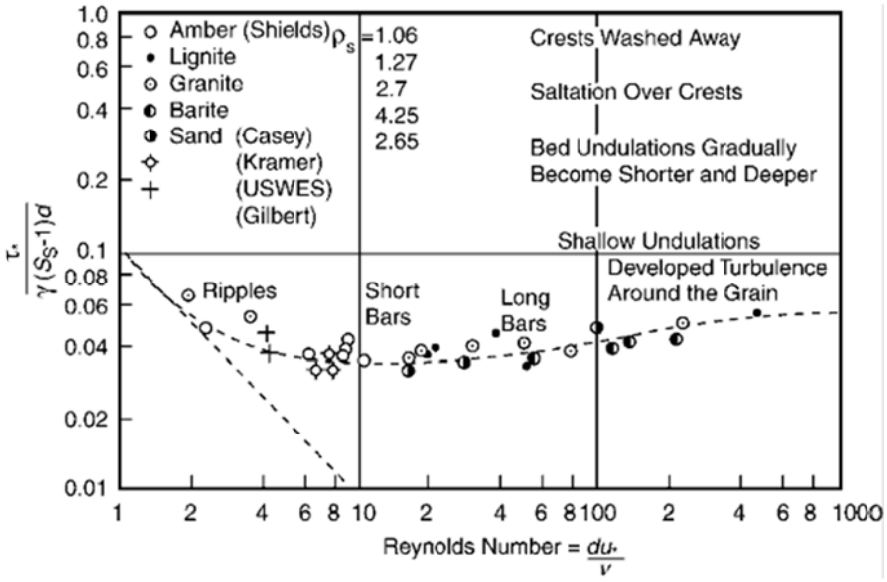


Figure 2 - 5 Shields curve for the initiation of motion for steady flow (from Raudkivi 1967)

(2) Transport Modes

There are several modes of transport once the sediment particles are initiated in motion. Different modes have different characteristics and consequently lead to different morphological response. In the coastal environment, the following three transport modes are usually considered.

- Bed load transport: the motion of sediment particles are in a thin layer close to the bed. There are continuous contact between the particles and the bed which provides the support for the particles. Bed load transport is able to happen at relatively low shear stresses. When the shear stresses are high enough, an entire layer of sediment may be put into motion which is called sheet flow transport.
- Suspended load transport: the sediment particles suspend and move in the water without being in contact with the bed. The motion of particles is supported by turbulent forces generated within the fluid.
- Sheet flow transport: the particles close to the bed start to move in multiple layers instead of rolling and saltating in a single layer when the shear stresses are higher (Shields parameters higher than 0.8-1.0). Interactions between particles, as well as grain-water interactions become very important in this mode. This mode is often recognized as bed load at higher bed shear stresses.

The mechanisms behind bed load and suspended load are different, so it is common to use different transport formulations for these loads. Detailed discussions can be found in some textbooks. It is worthwhile to mention that the predominant mode of transport is bed load for grains coarser than approximately 2mm and suspended load for grains finer than about 0.2mm in typical coastal environments (Rivaton, 1997).

2.4.2 Longshore Sediment Transport

Longshore sediment transport or drift can be defined as the net movement of sediment particles through a well-defined vertical plane perpendicular to the shoreline. The waves and tidal currents are usually the driving agents. The longshore drift is recognized as the major drive for long-term morphological development of beaches. Long-term in this context is usually at a timescale of years to decades or more. For shorter timescales such as a storm or tidal cycle, cross-shore transport can be important for the plan shape of beaches.

For further discussion, it is helpful to introduce the processes that cause the longshore sediment transport. As mentioned, waves and currents are the main drives for longshore drift. When the waves approach the shore and break at a certain depth, there are mainly two effects: (1) the longshore current is generated; (2) the material on the seabed is stirred up due to the wave breaking-induced turbulence. Therefore, the longshore currents are the mainly responsible for the net alongshore drift. Some typical forms of currents are listed below:

- Obliquely approaching waves breaking-induced currents;
- Tidal currents;
- Variations of breaking wave heights, or wave- induced set-up differences;
- Wind-induced currents;
- River flows;

Usually, the first two or three are the main drives for longshore transports while the last two can be important in some specific locations.

The waves, produced by winds, may change directions, so the longshore drifts also change directions. It is convenient to introduce the concepts of gross and net transports to describe the variability in transport directions. The gross drift is the sum of the volumetric transport regardless of directions. However, the morphological change of shoreline is usually the result of net longshore drift which can be obtained by subtracting the one directional drift component from the other directional component.

There have been many formulas for calculating the longshore sediment transport; each has its strong and weak points. Bayram et al (2001) studied six well-known published formulas developed by Bijker, Engelund-Hansen, Ackers-White, Bailard-Inman, Van Rijn and Watanabe, respectively. He concluded that Van Rijn's formula gave the most reliable predictions over the entire range of wave conditions. However, only the CERC formula (SPM, 1984) for longshore drift, which is widely used in engineering applications, will be discussed in this research.

The CERC formula has been criticized for ignoring many factors such as grain size and beach slope which are potentially important. Meanwhile, only the effects of the wave-generated longshore currents are considered; tidal currents or other longshore currents are not included. The basic CERC formula only gives a bulk volumetric drift rate integrated over the breaker zone. While in many cases, the cross-shore distribution of longshore drift is also important, eg. groynes arrangement. The most general form is given below:

$$Q = \frac{I}{\rho g(s-1)(1-p)} = \frac{K'}{\rho g(s-1)(1-p)}(Enc)_b \cos\alpha_b \sin\alpha_b \qquad (2-4)$$

Where，I the underwater weight of sediment transported, kg/s;

Q the deposited volume of sediment transported including pores, m^3/s;

ρ density of water, $Kg \cdot m^{-3}$;

g gravity acceleration, $m \cdot s^{-2}$;

s the relative density of the sediment ρ_s/ρ, dimensionless;

E wave energy density, $J \cdot m^{-2}$;

c the wave phase velocity, m/s;

n the ratio between group and phase velocity, dimensionless;

α the wave angle of incidence, rad;

b denotes breaking conditions, subscript;

K' calibration coefficient estimated as 0.77 by Komar and Inman (1970).

Considering the limitations of the basic CERC formula, many attempts have been done by different scholars over these years. Dean et al. (1982) and Kamphuis (1991) considered the grain size and beach slope effect. The modified version from Ozasa & Brampton (1980), which considered an additional transport term due to the alongshore variation in breaking wave height, is adopted in many one-line models including GENESIS and BEACHPLAN, which will be discussed later.

Longshore drift gradient has strong effects in determining the plan shape of beaches. As a common rule, beaches tend to adjust to a position where the net longshore transport is minimized so that the beach faces the prevailing waves. Therefore, there is mutual adjustment between beach morphology and hydrodynamic processes with sediment transport involved. The interactional effects between beach plan shape and longshore sediment transport can be explained by an example given in the figure (CIRIA, 2010) below:

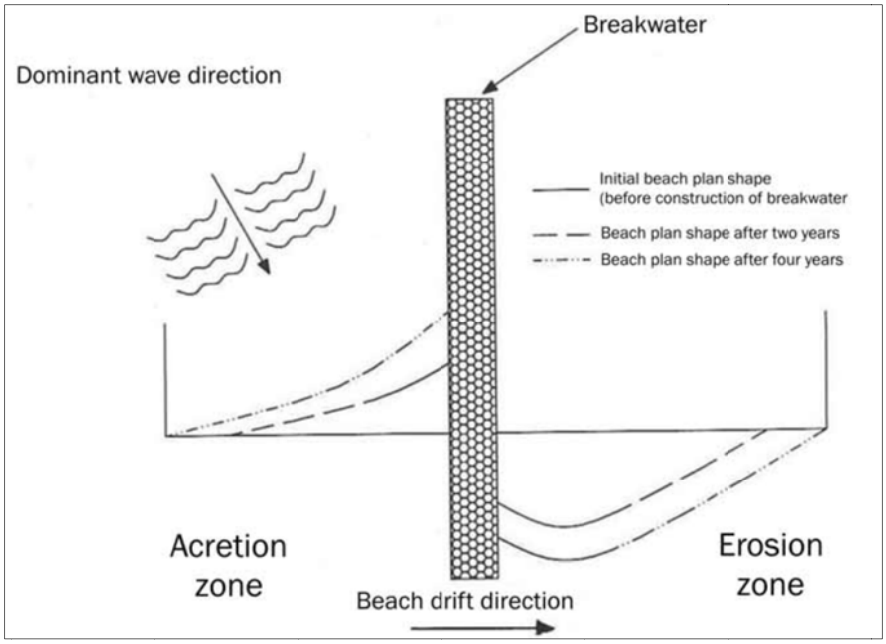


Figure 2 - 6 Effect of a breakwater on the beach plan shape (from CIRIA, 2010)

If a breakwater is built perpendicular to the shoreline, the longshore sediment transport is cut at the breakwater, thus significant morphological changes will happen near the breakwater. As depicted in the figure above, there will be accretion on the updrift side while erosion on the downdrift side of the breakwater after the breakwater is built for two and four years. However, if longer time is given, things may become more complicated when drift bypassing occurs.

2.4.3 Cross-shore Sediment Transport

As mentioned before, cross-shore sediment transport may dominate at relatively short time scales, say the order of one tidal cycle or a storm event. A typical cross-shore profile of a sandy beach has been described before, see Figure 2 - 1. When normal incident waves approach the coast from offshore, various hydrodynamic and sedimental processes occur. With the decrease of water depth, the waves start to feel the bottom when wave shoaling happens. To a certain depth, the flows at the bed become large enough to initiate the movement of sediment; bed load transport dominates at this stage.

As the waves move further onshore, the shear stresses become more intense, thus lead to suspended load transport. When waves come to surf zone, the sediment is significantly stirred by the strong turbulence due to breaking waves. Large amount of sediment suspends in the water column and is transported onshore or offshore by skewed waves and different currents.

There are many coastal engineering problems relating to cross-shore sediment transport, CEM (Coastal Engineering Manual Part3, 2006) listed several as follows:

- beach and dune response to storms,
- "profile nourishment" in which the sand is placed in the nearshore with the expectation that it will move landward nourishing the beach,
- shoreline response to sea level rise,
- seasonal changes of shoreline positions,
- overwash, the process of landward transport due to overtopping of the normal land mass due to high tides and waves.

Among which, seasonal change of shoreline position is a good example. It is well-known that the beach responds differently to summer and winter conditions. In summer, the beach is "rich" in sediment with a high beach profile and high slope while "poor" in winter with low beach profile and gentle slope. This summer-winter seasonality exists all over the world especially in places of storm wave climates.

Currently, simple analytical treatments to cross-shore hydrodynamics, sediment transport and beach profile dynamics don't exist because the constituent processes vary strongly over the whole shoreface. Processes such as undertow, bound long waves, short wave asymmetry and breaking-induced turbulence act on the upper shoreface. On the other hand, wave boundary layer streaming, bound long waves and wave asymmetry play important roles on middle and lower shoreface (Roelvink and Stive, 1989).

Some numerical models, such as SBEACH (Stormed Induced Beach Change) and COSMOS have been developed to study the cross-shore sediment transport. The underlying theoretical basis for COSMOS will be further introduced later.

2.4.4 Modelling techniques

Coastal processes, such as sediment transport, may be studied using physical or/and numerical modelling techniques. Depending on the complexity and importance of the project, research may need physical models or numerical models or a combination of both techniques.

However, it is worthwhile to mention that with the rapid improvement of computer capabilities, coastal modelling is developing towards a more quantitative and accurate manner. Numerical models, in many cases but not all, are replacing or acting as a verification of physical models.

Only for important or some specific projects, both numerical and physical models are required, which enables the complementary strengths possible.

On the other hand, measuring techniques are becoming more and more advanced. For example, dredging becomes easier and more accurate by using the global positioning system (GPS). Meanwhile, the widely used geographic information system (GIS) is also playing a more and more important role in coastal engineering and other fields. All these techniques also provide a better basis for the development of numerical models.

These years, more and more numerical models for coastal engineering have been developed for various purposes such as flood management, beach protection, shoreline prediction etc. Compared to physical models, these numerical models are generally cheaper and more effective to generate results. The models discussed in this research, such as BEACHPLAN and COSMOS, have been under continuous development for several decades and tested in many different projects. Generally speaking, they prove to be good tools for decision-making under some circumstances. However, model verification is always needed according to the practical conditions in the local project area before a final conclusion is made.

3 MODEL COMPONENTS

Basically, there are three components involved in this research: a one-line model (BEACHPLAN), a profile model (COSMOS) and a linking platform (OpenMI). This chapter aims to give a relatively detailed introduction to these components so as to provide a basis for the further linking stage.

3.1 One-line Model

Since Pelnard-Considere (1956) presented the first one-line model, much research has been done on this topic. Price et al. (1973) first numerically studied this one-line theory and many others followed (Rea and Komar, 1975; Horikawa et al, 1977; Willis, 1977; Perlin, 1979; Mimura et al, 1983; Kraus et al, 1985). Hanson (1987) summarized most of the previous work related to the one-line model in his PhD research of developing a generalized shoreline change numerical model called GENESIS (Hanson, 1989). The one-line model has been applied in many projects around the world and proven to be a useful tool for predicting the shoreline evolution.

Extending the concept of the one-line theory, multiple line models have also been under development since Bakker (1969) proposed a two-line model to study the dynamics of a coast with a groyne system. The main advantage of multiple line models is that cross-shore exchange of sediment is taken into account, which allows a non-equilibrium cross-section to be considered. However, the physical phenomena behind multiple line models are not fully understood and it is much more resource-consuming to run multiple line models, so they are of less engineering use for the time being.

This section will focus on the one-line model theory and this theory-based BEACHPLAN model, which is, to some extent, analogous to GENESIS model.

3.1.1 One-line Model Theory

Common observation shows that cross-shore profile of a specific beach maintains a relatively constant shape over the long term regardless of the extreme storm events. The sand beach morphology is thus represented by a single contour line in some models, so these models are named the one-line model which is short for one-contour line model. The basic assumption for one-line theory is the shape of the cross-shore profile does not change with time. The entire

profile moves seaward or landward with a distance Δy without changing shape, as can be seen in the figure (Coastalwiki, 2008) below.

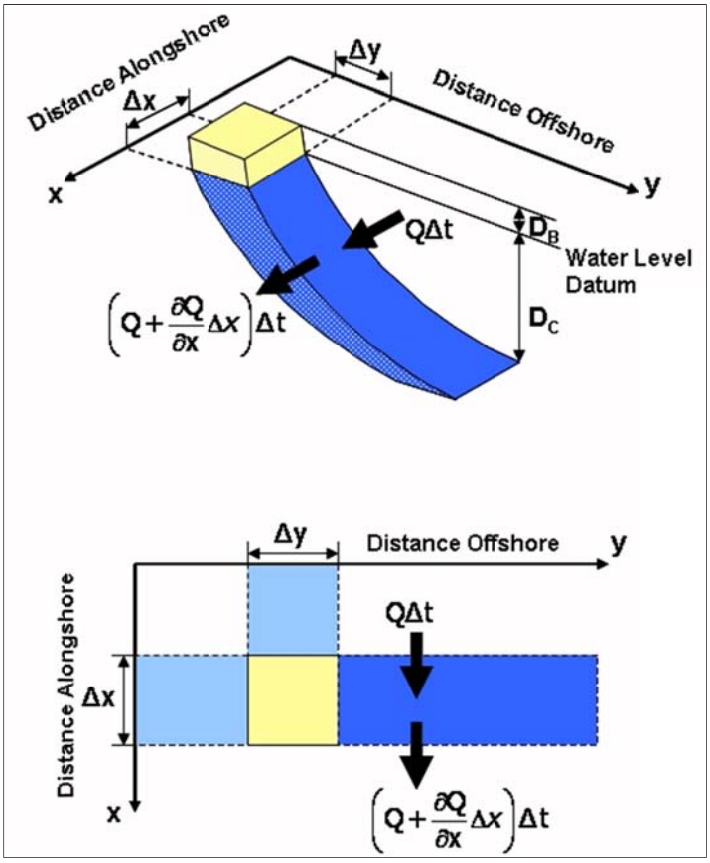


Figure 3 - 1 Definition sketch for one-line model (from Hanson, 1989)

The second assumption is the sediment is transported between two pre-defined limits over the profile: the swash limit and the depth of closure, which are defined before in Chapter 2. This assumption provides the simplest way to calculate the beach cross-sectional area and changes in sand volume, with which the shoreline movement can be predicted.

Based on the equation of continuity, the governing formulation for the change of shoreline position depicted in Figure 3 - 1 can be given:

$$\frac{\partial y}{\partial t} + \frac{1}{(D_B + D_C)} \frac{\partial Q}{\partial x} = 0 \qquad (3 - 1)$$

Where, y distance offshore, m;

x distance alongshore, m;

t time, s;

Q longshore sediment transport rate, m^3/s;

D_B landward limit, berm or swash height,m;

D_C seaward limit, depth of closure, m.

Price et al. (1973) was the first to study this one-line theory and many other scholars followed. To make this theory more practical, some improvement were made for engineering use such as considering the re-nourishment or sand mining, as well as the effects of implementing some coastal structures.

3.1.2 BEACHPLAN Model

BEACHPLAN model, which is based on one-line model theory, is one of the most helpful tools for beach protection and management. The model was developed at HR Wallingford around 30 years ago and has been in continuous development ever since. A overview of BEACHPLAN model structure is given in Appendix A2.

Applied in many projects worldwide, this model is proved to be a straightforward and reliable means for predicting long-term evolution of shorelines due to the influence of breaking waves. The dominant hydrodynamic processes are modelled in a quasi-3D fashion, although the model is termed “one-line”. Wave input is defined by specifying wave data at an offshore point in a known depth of water. Based on linear wave theory, waves are refracted to their breaking point at each beach section using an iterative process. The potential sediment transport at each section is then calculated and a sediment budget algorithm is performed along the beach to ensure continuity of material. Nourishment or extraction can also be defined at each beach section. The model can be run for prototype periods of 100 years or more and it is therefore extremely useful for planning and design purposes.

The following processes are considered in BEACHPLAN:

(1) Wave transformation: refraction, shoaling and diffraction;
(2) Structures: transmission, by-passing of groynes or breakwaters, effect of seawalls;
(3) Sediment transport: longshore drift by CERC formula as well as alongshore variation of breaking wave height, cross-shore distribution of longshore drift, limited beach toe depth;
(4) Active beach management techniques: beach re-nourishment, beach mining.

The beach plan shape is specified by the position of a single contour on the upper beach, which is usually defined as the mean water level, but can also be represented by the high water level. The model assumes a constant “average” beach slope, i.e. it does not consider short-term changes in the beach profile. Based on linear wave theory, the offshore wave conditions are refracted up to

the point of wave breaking and the breaking wave conditions are then used to calculate the longshore drift at specified sections of the model. The movement of the shoreline position is then calculated from differences in the wave induced longshore transport.

To consider the effect of groynes, it is important to estimate the portion of the longshore drift they stop, thus diffraction process is taken into account. BEACHPLAN models the efficiency of groynes by the rate of drift passing them, which depends on the distance between the wave-breaking point and the tips of the groynes. Meanwhile, the bypassing rate may also vary with time when the adjacent beach is eroded or accreted. In the presence of detached breakwaters, both the processes of transmission and diffraction should be considered (Blanco, 2003a).

For engineering use, the basic one-line theory Eq. (3-1) can be modified to:

$$\frac{\partial Q}{\partial x} + D\frac{\partial y}{\partial t} + q = 0 \qquad (3 - 2)$$

Where, D depth between swash limit to closure limit, m;

q volume of material brought onshore by wave action, or beach nourishment, or sand mining, $m^3/s/m$.

Starting from some initial position, y = y (x), the model evaluates successive beach positions at time intervals Δt, at points along the shore separated by Δx. So for each ordinate x(i), the values for yi(0), yi(Δt), yi(2Δt) and so on, can be calculated, thus the shoreline evolution is modelled. A more detailed grid system in BEACHPLAN model is shown in Figure 3-2. The beach is discretised into sections which are known as Q- and Y-sections.

The functionality of the Q- and Y-sections is as follows:

- Q-sections (odd section numbers): the values of the wave conditions and transport rates are calculated at Q-sections. Also, the groynes' positions are given at Q-sections.
- Y-sections (even section numbers): the shoreline position (included the initial position) and seawall position are given at the Y-sections, as well as any renourishment or mining taking place in the model and the characteristics of the beach profile (closure depth, swash height, beach slope, depth of sand over rocky platform). Also, the breakwater tips are given at Y-sections.

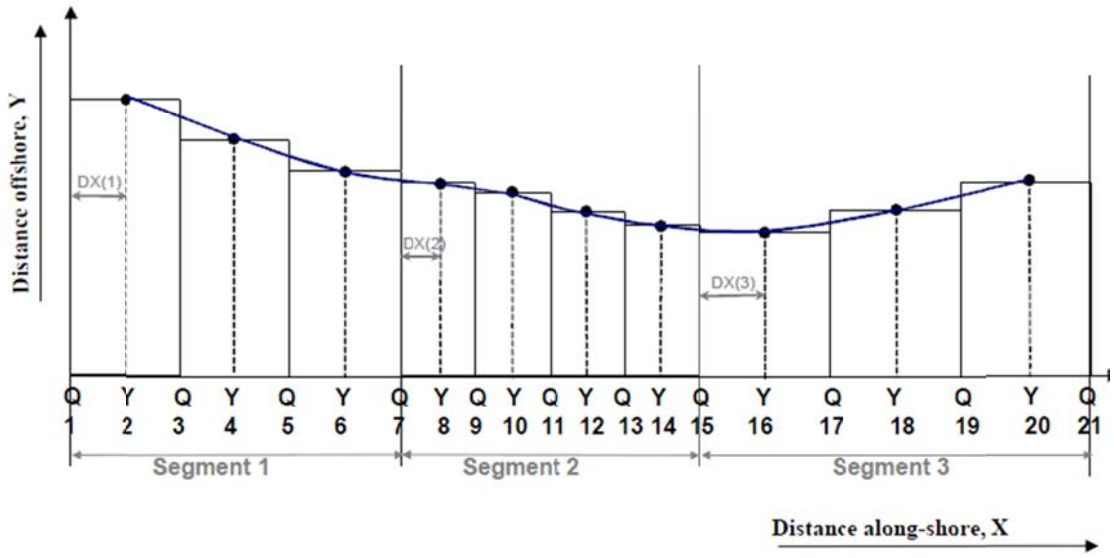


Figure 3 - 2 Grid system in BEACHPLAN model (from Blanco, 2003b)

The grid set-up in BEACHPLAN does not have to be uniform alongshore, so that a number of segments are allowed with equal spacing in each, see Figure 3-2 (Blanco, 2003b).

It is worthwhile to mention that the formula applied in this model to calculate rate of longshore transport is the modified CERC formula because the accuracy of the modelling results significantly depend on the formula used. The basic CERC formula given by Eq. (2 - 5) is modified to the following equation for BEACHPLAN:

$$Q = K_1(\gamma_s)^{-1} E_b(nC)_b \left(\sin 2\alpha_b - 2K_2 \frac{\partial H_b}{\partial x} \cot\beta \cos\alpha_b \right) \qquad (3 - 3)$$

Where,

K_1, K_2	non-dimensional coefficients;
E	the wave energy density, $J \cdot m^{-2}$;
H	the significant wave height, m;
g	the acceleration due to gravity, $m \cdot s^{-2}$;
ρ	the water density, $Kg \cdot m^{-3}$;
γ_s	the submerged weight of beach material in place;
nC	the group velocity of the waves, m/s;
α	the angle between their crests and the local depth contours, degree;
β	the mean slope of the beach face, degree;
b	subscript denotes breaking wave conditions.

The first term in the above equation is the well-known CERC formula and describes the alongshore sediment transport due to obliquely incident breaking waves. The second term considers the transport created by alongshore variation in breaking wave height, which becomes important for beaches in the lee side of headlands or breakwaters where diffraction effects are significant. As for the value of K_2, purely theoretical calculations gave a value of 3.2 (Ozasa and Brampton 1980). Later on, some other studies suggested the value was more reasonable in the range from 0.3 to 0.7. For sand beaches a value of 0.5 is usually used.

Considering the effects of coastal structures, the cross-shore distribution of longshore transport is important. In BEACHPLAN, the cross-shore distribution curves are used to automatically calculate the efficiency of the groyne. The model uses the Cumulative Cross-shore Distribution Curves (CCSD) contained within the model or one inputted by the user. These curves represent the efficiency (% material trapped by the groyne) for each non-dimensional parameter D*, where D* is the ratio between the water depth and the breaker depth. There are four types of given Cumulative Cross-shore Distribution Curves as well as the option of using a user-defined one, listed as follows: (1) Sand Experimental CCDS; (2) Sand COSMOS CCDS; (3) Shingle Experimental CCDS; (4) Shingle COSMOS CCDS; (5) User own CCDS.

The first four built-in cross-shore distribution curves have been represented in the figure below. It could be quite useful to figure out a new method to estimate the cross-shore distribution of longshore transport since the current way is too empirical and ignore the possible distribution diffences along the beach.

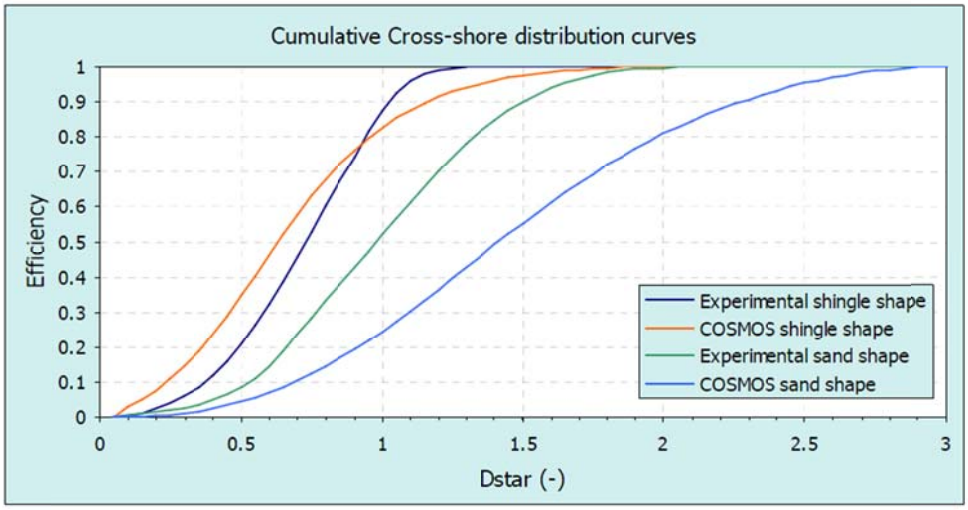


Figure 3 - 3 Cumulative cross-shore distribution curves in BEACHPLAN(from Blanco, 2003b)

Previously, there was no user interface to run BEACHPLAN model and the model was run by creating Batch files and executing in DOS system. The mondatory input files are listed below:

(1) Control file (*.bcn) – contains input data such as beach information and computational settings.
(2) Waves file (*.wav) – contains input wave information.

Recently, an advanced user interface called DAUBENTON has been developed and the model has become more user-friendly. A sample run of the model with the input files and output files is given in Appendix A8.

3.2 Cross-shore Profile Model

The models which focus more in the cross-shore direction are called cross-shore profile models or profile models for short. Many profile models have been in use since approximately 20 years ago to determine, for example, shoreline set-back, behaviour of beach nourishment and profile variations near coastal structures Roelvink and Broker (1993) compared five cross-shore profile models including: Nearshore Profile Model (HR Wallingford) which is the origin of COSMOS, UNIBEST from Delft Hydraulics, LITCROSS from Danish Hydraulic Institute (DHI), and etc. Unlike the one-line models, cross-shore profile models study more about the profile change due to the coastal processes. Usually, these models work for relatively short term, say hours to months. The spatial scale is metres to several hundred metres, which is much less than one-line models.

Since profile models work on smaller temporal and spatial scales, it is possible to make more accurate calculations along the profile. Meanwhile, more coastal processes may be taken into account compared with one-line models. COSMOS model, developed by HR Wallingford, is a good representation of this kind of models.

3.2.1 Theoretical Basis

The sediment transport over the profile basically depends on the cross-shore profile shape, sediment properties and seaward boundary conditions (wave height, direction and period), which is more straight-forward to use a mathematical expression:

$$\bar{q}(x) = f(\text{profile}[z_b], \text{sediment}[d_{50}, \rho_s, etc], \text{boundary}[H_s, T_m, \alpha, etc]) \qquad (3 - 4)$$

Where, $\bar{q}(x)$ time-averaged cross-shore rate of volume transport, m^3/s;

z_b bottom level, m;

d_{50} median grain size, m;

ρ_s sediment density, kg/m^3;

H_s, T_m, α wave height, period and direction.

Meanwhile, the continuity equation for sediment volume should be satisfied:

$$(1-p)\frac{\partial z_b}{\partial t}+\frac{\partial \bar{q}}{\partial x}=0 \qquad (3-5)$$

Where, p porosity of bed material;

t time,s;

x cross-shore coordinate, m;

Based on Eq. (3-5), the bottom level is updated after each time step, thus the cross-shore profile shape can be calculated. To be more specific, there are mainly three modules in a profile model: hydrodynamic module, sediment transport module and profile change module, see the figure below.

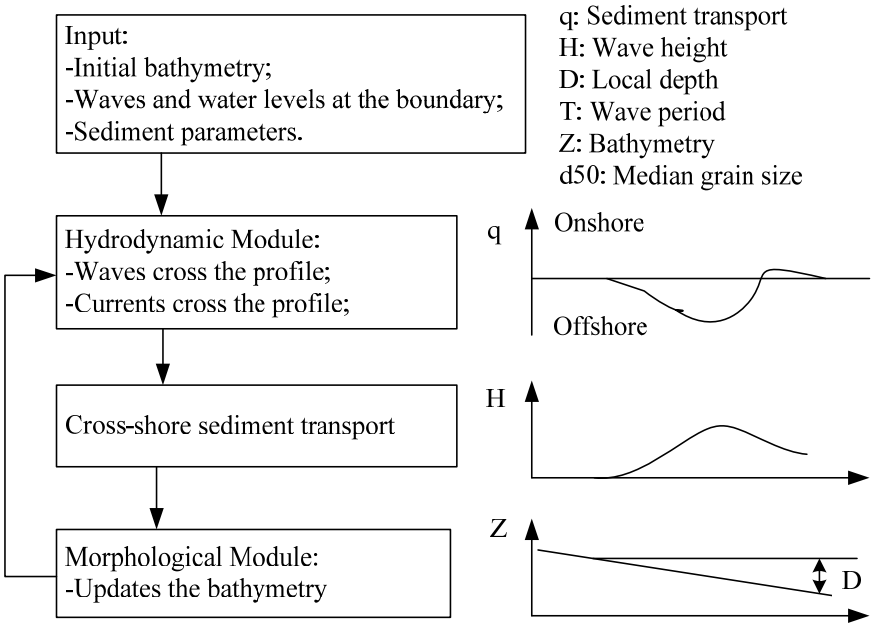


Figure 3 - 4 Generic structure of a cross-shore profile model

The time-averaged transport rate can be given by:

$$\bar{q}(x) = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} \int_{z_b}^{z_s} u(x,z,t)c(x,z,t)dzdt \qquad (3 - 6)$$

Where, t_1 starting time;

t_2 ending time considered;

z_s surface level;

z_b bed level;

$u(x,z,t)$ horizontal velocity;

$c(x,z,t)$ sediment volume concentration.

A common way to deal with Eq. (3 – 6) is to separate the velocity into four parts: time-averaged ($\bar{u}$), low-frequency variation (u_{lo}), wind-wave frequency (u_{hi}), turbulent variation (u'). Analogously for concentration, so the following expressions are obtained:

$$\begin{aligned} u &= \bar{u} + u_{lo} + u_{hi} + u' \\ c &= \bar{c} + c_{lo} + c_{hi} + c' \end{aligned} \qquad (3 - 7)$$

Insert the above expressions into Eq. (3 – 6), only the products of terms on the same time-scale give non-zero values, thus:

$$\bar{q}(x) = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} \int_{z_b}^{z_s} \left(\bar{u} \cdot \bar{c} + u_{lo}c_{lo} + u_{hi}c_{hi} + u'c' \right) dzdt \qquad (3 - 8)$$

Where, the first term is usually dominant in cases of severe erosion and the second term is import to describe interactions between short waves and long waves. The third term relates to wave asymmetry and time lag effects within the wave period while the last term considers the effect of turbulence, which is generally very small compared to other terms and can be neglected. More detailed explanations were given by Roelvink and Broker (1993) who comprehensively discussed the theoretical basis behind the cross-shore profile models. As a good representation of profile models, COSMOS will be further discussed in the next section.

3.2.2 COSMOS Model

COSMOS is a computational model of nearshore hydrodynamics, sediment transport and morphological changes (seabed evolution). The model has been validated against a wide range of experimental and field data, proving to be of good predictability. Over the past 20 years, it has been applied successfully in various sites to study the wave transformation and beach response.

The physical processes considered by the model are listed as follows (Wallace, 1994):

- Wave transformation: shoaling, refraction (by depth variation and currents), Doppler shifting, bottom friction and wave breaking;
- Wave set-up determined from the gradient of wave radiation stress;
- Driving forces for longshore wave-induced currents, determined from the spatial rate of wave energy dissipation;
- Longshore currents from pressure-driven tidal forces and wave-induced forces, and the interaction between the two types of current;
- Cross-shore undertow velocities using a three-layer model of the vertical distribution of cross-shore currents;
- Transition zone effects (the transition zone is the distance between the points where waves start to break and where turbulence becomes fully developed);
- Cross-shore and longshore sediment transport rates using energetics approach;
- Seabed level changes due to cross-shore sediment transport using Lax-Wendroff scheme;
- Downcutting of a cohesive profile due to abrasion by a covering layer of sand.

The program is coded using FORTRAN language and is structured in a three-tier hierarchy of modules; see the overall structure in the appendix. Two of the core modules are briefly introduced below.

(1) Hydrodynamic module

Profile models, such as SBEACH and COSMOS, assume a straight shoreline with parallel depth contours. Wave conditions are specified at the offshore end of the profile in terms of single wave height, period and direction. If a wave spectrum is to be represented, then the wave height, period and wave direction should be substituted with root-mean-square height, the peak or median period and wave energy average direction, respectively. The following processes can be considered: wave refraction, shoaling, Doppler shifting by depth variations, wave energy dissipation due to bottom friction and wave breaking. However, the interaction between wave and current should also be taken into account, see the figure below. The wave transformation module of COSMOS is mainly based on the research from Southgate (1989).

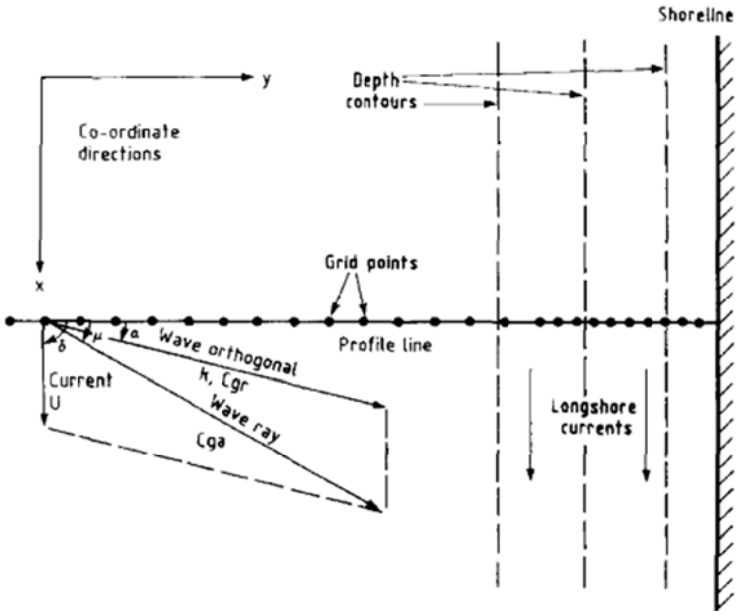


Figure 3 - 5 Model geometry of the nearshore region (from Southgate, 1989)

The main equation needs to be solved at each grid point is the dispersion relation with currents involved, which is given by:

$$\omega_a - Uk\cos(\delta - \alpha) = \sqrt{gk\tanh kh} \qquad (3 - 9)$$

Where, k wave number, needs to be solved;

ω_a absolute wave angular frequency, rad/s;

U longshore current velocity, m/s;

δ current's direction, degree;

α wave orthogonal direction, degree;

g the acceleration due to gravity;

h water depth, m.

The above equation is implicit with respect to wave number k and can be solved by Newton-Raphson technique. Once k is known, various related quantities such as the relative wave celerity and relative angular frequency can be determined. These quantities will be used for the next step when the wave dynamic quantities (wave energy E and wave height H) need to be calculated by the following wave-action integration equation (Christoffersen and Jonsson, 1980):

$$\frac{d}{dy}\left(\frac{EC_{ga}\cos\mu}{\omega_r}\right) = -\frac{D_f + D_b}{\omega_r} \qquad (3 - 10)$$

Where, C_{ga} absolute group velocity, m/s;

ω_r relative wave angular frequency, rad/s;

D_f wave-energy dissipation due to seabed friction;

D_b wave-energy dissipation due to wave breaking;

μ direction of absolute wave group velocity, refer to Figure 3-4;

y co-ordinate in the cross-shore direction;

E wave energy density.

The quantities such as C_{ga}, μ and ω_r can be obtained after k is determined. For linear monochromatic waves, E can be related to wave height H by:

$$E = \frac{1}{8}\rho g H^2 \qquad (3 - 8)$$

Where, ρ is the water density. By combining the above two equations, the wave height can be determined at each grid point through integration. If the expressions of the wave-energy dissipation terms D_f and D_b are known, the integration can be realized. Southgate (1987) concluded the wave height expression as follows:

$$H_i = H_o K_s K_r K_d \left(\frac{1}{1 + \beta H_o} \right) \qquad (3 - 9)$$

Where, H_o wave height at one grid point, m;

H_i wave height at the next grid point, m;

K_s shoaling coefficient;

K_r refraction coefficient;

K_d Doppler coefficient;

β integration function of wave characteristics.

It is worthwhile to mention that the model contains two criteria for wave breaking calculation. Weggel's formula (1972) is applied for regular waves while the formula of Battjes and Stive (1985) is used for the condition of random waves.

(2) Sediment transport with Energetics approach

The energetics approach for calculating sediment transport is based on the common sense that certain amount of fluid energy is needed to keep the bed load moving and the suspended load at a certain height above the bed, which was first developed by Bagnold (1963, 1966) for rivers and followed by Bowen (1980) who extended the method to calculate coastal sediment transport. This

approach assumes the sediment is mobilized by wave action and transported by three components: time-averaged flows such as undertow or longshore currents, asymmetric orbital velocities and gravity in the downslope direction.

Nairn and Southgate (1993) extensively discussed the energetics approach which laid the foundation for sediment transport module of COSMOS. Some key concepts and equations about the energetics approach are introduced below.

Bagnold assumed that the fluid acts as a machine expending energy at a prescribed efficiency to offset the work done in suspending and transporting sediment. A so-called immersed weight transport rate is defined as:

$$I = (\rho_s - \rho)(1 - p)S \qquad (3 - 11)$$

Where, I immersed weight transport rate, $kg/m/s$;

ρ_s density of sediment;

ρ density of water;

p porosity;

S volumetric transport rates of deposited material, $m^3/m/s$.

To be more specific, the immersed weight transport rates for bed load and suspended load can be given by the following expressions respectively.

$$I_b = \frac{\varepsilon_b c_f \rho u^3}{\tan\varphi - u\tan\beta/|u|} \qquad (3 - 12)$$

$$I_s = \frac{\varepsilon_s c_f \rho u^3 |u|}{w_s - \tan\beta |u|} \qquad (3 - 13)$$

Where, ε_b prescribed bed load efficiency;

ε_s prescribed suspended load efficiency;

c_f friction coefficient;

u near-bed fluid velocity;

ρ density of fluid;

φ angle of internal friction;

$\tan\beta$ bed slope;

w_s sediment falling velocity.

Sum Eq. (3-12) and (3-13) and rewrite the summed equation into the vector form, gives:

$$\left\langle I_t \right\rangle = \frac{\varepsilon_b c_f \rho}{\tan\varphi}\left(\left\langle |u|^2 u \right\rangle - \frac{\tan\beta}{\tan\varphi}\left\langle |u|^3 \right\rangle i \right) + \frac{\varepsilon_s c_f \rho}{w_s}\left(\left\langle |u|^3 u \right\rangle - \frac{\varepsilon_s \tan\beta}{w_s}\left\langle |u|^5 \right\rangle i \right) \quad (3 - 14)$$

Where, the angled brackets $\langle\ \rangle$ is the time-averaged operator and i is the direction of the vector velocity u which was expanded by Stive (1986) as:

$$u = \overline{u} + \tilde{u} \quad (3 - 15)$$

Where, $\overline{u}$ mean component of the horizontal velocity;

$\tilde{u}$ time-varying component of the horizontal velocity.

Use Taylor Series expansion based on the assumption that the time-varying component is much larger than the mean component, which is true in energetic conditions when most sediment is transported according to Bowen, and then the following expression is obtained:

$$|u|^n u = \tilde{u}^n |\tilde{u}| + (n+1)\overline{u}\tilde{u}^{n-1}|\tilde{u}| + \frac{n(n+1)}{2}\overline{u}^2\tilde{u}^{n-2}|\tilde{u}| + \ldots \quad (3 - 16)$$

Substitute Eq. (3-16) into Eq. (3-14), Stive (1986) derived the following expression for cross-shore sediment transport based on the energetics approach:

$$\left\langle I_t \right\rangle = \frac{\varepsilon_b c_f \rho u_m^3}{\tan\varphi}\left(\chi_1 + \frac{3}{2}\delta_u - \frac{\tan\beta}{\tan\varphi}(u3)^* \right) + \frac{\varepsilon_s c_f \rho u_m^4}{w_s}\left(\chi_2 + 4\delta_u (u3)^* - \frac{\varepsilon_s u_m \tan\beta}{w_s}(u5)^* \right) \quad (3 - 17)$$

Where, u_m the peak bed orbital velocity;

$\delta_u = \overline{u}/u_m$ dimensionless steady flow;

$\chi_1 = \left\langle \tilde{u}^2|\tilde{u}| \right\rangle / u_m^3$ 1st odd moment;

$\chi_2 = \left\langle \tilde{u}^3|\tilde{u}| \right\rangle / u_m^4$ 2nd odd moment;

$(u3)^* = \left\langle |u|^3 \right\rangle / u_m^3$ 3rd central even moment;

$(u5)^* = \left\langle |u|^5 \right\rangle / u_m^5$ 5th central even moment.

The volumetric transport rate can then be related to the immersed weight sediment transport by the following equation:

$$q = \frac{I_t}{(\rho_s - \rho)gp} \tag{3 - 18}$$

Where, p is the porosity, typically 0.6.

So far, the energetics approach to calculate the sediment transport rate has been briefly introduced. The reader is referred to the above mentioned papers for detailed explanations. A overview of COSMOS model structure is given in Appendix A3 and a sample run of the model is provided in Appendix A9.

There are two modes for calculations in COSMOS model: the cross-shore mode and longshore mode. A switch flag parameter is used to set the calculation mode and the default setting is cross-shore mode which predicts the cross-shore profile change under the assumption that there is no longshore transport gradient. On the other hand, longshore mode aims to calculate the cross-shore distribution of the longshore transport rate with stable profile. In this research, only the longshore mode is applied since longshore drifts calculated in COSMOS are to be used to improve BEACHPLAN model.

3.3 Linking Platform

As mentioned, it is going to be resource-consuming and even unnecessary to develop a completely new model that meets people's needs if we already have some similar models. Therefore, to link these existing models is another potential way to solve the problems, which is the initiative of this research.

However, it is usually difficult for different models to exchange data during run-time, which drives the development of a linking platform OpenMI (acronym for Open Modelling Interface). OpenMI is a standard that allows models from different vendors to run simultaneously and share information as required, according to The OpenMI Association (Scope Report, 2010). To support the configuration of linked components, a Graphical User Interface is needed. Pipistrelle is one kind of this interface that was developed at HR Wallingford and is now open source through the Fluid Earth initiative (https://fluidearth.net). Some further introductions to the OpenMI standard and Pipistrelle interface are given in the following sub-sections.

3.3.1 OpenMI Standard

The need of integrated water management, initiated by the Water Framework Directive (WFD), requires a standard that moves single domain modelling to integrated modelling. The aim of this standard is to provide a mechanism by which physical and socio-economic models can be linked to each other so that the process interactions between models can be better modelled. An overview of the OpenMI standard interface is given in Appendix A4.

To set up and test this standard, fourteen organizations from seven countries are working together to establish a European and potentially worldwide standard for linking models in environmental domain but not limited to the environmental domain.

The OpenMI standard is described at two levels on OpenMI organization website, one is based on users' level and the other is based on IT level. At the users' level, OpenMI allows models which may be from different suppliers to exchange data at the run-time. These models may be based on different concepts and have different spatial and temporal resolutions. Therefore, OpenMI is analogous to a USB cable from this point of view.

At the IT level, OpenMI standard acts as a software component interface for the modellers to define the computational core (i.e. the engine) of the models in the environmental domain. The advantage is that the linked models may run asynchronously with respect to time steps. Meanwhile, the data for different grids can be exchanged seamlessly. Thus, modellers don't need to code for exchanging data during the run-time if their models comply with the OpenMI standard.

The development of OpenMI standard is a huge project with all kinds of experts from different fields such as Hydraulic Engineering, Computer Science, Environmental Engineering, Economic Science and etc. The current released OpenMI standard is 2.0, which has been tested to be more flexible. To better understand this standard, the reader is encouraged to visit OpenMI website (OpenMI organization).

3.3.2 Pipistrelle Interface

Pipistrelle is an interface application developed by HR Wallingford to help modellers create and run compositions of models that implement the OpenMI standard. Many models developed by HR Wallingford have been re-written to comply with the OpenMI standard so that they can be linked through Pipistrelle. The interface is shown by the example given in the figure below.

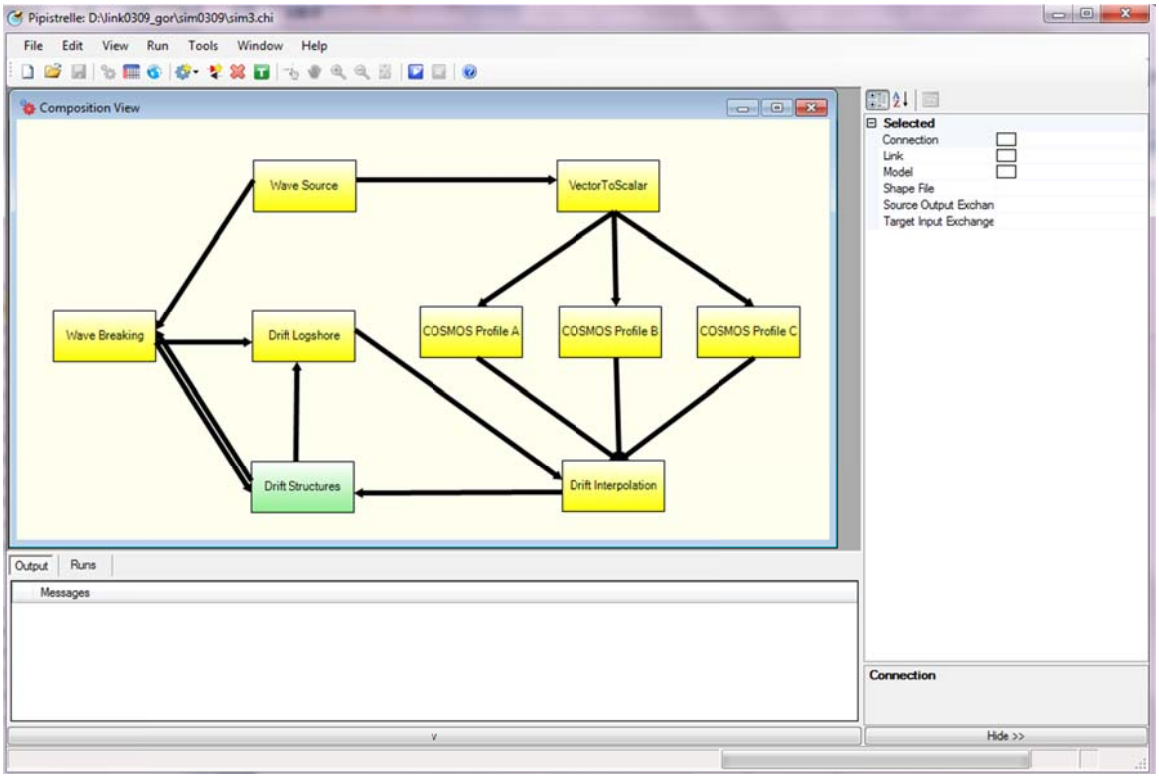


Figure 3 - 6 Example of Pipistrelle Interface developed at HR Wallingford

As can been seen in the overview, the interface comprises of a Composition window with all models loaded, a Message window in the lower part showing the running status, a Property window on the right side and the main Menu options at the very top of the interface. The user is able to track the problems when Pipistrelle starts running either by the Message window or the more detailed log file created by Pipistrelle. The log file is important for debug purpose as there are always potential problems when models are linked.

In this research, different compositions will be tested, so it is convenient to have a short introduction to the objects in the Composition window. The yellow and green boxes shown are the modules added in Pipistrelle interface. Only one box is green, which is the trigger of the whole composition that makes all other modules run when necessary. The black arrows are the links aim to exchange data during the run-time. More detailed explanation regarding the composition using the BEACHPLAN example is given in the next section.

Currently, the Pipistrelle Interface is free to use for studying and research purpose and can be downloaded from the Fluid Earth Portal website.

3.4 Models in Pipistrelle

Both BEACHPLAN and COSMOS models need to be re-written following the OpenMI standard so that they can be linked through Pipistrelle interface. HR Wallingford has already wrapped these two models and the individual model works as expected. However, few tests have been done regarding the linking of these two models.

3.4.1 BEACHPLAN in Pipistrelle

BEACHPLAN model has recently undergone a complete re-write and is now four modules linked within OpenMI. To give a general impression what the modules look like, a composition view in Pipistrelle is given below:

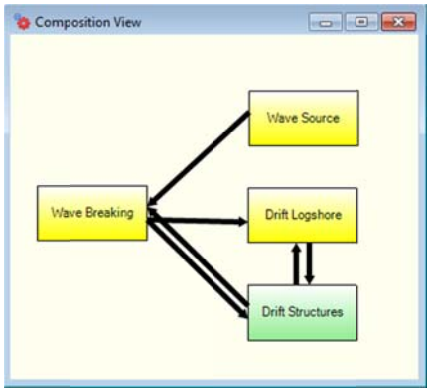


Figure 3 - 7 BEACHPLAN model represented in the Pipistrelle Interface

The four modules are shown in the boxes named Wave Breaking, Wave Source, Drift Longshore and Drift Structures, which are connected by the black arrows so that the data are exchanged during the run-time. One module named "Drift Structure", which is in green colour, is set as trigger. The trigger should be the last component in the composition chain which requires data and makes all other components exchange data when necessary.

The composition in Figure 3-6 can be recognized as the OpenMI version of BEACHPLAN, which gives the same modelling results as ordinary BEACHPLAN model. The main advantage of OpenMI version is that four modules in BEACHPLAN are now able to work independently. These modules are connected only when one module requires data from others. This makes it possible to add more modules in the composition and all the components are able to work potentially as a whole model when proper connections are made.

On the other hand, it makes easier to improve or upgrade a model since the model is divided into several independent modules. Modifications of one module may be enough to make the improvement rather than change the whole model.

Back to the BEACHPLAN model, it is convenient to briefly introduce the four modules in the composition view. "Wave Source" module provides the wave information to "Wave Breaking" module which calculates wave transformation conditions till wave breaking. Then, the obtained parameters such as breaking depth, inshore wave angle, inshore wave height and wave period are passed to "Drift Logshore " module. The trigger "Drift Structures" module also requires breaking wave information for calculation and passes the results to "Drift Logshore". When all required data reach "Drift Logshore" module, it finishes its calculation and passes back the results to other modules at the run-time for further computations.

It has been tested that the data-exchanging time used by the OpenMI platform is very limited compared to the model calculation time, so the modelling efficiency still depends on the model itself. This point is very important because it will be no practical meaning if it is extremely time-consuming to exchange data using the OpenMI platform.

3.4.2 COSMOS in Pipistrelle

Unlike BEACHPLAN model, COSMOS hasn't been rewritten into modules but instead it acts as a whole in Pipistrelle, see the figure below. To run COSMOS in Pipistrelle, the only model component should be set as a trigger which is in green.

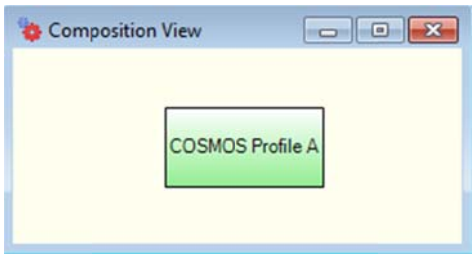


Figure 3 - 8 COSMOS model represented in the Pipistrelle Interface

The OpenMI version of COSMOS, or say COSMOS in Pipistrelle, hasn't been tested before at HR Wallingford whether it works well when it is linked with other models. Therefore, this research also provides an opportunity to study the feasibility of COSMOS for linking. As COSMOS acts as a whole in Pipistrelle, it brings a question that how to couple the wave source so that BEACHPLAN and COSMOS use the same wave information.

3.5 Model Comparison

The one-line model (BEACHPLAN) and the profile model (COSMOS) give different longshore sediment transport because they adopt different methods for calculation. To be more specific, the formula for sediment transport used in each model is different and the consideration of hydrodynamics is different as well.

3.5.1 Difference in Formulae

These two models apply two different approaches to calculate longshore drift and their characteristics are listed below:

(1) Modified CERC formula (Osaza and Brampton, 1980) in BEACHPLAN
   a) Simple calibration due to the reduced number of calibration parameters (K_1 and K_2)
   b) Inclusion of the term that takes into account the variability of the wave height alongshore (dH/dx). This term essentially drives sediment from area of high waves to area of low waves.

(2) Energetics approach in COSMOS longshore mode
   a) Consideration of the real sediment size
   b) The effects of bars is included, or in other words the profile does not need to be always descending
   c) The effect of sills or similar submerged non-erodible features is included.

3.5.2 Difference in Consideration of Hydrodynamics

COSMOS model considers more detailed hydrodynamics and the one-line model BEACHPLAN may be improved by linking with COSMOS. Some points that worthwhile to mention are listed below:

(1) BEACHPLAN model
   a) Simple consideration of shoaling, refraction and breaking
   b) Simplified straight cross-shore profile for wave transformation

(2) COSMOS model
   a) Inclusion of tidal currents
   b) The effect of the seawall is properly represented, for example in terms of reflection.
   c) The directional spread is taken into account in the refraction calculations
   d) Wave energy dissipation by bottom friction and breaking

3.5.3 Improvement of BEACHPLAN through Linking

Based on the discussions before, several reasons that the one-line model (BEACHPLAN) can be improved by linking with the profile model (COSMOS) are:

(1) COSMOS model considers detailed calculation of hydrodynamics
(2) Real cross-shore profile
(3) Real sediment size, and
(4) Detailed cross-shore distribution of longshore sediment transport;

4 METHODOLOGIES AND MODEL COUPLING

This Chapter describes how the two existing models (BEACHPLAN and COSMOS) are linked through OpenMI-based Pipistrelle Interface to form a coupled model. To begin with, a general introduction is given to the proposed methodologies that are applied to carry out this research. Then, some potential key problems during the linking stage are explained. To solve these problems, three additional modules (Drift Interpolation Module, Vector-To-Scale Module and Orientation Updating Module) are developed and tested. The last section presents an overview of the coupled model and the working principle is also introduced.

4.1 Methodological Steps and Model Coupling Approaches

The drift values calculated by COSMOS are to be applied for further calculations in BEACHPLAN to make better prediction of shoreline evolution. However, BEACHPLAN model requires drift value for each grid point while it's not reasonable to run COSMOS in each grid point currently since it is going to be time-consuming. However, it is thought to be possible in the future when OpenMI standard is further improved so that each COSMOS model can be run at the same time instead of one-by-one manner. In this research, the idea is to run COSMOS in several primary profiles. A primary profile is the user-defined profile which is assumed to be perpendicular to the shoreline. To start with, three primary profiles are chosen along the beach for COSMOS to run.

To better control the progress, the research is divided into several stages from the model-development point of view. Meanwhile, two alternative approaches for linking the models are also raised and discussed in the following sections.

4.1.1 Coupling Stages

Basically, there are four stages to carry out the research. Each stage needs to be completed and tested before coming to the next one.

Stage 1:

Set COSMOS-LS (LS stands for longshore mode) in x primary profiles (x is thought to be less than 20) along the beach. Take the bulk drift of each profile from COSMOS-LS and modify them based on the changing tendency of drifts produced by BEACHPLAN.

Stage 2:

Apply the modified drifts at every time-step of BEACHPLAN (normally 1 or 3 hours). Run the whole composition. Profile orientation in COSMOS-LS is not updated at this stage.

Stage 3:

Generate proper method to update the profile orientation in COSMOS-LS at each time step based on the updated shoreline position calculated by the new coupled model at each time step.

Stage 4:

Pass the bulk drift values as well as the cross-shore distribution of longshore transport from COSMOS-LS to BEACHPLAN. The model should be tested with coastal structures such as groynes and detached breakwaters.

4.1.2 Coupling Alternative Approaches

There are two alternative approaches that can realize the linking target. Both the pros and cons are discussed and the second approach is chosen for this research.

Approach 1:

Replace the "Drift Longshore" module in BEACHPLAN with the same functional module in COSMOS model.

This method looks quite promising in the long run when COSMOS model is divided into more detailed functional modules. It can be expected that these two models are able to exchange data and exchange the modules as well to form new compostions and models. Unfortrnately, COSMOS works as a whole (not in modules) in Pipistrelle, thus there will be much work to be done to split COSMOS model into modules that can run independently in Pipistrelle, which will take months or even longer time. Therefore, this is not very reasonable for this research due to the time limitation.

Approach 2:

Create some additional modules externally to make the connections.

To couple these two models, another alternative is to add more modules to connect the models. The disadvantage is that new modules are to be created and tested whenever they are needed. Therefore, there will be potential changes to the compositions at every stage. However, the advantages overweigh the disadvantages for this research because of the following reasons: (1)

the research process can be divided into controllable steps; (2) it takes relatively less time to add an independent module to fulfill some specific requirments; (3) very few changes need to be done to the existing BEACHPLAN and COSMOS models.

Based on the analysis, Approach 2 is chosen for this research. Some more modules are added for each stage, which will be discussed later.

4.2 Key Problems

It is theoretically feasible to link two different models through OpenMI platform based on the previous introductions. However, there are always some potential problems to be addressed when it comes to the linking stage. Actually, more and more questions need to be answered with the research going on since a solution to one problem may invoke another problem.

Problem 1:

The first question to be answered for the linking stage is that which drift values should be passed to BEACHPLAN model. In this research, COSMOS model runs for only three profiles (three grid points in BEACHPLAN coordinate system) while each grid requires a drift value to run BEACHPLAN. Therefore, an interpolation method is developed to give all the grids a drift value, which is discussed in the Drift Interpolation Module section.

Problem 2:

To couple these two models, another problem is how to couple the wave source input. As for COSMOS model, it accepts only one wave point' data because it is a profile model. However, BEACHPLAN usually works with several wave points' data along the beach with linear interpolation between two neighbouring wave points. From a mathematical point of view, wave source in BEACHPLAN is a vector while a scalar in COSMOS. Therefore, research should be carried out to find a proper way to pass wave source from BEACHPLAN to COSMOS model.

Problem 3:

Moreover, COSMOS profile orientations should be updated when the shoreline position is updated after each time step. This is because COSMOS model is working under the assumption that the local shoreline is straight and the profile is perpendicular to the local shoreline. The profile orientations change accordingly when the shoreline changes. Therefore, it is a question to be answered during the third stage.

Hence, three new modules are required: Drift Interpolation Module, Vector-To-Scalar Module and Orientation Updating Module. The development of each of these modules is discussed in turn. There are also other potential problems to be addressed during the testing stage.

4.3 Drift Interpolation Module

It has been argued in the last section that to add several more modules to link the models is the most potential way for this study and the further research. In this section, one of the core added modules, the Drift Interpolation module, is discussed. The mathematical basis is given and several tests are performed to check if the module works as expected. The primary composition view without COSMOS models is shown by the figure below.

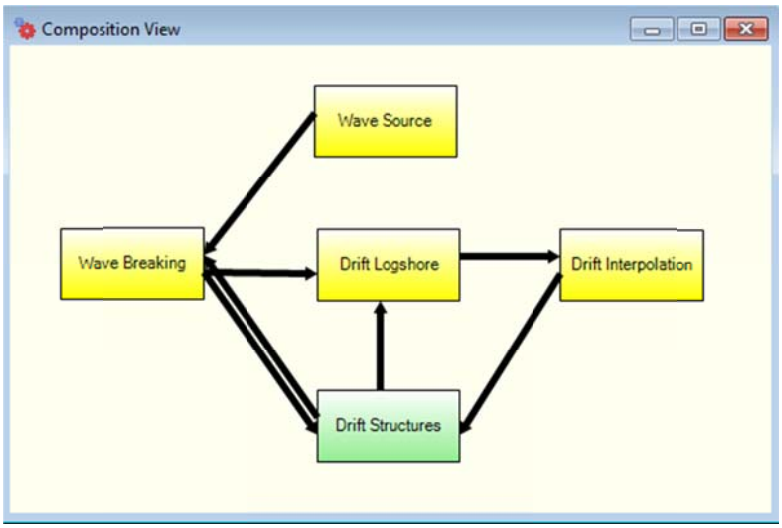


Figure 4 - 1 BEACHPLAN model linked with Drift Interpolation module

When comparing BEACHPLAN composition (Figure 3 - 6) with this composition, it can be noticed that the black arrow from "Drift Logshore" to "Drift Structures" has disappeared in the new composition. Instead, the link is substituted by two black arrows: one is from "Drift Logshore" to "Drift Interpolation" and the other is from "Drift Interpolation" to "Drift Structures". In theory, the modelling results won't be changed if no COSMOS inputs are introduced to this composition, meaning the "Drift Interpolation" module only acts as a transition module for passing values. This point is confirmed to be correct by a primary test later.

This "Drift Interpolation" module is developed based on OpenMI standard so that it can be linked to other models through Pipistrelle interface. The computational part of the module is coded in C# programming language. Parts of the core codes are attached in Appendix A5.

4.3.1 Theoretical Basis

As mentioned before, some kind of interpolation method should be applied because only several profile drift values are known from COSMOS while drift values at each grid point in BEACHPLAN model are required to make the prediction. Therefore, an interpolation method should be generated. If linear interpolation method is applied between two successive primary profiles, the changing tendency information of drifts in different grid points calculated by BEACHPLAN due to the orientation of the coast and the variation of the wave height alongshore will be lost. Thus, the interpolation of drifts between two neighbouring COSMOS profiles will be done based on not only the bulk drift values from COSMOS but also the changing tendency from BEACHPLAN, see the figures below.

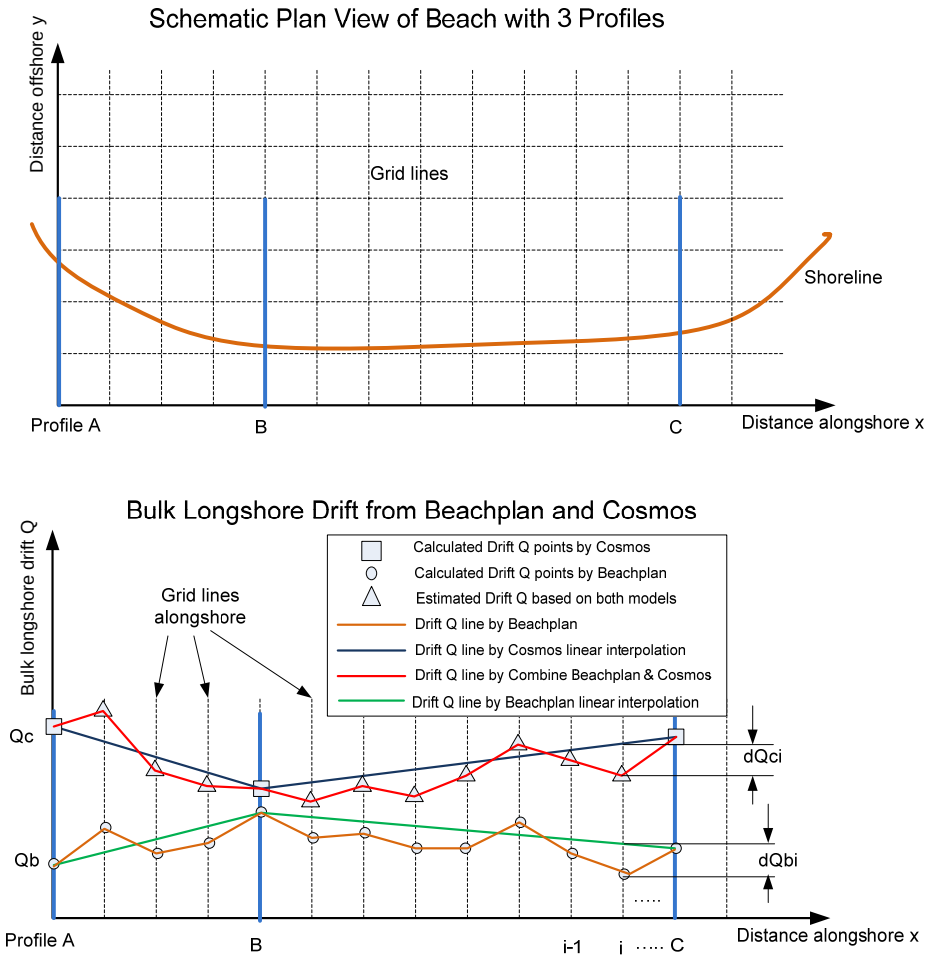


Figure 4 - 2(a) Schematic plan view of beach with three primary profiles (upper); (b) Explanation of drift interpolation method (lower)

As can be seen in Figure 4 – 2(b) above, there are three primary profiles denoted by A, B and C. For each profile, COSMOS calculates the drifts (denoted by 3 small squares) which are different from the values calculated by BEACHPLAN (denoted by small circles). The drifts in each grid

point between two successive profiles are not calculated by COSMOS simply because it's not reasonable to run COSMOS at each grid point of BEACHPLAN. Therefore, proper interpolation is necessary to estimate the drift values at each grid point between Profiles A, B and C. If linear interpolation (see the blue drift line) is used, the information of drift changing tendency from BEACHPLAN (see the brown drift line) will be completely lost. To take this into account, the following method is applied to make the interpolation, see the small triangles in the figure.

First, linear interpolation is used between two successive profiles in BEACHPLAN, see the green line in the above figure. Take the section between Profiles B and C as an example, the real and linear-interpolated drift values of BEACHPLAN for grid point i are denoted by Q_{bi} and Q'_{bi}. The difference between these two is:

$$dQ_{bi} = Q'_{bi} - Q_{bi} \quad (4 - 1)$$

Analogously, the expected and linear-interpolated drift values of COSMOS for grid point i are denoted by Q_{ci} and Q'_{ci} and the difference is:

$$dQ_{ci} = Q'_{ci} - Q_{ci} \quad . \quad (4 - 2)$$

The differences dQ_{bi} and dQ_{ci} are assumed to be equal so that Eq. (4 - 1) and (4 - 2) can be linked. This simple assumption considers the information of drift changing tendency in BEACHPLAN; however, further research can be done to give more reasonable assumption. Thus the expected drift values can be calculated by:

$$Q_{ci} = Q'_{ci} - Q'_{bi} + Q_{bi} \quad . \quad (4 - 3)$$

Where, Q'_{ci}, Q'_{bi}, Q_{bi} are known values;

Q'_{ci} linear-interpolated drift values of COSMOS for grid point i, m^3/s;

Q'_{bi} linear-interpolated drift values of COSMOS for grid point i, m^3/s;

Q_{bi} real drift values of BEACHPLAN for grid point i, m^3/s;

When Q_{ci} is obtained, the drift values are passed back to BEACHPLAN for further calculations.

4.3.2 Module Test

(1) Primary Test without COSMOS Inputs

In theory, the composition shown by Figure 3-6 should give the same modelling results as the original BEACHPLAN composition if no COSMOS inputs are involved. A simple test is performed to check if this is true, which is essential for the further research.

Given the same wave input (7-day wave data in this case) and beach conditions, the two compositions are run separately. The results by original BEACHPLAN composition and the new composition are given by Table 4-1 and 4-2, respectively.

Table 4 - 1 Drift results given by original BEACHPLAN composition

chain(i), q(i,t). Drift results m3/s every 1 day(s)								
ch(i)\day	0	1	2	3	4	5	6	7
0	0	-16233	-20613	-20617	-20621	-20626	-20633	-20638
100	0	-16233	-20613	-20617	-20621	-20626	-20633	-20638
200	0	-16242	-20623	-20626	-20631	-20637	-20641	-20644
300	0	-16243	-20627	-20630	-20629	-20625	-20617	-20608
400	0	-16227	-20593	-20576	-20556	-20534	-20512	-20490
500	0	-16120	-20430	-20394	-20362	-20332	-20305	-20280
700	0	-15439	-19603	-19602	-19601	-19599	-19596	-19593
900	0	-14880	-18896	-18897	-18898	-18899	-18899	-18899
1100	0	-14332	-18201	-18202	-18203	-18203	-18204	-18205
1300	0	-13796	-17522	-17523	-17523	-17524	-17525	-17526
1500	0	-13272	-16857	-16858	-16859	-16860	-16861	-16861
1700	0	-12759	-16208	-16208	-16209	-16210	-16210	-16211
1900	0	-12257	-15572	-15572	-15572	-15573	-15573	-15573
2100	0	-11767	-14948	-14948	-14949	-14951	-14954	-14958
2300	0	-11298	-14377	-14400	-14421	-14441	-14459	-14476
2500	0	-11298	-14377	-14400	-14421	-14441	-14459	-14476

Table 4 - 2 Drift results given by the new composition with Drift Interpolation module

chain(i), q(i,t). Drift results (m3/s) every 1 day(s)								
ch(i)\day	0	1	2	3	4	5	6	7
0	0	-16023	-20613	-20617	-20621	-20626	-20633	-20638
100	0	-16023	-20613	-20617	-20621	-20626	-20633	-20638
200	0	-16032	-20623	-20626	-20631	-20637	-20641	-20644
300	0	-16033	-20627	-20630	-20629	-20625	-20618	-20608
400	0	-16018	-20594	-20577	-20556	-20534	-20512	-20490
500	0	-15913	-20431	-20395	-20362	-20333	-20305	-20280
700	0	-15240	-19603	-19602	-19601	-19599	-19596	-19593
900	0	-14688	-18896	-18897	-18898	-18899	-18899	-18899
1100	0	-14147	-18201	-18202	-18203	-18203	-18204	-18205
1300	0	-13618	-17522	-17523	-17523	-17524	-17525	-17526
1500	0	-13100	-16857	-16858	-16859	-16860	-16861	-16861
1700	0	-12594	-16207	-16208	-16209	-16210	-16210	-16211
1900	0	-12099	-15572	-15572	-15572	-15573	-15573	-15573
2100	0	-11614	-14948	-14948	-14949	-14951	-14954	-14958
2300	0	-11151	-14377	-14399	-14421	-14440	-14459	-14476
2500	0	-11151	-14377	-14399	-14421	-14440	-14459	-14476

Compare these two tables carefully, one may find there is slight difference for some drift values, which is because the time step chosen in the “Drift Interpolation” module is not small enough. If smaller time step is used, the difference will be even slighter and tending to zero in theory.

(2) **Test with COSMOS Inputs**

The model also needs to be tested with COSMOS inputs to check if it works as expected. Rather than test in Pipistrelle, it is easier to test it using Console application mode based on C#. The

results calculated by the codes are compared to the results computed by Microsoft Excel for checking purpose, see Table 4-3.

In this example, eleven grid points are chosen with grid points 0, 7 and 10 as COSMOS inputs, see the blue shaded area in the table below. The BEACHPLAN results are known and shown in the third row in the table, i.e. {5.00, 6.00, 5.00, 7.00, 5.00, 4.00, 5.00, 7.00, 3.00, 8.00, 5.00}. Only three COSMOS drift values are known at Profile A, B and C, they are 6.00, 10.00 and 12.00 shown in the fourth row.

Table 4 - 3 Interpolation results

	Profile A							Profile B			Profile C
Grid Points	0	1	2	3	4	5	6	7	8	9	10
Beachplan results	5.00	6.00	5.00	7.00	5.00	4.00	5.00	7.00	3.00	8.00	5.00
Cosmos results	6.00							10.00			12.00
Linear Interpolation Cosmos	6.00	6.57	7.14	7.71	8.29	8.86	9.43	10.00	10.67	11.33	12.00
Linear interpolation Bplan	5.00	5.29	5.57	5.86	6.14	6.43	6.71	7.00	6.33	5.67	5.00
Difference Bplan	0.00	(0.71)	0.57	(1.14)	1.14	2.43	1.71	0.00	3.33	(2.33)	0.00
Calculated results	6.00	7.29	6.57	8.86	7.14	6.43	7.71	10.00	7.33	13.67	12.00

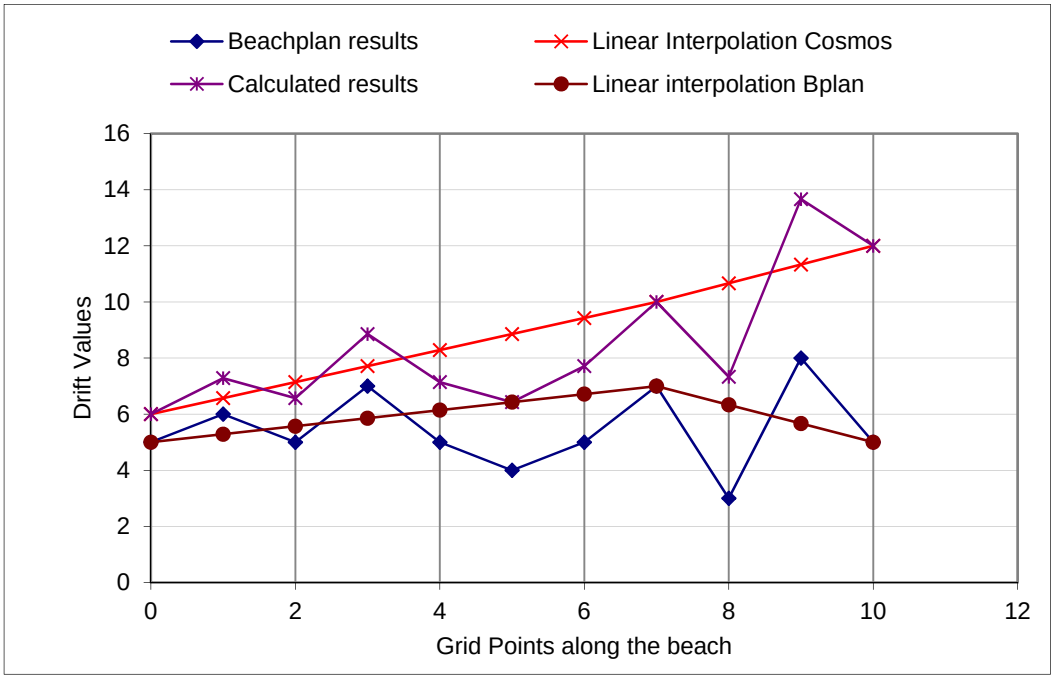


Figure 4 - 3 Interpolation based on results in Table 4- 3

According to the theoretical basis in the section 4.3.1, the expected final results are calculated and given by the last row of the table which is shaded in grey colour, listed as:

{6.00, 7.29, 6.57, 8.86, 7.14, 6.43, 7.71, 10.00, 7.33, 13.67, 12.00}. Array(1)

Then, the same conditions are calculated by “Drift Interpolation” module. The results given by the new model (with the added module) are printed in the console window, see the figure below, the drift values at each grid point are:

{6.00, 7.29, 6.57, 8.86, 7.14, 6.43, 7.71, 10.00, 7.33, 13.67, 12.00}. Array(2)

Array (1) and (2) are exactly the same, so Drift Interpolation module works as expected.

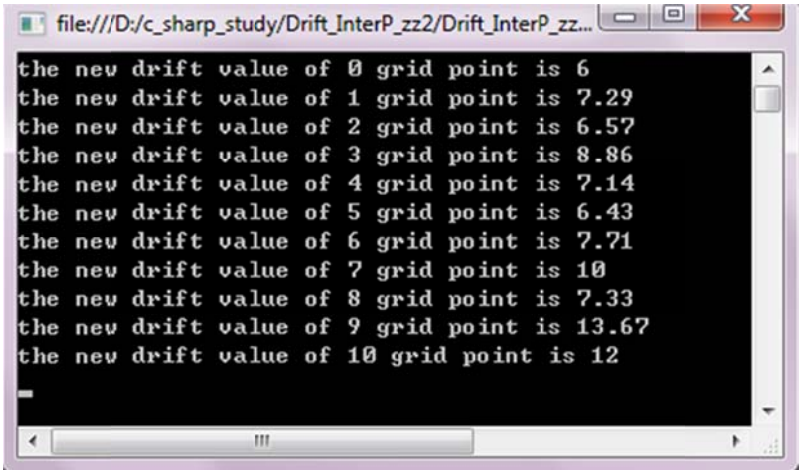


Figure 4 - 4 Example of Drift values calculated by “Drift Interpolation” model

4.4 Vector-To-Scalar Module

To couple the two models, the same wave input information should be used for both models. The wave input formats of the two models are totally different, and then one more module is designed to couple the wave inputs.

4.4.1 Theoretical Basis

BEACHPLAN model allows several wave points along the coastline, linear interpolation of wave conditions is made between two successive wave points. On the other hand, COSMOS is a profile model, which needs only one wave point. Typical wave input formats and examples of these two models are presented below.

(1) BEACHPLAN model wave input format:

Date	Period	Hs(1)	Dir(2)	Hs(2)	Dir(2)	Hs(3)	Dir(3)	… Hs(n)	Dir(n)
20050101	2.5	0.2	210.5	0.2	212	0.18	221.3		

(2) COSMOS model wave input format:

Period	Direction	Height	Duration/Probability	Water Level	Output Flag
6.0	0.0	1.5	12660.0	0.0	1

More information about the parameters in these two wave files can be referred to the manuals of BEACHPLAN and COSMOS (Blanco 2003a, Wallace 1994).

Basically, COSMOS needs wave period, direction and height information from the wave source module of BEACHPLAN so that COSMOS can run at each profile using the right wave input. For example, there are three wave points used in BEACHPLAN, the function of the Vector-To-Scalar model is to split the three wave points into individual wave point which is then applied for three separate profiles along the shoreline using COSMOS. This module is coded in FORTRAN language, which is provided in Appendix A6.

4.4.2 Module Test

The module can be simply tested by running a composition with three wave input points. A short passage from the log file of the whole composition shows it works as expected, see the log file below. The log file is generated by Pipistrelle during the run-time to trace the working conditions of the whole composition, which is quite helpful during debug stage.

```
Input Array Length 12, [0..12)
  Index Length     Type Count Link "Quantity","ElementSet" (TimeNextRequired) = [Values]
  ===== ====== ====== ===== ==== ======================
      0        3 Scalar     3   195 "ANGLE_IN","Vector" (51544) = [-2.6092672,-2.5830873,-2.4207717]
      3        3 Scalar     3   196 "DEPTH_IN","Vector" (51544) = [7.5,7.5,7.5]
      6        3 Scalar     3   197 "HEIGHT_IN","Vector" (51544) = [0.2,0.2,0.18]
      9        3 Scalar     3   198 "PERIOD_IN","Vector" (51544) = [2.5,2.5,2.5]
Output Array Length 9, [0..9)
  Index Length     Type Count Link "Quantity","ElementSet" (TimeNextRequired) = [Values]
  ===== ====== ====== ===== ==== ======================
      0        1 Scalar     1   202 "ANGLE_OUT_1","Scalar" = [-2.6092672]
      1        1 Scalar     1   203 "HEIGHT_OUT_1","Scalar" = [0.2]
      2        1 Scalar     1   204 "PERIOD_OUT_1","Scalar" = [2.5]
      3        1 Scalar     1   208 "ANGLE_OUT_2","Scalar" = [-2.5830873]
      4        1 Scalar     1   209 "HEIGHT_OUT_2","Scalar" = [0.2]
      5        1 Scalar     1   210 "PERIOD_OUT_2","Scalar" = [2.5]
      6        1 Scalar     1   214 "ANGLE_OUT_3","Scalar" = [-2.4207717]
      7        1 Scalar     1   215 "HEIGHT_OUT_3","Scalar" = [0.18]
      8        1 Scalar     1   216 "PERIOD_OUT_3","Scalar" = [2.5]
```

As can be seen in the above log file, the input elements are given in vectors which are comprised of three scalars. The model Vector-To-Scalar then splits the vectors and transfers them into single scalars which can be used by COSMOS model.

4.5 Profile Orientation Updating Module

The shoreline position in BEACHPLAN is updated after each time step so the COSMOS profile orientations should be updated after each time step as well. This is because COSMOS model is working under the basic assumption that the local shoreline is straight and the profile is more or less perpendicular to the shoreline. The profile orientations change accordingly when the shoreline changes.

4.5.1 Theoretical Basis

To start with, it is convenient to briefly introduce the coordinate system used in BEACHPLAN and COSMOS models. As the wave data is specified with respect to the North in BEACHPLAN, the local coordinates are transformed according to the global coordinate system for calculation (Blanco, 2003a). Similarly for COSMOS model, a profile angle has to be specified to describe the orientation of the profile with respect to the North (Wallace, 1994). A schematic explanation of the coordinate systems is given in Figure 4-5 below.

x-y system = Local BEACHPLAN system
X-Y system = Global BEACHPLAN system
α = COSMOS profile angle with North
β = BEACHPLAN coordinate angle with North

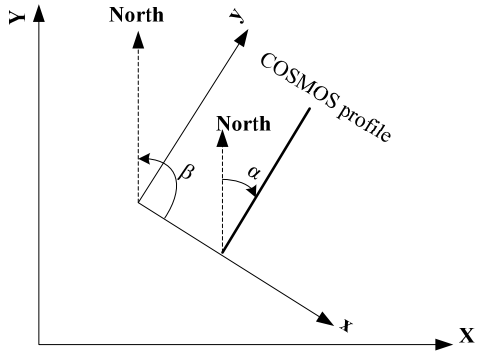


Figure 4 - 5 Coordinate systems of BEACHPLAN and COSMOS models

As shown in Figure 4-5, the coordinate systems describe the conventions of the angles used in BEACHPLAN and COSMOS models. The angle β (positive anticlockwise) from x-axis to the North has to be specified in BEACHPLAN model to transform the local coordinate system (x-y) to global coordinate system (X-Y). It is worthwhile to mention that the global coordinate system only contains the grid location information on x-axis of the local coordinate system, without any information about shoreline position which can be explained by Figure 4-6 below. For example, the grid point (x2, 0) in the local coordinate system is actually (X2, Y2) in the global coordinate system. Therefore, one of the functions of the global coordinate system is to describe the x-axis in the local coordinate system in BEACHPLAN model.

On the other hand, the angle α (positive clockwise) from the North to y-axis is to specify the profile orientation used in COSMOS model (Figure 4-5). If the local shoreline is parallel to x-axis in BEACHPLAN model, the profile in COSMOS model is then perpendicular to x-axis according to the basic assumption. Under this condition, the quantity angle α is exactly 90 degree smaller than β, which can be mathematically described as:

$$\alpha = \beta - 90^{o} \tag{4-4}$$

Where, the angles α and β are in degree. However, if the COSMOS profile is not normal to the x-axis, as for example Profile A' (in red colour of local coordinate system in Figure 4-6), the quantity profile angle α in this case can be obtained by:

$$\alpha = \beta - 90^{o} + \theta \tag{4-5}$$

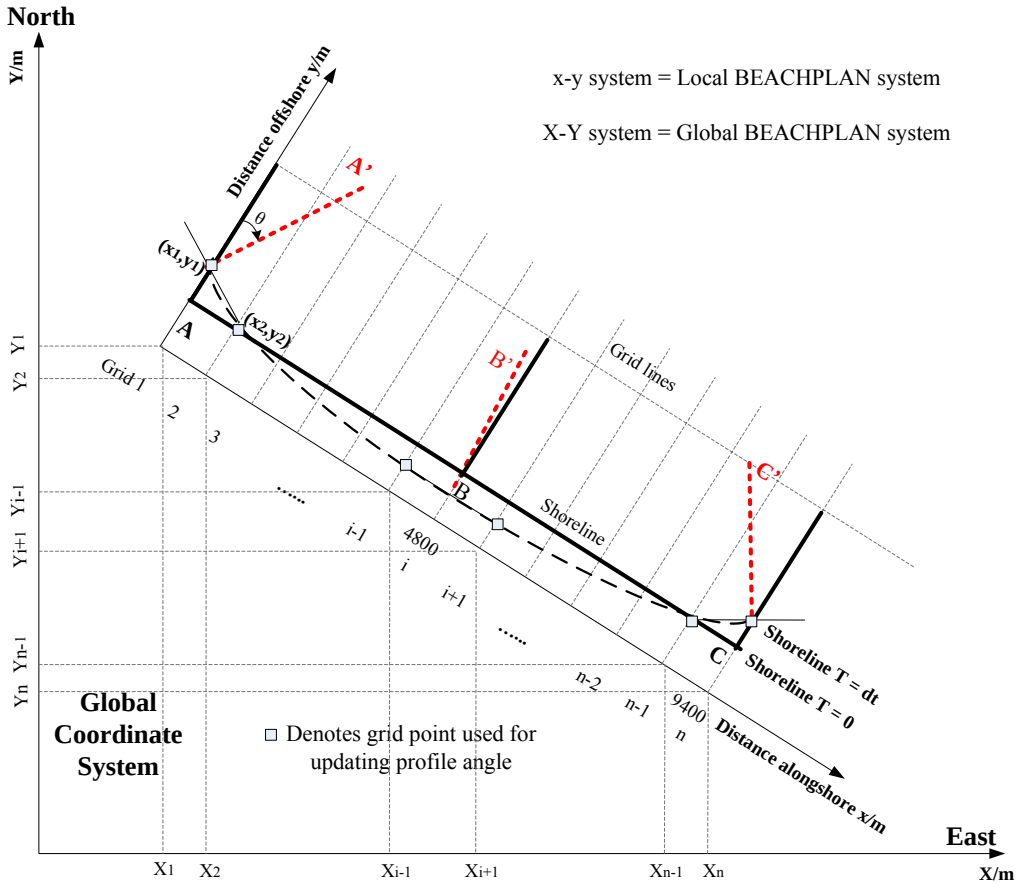


Figure 4 - 6 Working principle behind profile Orientation Updating module

The main purpose of Profile Orientation Updating module is to figure out the quantity value of the profile angle α after each time step. It is obvious that the value of angle β is fixed once the BEACHPLAN coordinate system is chosen. Hence, the angle α is just a simple linear function of angle θ.

To find out the value of angle θ after each time step, the evolution of shoreline position should be analyzed. In Figure 4-6, the initial shoreline (T=0) is assumed to be straight and COSMOS profile A is normal to the shoreline, so in this case $\theta = 0$. After a time step dt (T=dt), the straight shoreline is shaped to a curved shoreline under certain wave conditions, see the dashed line. All the three updated COSMOS profiles (A', B' and C') are no longer normal to the x-axis, while they should be normal to the local shoreline according to the basic assumption of COSMOS model.

The method to figure out the angle θ for Profile A and C is the same since they are both boundary profiles. As for the middle Profile B, the method can be different. Hence, the mathematical treatments for boundary Profiles A, C and middle Profile B will be discussed in turn. Meanwhile, there can be different methods to find a local representative shoreline for each profile location. In this research, two different methods are explored: simple treatment and least squares fitting method.

4.5.1.1 Simple Method for Representation of Local Shoreline

The simplest method to represent the local shoreline is just to connect two neighbouring grid points to make a straight line. To find the angle θ, the slope of the straight line needs to be figured out. The grid points used to represent the local shoreline for the two boundary profiles A and C and the middle profile B are different in this research, see Figure 4 - 7.

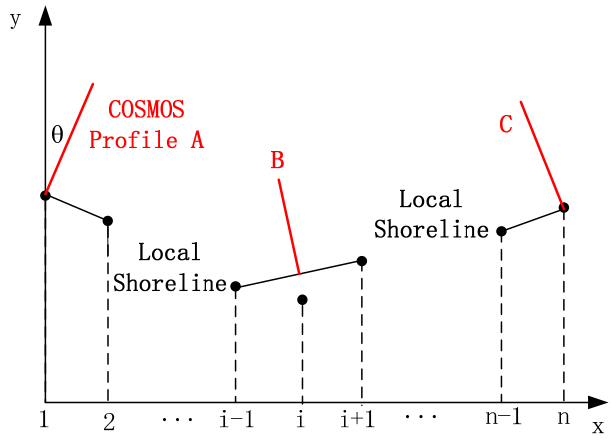


Figure 4 - 7 Schematic explanation of simple method for representation of local shoreline positions

(1) Boundary Profile A and C

At both ends of the study shoreline (Figure 4-7), the method to calculate the profile orientations should be based on the neighbouring grid points of the boundary grid points. In the following discussion, Profile A is taken as an example for illustration.

When the shoreline is updated after a time step dt, Profile A should be re-orientated to Profile A' which is represented in red colour in Figure 4-6. To find the angle θ, grid points 1 and 2 are chosen in this case. However, more grid points may be used depending on the shoreline conditions, which will be discussed later.

Based on the local coordinate system in Figure 4-6, points 1 and 2 are located at (x1, y1) and (x2, y2), which are marked by small squares. These two points are then connected with a straight line and the new Profile A' is assumed to be perpendicular to this straight line. Thus the angle θ can be given by the following expression:

$$\theta = \frac{180^o}{\pi} \times \arctan(\frac{dy}{dx}) = \frac{180^o}{\pi} \times \arctan(\frac{y2 - y1}{x2 - x1}) \tag{4-6}$$

Where, angle θ is in degree and *x1, x2, y1* and *y2* are in meter. In Eq. (4-6), y1 and y2 are known from BEACHPLAN model while the value of the subtraction (*x2-x1*) is to be obtained based on the global coordinate system X-Y. This is because global coordinate system is used to deal with the grid points on x-axis of the local coordinate system as mentioned before. Based on the transformation of the coordinate systems, the subtraction (*x2-x1*) can be expressed as:

$$x2 - x1 = \sqrt{(X2 - X1)^2 + (Y2 - Y1)^2} \tag{4-7}$$

Substituting Eq. (4-6) and (4-7) into Eq. (4-5), the profile angle α is then obtained:

$$\alpha = \beta - 90^o + \frac{180^o}{\pi} \times \arctan(\frac{y2 - y1}{\sqrt{(X2 - X1)^2 + (Y2 - Y1)^2}}) \tag{4-8}$$

In fact, the subtraction (*x2-x1*) in Eq. (4-7) won't change once the grid points are chosen along x-axis and the angle β is constant as well. Therefore, the profile orientation is only a function of the subtraction (*y2-y1*) for each time step.

Analogously, the profile angle α for the other boundary Profile C can be given by:

$$\alpha = \beta - 90^o + \frac{180^o}{\pi} \times \arctan(\frac{y(n) - y(n-1)}{\sqrt{[X(n) - X(n-1)]^2 + [Y(n) - Y(n-1)]^2}}) \tag{4-9}$$

Where *X(n), X(n-1), Y(n)* and *Y(n-1)* are the global coordinates while y(n) and y(n-1) are local coordinates (see Figure 4-6).

(2) Middle Profile B

As for the middle profile, two neighbouring grid points (one left and one right to Profile B) are used to describe the local shoreline. More grid points around Profile B may be chosen to find a more reasonable representative local shoreline. Analogously, the profile angle α for the middle Profile B can be given by:

$$\alpha = \beta - 90^o + \frac{180^o}{\pi} \times \arctan\left(\frac{y(i+1) - y(i-1)}{\sqrt{[X(i+1) - X(i-1)]^2 + [Y(i+1) - Y(i-1)]^2}}\right) \qquad (4\text{-}10)$$

Where *X(i+1), X(i-1), Y(i+1)* and *Y(i-1)* are the global coordinates while *y(n)* and *y(n-1)* are local coordinates (see Figure 4-6). This module is coded in C# language, some core codes for this simple method are provided in Appendix A7.

4.5.1.2 Least Squares Fitting Method for Representation of Local Shoreline

One obvious problem that can be noticed about the simple method is that the local shoreline may be not representative when the grid space is relatively small. Simply connecting two points may cause significant error since the local shoreline in reality may be quite curved and more points should be included around the profiles to find a good representation of the local shoreline. Hence, least squares fitting method is also applied in this research. The basic theory about least square linear fitting method can be explained as follows.

In BEACHPLAN model, the entire shoreline is actually made of each individual grid point. Less grid space means better accuracy of the shoreline. If the representative local shoreline at grid point i is to be found, some of its neighbouring grid points should be used to find the best linear fit of these points (see Figure 4-8).

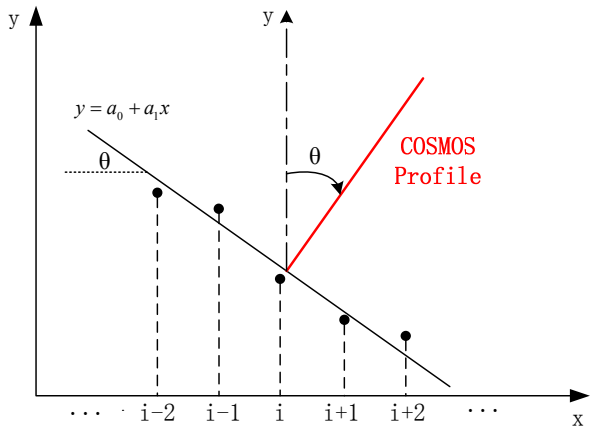


Figure 4 - 8 Schematic explanation of Least Square Fitting method for representation of local shoreline positions

If the linear fit line can be expressed by the following equation:

$$y = a_0 + a_1 x \qquad (4\text{-}11)$$

Where a_0 and a_1 are fitting parameters. To apply least squares fitting method, the summation of the squares for the deviation between y_i and $a_0 + a_1 x_i$ should be the minimum:

$$\sum_{i=1}^{N}\left[y_i-\left(a_0+a_1x_i\right)\right]^2\Big|_{a=\hat{a}}=\min \tag{4-12}$$

To satisfy Eq. (4-12), the following equations are obtained:

$$\frac{\partial}{\partial a_0}\sum_{i=1}^{N}\left[y_i-\left(a_0+a_1x_i\right)\right]^2\Big|_{a=\hat{a}}=-2\sum_{i=1}^{N}\left(y_i-\hat{a}_0-\hat{a}_1x_i\right)=0, \tag{4-13}$$

$$\frac{\partial}{\partial a_1}\sum_{i=1}^{N}\left[y_i-\left(a_0+a_1x_i\right)\right]^2\Big|_{a=\hat{a}}=-2\sum_{i=1}^{N}\left(y_i-\hat{a}_0-\hat{a}_1x_i\right)=0. \tag{4-14}$$

By solving Eq. (4-13) and (4-14), the best estimation of a_1, which is also the slope of the straight fitting line, can be given by the following expression:

$$\hat{a}_1=\frac{N\left(\sum x_iy_i\right)-\left(\sum x_i\right)\left(\sum y_i\right)}{N\left(\sum x_i^2\right)-\left(\sum x_i\right)^2} \tag{4-15}$$

Thus, the angle θ can be expressed by: $\theta=\arctan(\hat{a}_1)$, the profile angle α for this profile can be given by:

$$\alpha=\beta-90^o+\frac{180^o}{\pi}\times\arctan\left(\frac{N\left(\sum x_iy_i\right)-\left(\sum x_i\right)\left(\sum y_i\right)}{N\left(\sum x_i^2\right)-\left(\sum x_i\right)^2}\right) \tag{4-16}$$

Where x_i and y_i are the local coordinates in meters.

Typically, the number of the grid points that should be used depends on the resolution of the grid space and the local shoreline conditions. If the resolution is very large (i.e. grid space is very small), more grid points are needed. If the resolution is relatively small and the local shoreline is not very curved, several grid points are enough, say 4 or 5.

4.5.2 Module Test

The module can be simply tested by a run of a composition with three wave input points. A short passage from the log file of the whole composition shows it works as expected, see the log file below. The log file is generated by Pipistrelle during the run-time to trace the working conditions of the whole composition, which is quite helpful during debug stage.

Log file passage:

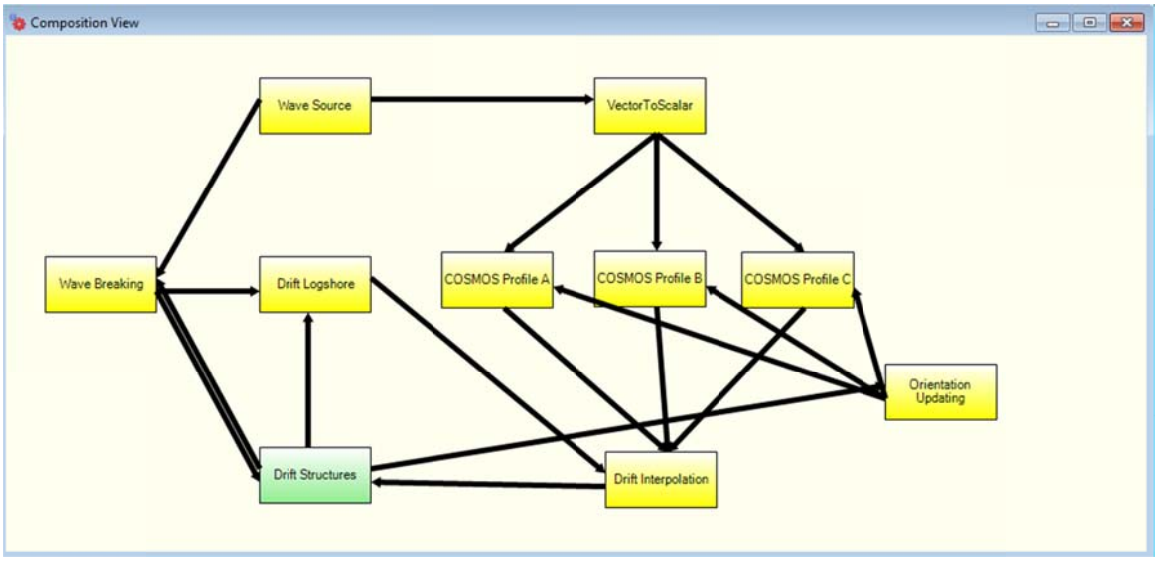
```
Input Array Length 30, [0..30)
   Index Length      Type Count Link "Quantity","ElementSet" (TimeNextRequired) = [Values]
   ===== ====== ====== ===== ==== ======================
         0         30 Scalar       30    164 "Beach Position","Ypoint" (51544.8333333333) = [
842.52426,758.46602,668.85689,579.19289,489.52694,399.96948,321.01474,217.10781,156.28507,111.7226,
120.8091,130.2446,141.59469,168.04832,202.89401,246.84549,275.43454,315.43297,365.55449,419.44826,
477.17577,527.71732,578.04603,628.36946,678.6896,729.01777,779.34358,829.67636,878.99354,909.51553,]
Output Array Length 3, [0..3)
   Index Length      Type Count Link "Quantity","ElementSet" (TimeNextRequired) = [Values]
   ===== ====== ====== ===== ==== ======================
         0          1 Scalar         1    158 "CosmosProfileAngle to N-axis","FirstSection" = [147.68299]
         1          1 Scalar         1    160 "CosmosProfileAngle to N-axis","MiddleSection" = [136.28403]
         2          1 Scalar         1    162 "CosmosProfileAngle to N-axis","LastSection" = [130.19141]

2011-04-27T09:12:28,Progress, 5280,OrienUp(S)    ,?? = DoTimeStep(51544.8333333333, ref in[], ref out[]);
2011-04-27T09:12:28,Debug1    , 5280,OrienUp(S)    ,in[] = [
    842.52426,       758.46602,       668.85689,       579.19289,       489.52694,       399.96948,       321.01474,
217.10781,     156.28507,       111.7226,
     120.8091,         130.2446,       141.59469,       168.04832,       202.89401,       246.84549,       275.43454,
315.43297,     365.55449,     419.44826,
    477.17577,       527.71732,       578.04603,       628.36946,         678.6896,       729.01777,       779.34358,
829.67636,     878.99354,     909.51553,]
2011-04-27T09:12:28,Status    , 5280,OrienUp(S)    ,51544.8749999999 = DoTimeStep(...);
2011-04-27T09:12:28,Debug1    , 5280,OrienUp(S)    ,out[] = [     147.68299,     136.28379,     130.19076]
```

As can be seen from the log file passage, three profile angles (marked in blue) at three locations of the beach are calculated based on an input array of beach positions. After a time step (1 hour in this case), the profile angles are updated and marked in red colour. There are only slight changes, which is because the time step (1 hour) is rather small. The shoreline won't change much after one-hour or even one-month wave action.

4.6 Final Composition of the Coupled Model

After all the additional modules are developed, the final composition of the coupled model is obtained as shown below by Figure 4-9(a) and (b).



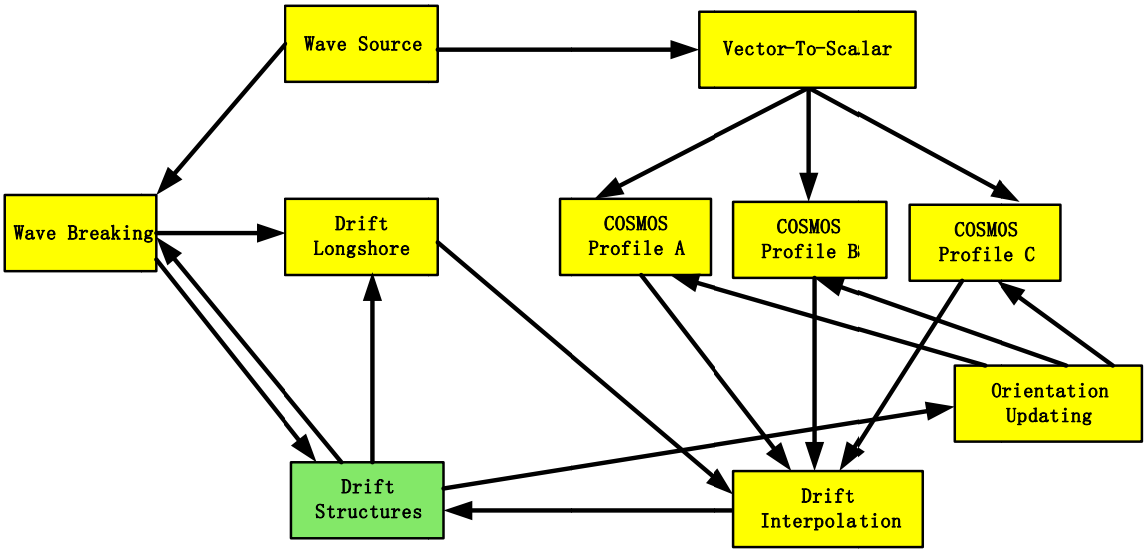


Figure 4 - 9(a) The final coupled model represented in the Pipistrelle Interface (upper); (b) Schematic view of the composition (lower)

To give a better view of directions of the arrows, a schematic overview is given by Figure 4-9(b).

4.6.1 Working Principle

The working principle of the coupled model can be explained as follows: the trigger module Drift Structures firstly starts to run and require data from Wave Breaking module. Based on the direction of the black arrow, Wave Breaking module needs data from Wave Source module which also provides data to Vector-To-Scalar module.

Then, the Vector-To-Scalar module converts the vector wave information from BEACHPLAN into scalar wave inputs for COSMOS model to run at three individual primary profiles A, B and

C. After that, the longshore sediment transport rate calculated at each COSMOS profile is passed to Drift Interpolation module which also receives the drift values from Drift Longshore module of BEACHPLAN model, and then the interpolation method discussed in section 4.3 is implemented by this module.

After that, the modified longshore drift values are passed into Drift Structures module which calculates the shoreline positions based on Eq. (3-2). Then, the shoreline positions are passed to Orientation Updating module to calculate the new profile orientations, which will be passed back to three COSMOS profiles for the next time step. One time step is then finished after all these modules are run. The next time step starts again with the trigger module and the whole composition runs following the same route as the first time step. The coupled model stops running when the time window of any module is reached.

4.6.2 Running Preparation

The coupled model is developed based on two existing models, so some preparations are required to run the model. Generally, the following steps should be done before running the coupled model using Pipistrelle interface.

(1) Set up BEACHPLAN model and run it to get *.xml files, which contain information for exchanging on Pipistrelle interface;

(2) Set up COSMOS model for each primary profile, such as the cross-shore profile shapes, sediment information and hydrodynamic settings;

(3) Find the exact positions of primary profiles along the beach where COSMOS model needs to run and locate them on BEACHPLAN coordinate system;

(4) Make the links and run the coupled model.

5 MODEL TESTS AND DISCUSSIONS

It is imperative to verify a numerical model before applying it into practical projects. This chapter aims to test the coupled model starting with an idealized straight coast and then a real coast in the UK. The model set-up for each case is introduced and modelling results are discussed in turn. After that, some comments and discussions are made, such as the model performance in terms of efficiency and stability. The extension of the model to accommodate more cross-shore profiles and some lessons learned during the research are also presented.

5.1 Application to an Idealized Straight Coast

To start with, it is always interesting to test a coastline evolution model with a straight coast to explore what the coastline will look like under certain wave conditions after some time. This is because the shoreline change is very obvious to see compared to the original straight shoreline. In this experiment, the results calculated by the original BEACHPLAN model are used as reference to check if the coupled model is able to give reasonable predictions with and without the profile Orientation Updating module. Both models are run under the same wave conditions for eight months, starting with the same straight coastline.

5.1.1 Model Set-up

For test purpose, a 2500-metre straight coast is assumed with three offshore wave points and cross-shore profiles at the Chainages 0, 500m and 2500m, see the figure below. Both models are run using 8-month wave data.

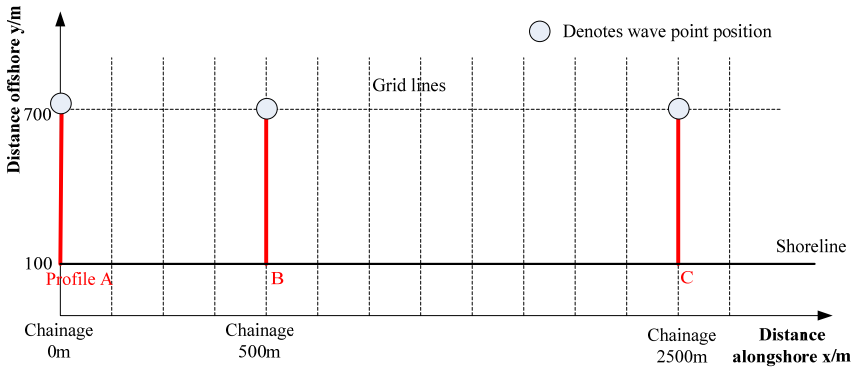


Figure 5 - 1 Locations of the cross-shore profiles and input wave points for the coupled model

The wave conditions of these three locations are different and BEACHPLAN model automatically makes linear interpolation between two successive wave points. Figure 5-2

presents the representative cross-shore profile used in BEACHPLAN model (the solid line). As for the coupled model, three cross-shore profiles are chosen along the coastline at the same chainages as wave point locations (Figure 5-1). The profile shapes are based on real field measurements, for example, the cross-shore profile A is shown in Figure 5-2 by the dashed line. The profile shapes may vary at different locations based on the local topography. However, BEACHPLAN model always assumes straight cross-shore profile shape (the solid line in Figure 5-2).

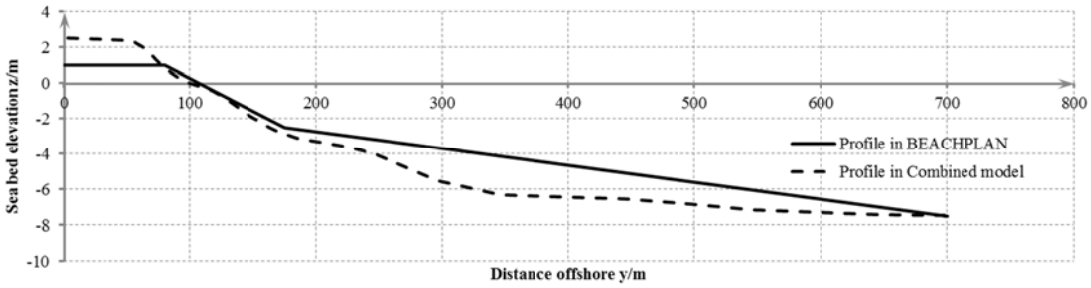


Figure 5 - 2 The cross-shore profile shape of Profile A used in the coupled model (dashed line) and the assumed profile shape used in BEACHPLAN model (solid line)

Some common settings for both models are the same, see the table below. It is worthwhile to mention that the calibration parameter K_1 value is very important. COSMOS model normally gives 0.5 to 8 times larger longshore transport rate than BEACHPLAN model does (Rivaton, 1997) depending on the value of K_1 in Eq. (3-3). Rivaton (1997) found the ratio of monthly sediment transport between COSMOS and BEACHPLAN model ranges from 1.0 to 4.0 when K_1 is 0.32 and the ratio increases when K_1 decreases. When K_1 is 0.1, the ratio is found to be 4.0 to 10.0.

Table 5 - 1 Common settings for BEACHPLAN and the coupled model

Parameters	Values
K_1 in Eq. (3-3) CERC-formula	0.28
K_2 in Eq. (3-3) CERC-formula	1.08
Space step	Chain 0-500 : 100m; Chain 500-2500 : 200m
Time step	3600s
Shoreline reference level	MHW (mean high water)
Water density	1030 $Kg \cdot m^{-3}$
Sediment density	2650 $Kg \cdot m^{-3}$
Boundary conditions	Open boundaries
Wave action period	8 month

Some other settings of parameters can be found in the sample run of BEACHPLAN model, which is given in Appendix A8.

5.1.2 Results without Orientation Updating Module

It is interesting to see the difference of the modelling results before the profile orientations are updated. The whole composition in this case is shown by the following figure without Orientation Updating module. The working principle is almost the same as introduced in section 4.6. The main difference is that the cross-shore profile orientations keep the same for all time steps.

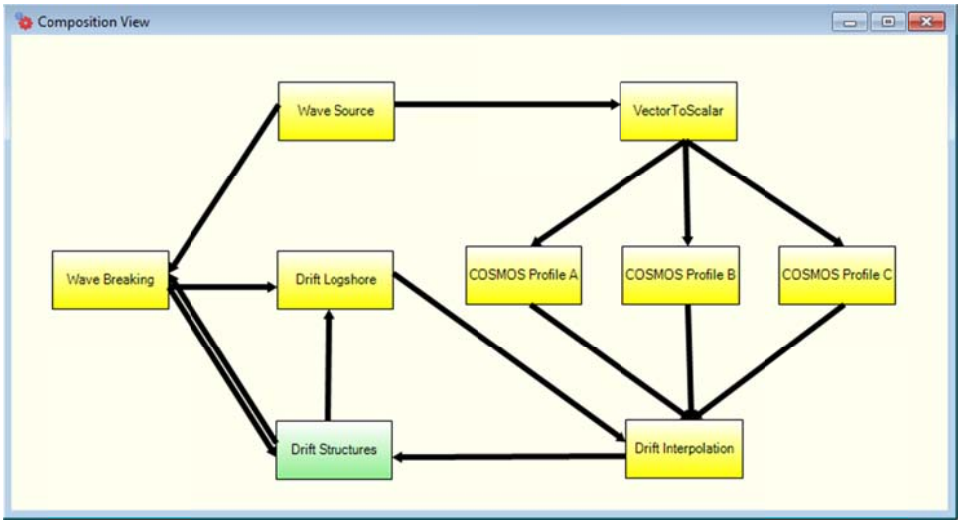


Figure 5 - 3 Composition view of the whole model before the profile orientations are updated in the Pipistrelle Interface

Since wave conditions are different at each grid point, the shoreline changes after some time as predicted by BEACHPLAN model shown in Figure 5-4. If the input wave conditions are exactly the same at these three wave points, the shoreline position won't change in BEACHPLAN model. This is because all the factors that determine the longshore transport rate are exactly the same along the shore, thus there is no sediment transport gradient. It is noticeable that the maximum erosion is around 17m which occurs at the chainage around 250m.

As for the coupled model, the modeling results are given by Figure 5-5 below if the cross-shore profile orientations are not updated. It is obvious that the shoreline changes follow the same trend as shown in Figure 5-4 which is calculated by BEACHPLAN model, which means the coupled model inherits some characteristics of BEACHPLAN model. The main difference is that much more erosion (from Chainage 0 to approximately 700m) is predicted by the coupled model before the profile orientations are updated. The erosion reaches 23m around the chainage 250m, which is 6m larger predicted by BEACHPLAN model.

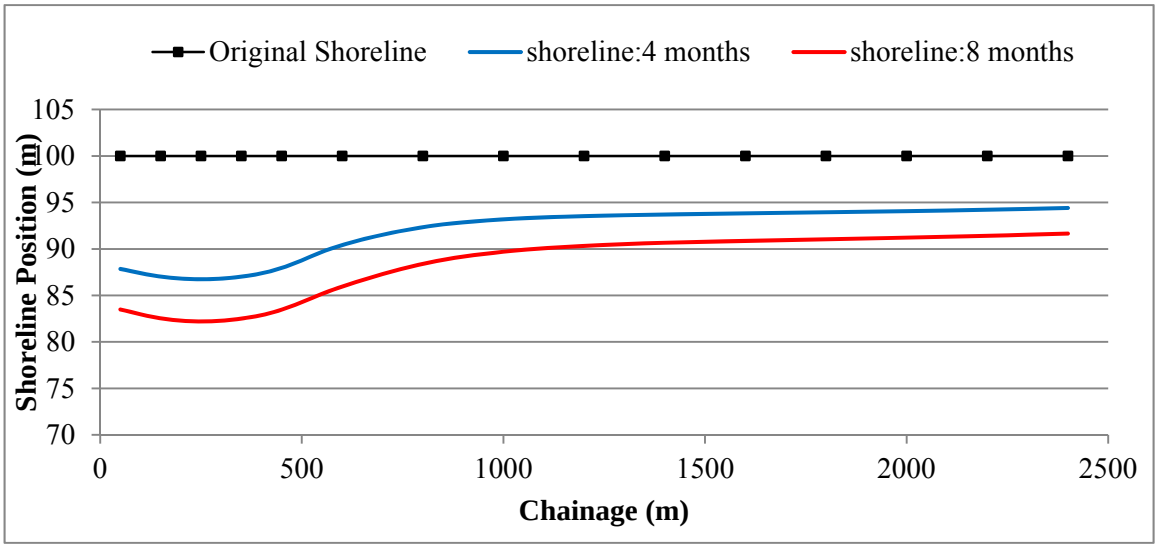


Figure 5 - 4 Shoreline evolution predicted by BEACHPLAN model at an idealised straight coast

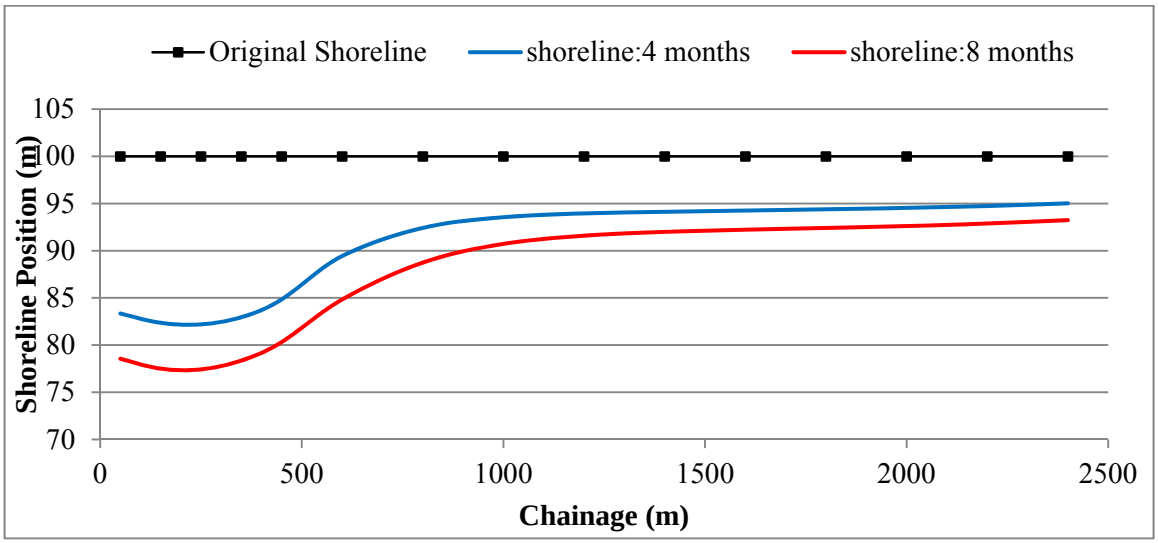


Figure 5 - 5 Shoreline evolution predicted by the Coupled model (orientations not updated) at an idealised straight coast

The calculated longshore sediment transport for each month by BEACHPLAN model and the coupled model (orientation not updated) are shown by Table 5-2 and Table 5-3, respectively. The negative sign of the drift value denotes certain transport direction convention.

Table 5 - 2 Longshore sediment transport calculated by BEACHPLAN model

Month	0	1	2	3	4	5	6	7	8
Drift (m^3)	0	-1079369.8	-40191.3	23707.9	-169553.2	-172274.1	17694.6	-119589.2	-35279.3

Table 5 - 3 Longshore sediment transport calculated by the coupled model before orientation is updated

Month	0	1	2	3	4	5	6	7	8
Drift (m^3)	0	-1315946.9	-42750.3	48143.0	-94968.9	-166768.4	53319.0	-123091.5	-23055.7

It is noticed that most of the monthly total longshore drifts in Table 5-3 are larger, which means the shoreline positions should change more significantly predicted by the coupled model. This is confirmed by Figure 5-5 which clearly shows that the shoreline is eroded much more studied by the coupled model when the orientations are not updated. It is because COSMOS model normally gives 0.5 to 8 times larger longshore transport rate than BEACHPLAN model does (Rivaton, 1997) depending on the value of K_1 in Eq. (3-3). The ratio of monthly sediment transport between COSMOS and BEACHPLAN model ranges from 1.0 to 4.0 when K_1 is 0.32 and the ratio increases when K_1 decreases. In this experiment, the value of K_1 is set to be 0.28. Therefore, the ratio is expected to fall in the range from 1.0 to 5.0, which is confirmed by comparing Table 5-2 with Table 5-3.

If the initial shoreline is not very curved and the modeling time scale is small (say weeks or months), the coupled model may be able to give relatively reasonable prediction of shoreline change. This is because the cross-shore orientation won't change much under such conditions. However, the profile orientations should be updated if the model is run for long time, say years to decades.

5.1.3 Results with Orientation Updating Module (Final Composition)

After the profile orientations are updated, the modeling results of the final coupled model, BEACHPLAN model and the coupled model (orientation not updated) are compared in the figure below.

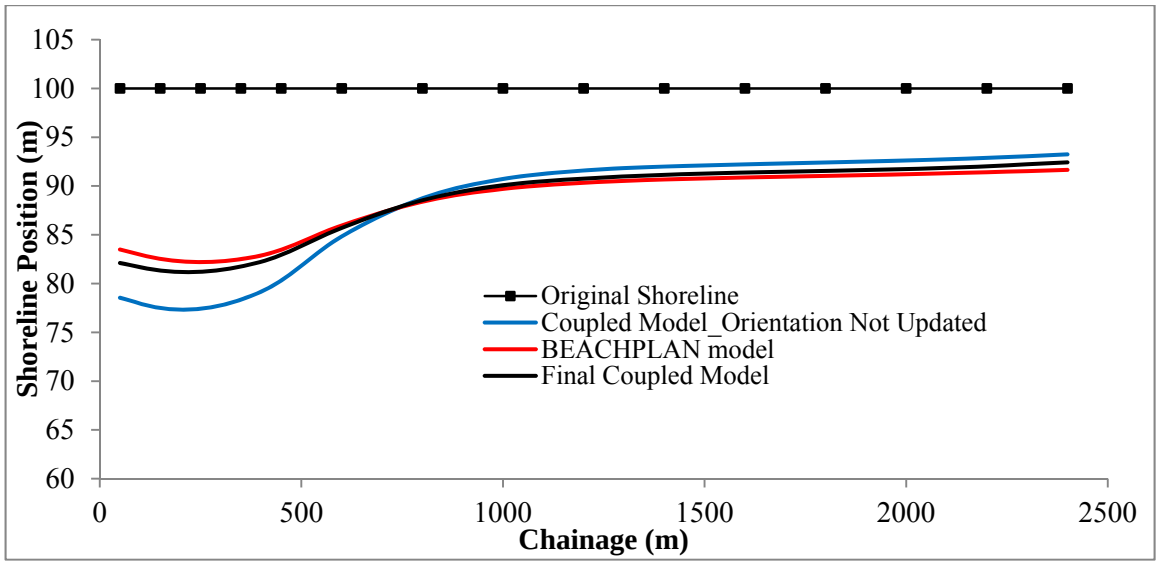


Figure 5 - 6 Comparison of results between BEACHPLAN, the Coupled model (orientation not updated), and the final coupled model.

The final coupled model gives close modeling results compared to BEACHPLAN model, see the black line in Figure 5-6. If the profile orientations are not updated, the model predicts much more erosion which is not quite reasonable for 8-month wave input. Therefore, it is proved that the profile orientation module works as expected.

5.2 Application to Poole Bay

The final coupled model is also tested using a real project at Poole Bay, United Kingdom. HR Wallingford has been involved in this project, so abundant data about the shoreline positions and wave conditions are available (HR Wallingford, 2008; 2010).

5.2.1 Project Introduction

The modelling area is between Sandbanks and Branksome Dene Chine in Poole of the United Kingdom. The beach along this part of the shoreline of Poole Bay is relatively straight (see Figure 5-7) and has been improved by a recharge scheme. The recharge scheme was implemented in winter 2005/2006 using sand dredged from the approach channel to Poole Harbour. The changes in beach width have been monitored by the Channel Coastal Observatory as part of the South-East Regional Monitoring Programme.

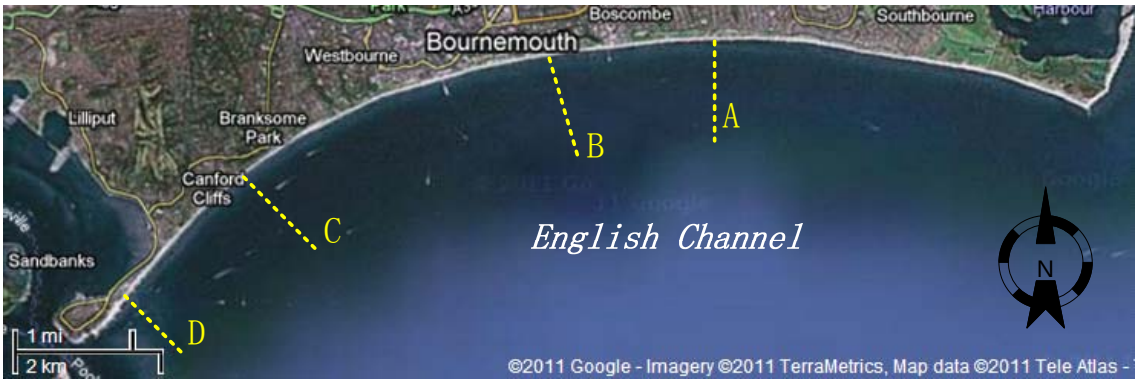


Figure 5 - 7 Overview of the interested research shoreline

The recharge scheme simplifies the modeling processes, since the existing short timer groynes between Borough Boundary and Shore Road were buried and therefore there was no need to represent them. It is assumed there was little influence of the recharge scheme on the natural evolution of the shoreline after two years. Therefore, data of shoreline positions from surveys in June 2007 and May 2009 are to be used to verify the model. The shoreline positions in June 2007 will be used as the initial input for modeling set-up. The real shoreline positions obtained during a survey in May 2009 is used to verify the model. The model can't be validated against field data

after May 2009 because some beach control structures were installed, which may cause significant inaccuracy.

Along the Poole Bay coastline, beach sediment transport and induced changes in the plan shape and profile of its beaches, are dominated by wave action. Consequently, a good knowledge of wave conditions along the coastline is required. Based on the previous studies, HR Wallingford held a 17-year long sequence of predicted nearshore wave conditions that could be used for beach plan shape modeling. In this study, only 22-month wave data will be used from June 2007 to May 2009.

5.2.2 Model Set-up

The modelling distance is 9400m in total while only the middle part of the shoreline is the research interest. The existence of 3000m shoreline on either end of the study frontage ensures that the model's boundary conditions are correct, and that no "end effects" influence the model results.

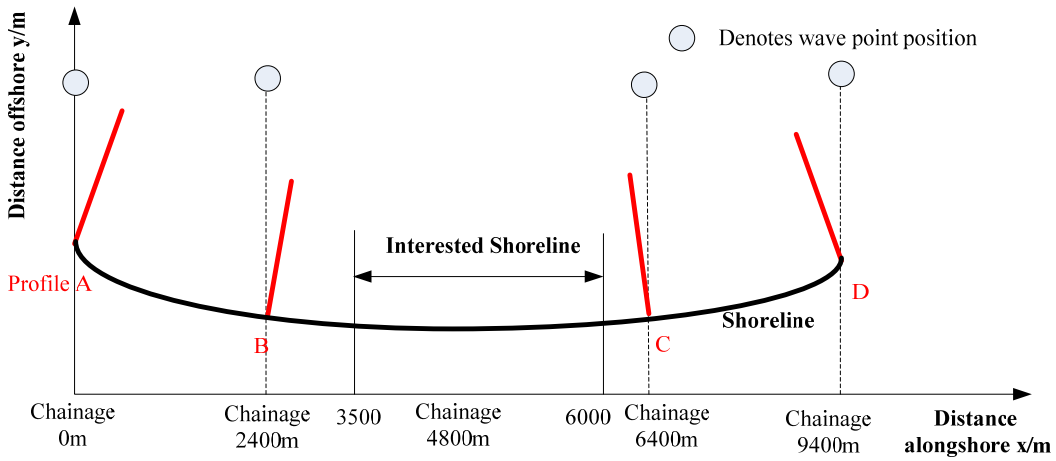


Figure 5 - 8 Schematic view of locations of the cross-shore profiles and input wave points

To better simulate the shoreline evolution, four cross-shore profiles are chosen along the shoreline which are located at Chainage 0, 2400m, 6400m and 9400m respectively, see Figure 5-7 and 5-8. Accordingly, four wave points are also located at the same chainages. The representative wave roses for Profile B and C are given by Figure 5-9(a) and 5-9(b), which show that the dominant wave direction in this area is SSW and the secondary dominant waves come from SEE. The interested shoreline passage is from approximately 3500m to 6000m, which has been marked in the figure above.

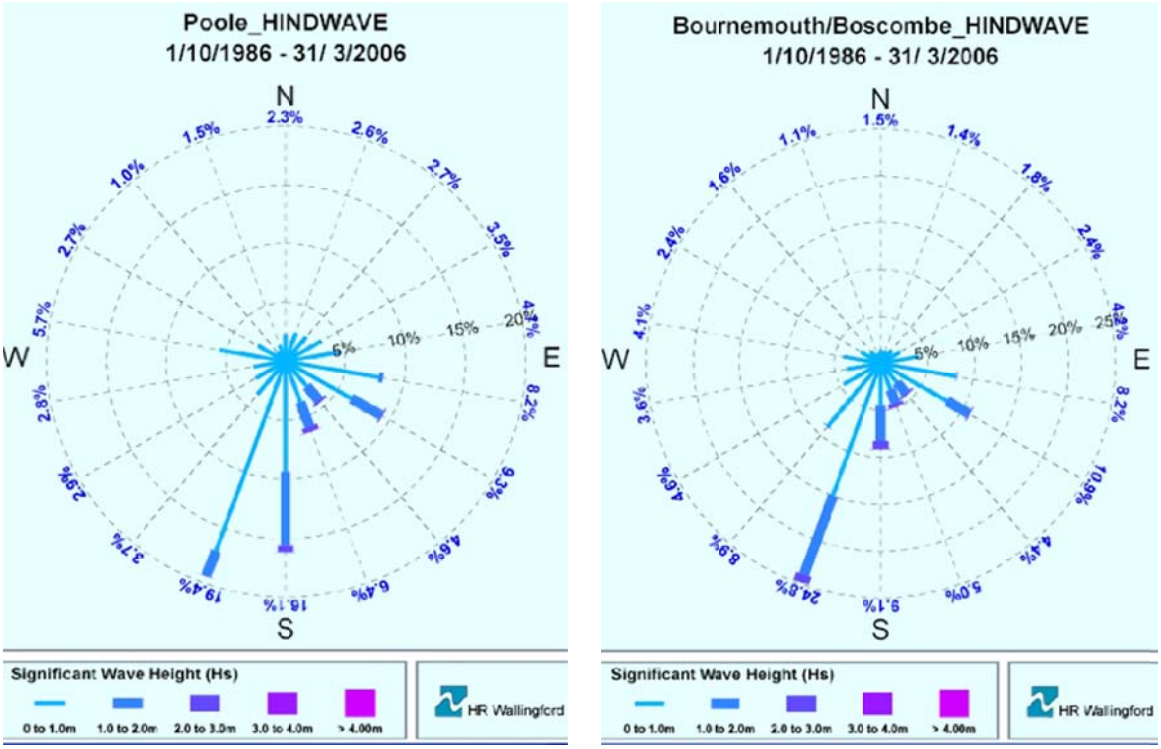


Figure 5 - 9(a) Wave rose for Profile C (left); (b) Wave rose for Profile B (right) (from HR Wallingford, 2010)

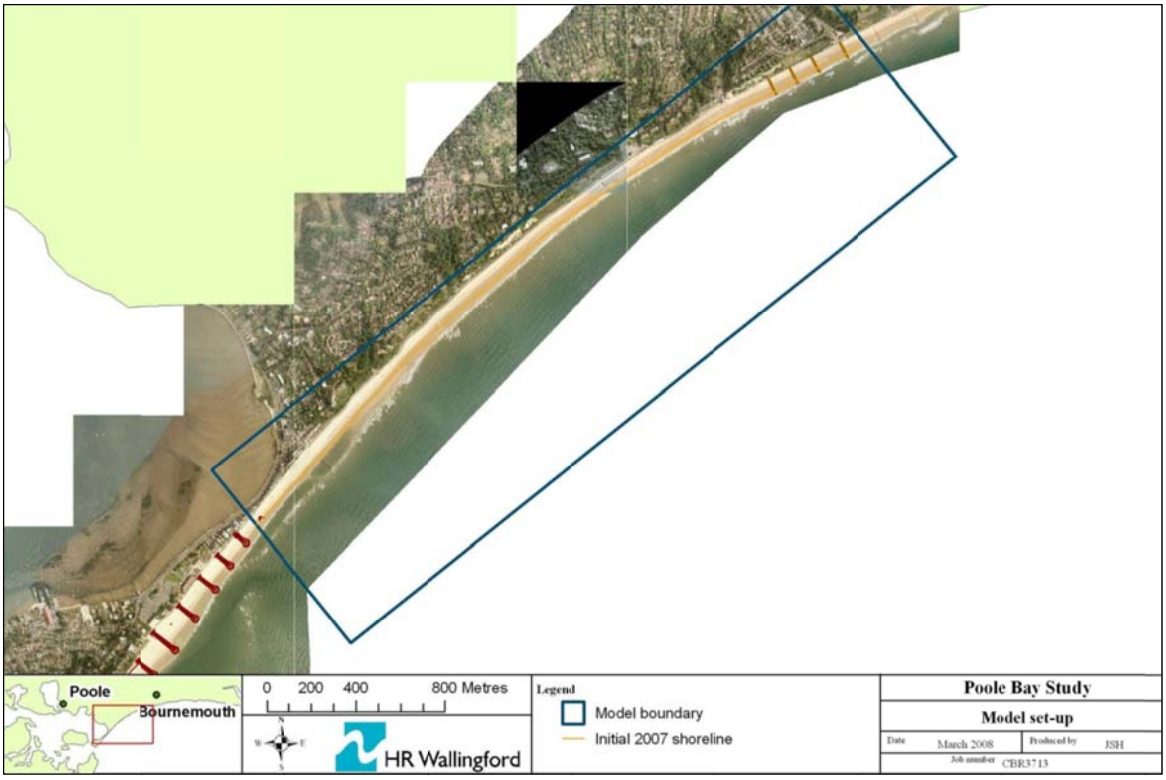


Figure 5 - 10 Model set up for BEACHPLAN (from HR Wallingford, 2008)

An overview of the model set-up for BEACHPLAN model is given by Figure 5 -10. The area marked by a blue square is the model boundary and the upward direction is north. Some other common settings for both BEACHPLAN model and the coupled model are listed in the table below.

Table 5 - 4 Common settings for both models

Parameters	Values
K_1 in Eq. (3-3) CERC-formula	0.28
K_2 in Eq. (3-3) CERC-formula	1.08
Space step	Chain 0-2400: 400m; Chain 2400-6400: 100m; Chain 6400-9400: 500m
Time step	3600s
Shoreline reference level	MHW (0.5m ODN)
Water density	1030 $Kg \cdot m^{-3}$
Sediment density	2650 $Kg \cdot m^{-3}$
Boundary conditions	Open boundaries
Wave action period	22 months
Angle between X-axis and North	227.75°

In this real case, it is also worthwhile to mention some settings for COSMOS model. As mentioned, COSMOS model takes the real cross-shore profile into consideration; one example is given in Figure 5-2. Meanwhile, the grain size can also be explicitly defined while BEACHPLAN model can not specify. The table below summarizes some settings that are of interest.

Table 5 - 5 Settings for COSMOS model

Parameters	Profile A	Profile B	Profile C	Profile D
Grain size (mm)	0.4	0.4	0.4	0.4
Profile angle to north (°)	127.75	127.75	107.75	107.75

5.2.3 Results and Verification

As mentioned in Section 4.6.2, the coupled model is run based on information provided by both BEACHPLAN and COSMOS model. To verify the coupled model, the first thing needs to do is to calibrate BEACHPLAN model so that it gives relatively reasonable modeling results. The other reason to run BEACHPLAN model first is because some files generated by BEACHPLAN model are required to run the coupled model.

In this study, the modeling results of the coupled model are verified by comparing with field data. The survey data was only available from the Chainage 3500m to 6000m, thus this part of shoreline is scrutinized in the figure below.

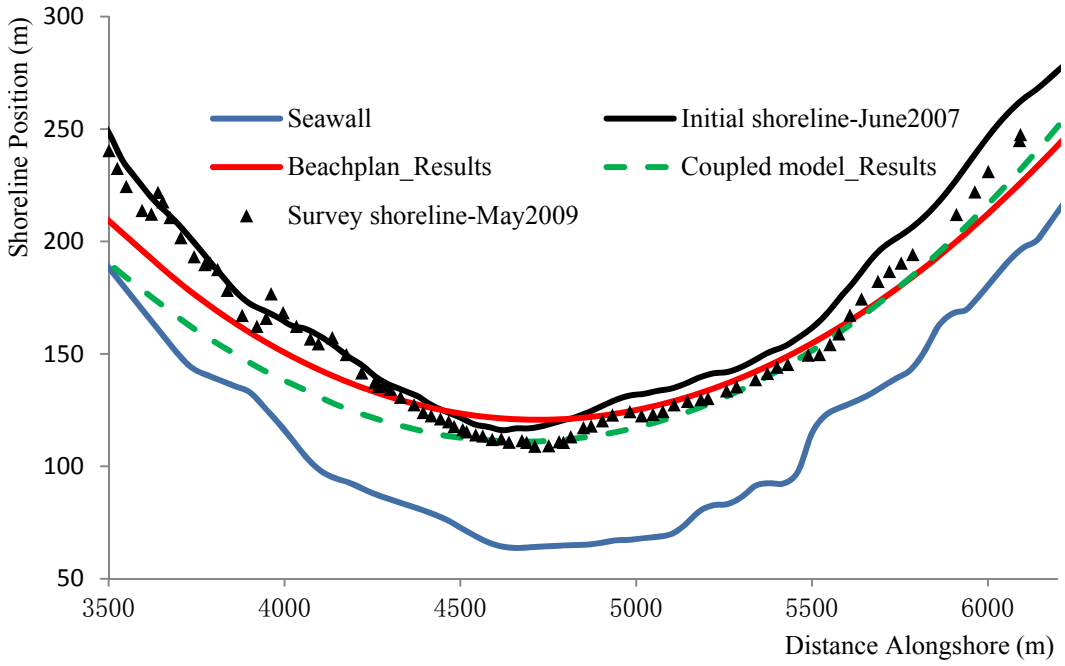


Figure 5 - 11 Verification of the coupled model at Poole Bay

By comparing the shoreline positions between June 2007(the black line) and May 2009 (denoted by small triangles), it is noticed that there was almost no shoreline change from Chainage 3500m to 4500m. This is because there were four groynes located from Chainage 2500m to 3200m, which can be noticed on the upper right side of the marked square area of Figure 5-10. The groynes were effective to trap the longshore-transported sand and keep the local shoreline stable, so there was only slight change. From Chainage 4500m to 6000m, the shoreline had a retreat ranging from 5m to 10m along the shore.

To run the coupled model, BEACHPLAN model was run first and calibrated against the field data, giving the prediction by the red line which is a generally reasonable fit. Then, some output files (*.xml) generated by BEACHPLAN model were used by the coupled model. Four primary profiles were chosen along the shoreline (Figure 5-8) where COSMOS model was set up and run. The green dashed line of Figure 5-11 was the modelled shoreline after 22-month wave action by the coupled model. It was found that the coupled model generally presented reasonable results. From Chainage 4500m to 5500m, there was good fit between the shoreline modelled by the coupled model and the field survey data. Prior to Chainage 4500m, the coupled model gives

rather bad prediction, which is due to the presence of the four groynes. After Chainage 5500m, the coupled model presents relatively similar results compared to BEACHPLAN model.

It is also worthwhile to mention that the coupled model inherits some characteristics of BEACHPLAN model. For example, BEACHPLAN model predicts a "smoothing" of the initial beach plan-shape, i.e. rapidly flattening out the seaward bulge, which in reality has persisted. The reasons for the formation and persistence of this bulge are not known, but may well be related to the pattern of tidal currents along this part of the coastline. Since the BEACHPLAN model does not attempt to include such currents, or their effects, it cannot replicate this localised widening of the beach correctly. The coupled model also has such "smoothing" effect, which is not true in reality. However, this usually does not affect the recommendations that are reached regarding the preferred beach control scheme in practical projects.

However, it is currently too early to reach the conclusion that the coupled model is better than the original one-line model since few validations have been made due to the limitations of field data and research time. Therefore, the outcome at this stage can be more precisely recognized as a proof of concept which demonstrates that it is theoretically reasonable and technically feasible to couple the one-line model and cross-shore profile model.

5.3 Model Performance

From the applications to different conditions, it is proved that the coupled model is tested to be numerically stable under most of the conditions. However, the model may be unstable when the grid space is chosen to be too small. Generally, the coupled model works smoothly if BEACHPLAN model is stable to run.

The coupled model takes longer time than BEACHPLAN model to complete the run, which is because the COSMOS module of the coupled model has to run for three profiles one by one (not at the same time). However, the data-exchanging time between different modules is negligible, which provides the basis for linking. The approximate time needed for some test runs using a normal PC are concluded in the Table 5-6.

The typical running time needed of the Coupled model (3 profiles) is approximately twice the time needed of BEACHPLAN model. If more profiles are added, the running time required increases accordingly but not necessarily in a linearly increasing manner. It can be noticed that it takes around 10 minutes to run the model with 5-year wave data, which is quite effective considering COSMOS model needs to be run for 3 times.

Table 5 - 6 Comparison of running time between different models

Wave input \Models		BEACHPLAN model Running time (sec)	Coupled model running time (sec)	
			3 profiles	4 profiles
Running period	1-year	45	120	130
	2-year	80	190	205
	3-year	120	240	360
	4-year	155	360	480
	5-year	220	480	600

It is expected in the near future that COSMOS model can be run for all the primary profiles at the same time so that the efficiency of the coupled model will be highly improved in case of many primary profiles. This can be done based on the new version of OpenMI standard.

5.4 Extension to Additional Profiles

It has been demonstrated that the coupled model is relatively easy to be extended from 3 to 4 profiles. It is expected that the coupled model can hold as many profiles as required to give better predictions in the near future when the computational capacity of the computers are more powerful and the OpenMI standard is further improved.

As an example, below are some key steps to extend the model from 3 COSMOS profiles to 4 COSMOS profiles.

1) The user should first specify 4 profile shapes and 4 wave points' information.
2) Run Beachplan control panel (old Beachplan version) to generate *.xml files.

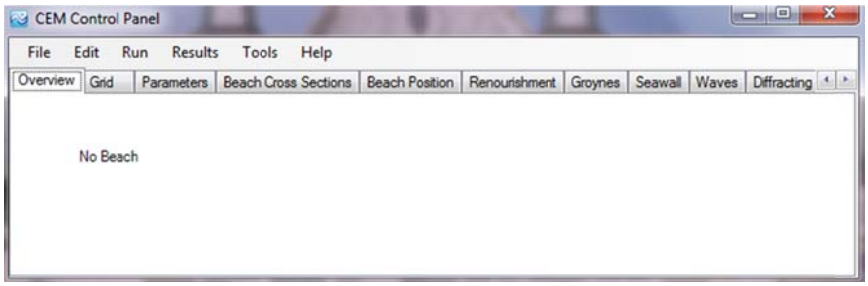
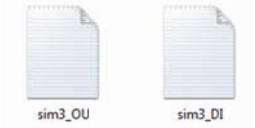
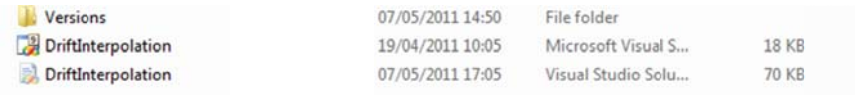


Figure 5 - 12 Old BEACHPLAN working interface

3) Modify DI.xml for Drift Interpolation module and OU.xml for Orientation Updating module (see the small figures below), mainly the coordinates of the beach positions and some exchange items.



4) Modify the program code (only engine) of Drift Interpolation module and Orientation Updating module (the code for Orientation Updating module is also written in the engine of Drift Interpolation module); the code is not generic, only for 3 profiles, we should extend to 4 profiles. Build the solution.



5) Modify the xml file for Vector-To-Scalar module (add 4th wave info. Exchange items, period, water depth, height, angle). The module has been updated and is not limited to only 9 profiles.
6) Add one COSMOS box based on the previous model composition and modify the xml file.
7) Modify the *.chi file and make the links.
8) Load the *.chi file and run the whole composition.

6 CONCLUSIONS AND FURTHER RESEARCH

6.1 Conclusions

A one-line model for longshore sediment transport and beach morphological response has been extended in this dissertation. Two existing models (i.e. a one-line model BEACHPLAN and a profile model COSMOS) are now coupled by three linking modules that were developed to facilitate the integration (i.e. Drift Interpolation, Vector-To-Scalar and Orientation Updating module).

The Drift Interpolation module acts as the theoretical basis for extending the one-line model in terms of longshore sediment transport rate. The Vector-To-Scalar module aims to couple the wave input information between two different models. The Orientation Updating module updates the angle of cross-shore profile after the shoreline is changed at each time step.

To link the two existing models, a state-of-the-art linking standard OpenMI, which represents a new philosophy for the development of numerical models, is briefly introduced. The existing two models and the new modules work together as a whole composition (i.e. the coupled model) which aims to improve the one-line model in terms of longshore sediment transport and morphological response predictability. Some lessons learned on the evolution of the design of the coupled model are given in Appendix A10.

This coupled model takes detailed alongshore coastal processes and the real cross-shore profile into account when calculating the longshore sediment transport rate. Numerous tests have proved that the model is numerically stable and effective in computing. Applications of the model at both an idealized coast and a real coast show that it is able to give reasonable predictions of sediment transport and shoreline evolution. Therefore, the concept of linking different models to develop new models is proved to be feasible and potentially promising since it is a more economical and also easier way to achieve the functionalities that practitioners require.

However, it is currently too early to reach the conclusion that the coupled model is better than the original one-line model since few validations have been made due to the limitations of field data and research time. Meanwhile, the working principle behind the coupled model needs further exploration and re-examination before a sound conclusion can be made. Therefore, the outcome of this research at this stage can be more precisely recognized as a proof of concept, which

demonstrates that it is theoretically reasonable and technically feasible to couple the one-line model and cross-shore profile model so as to realize practitioners' certain requirements.

6.2 Further Research

The coupled model is still under development and further research is being carried out to improve the model. Some further research includes:

(1) Merge two modules and make the composition neat ;

(2) Introduce the detailed cross-shore distribution of longshore transport (Bayram et al, 2001) produced by the profile model into the one-line model so that the one-line model gives better predictions when coastal structures are involved, such as groynes and detached breakwaters;

(3) Run COSMOS at each grid point of BEACHPLAN model and consider the alongshore set-up variation through COSMOS model;

(4) Make the preparation for the development of a strip model based on the current linking method.

All these three recommendations are briefly discussed below in turns.

6.2.1 Merge Two Modules

The composition of the final coupled model shown by Figure 4-9 is complicated with too many arrows crossed. It is noticed that Drift Interpolation and Orientation Updating modules are connected with the same modules (i.e. Drift Structures, COSMOS profile A, B and C). Therefore, it is possible to merge these two modules as one which is named "Drift Interpolation & Orientation Updating" in the figure below. Compared to Figure 4-8, this composition is much easier to read.

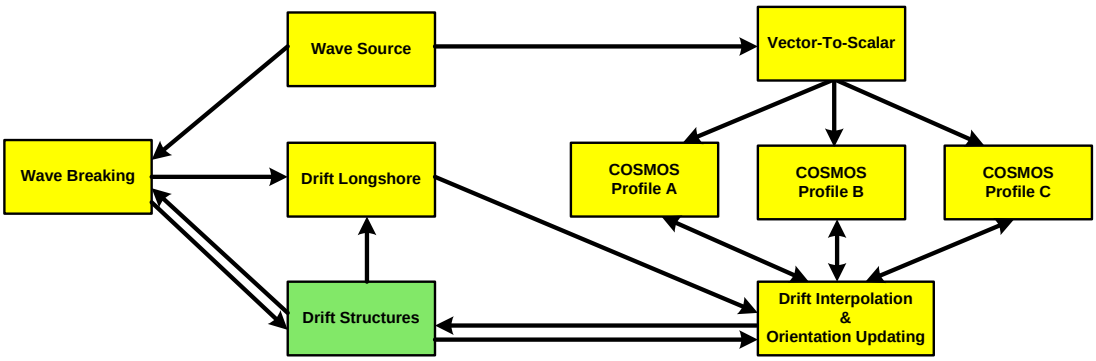


Figure 6 - 1 Recommended future composition of the coupled model

6.2.2 Introduce Cross-shore Distribution of Longshore Transport

Due to time limitation, the proposed coupling stage 4 stated in Section 4.1.1 is not carried out in this research. It will be very useful if the cross-shore distribution of longshore transport produced by COSMOS model can be introduced to the one-line model, especially under the conditions that coastal structures are involved. However, it is envisaged that this objective is relatively difficult to reach. Two potentially possible methods are:

(1) Divide the entire shoreline into several segments and find the representative cross-shore distribution of longshore transport based on COSMOS model for each segment.
(2) Interpolate the longshore transport rate between two primary profiles for each cross-shore profile point.

Method (1) is easier to reach; however, this method is not able to provide the cross-shore distribution of longshore transport at each grid point. Method (2) could provide the detailed cross-shore distribution at each grid point of BEACHPLAN, however, there are many potential problems to be solved.

6.2.3 Run COSMOS at Each Grid Point of BEACHPLAN Model

It is expected that the coupled model can hold as many profiles as expected to give better predictions in the near future when the computational capacity of the computers are more powerful and the OpenMI standard is further improved. However, the information of alongshore set-up variation produced by BEACHPLAN model will be lost if COSMOS model is run at all the grid points.

According to Ozasa and Brampton (1980), the set-up variation is very important in driving the longshore sediment transport. One potential way to deal with this problem is to introduce this set-up variation term in COSMOS model since COSMOS model takes wave set-up into account. To be more specific, a calibration coefficient maybe introduced (e.g. similar to K_2 term in Eq. 3-3) to reflect the alongshore set-up variation.

6.2.4 Development of a Strip Model

It is also expected that this research makes the preparation for the development of the proposed strip model in the near future. The strip model will be able to simulate the longshore sediment transport in strips rather than in one line, thus the model can be recognized as the improved version of BEACHPLAN. This will not only unify the models in terms of sediment transport predictors but also allow the one-line models to include a different shape per profile for the cross-shore distribution of the longshore transport. Thus, the accuracy and predictability of the one-line models are expected to be improved.

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Appendix A1 Introduction to HR Wallingford

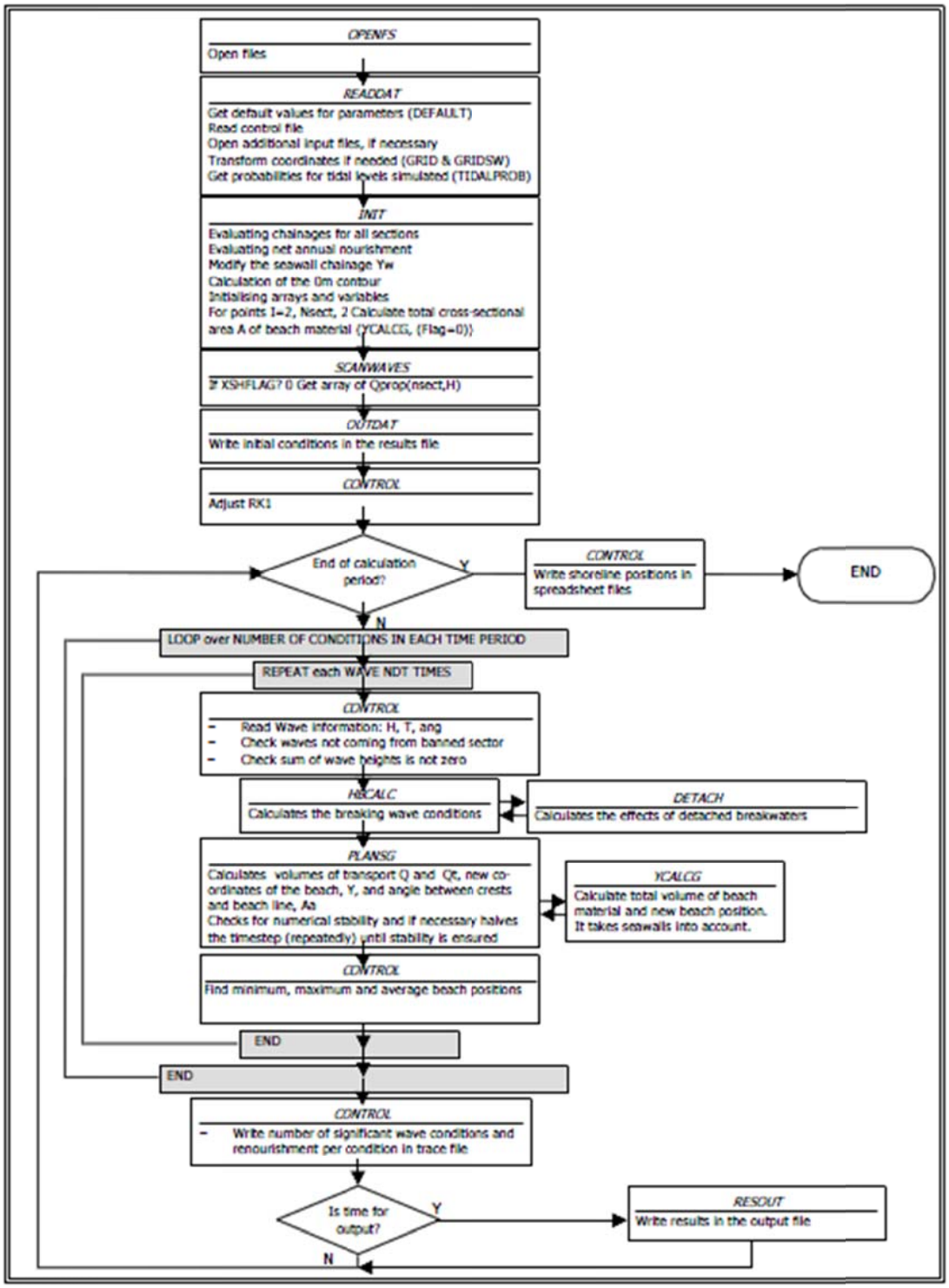
HR Wallingford was the Hydraulics Research Station of the British Government originally founded in 1947 and became a private limited company in 1982. It is located in Wallingford, South Oxfordshire. Nowadays, it offers strategic research, specialist consultancy and water-related training services in civil engineering to clients around the world. Based on over 60 year development and achievement, the company has competent resources for hydraulic research including advanced physical modelling laboratories, a full range of modelling software packages and professional staff with world-renowned skills.

After more than six decade development, HR Wallingford covers a wide range of research fields, including the following groups:

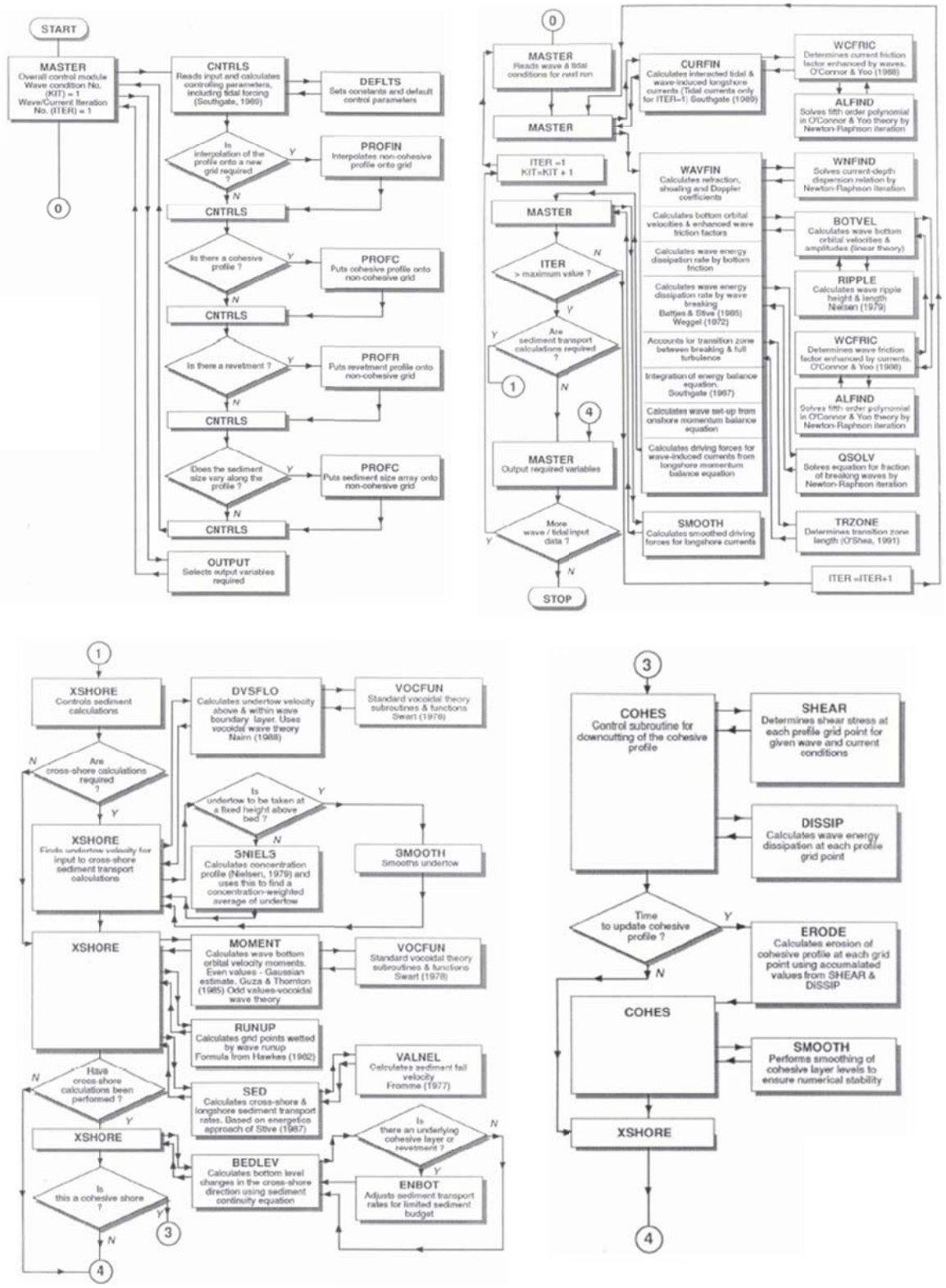
- Coastal Structures
- Coasts and Estuaries
- Hydrodynamics and Metocean
- Ships
- Engineering
- Water Management
- Quality, Safety and Environment
- Dredging Research
- Flood Management
- Energy
- Environment
- Support Services

Each group works independently but in a cooperative way with other groups, thus the company as a whole works effectively. This research is carried out based on Coast and Estuaries Group which hires approximately 30 staff working on research fields such as longshore and cross-shore sediment transport, shoreline protection, salt marsh protection, beach management and so on. Both the two models BEACHPLAN and COSMOS mentioned above which will also be studied in this research have been widely used in the group.

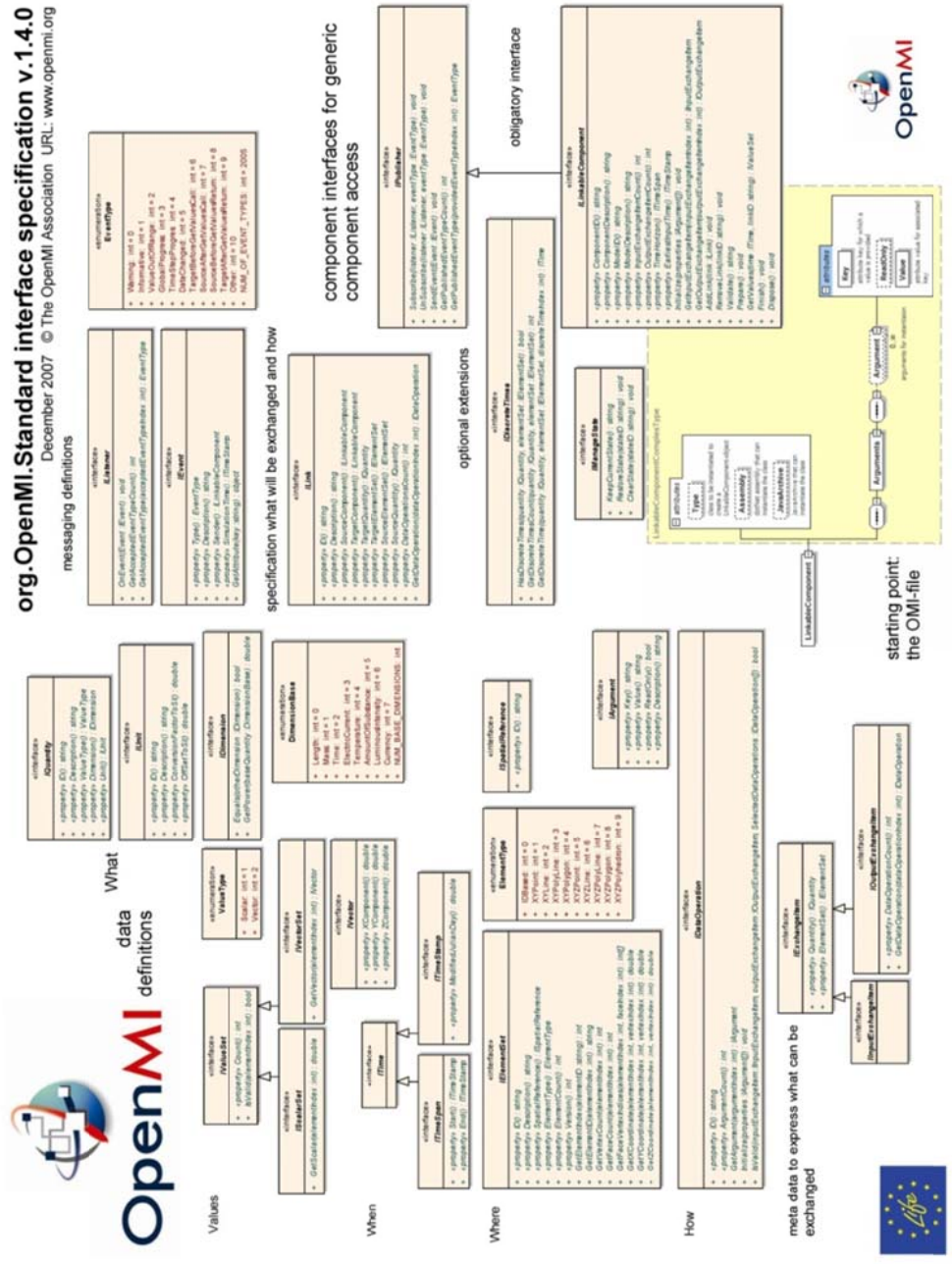
Appendix A2 Overall Structure of BEACHPLAN Model



Appendix A3 Overall Structure of COSMOS Model



Appendix A4 Overview and Knowledge Basis of the OpenMI Standard



The knowledge base of OpenMI includes the following bodies:

- CEH-Center for Ecology and Hydrology
- RIZA-Rijksinstituut Voor Integraal Zoetwaterbeheer en Afvalwaterbehandeling
- DHI-DHI Water and Environment
- WL-Delft Hydraulics
- WSL-Wallingford Software Ltd
- Uni Do-University of Dortmund
- IRSA-National Technical University of Athens
- WRc-WRc plc
- DHI HIF-DHI Hydroinform a.s.
- PL-Povodi Labe. s.p.
- HDP-Hydroprojekt CZ a.s.
- Alterra-Alterra B.V.
- Cemagref-Centre National du Machinisme Agricole, du Genie Rural, des Eaux et. Des Forets

Appendix A5 Core Codes for Drift Interpolation Module (C#)

```
        public void QLinearInter(double[] qArray, double[] qInter, int index1, int index2)
        {
            double q1 = qArray[index1];
            double q2 = qArray[index2 - 1];
            double deltaq;
            deltaq = (q2 - q1) / (index2 - 1 - index1);
            int inter = 0;

            for (int j = index1; j < index2; ++j, ++inter)
                qInter[j] = q1 + deltaq * inter;
        }

        public void FuncQ(double[] qFinal, double qCosA, double qCosB, double qCosC)
        {
            int IndexA, IndexB, IndexC;
            double[] qBPlanLinearInter = new double[qFinal.Length];
            double[] qCosmosLinearInter = new double[qFinal.Length];

            IndexA = 0;
            IndexC = qFinal.Length;
            IndexB = 6;
            qCosmosLinearInter[IndexA] = qCosA;
            qCosmosLinearInter[IndexB - 1] = qCosB;
            qCosmosLinearInter[IndexC - 1] = qCosC;

            // drift interpolation between Profile A and B
            QLinearInter(qFinal, qBPlanLinearInter, IndexA, IndexB);
            QLinearInter(qCosmosLinearInter, qCosmosLinearInter, IndexA, IndexB);

            for (int locIndex = IndexA; locIndex < IndexB; ++locIndex)
            {
                qFinal[locIndex] = qCosmosLinearInter[locIndex] - qBPlanLinearInter[locIndex] +
qFinal[locIndex];
            }

            qBPlanLinearInter[qBPlanLinearInter.Length - 1] = qFinal[qFinal.Length - 1];
            // drift interpolation between Profile B and C
            QLinearInter(qBPlanLinearInter, qBPlanLinearInter, IndexB - 1, IndexC);
            QLinearInter(qCosmosLinearInter, qCosmosLinearInter, IndexB - 1, IndexC);

            for (int locIndex = IndexB; locIndex < IndexC; ++locIndex)
                qFinal[locIndex] = qCosmosLinearInter[locIndex] - qBPlanLinearInter[locIndex] +
qFinal[locIndex];
        }

          public double DoTimeStep(double timeIn, ref double[] dataIn,    ref double[] dataOut)
          {
            try
            {
                Utilities.ArrayUnpack(_runtimeData, dataIn,     _controller);

                //double qCosmosA = 6; just an example
                //double qCosmosB = 10;
                //double qCosmosC = 12;

                DriftInterpolation funcq = new DriftInterpolation();

                // call each drift
                funcq.FuncQ(_controller.qBPlanLeft, _controller.qCosmosA, _controller.qCosmosB,
_controller.qCosmosC);
                funcq.FuncQ(_controller.qBPlanRight, _controller.qCosmosA, _controller.qCosmosB,
```

```
_controller.qCosmosC);
                    funcq.FuncQ(_controller.qBPlanAverage, _controller.qCosmosA, _controller.qCosmosB,
_controller.qCosmosC);


                    Utilities.ArrayPack(_runtimeData, dataOut, _controller);
                }
            catch (Exception e)
            {
                ThrowToServer(new ExceptionEngine(e));
            }

            _controller.TimeCurrent += _controller.TimeDelta;
            return _controller.TimeCurrent;
        }
```

Appendix A6 Codes for Vector-To-Scalar Module (FORTRAN)

```
module engine
    use fluidearth_exceptions
    implicit none
    private
    ! Fluid Earth interface
    public :: initialise_pre, property_pair, initialise_post, get, compute, set, finish
    integer, parameter :: dp = kind(0.0d0)
    integer, parameter :: arg_count_mandatory = 3
    logical, allocatable, dimension(:) :: args_set_mandatory
    character(100), allocatable, dimension(:) :: args_keys_mandatory
    real(dp), allocatable, dimension(:) :: args_mandatory_reals
    real(dp), parameter :: unspecified_value = -999.999
    ! Engine specific
    integer :: ios, IncomingArraySize
    real(dp) :: TimeCurrent, TimeDelta
    real(dp), dimension(:,:), allocatable :: ExchangeItem
contains

    subroutine initialise_pre()
        allocate(args_set_mandatory(arg_count_mandatory))
        allocate(args_keys_mandatory(arg_count_mandatory))
        allocate(args_mandatory_reals(arg_count_mandatory))

        args_set_mandatory(1:arg_count_mandatory) = .false.

        args_keys_mandatory(1) = "VectorToScalar.ArgDouble.TimeStepInSeconds"
        args_keys_mandatory(2) = "VectorToScalar.ArgDouble.IncomingArraySize"

        ! This argument is generated from the information in the .xml file
        args_keys_mandatory(3) = "FluidEarth_SDK.ArgDouble.HorizonStartModJulian"

    end subroutine initialise_pre

    subroutine finish()
    end subroutine finish

    integer function property_pair(key, value)
        character(len=100) key, value
        integer n
        property_pair = 0

        do n = 1, arg_count_mandatory
            if (key == args_keys_mandatory(n)) then
                read(value, '(f100.0)', iostat=ios) args_mandatory_reals(n)
                if (ios /= 0) then
                    call RAISE_IO_EXCEPTION(12, ios, &
                     & "Cannot parse to real: " // trim(key) // " != " // trim(value))
                     property_pair = -1
                    return
                  end if
                 args_set_mandatory(n) = .true.
                  return
               endif
        end do

    end function property_pair

    real(dp) function initialise_post()
        integer i, n
          initialise_post = -1
```

```
        do n = 1, arg_count_mandatory
            if (args_set_mandatory(n) .eqv. .false.) then
                call RAISE_EXCEPTION("Missing Mandatory Argument: " // args_keys_mandatory(n))
                return
            end if
        end do

        TimeDelta = args_mandatory_reals(1)/(24.*60.*60.)
        IncomingArraySize = args_mandatory_reals(2)

        allocate(ExchangeItem(IncomingArraySize,4)); ExchangeItem = -999 ! 1.0
        TimeCurrent = args_mandatory_reals(3)

        if (allocated(args_set_mandatory)) then
            deallocate(args_set_mandatory, stat = ios)
            if (ios /= 0) then
                call RAISE_EXCEPTION("deallocation: args_set_mandatory")
                return
            end if
        end if

        if (allocated(args_keys_mandatory)) then
            deallocate(args_keys_mandatory, stat = ios)
            if (ios /= 0) then
                call RAISE_EXCEPTION("deallocation: args_keys_mandatory")
                return
            end if
        end if

        if (allocated(args_mandatory_reals)) then
            deallocate(args_mandatory_reals, stat = ios)
            if (ios /= 0) then
                call RAISE_EXCEPTION("deallocation: args_mandatory_reals")
                return
            end if
        end if

        initialise_post = TimeCurrent

    end function initialise_post

    subroutine set(key, value_count, value)
        character(*), intent(in) :: key
        integer, intent(in) :: value_count
        real(dp), intent(in) :: value(value_count)
        integer index, n, var_index

        if(key(1:4)=="_ANG")then
            var_index = 1
        elseif(key(1:4)=="_DEP")then
            var_index = 2
        elseif(key(1:4)=="_HEI")then
            var_index = 3
        elseif(key(1:4)=="_PER")then
            var_index = 4
        else
            goto 777
        endif

        if(value_count > 0)then
            do index = 1, value_count
                ExchangeItem(index,var_index) = value(index)
            enddo
        else
            goto 777
        endif
```

```
777       continue

    end subroutine set

    subroutine get(key, value_count, value)
        character(*), intent(in) :: key
        integer, intent(in) :: value_count
        real(dp), intent(out) :: value(value_count)
        integer n, index, var_index, exch_index(4)
        character(1) :: tmpKey5, tmpKey6, tmpKey7

        tmpKey5 = key(5:5); tmpKey6 = key(6:6); tmpKey7 = key(7:7)

        value = 0.0

        if(key(1:4)=="_ANG")then
            var_index = 1
        elseif(key(1:4)=="_DEP")then
            var_index = 2
        elseif(key(1:4)=="_HEI")then
            var_index = 3
        elseif(key(1:4)=="_PER")then
            var_index = 4
        else
            goto 888
        endif

        if(value_count > 0)then
            do index = 1, value_count
                read(tmpKey5, '(i1)', iostat=ios) exch_index(1)
                read(tmpKey6, '(i1)', iostat=ios) exch_index(2)
                read(tmpKey7, '(i1)', iostat=ios) exch_index(3)
                  if (ios /= 0) then
                      call RAISE_IO_EXCEPTION(12, ios, &
                        & "Cannot parse to integer: " // " != " // trim(key))
                        goto 888
                  end if
                exch_index(4) = 100*exch_index(3) + 10*exch_index(2) + exch_index(1)
                  value(index) = ExchangeItem(exch_index(4),var_index)
            enddo
        endif

888       continue

    end subroutine get

    real(dp) function compute()

        TimeCurrent = TimeCurrent + TimeDelta
        compute = TimeCurrent

    end function compute

end module
```

Appendix A7 Core Codes for Orientation Updating Module (C#)

```
public class OrientationUpdating : IEngine5
    {
        const string _argTimeDelta = "Hrw.Cem3.ArgDouble.TimeDelta";

        RuntimeData _runtimeData;
        ILogger _logger = null;
        OrientationUpdatingControl _controller;
        ExceptionEngine _exceptionLast;

        #region IEngine5 Members


        public double DoTimeStep(double timeIn, ref double[] dataIn, ref double[] dataOut)
        {
            try
            {

                Utilities.ArrayUnpack(_runtimeData, dataIn, _controller);

                double[] yCoord = _controller.BeachPosition;

                double Plxton = 227.75;
                double dxLeft, dxMid, dxRight;

                int IndexA, IndexB, IndexC;

                IndexA = 0;
                IndexC = _controller.BeachPosition.Length;
                IndexB = 11;
//Simple method
                dxLeft = Math.Sqrt((_controller.x[1] - _controller.x[0]) * (_controller.x[1] - _controller.x[0]) +
(_controller.y[1] - _controller.y[0]) * (_controller.y[1] - _controller.y[0]));
                dxMid = Math.Sqrt((_controller.x[IndexB - 1] - _controller.x[IndexB - 2]) *
(_controller.x[IndexB - 1] - _controller.x[IndexB - 2]) + (_controller.y[IndexB - 1] - _controller.y[IndexB - 2]) *
(_controller.y[IndexB - 1] - _controller.y[IndexB - 2]));
                dxRight = Math.Sqrt((_controller.x[IndexC - 1] - _controller.x[IndexC - 2]) *
(_controller.x[IndexC - 1] - _controller.x[IndexC - 2]) + (_controller.y[IndexC - 1] - _controller.y[IndexC - 2]) *
(_controller.y[IndexC - 1] - _controller.y[IndexC - 2]));

                _controller.AngleLeft = Plxton - Math.Atan((yCoord[1] - yCoord[IndexA]) / dxLeft) * (180 /
Math.PI) - 90;
                _controller.AngleMid = Plxton - Math.Atan((yCoord[IndexB - 1] - yCoord[IndexB - 2]) /
dxMid) * (180 / Math.PI) - 90;
                _controller.AngleRight = Plxton - Math.Atan((yCoord[IndexC - 1] - yCoord[IndexC - 2]) /
dxRight) * (180 / Math.PI) - 90;


                Utilities.ArrayPack(_runtimeData, dataOut, _controller);
            }
            catch (Exception e)
            {
                ThrowToServer(new ExceptionEngine(e));
            }

            _controller.TimeCurrent += _controller.TimeDelta;
            return _controller.TimeCurrent;
        }
```

Appendix A8 Sample Run of BEACHPLAN

Control File: *.con

```
TITLE
Poole Bay - ZEZ
(1)DetailsBeach
GRIDINFO
 219   3
SEGMENTSINFO
 14 200
 204 20
 218 200
REFERENCELEVEL
MHW
BEACHLEVEL
0 0
COORDINATES
LAB
BEACHCONTOUR
 855.680  780.960  706.240  631.520  556.800  482.080  407.355  366.254  358.782  351.310
 344.417  337.523  330.630  329.510  325.990  316.600  306.170  299.080  292.820  287.170
 281.380  272.650  265.480  257.650  248.510  235.900  227.740  219.790  213.610  207.400
 200.140  192.530  185.300  177.930  172.470  169.440  166.330  162.630  161.140  157.980
BOUNDARIES
 0
 1 1 1 1
KPARAMETERS
 0.28 1.08
ANGLE
227.75
CLOSUREDEPTH
1
-2.5
SWASHHEIGHT
1
1.0
BEACHSLOPE
1
0.033
SPREADING
1
TYPEXSHDIST
1
DEPTHOVERROCK
0
TIDALINFO
0
(2)DetailsSeawall
SEAWALL
0 999.9
SEAWALLYX
0
 3.000  3.000  3.000  3.000  3.000  3.000  3.000  3.000  3.000  3.000
 3.000  3.000  3.000  3.000  3.000  3.000  3.000  3.000  3.000  3.000
 3.000  3.000  3.000  3.000  3.000  3.000  3.000  3.000  3.000  3.000
 3.000  3.000  3.000  3.000  3.000  3.000  3.000  3.000  3.000  3.000
793.775  719.035  644.295  569.555  494.815  420.075  345.350  304.254  296.782  289.310
 287.917  286.523  285.130  276.960  268.170  259.870  251.820  243.760  235.860  228.020
 220.070  212.010  204.070  196.260  188.450  180.630  172.820  165.010  157.220  149.490
 143.440  140.630  138.100  135.590  133.120  126.790  119.750  112.290  104.350  98.380
1
-2.0
(3)DetailsRenourishment
RENOURISHMENT
```

```
1
0.0
(4)DetailsRun
TIMESTEP
   2    60    12    1
(5)DetailsInputWaves
WAVESDEPTH
-6.0
WAVEPOINTS
2
   3000 6000
BANNEDWAVES
   220 60
MINIMUM_H
0.1
WAVETYPE
1
724 1
(6)DetailsGroynes
NGROYNES
3
GROYNESINFO
     9    648 650 1 -2.5
     15    333 335 1 -2.5
(7)DetailsBreakwaters
NBREAKWATERS
0
(8)AditionalDetails
FLUID
1030
SEDIMENT
2650 0.5
END
```

Wave File: *.waves

Time	T	H1	D1	H2	D2	H3	D3	H4	D4
81111	4.9	1.53	164	1.53	164	1.53	135.25	1.53	135.25
81112	4.8	1.53	165	1.53	165	1.53	136.25	1.53	136.25
81113	5.4	1.88	163	1.88	163	1.88	134.25	1.88	134.25
81114	5.4	1.88	164	1.88	164	1.88	135.25	1.88	135.25
81115	5.4	1.88	164	1.88	164	1.88	135.25	1.88	135.25
…	…	…	…	…	…	…	…	…	…
…									

Appendix A9 Sample Run of COSMOS

Control File: *.con

PROFILE
32 0
1 2 3 4 5 10 15 20 25 30 35 40 45 50 60 70 80 90 100 120 140 160 180 200 250 300 350 400 450 500 600 700
-2 -2.53 -2.50 -2.47 -2.44 -2.28 -2.10 -1.86 -1.47 -1.09 -0.79 -0.54 -0.30 -0.10 0.14 0.36 0.75 1.25 1.78 2.62 3.14 3.37 3.63 4.01 5.52 6.32 6.44 6.55 6.83 7.16 7.43 7.51
INTERPOLATION
-1
2 698 5
PROFILEANGLE
127.75
LONGSHORE
1 0
BREAKING
1 -1 0.6 0 0
OUTPUT
1 2 1 -1 1
dist
700 -1
depin
0 -1
SEDIMENT
1 -2 0.016
2650
400
SEDTRANSPT
0.6 0.566 1.128 0.63 0.1 0.02 1 1 1 0.325 0.488 0.1 0
DATUM
0.8
INPUT
-1
ITERATIONS
4
END

Wave File: *.waves

T	D	H	Duration	Water level	Flag
2.3	193.6	0.21	3600	0	0
2.4	192.4	0.25	3600	0	0
2.4	191.3	0.25	3600	0	0
2.9	190.5	0.35	3600	0	0
…	…	…	…	…	

…

Appendix A10 Evolution of Design of the Coupled Model

There are four research stages as described in Section 4.1.1. Different model designs were proposed and evaluated during each stage. As a result, the design evolved as outlined below.

Stage 1:

Set COSMOS-LS (LS stands for longshore mode) in x primary profiles (x is thought to be less than 20) along the beach. Take the bulk drift of each profile from COSMOS-LS and modify them based on the changing tendency of drifts produced by BEACHPLAN. The proposed composition is given below.

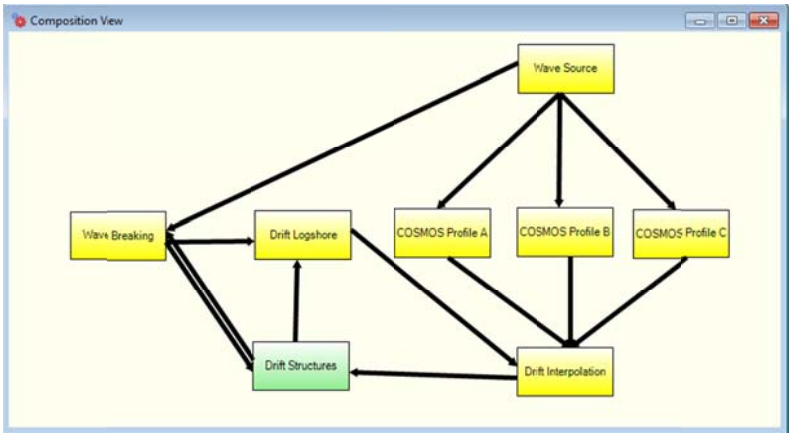


Figure A10 - 1 Proposed initial model composition

Stage 2:

Apply the modified drifts at every time-step of BEACHPLAN (normally 1 or 3 hours). Run the whole composition. Profile orientation in COSMOS-LS is not updated at this stage. However, it was found that the wave source formats are different between BEACHPLAN and COSMOS, so Vector-To-Scalar module was added, see the figure below.

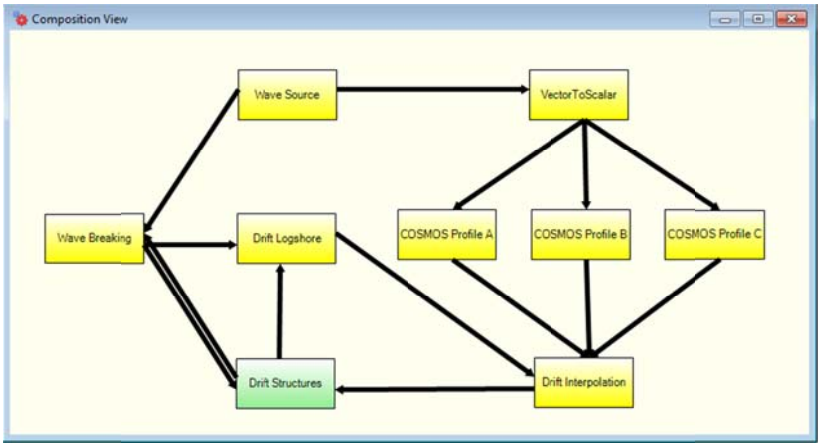


Figure A10 - 2 Model composition after Stage 2

Stage 3:

Generate proper method to update the profile orientation in COSMOS-LS at each time step based on the updated shoreline position calculated by the new coupled model at each time step. It was thought that another Vector-To-Scalar module is needed to pass the three angles from Orientation Updating module to three individual COSMOS run.

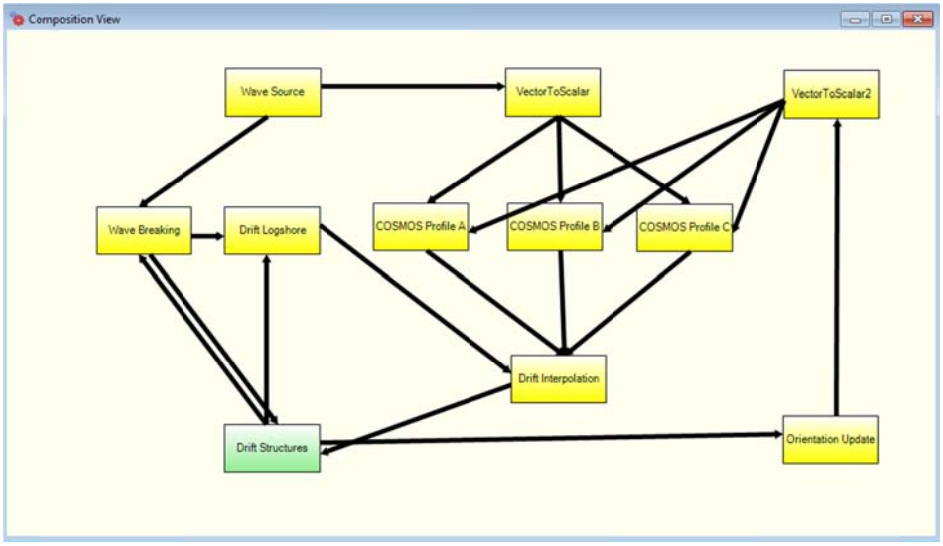


Figure A10 - 3 Proposed model composition for Stage 3

The second Vector-To-Scalar was later believed to be unnecessary, thus the final composition is given below.

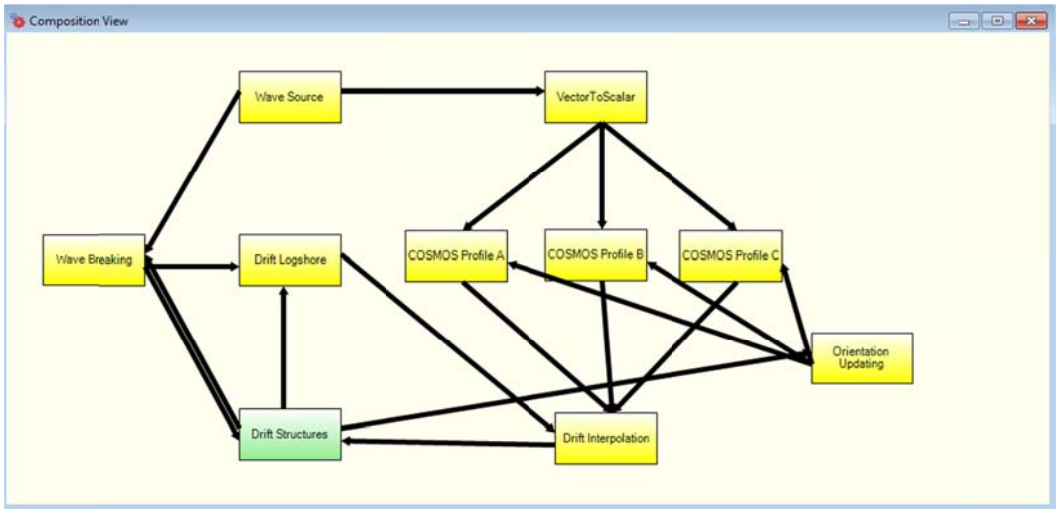


Figure A10 - 4 Final model composition used in this research

It is possible to further simplify the composition by merging Orientation Updating module and Drift Interpolation module, then the proposed future composition is given by the figure below.

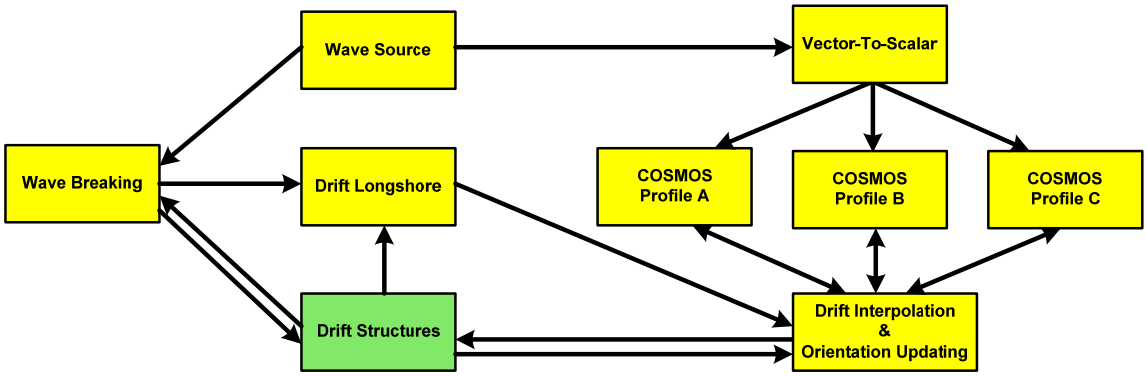


Figure A10 - 5 Proposed future composition

Stage 4:

Pass the bulk drift values as well as the cross-shore distribution of longshore transport from COSMOS-LS to BEACHPLAN. The model should be tested with coastal structures such as groynes and detached breakwaters.

This stage is recommended for further consideration.