Infra-gravity wave transformation across macro-tidal rocky shore platforms

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INFRA-GRAVITY WAVE TRANSFORMATION ACROSS MACRO-TIDAL ROCKY SHORE PLATFORMS

by

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Rocky shore platforms are low-gradient rock surfaces that occur within or close to the intertidal zone, usually in front of sea cliffs. Characterised by their complex, rough and dissipative surfaces they are one of the distinctive morphological features of many rock coasts. Recent studies of wave transformation across rocky shore platforms, mainly in micro-tidal environments, demonstrate comparable hydrodynamic processes known from dissipative beaches. Incident wave energy at gravity wave frequencies (0.05 Hz – 0.125 Hz) dissipates in the landward direction, while energy at the infra-gravity wave frequencies (< 0.05 Hz) tends to dominate at the base of the cliff (e.g. Beetham and Kench, 2011; Ogawa et al., 2011). These low-frequency motions can modulate the depth close to the cliff-toe which provide several mechanisms to enhance the erosion and subsequent retreat of rocky cliffs.

Despite their significance for geomorphic development, the transformation processes of infra-gravity waves are virtually unstudied. Therefore, this research objective is set to determine how infra-gravity waves are generated, shoal and reflect on a gently sloping (A-type) rocky shore platform. This research thereby contributes to the Waves Across Shore Platforms (WASP) project that was initiated in 2014 to increase understanding of wave transformation across these rocky shore platforms. The case study used for this research is the ~ 220 m wide, mid-sloping, platform at the beach of Lilstock, located on the margins of the Severn Estuary (UK), famous for its macro-tidal environment. Field data from the Lilstock platform were collected by the WASP team in December 2014 for seven tidal cycles.

Four sub-research questions are formulated regarding (1) the significance of infra-gravity waves at the platform, (2) the governing generation mechanism, (3) the shoaling across the platform and (4) the reflection at the shoreline. The methodology to answer these questions comprises a few elements, among them an analysis of the field data in terms of bulk wave parameters and the calibration of the one-dimensional XBeach model. Both the field data and XBeach model results are used to investigate the transformation processes for different tidal phases. In order to identify the mechanisms responsible for the generation of infra-gravity waves, a cross-correlation analysis is performed to examine the evolution of the interaction between the short wave group and the infra-gravity wave across the platform. Furthermore, the low-frequency motions are decomposed to incoming and reflecting constituents, using a three-point method for the field data and the kinematic relation for the model results, to assess the shoaling and reflection of infra-gravity waves.

Based on an analysis of the field data, infra-gravity wave heights are found to increase up to $H_{inb} = 0.34 m$ near the base of the cliff, for energetic offshore conditions, which is in the same order of magnitude compared to other morphological settings with similar offshore wave conditions. Furthermore, a strong tidal modulation of the infra-gravity wave height is observed, with increasing wave heights for higher tidal phases. The bulk wave parameters are modelled within acceptable error margins by XBeach. As a result of the calibration of three model parameters, it is found that, for the platform of Lilstock, dissipation of short wave energy is governed by breaking and, to a lesser extent, by bottom friction. For the low-frequency motions and mean currents, the associated friction coefficient approaches $c_f = 0.08$, which is close to the value found for the calibration of XBeach for coral reefs. This suggests that infra-gravity waves at rocky shore platforms experienced a rough surface and dissipate their energy across the platform by bottom friction.

Infra-gravity waves are generated either offshore as bound long waves or at the edge of the surf-zone as free waves. Both known mechanisms are investigated in order to identify the governing mechanism.
From the cross-correlation analysis, neither the field data nor the XBeach results show convincing evidence of locally generated free infra-gravity waves, neglecting the effect of a forcing mechanism by a time-varying breakpoint. However, for all tidal phases, the results do indicate a strong negative correlation between the envelope of the short wave group and the infra-gravity wave in the shoaling zone, from which the offshore generation of bound long waves is concluded for the A-type rocky shore platform of Lilstock.

Once generated and propagating towards the surf-zone, the incoming bound infra-gravity waves shoal as a combination of the conservation of energy flux and the transfer of energy from the short wave group. The growth rate of the incoming wave is expressed in terms of $\eta \sim h^{-\alpha}$. For high-tide the growth rate $\alpha$ across the shoaling zone is in the order of $[0.4 - 0.8]$, which is considerably less than the theoretical limit for bound long waves ($\eta \sim h^{-5/2}$) but indicates a stronger enhancement than free wave shoaling consistent with Green’s Law ($\eta \sim h^{-1/4}$). Therefore the computed growth rate is compliant to the observed generation mechanism. For mid-tidal phases, i.e. when the shoreline faces the mild-sloping platform and the water depth is small, there is a reduction in growth rate and in some cases, the incoming infra-gravity wave height is even observed to decrease. This is mainly attributed to the interaction with the rough surface as investigated using the calibrated XBeach model. The moderate values of $\alpha$ are also substantiated by the normalised bed slope $\beta_b$, that shows values well within the ranges for mild- and steep-sloping regimes as defined by Van Dongeren et al. (2007). Furthermore, it is found that the amplification of the incoming waves across the shoaling zone increase with lower offshore steepness and higher tidal phases.

During high-tide the shoreline faces the steep-sloping cliff where reflection coefficients of $R \approx 0.8$ result in low-frequency standing waves, as opposed to during mid-tidal phases when $R \approx 0.35$ and a large portion of the infra-gravity wave energy is dissipated. Relating the shoreline reflection, at a depth contour of $0.75 \text{ m}$, to the relative steepness parameter $\beta_H$, yields data that is reasonably well represented by $R = 0.2 \pi \beta_H^2$. Although, values of $\beta_H$ are found to deviate significantly from the theoretical relation when computed for smaller frequency domains than the total infra-gravity domain. As a result of the dependency by $\beta_H \sim \frac{1}{f \sqrt{m_\xi}}$ the wave steepness is not derived properly for irregular waves. Although there are some reservations on the validity of $\beta_H$, the relation between $R$ and $\beta_H$ suggests that high-frequency infra-gravity waves ($0.025 - 0.055 \text{ Hz}$) tend to dissipate by long-wave breaking, whereas low-frequency infra-gravity waves ($0.004 - 0.014 \text{ Hz}$) almost completely reflect for all tidal-phases.

Recommendations and opportunities for further research comprise, among others:

- Calibration of XBeach-SurfBeat parameters for other rocky shore platforms to investigate the parametrisation of surface roughness.
- Application of moving window analysis for field data of other coastal morphologies to quantify the natural variability and validate the proposed method.
- Examine modifications to the $\beta_H$-parameter, and its relation to $\xi$ and $R$, to obtain a more reliable parameter to described the relative steepness for infra-gravity waves.
- Investigate the hypothesis of increasing importance of infra-gravity waves as a consequence of sea level rise for rocky shore platforms.

To conclude, the main objective is fulfilled by identifying the generating mechanism and determine how infra-gravity waves shoal and reflect for different tidal phases. It has been found that the infra-gravity waves on an A-type rocky shore platform of Lilstock increase for increasing tidal levels, owing to effective bound long wave shoaling, decreasing interaction with the rough platform surface and an increasing reflection coefficient at the shoreline.
This thesis symbolises the last milestone to complete the MSc programme of Hydraulic Engineering at the Technical University in Delft. The research has been conducted at Deltares in Delft in collaboration with the School of Marine Science and Engineering (Plymouth University, UK) and the School of Ocean Sciences (Bangor University, UK) and is part of the Waves Across Shore Platform project.

After almost nine months there is getting an end to this very interesting process. I received a lot of support from everyone who has stood beside me during this process and I would like to thank all of you, without whom I could not have accomplished this thesis. Your help has been of vital essence.

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1

INTRODUCTION

1.1. ROCK COAST GEOMORPHOLOGY
Rock coasts are erosional environments which form as a result of the landward retreat of bedrock at the shoreline (Kennedy et al., 2014; Naylor et al., 2010). They are often associated with tectonically active convergent margins, creating hard rock surfaces containing high percentages of basalt and granite. However, their presence in environments that lack tectonic movement is equally common, where they are usually formed by hard carbonate-rich sedimentary deposits creating consolidated layers with varying properties. Furthermore, their origin can be linked to glacial activity, where rocky coasts are formed by scouring Pleistocene glaciers compressed sediments by glacial drift.

Consequently, rocky coasts can be found at all latitudes and in all morphogenetic environments, including lakes and estuaries (Trenhaile, 1987). In fact, 80% of the world’s coastlines are rocky and characterised by cliffs, reefs and inter-tidal shore platforms formations (Emery and Kuhn, 1982). Naylor et al. (2010) advocated this figure based on the fact that many cliffed coasts are fronted by (peddle or gravel) beaches and as a result the classification is ambiguous. This being said, rocky coasts are nonetheless considered the most common type on earth.

By their nature, all rocky coasts erode and their evolution is inherently driven by the action of sub-aerial, biological and marine processes. Sub-aerial weathering and biological activity break down the bedrock by either directly removing material or making it more susceptible to erosion by waves and tide (Kennedy et al., 2014). Typical for rock coasts erosion, is the irreversible character of this process, i.e. they have no capacity to recover from storm events in the way that beaches can rebuild, as sediment is transported onshore. Therefore changes in form are long-lasting, or even permanent (Masselink and Gehrels, 2014).

1.2. ROCKY SHORE PLATFORMS
One of the distinctive morphological features of many rock coasts are their shore platforms. These sub-horizontal or low-gradient rock surfaces occur within or close to the intertidal zone, usually in front of sea cliffs (Sunamura, 1992; Trenhaile, 1987).

Despite extensive research on the development of rocky shore platforms, there remains a lack of consensus regarding the formative processes (Marshall and Stephenson, 2011; Naylor et al., 2010). It is generally agreed that both weathering and wave processes are a critical control on cliff retreat, as well as the initiation and subsequent development of shore platforms, although the relative contribution of these processes remains unclear.

CLASSIFICATION
The platform surfaces are mainly characterised by complex, rough and dissipative surfaces due to erosion of the softer rocks, leaving harder parts exposed. Two generalised types of shore platform morphologies are distinguished: sloping platforms (type A) and (sub-)horizontal platforms (type B). The
first type (1.1a) is gently sloping (gradients between 1° to 5°) and extending into the sub-tidal zone usually backed by a cliff. The second type (1.1b) has a sub-horizontal platform with a sharp seaward boundary; this type is also referred to as the low-tide cliff as the upper part of the cliff is seen at low tide.

(a) Schematic cross-section (left) and a characteristic example of an A-type cliff in Nashpoint, South Wales, UK (right).

(b) Schematic cross-section (left) and a characteristic example of a B-type cliff in Hobarrow Bay, Dorset, UK (right).

Figure 1.1: Schematic cross-section and characteristic example (at low tide) of the two generalised types of shore platform morphologies after (Trenhaile, 1987) and (Sunamura, 1992).

Relation to tidal environment

The prevailing platform type depends on, among other aspects, the tidal environment to which it is subjected (Dickson et al., 2013). There are two main variables by which tidal environments can be classified namely, the magnitude of the tidal range (TR) and the tidal character described by the form factor (F) (Bosboom and Stive, 2013). Although the latter could influence the platform’s geomorphology due to different wetting and drying cycles, the prevailing type is mainly depending on the classification based on the tidal range. Davies and Moses (1964) defined three categories of tidal environments based on the tidal range:

- Micro-tidal range: mean spring tidal range < 2 m;
- Meso-tidal range: mean spring tidal range 2-4 m;
- Macro-tidal range: mean spring tidal range > 4 m.

Shore platforms in environments with meso- to macro-tidal ranges tend to be gently sloping seaward (type A) (Trenhaile, 2014) as opposed to sub-horizontal forms (type-B), which mainly occur in environments with micro- to meso-tidal ranges (Dickson and Stephenson, 2014; Kennedy, 2014). This indicates a strong influence of the tidal environment on the rock coast geomorphology.
1.3. MOTIVATION AND SIGNIFICANCE

In recent decades, coastal research has been focused on hydrodynamics, sediment transport and morphodynamic processes in depositional coastal environments such as sandy beaches, tidal flats and estuaries, since they are perceived to have a high social and economic value. Rock coasts have been considered a neglected coastal land-form and are therefore virtually unstudied (e.g. Stephenson and Kirk, 2000a; Trenhaile, 1980). As a result the sub-discipline is still in its infancy. However, in recent years there has been a growing interest in rocky coasts, which is reflected in both the number of scientific papers published and the number of active researchers on this topic (Naylor et al., 2010).

One of the incentives is the high social relevance of the knowledge on rock coast morphology. Since all rocky coasts, by their very nature, erode, it is essential to investigate their sensitivity to future climate and sea level rise scenarios. Another major driver for the increasing interest has been the advent of new technologies that enable scientists to address problems not previously accessible and at scales not previously achievable (Masselink and Gehrels, 2014). In particular, the number of field experiments has increased in recent years using more advanced equipment, such as terrestrial laser scanners and high frequency pressure transducers to be able to examine the erosion potential due to waves and their transformation processes. There are several recent studies using field measurements in Australia and New Zealand to indicate the wave transformation across inter-tidal shore platforms in micro- and meso-tidal environments (e.g. Dickson and Pentney, 2012; Marshall and Stephenson, 2011; Ogawa et al., 2011, 2015). These studies mainly focus on the temporal and spatial distribution of wave energy looking at wave height attenuation, dissipation of short waves and possible cliff impact.

WAVES ACROSS SHORE PLATFORMS

Until now, wave processes at rocky shore platforms have been based on empirical data only. In order to predict coastal processes along rocky coasts, the wave transformation should be understood quantitatively. To increase the understanding and modelling capabilities of wave transformation processes on rocky shores, the Waves Across Shore Platforms (WASP) project was initiated in 2014. This complex and comprehensive project is conducted by a multidisciplinary research team with members from the universities of Plymouth (England), Bangor (Wales) and Auckland (New Zealand), and Deltares. The subject of the WASP project is to understand how waves propagate across shore platforms and to develop a capability to reliably model this process. The research methodology comprises two main elements: field measurements and numerical modelling. It is believed that such a combined approach is absolutely necessary to facilitate a step change in the understanding of wave transformation processes across rocky shore platforms. Using this methodology is also what sets the WASP project apart from all previous investigations on this topic.

Field measurements are conducted in the UK (among others) where most rocky shore platforms are dominated by a macro-tidal environment and, as expected based on Trenhaile (2014), predominantly of type-A. One aspect of the WASP project that has not yet been fully developed is the effect of infra-gravity (IG) waves on such rocky shore platforms. This research is part of the WASP project and will use its field data to investigate the infra-gravity wave transformation across rocky shore platforms.

INFRA-GRAVITY WAVES

Infra-gravity (IG), or sub-harmonic gravity waves, are low-frequency motions typically in the order of $0.005 \text{Hz} - 0.05 \text{Hz}$. These low-frequency motions in coastal regions were first observed by Munk (1949) and Tucker (1950) who called them ‘surf-beat’ and linked the generation of these motions to the group structure of the incident (high-frequency) short waves (Longuet-Higgins and Stewart, 1962). Since their first observations many others have dedicated their research to the generation and transformation processes of infra-gravity waves. Most of them based on field data, wave flume experiments and numerical modelling for gently sloping dissipative beaches and, in more recent studies, for coral reefs (e.g. Gawehn, 2015; Quataert, 2015; Van Dongeren et al., 2013).
IG-waves can play an important role in the erosion and geomorphic development of rocky shore platforms. In case of erosion, and for engineering purposes, it is critical to quantify the amount of wave energy delivered to the cliff under specific conditions. Long period oscillations due to IG-waves provide a mechanism to periodically increase the local water depth, allowing incident waves of higher frequencies to access a larger portion of the cliff (Dickson et al., 2013). This mechanism could be enhanced even further by the occurrence of standing wave patterns due to IG-wave reflection at the shoreline. Another potential mechanisms by which IG-waves can influence the geomorphology of rocky platforms is the potential direct impact of the super-elevation on the repeated wetting and drying cycles of the platform, augmenting the erosion of weak sedimentary rocks. Furthermore, the reflected IG-wave energy, in combination with the tide, can play a critical role in the removal of cliff-toe debris. These mechanisms demonstrate an important role of IG-waves at rocky shore platforms and link to the significance of this research.

**Recent field studies**

Interestingly, all aforementioned recent field studies on wave transformation across rocky shore platforms indicate the presence of IG-waves and make reference to their increasing relative importance close to the cliff-toe. Beetham and Kench (2011) dedicated their research to the transformation of IG-waves by analysing data of two near horizontal B-type platforms (Oraka and Rothesay Bay, both in New Zealand). They concluded, independently of other scientists, the same increasing importance of IG-waves near the base of the cliff with the highest records of IG-band energy during high tide. Furthermore, they observed a strong tidal modulation on the dissipation of incident wave energy and the importance of IG-waves.

Most of the recent field studies, indicating the importance and tidal modulation of IG-waves on rocky shore platforms, focused on B-type platforms in micro-tidal regimes. In a macro-tidal environments the extreme tidal range result in larger fluctuations of the local water depth compared to a micro-tidal regime which could result in a larger differences of the IG-wave transformation for different tidal phases. In addition, the tidal level is linked to the effective bed slope at the shoreline which varies significantly between the mild-sloping platform and the steep cliff influencing the reflection behaviour of IG-waves. Therefore it is expected that there will be a strong modulation of the IG-wave transformation at macro-tidal platforms, although no research has been conducted yet to investigate this.

**1.4. Objective and research approach**

As previously mentioned, many studies have already indicated the importance of infra-gravity waves at rocky shore platforms. Despite these observations, the individual transformation processes across these roughly surfaced platforms are virtually unstudied. As a result, it is unknown how infra-gravity waves are generated and develop on rocky shore platform.

**Objective**

Considering the above, in combination with the important role of IG-waves in the geomorphic development of shore platforms, a more fundamental research investigation on the transformation processes of infra-gravity waves is a logical next step. The objective of this research is therefore to determine how infra-gravity waves are generated, how they develop across the platform and reflect their energy at the shoreline using both field data and numerical modelling. In this way, the research conducted will contribute to the overall objective of the WASP project and to the development of a numerical model with the emphasis on infra-gravity wave transformation. As this research is part of the WASP project and low-frequency energy at macro-tidal platforms is virtually unstudied, this research will focus on the infra-gravity wave transformation across an A-type rocky shore platform, and consider the influence of the macro-tidal range on the infra-gravity wave transformation processes.
RESEARCH QUESTIONS
In order to fulfil the research objective, questions have been derived to better guide the investigation. The main research question (MRQ) of this MSc. thesis is defined as:

What is the significance of infra-gravity waves on A-type rocky shore platforms and how are the transformation processes modulated by the macro-tidal range?

This question is separated into four sub-research questions (SRQ):

1. What is the magnitude of infra-gravity waves on A-type macro-tidal rocky shore platforms for different tidal phases and how does this compare to other morphological settings?
2. What is the governing generating mechanism of infra-gravity waves for different tidal phases?
3. How do infra-gravity waves shoal during different tidal phases and does this comply with the governing generating mechanism?
4. How is the reflection behaviour of infra-gravity waves affected by the macro-tidal range?

APPROACH AND SCOPE

Figure 1.2 shows the framework used to answer the research questions and fulfil this research objective.

As indicated, both field data analysis and numerical modelling will be conducted to analyse the infra-gravity wave processes. This research will thus take the first step into numerical modelling of
waves across shore platforms using XBeach. The reason that both are used is twofold. First of all, a numerical model allows to extend the spatial domain beyond that of the measurements. Wave processes can thereby be investigated at each preferred location at the platform and the analysis is not restricted to the positions of the measurements devices. Secondly, the numerical model can be used as a tool to increase the understanding of the wave interaction with the rough platform surface by calibration of the dissipation parameters. However, first an analysis of the field data is required as a reference to calibrate the model, therefore both are essential in this research.

The WASP project conducted field measurements at five sites in the UK, of which one platform has been selected for a detailed analysis. The field data analysis is based on bulk parameters derived from representative and comparable signals obtained from the measured data. Although not stated explicitly, the derivation of bulk parameters in a macro-tidal environment is challenging, as will be explained in Chapter 3.

XBeach (Roelvink et al., 2009) has been selected for numerical modelling of the wave hydrodynamics, although it had already been chosen by the WASP project. Consequently, the reasons for choosing XBeach are outside the scope of this research. The choice for XBeach does, however, seem logical as this model has already been calibrated for the modelling of wave hydrodynamics across coral reefs (Van Dongeren et al., 2013) which share similarities with B-type rocky shore platforms. Furthermore the XBeach model is capable of resolving the low-frequency motions across the wave-group scale which are of great interest for this research. However, since this research will take the first step into modelling waves across shore platforms using XBeach, the model parameters have to be re-calibrated. Given that the field measurements are performed with pressure transducers in a cross-shore array the analysis of the wave transformation processes is limited to one dimension. Therefore, numerical modelling of the wave processes will also be performed for one cross-shore array (1D) to make a better comparison with the field data analysis.

1.5. THESIS OUTLINE
This report is roughly divided in three parts: data analysis of the field observations, numerical modelling of the wave transformation across rocky shore platforms using XBeach and the analysis of infra gravity wave transformation. Chapter 2 summarises previous field studies and gives a theoretical background on the infra-gravity wave transformation. Chapter 3 will focus on the WASP-site and the wave transformation across the rocky shore platform based on the analysis of the bulk parameters as determined from the field observations. In Chapter 4 the XBeach model is introduced to reproduce the wave transformation. The model set-up, calibration and validation of the model are described and the results are compared to the findings of Chapter 3 to discuss the capabilities and the applicability of the XBeach model. The results of the previous chapters are subsequently both used to investigate the transformation of infra gravity waves across rocky shore platforms. In Chapter 5 the generation mechanism of the infra-gravity wave is investigated using a cross-correlation analysis. Chapter 6 describes how infra-gravity waves shoal and elaborates on the reflection behaviour across rocky shore platforms. To conclude the research, Chapter 7 will answer the main research question, discuss the results of Chapter 3 to 6 and indicate opportunities and recommendations for further research.
This chapter provides background information for this research by describing the shore platform hydrodynamics based on recent field studies and by comparing this to the hydrodynamics at coral reefs. Since the core of this research focuses on the transformation processes of infra-gravity waves, section 2.3 will give a theoretical background.

2.1. SHORE PLATFORM HYDRODYNAMICS

There are several recent studies reporting field measurements at B-type rocky shore platforms in micro- and meso-tidal environments describing the wave transformation processes (e.g. Beetham and Kench, 2011; Marshall and Stephenson, 2011; Ogawa et al., 2011, 2015) and the erosion potential of waves (e.g. Stephenson and Kirk, 2000b; Trenhaile and Kanyaya, 2007). According to Dickson and Pentney (2012) cliffs and shore platforms are linked dynamically because shore platform characteristics (elevation, gradient, width and surface roughness) directly control the wave transformation processes across the platform, and thereby the wave impact on the cliff.

Based on field studies at four morphologically different platforms Marshall and Stephenson (2011) indicated platform gradient and water depth to be a strong control on the dissipation of wave energy across the platform. Furthermore, at three of the four investigated sites, infra gravity waves were found to be the most important energy components on the platform. Ogawa et al. (2011) conducted a field experiment on a 250m wide, B-type, platform near Gisborne (New Zealand) and concluded a strong control of tidal modulation on the rate of wave energy attenuation and the relative importance of (infra-) gravity waves across the platform. Their study also highlights the occurrence of depth-limited inci-

Figure 2.1: Linear dependence of the incident wave height $H_m$ and water depth $h$ (left) and the relative submergence (right), after Ogawa et al. (2015).
dent waves when the platform experiences breaking waves, a concept well-known from sandy beach studies and referred to as surf-zone saturation. This was also observed by Ogawa et al. (2015) who discussed the relationship between wave height \(H\) and water depth \(h\) across the Rothesay Bay platform, where a strong linear dependence between \(H\) and \(h\) is demonstrated, as indicated in figure 2.1. In relation to the presence of gravity waves on the platform, Ogawa et al. (2015) observed the formation of a relative submergence threshold \((h/H_{m0})\) at the seaward edge of a type-B platform. If this threshold exceeds a value of 1.1, the wave spectra at the platform are dominated by gravity wave energy, below this value infra-gravity wave energy dominates the wave spectra. This builds on the observations by Marshall and Stephenson (2011) and Ogawa et al. (2011) who already briefly discussed this relationship and concluded strong control of wave transformation by water depth and platform elevation, hence modulated by the tide.

Beetham and Kench (2011) dedicated their research to IG-waves and investigated the shoaling behaviour of the IG-wave signal across two B-type rocky shore platform. They concluded some broad similarities in the behaviour of IG-waves on rocky platforms and sand beach systems. The rate of shoaling, defined as the IG-wave height at the cliff toe divided by the incident IG-wave height, was shown to increase with increasing offshore wave conditions and increasing water level, indicated by figure 2.2. The higher rate of shoaling during high tide results in a super-elevation of the water level at the cliff-toe which is linked to the presence of standing waves. Besides, a higher rate of shoaling was observed at the wider (Oraka) platform. For sandy coasts it is well-established that infra-gravity wave shoaling dependents on the incident wave height and according to Beetham and Kench (2011) and Ogawa et al. (2015) the same relationship is expected to hold for infra-gravity wave shoaling across rocky shore platforms.

![Figure 2.2](image)

**Figure 2.2:** Relationship between incident \(H_s\) and cliff toe IGW height (a). Relationship between water depth at the cliff toe \(h/\text{reef width (Rw)}\) and proportional increase in IGW height across the platform (cliff toe IGW height/incident IGW height), after Beetham and Kench (2011).

### 2.2. Similarities with Coral Reef Environments

Distinct from sandy coastlines, rocky shore platforms share morphological and hydrodynamical similarities with coral reefs. By their nature, coral reefs are mainly located in micro-tidal regions and the reef flat tends to show a similar form as the type-B platform. Recent studies of wave interaction with coral reefs (e.g. Lowe et al., 2005; Symonds et al., 1995) and wave transformation across reef platforms (Kench and Brander, 2006) provide key insights to these processes.

Most importantly, as with intertidal shore platforms, coral reefs possess high friction values due to bed roughness introduced by coral. This friction dissipates waves at a higher rate than on sandy coasts with consequences for the distribution of wave energy across a reef, wave setup and run-up. Dissipation over reefs is often found to be dominated by wave breaking (e.g. Lee and Black, 1978) although Lowe et al. (2005) conducted field experiments on a barrier reef at Kaneohe Bay (Hawaii), where the
The majority of the wave energy was dissipated by bottom friction. Currently friction effects have not been evaluated on rock platform surfaces, therefore these studies are of great interest.

As observed by Lee and Black (1978) incident short waves tend to dissipate on the steep fore-reef resulting in the same shift in energy toward lower frequencies which indicates the importance of infra-gravity waves on the reef flat (Kench and Brander, 2006). This was also observed with flume experiments by Bodde et al. (2014). Bottom roughness and water levels in a fringing reef environment were shown to have an influence on many processes such as short wave breaking, infra-gravity wave transformation, seiching, wave-induced setup and wave reflection. It was observed that near the beach short wave height is controlled by depth-induced breaking and that the infra-gravity wave height is controlled by bed roughness. This was also confirmed by Pomeroy et al. (2012) who found that the onshore propagating infra-gravity waves across the reef flat were attenuated by bottom friction and strongly depend on the water depth over the reef, hence modulated by the tide.

In relation to infra-gravity wave generation on coral reef environments, Pomeroy et al. (2012) found that the surf zone generation of free infra-gravity wave motions on the steep (1:20) fore-reef slope was dominated by breakpoint forcing (as opposed to the release of bound long waves). This was also supported by detailed numerical simulations of the generation process. Modelling these low frequency wave dynamics over fringing coral reefs using XBeach has recently been investigated and appears promising (Buckley et al., 2014). Modification of the XBeach model equations was required and has been performed by Van Dongeren et al. (2013). A bottom friction dissipation term in the short wave energy balance has been added and the calibration of two bed friction coefficients to higher values than commonly applied to sandy coasts environments was required. This modified XBeach model has already been used to understand the wave runup processes (Quataert, 2015) and to model the wave field (very low frequency motions, infra-gravity waves and incident waves) on the Kwajalein atoll (Gawehn, 2015).

Despite the difference in tidal environment between coral reefs and the rocky shore platforms in the UK, the similarities in wave transformation and the extensive research in the propagation of IG-waves make these studies of great interest for the understanding of wave transformation across rocky shore platforms.

### 2.3. INFRA GRAVITY WAVE TRANSFORMATION

In general infra-gravity waves are forced by variations in wave energy of the short waves group. In deep water the energy transfer is non-resonant and the sub-harmonic motions are only a few millimeters at most. In coastal waters the energy transfer becomes near-resonant and infra-gravity wave height could increase to over 1m.

**Short Wave Groups**

Short waves tend to propagate in groups. The grouped structure originates from the dispersive behaviour of free harmonic waves propagating at the surface in offshore waters. This behaviour is described by equation (2.1) which implies that, in deep water ($h/L > 0.5$), the propagation speed ($c$) is frequency dependent with lower frequency waves traveling faster than higher frequencies.

$$\omega^2 = gk \tanh(kh) \quad (2.1)$$

Where $\omega$ the radial frequency ($2\pi/T$), $k$ the wave number ($2\pi/L$), $h$ the water depth and $g$ the gravitational acceleration of $g = 9.81 \text{m/s}^2$. During a storm offshore a broad spectrum of waves is generated propagating in multiple directions. Due to the dispersive behaviour the storm will disintegrate in frequencies, and in directions, resulting in fields of more regular wave trains with approximately the same frequencies, such as long crested swell waves. The later is critical for the occurrence of wave groups. Due to a slight difference in frequency, the individual free waves have a slightly different wave length.

1To comply to the free-wave condition there should be atmospheric pressure at the water surface and no external forcing other than the gravitational acceleration (Holthuijsen, 2007).
and start to interfere. This is easily illustrated with a bi-chromatic wave in figure 2.3, described by equation (2.2) and consisting of two free waves with neighbouring frequencies.

\[ \eta = \eta_1 + \eta_2 = a_1 \sin(\omega_1 t - k_1 x) + a_2 \sin(\omega_2 t - k_2 x) \]  \hspace{1cm} (2.2)

The group will have the highest surface elevation when \( \eta_1 \) and \( \eta_2 \) are in phase and vice-versa. By rearranging the terms equation 2.2 can be written as a carrier wave, second term in equation 2.3, and its low-frequency modulating envelope, first term in equation 2.3.

\[ \eta = A \cos \left( \frac{\omega_1 - \omega_2}{2} t - \frac{k_1 - k_2}{2} x \right) \sin \left( \frac{\omega_1 + \omega_2}{2} t - \frac{k_1 + k_2}{2} x \right) \]  \hspace{1cm} (2.3)

### Radiation stress

Waves can transfer momentum with the particle velocity or via the wave-induced pressure. The excess momentum flux due to the presence of waves is referred to as the radiation stress, defined by Longuet-Higgins and Stewart (1964). For a plane, perpendicular to the cross-shore \( x \)-direction, the flux of \( x \)-momentum through the plane, in one dimension, is defined by equation (2.4).

\[ S_{xx} = \int_{-h_0}^{\eta} (\rho u_x)dz + \int_{-h_0}^{\eta} p_{\text{wave}}dz \]  \hspace{1cm} (2.4)

with \( \rho \) the fluid density, \( u_x \) the particle velocity and \( p_{\text{wave}} \) the wave-induced pressure. Using linear wave theory this reduces to,

\[ S_{xx} = \left( 2n - \frac{1}{2} \right) E \quad \text{with} \quad n = \frac{1}{2} \left( 1 + \frac{2kh}{\sinh 2kh} \right) \quad \text{and} \quad E = \frac{1}{8} \rho g H_{rms}^2 \]  \hspace{1cm} (2.5)

where \( E \) is the energy per square meter of water surface which propagates with the wave group speed \( c_g = nc \). Gradients in the radiation stress, due to variations in \( E \) or \( n \), will induce a force on the water column which is balanced by, among others, hydrostatic pressure gradients, resulting in variations of the surface elevation. This concept is used to explain the generation of forced low-frequency waves and wave induced setdown at the point of breaking.
2.3. INFRA-GRAVITY WAVE TRANSFORMATION

GENERATING MECHANISMS

The mechanisms of the generation of infra-gravity waves have been studied over the last fifty years and two important mechanisms can be distinguished. Longuet-Higgins and Stewart (1962, 1964) related the generation of infra-gravity waves to the time-varying setdown on the wave group scale resulting in the generation of a bound long wave, forced by the wave group and propagating with group celerity $c_g$. For a one-dimensional case where the short wave groups are much longer than the water depth, the surface elevation of the accompanying forced wave can be expressed in terms of the radiation stress by equation (2.6), after Battjes et al. (2004).

$$\eta(x,t) = -\frac{S_{xx}(x,t)}{\rho(g h - c_g^2)} + \text{constant}$$  (2.6)

For the steady state equilibrium solution of equation (2.6) the forced wave is $180^\circ$ out of phase with the short wave envelope meaning that the trough of the bound long wave coincides with the crest of the short wave envelope. In the surf-zone, sea and swell waves start to dissipate and the wave group structure is lost, i.e. there is no longer a forcing term, and consequently the bound long wave is released from the wave group, propagating towards the shoreline as a free waves with $c = \sqrt{g h}$.

The second mechanism postulates the generation of free waves by a moving breakpoint (Symonds et al., 1982). Shore ward of the breakpoint the negative gradient of the radiation stress is counteracted by a hydrostatic pressure gradient resulting in wave induced setup at the shoreline. If the incident waves arrive in groups the wave height will vary across the wave group and due to depth-induced breaking the position of the breakpoint varies spatially resulting in a time-varying setup. This is recognised as the generation of low-frequency free waves at the seaward edge of the surf-zone propagating in onshore and offshore direction. In nature both mechanisms will occur simultaneously although, depending on the situation and boundary conditions, usually one of these two tends to dominate.

INFRA-GRAVITY WAVE SHOALING

Free wave shoaling is defined as the increase of wave height while waves are propagating towards shallower water. The evolution of the wave height can be described using Green’s Law which is the result of linear wave theory and assumes the conservation of energy flux of onshore propagating periodic waves on a plane beach. According to Green’s Law the increase of the free wave amplitude is proportional to the water depth by $\bar{\eta} \sim h^{-1/4}$. In general the increase of infra-gravity wave height increases in the surf-zone with increasing offshore wave height. Although recent studies have revealed that under very energetic wave conditions infra gravity waves may become saturated and their wave height becomes limited (e.g. De Bakker et al., 2014; Guedes et al., 2013).

The shoaling of bound long waves across a sloping bottom can be derived from equation (2.6) according to Longuet-Higgins and Stewart (1962, 1964). Approaching shallow water, the group celerity $c_g$ tends to $\sqrt{g h}$ and equation (2.6) becomes near-resonant. Since $S_{xx} \sim h^{-1/2}$, the bound long waves will shoal with $\bar{\eta} \sim h^{-5/2}$. However, as mentioned by Longuet-Higgins and Stewart (1962), the validity is limited since the solution of equation (2.6) is derived for an infinitely long and very mild-sloping beach, i.e. the resonance needs time to build up. From a physical point of view, the additional forcing of the bound long waves is explained by a net time-averaged transfer of energy from the short wave group to the bound long waves. This is only possible if there is an additional phase shift between the short wave group and the bound long wave, different from the equilibrium value of $\pi$. This phase shift, lagging behind the short wave group, has been reported by many authors (e.g. Janssen et al., 2003; Masselink, 1995; Van Dongeren et al., 1996). Furthermore the phase lag appears to increase with increasing frequency indicating a stronger enhancement of the forced infra-gravity waves for higher frequencies of the long waves Battjes et al. (2004).

Whether an infra-gravity wave is shoaling as a bound or as a free long wave can be described using the normalised bed slope $\beta$. This dimensionless parameter, described with equation (2.7), is used to express the relative depth change per wave length (e.g. Battjes et al., 2004; Van Dongeren et al., 2007).
Calculating $\beta_b$ for the depth at breaking $h_b$ and the bed-slope $h_x$, different regimes are defined. Values of $\beta_b < 0.1$ indicate a mild-sloping regime in which incident forced infra-gravity waves are expected to dominate over breakpoint generated waves. In a mild-sloping regime infra-gravity waves are expected to shoal as a bound long wave, hence proportional to $\sim h_b^{-5/2}$. Breakpoint forcing is weak in the mild-slope regime since the forcing (breaking) region becomes large in comparison to the wave length of the long waves (Baldock, 2012; Baldock and Huntley, 2002). Opposed to the mild-sloping regime, a steep-sloping regime is defined by values of $\beta_b > 0.45$ where the breakpoint forcing mechanism of free infra-gravity waves prevails. As a consequence the long waves are expected to shoal according to Green’s Law, since there is no additional forcing.

**Dissipation**

Once generated and propagating towards the shoreline there can be several mechanisms responsible for the dissipation of infra-gravity wave energy. Although some consensus on the governing mechanisms has been reached in recent years the energy dissipation of infra-gravity waves in the surf-zone remain poorly understood De Bakker et al. (2015).

In the mild-slope regime the dissipation of infra-gravity waves in the vicinity of the shoreline is attributed to bore-like breaking (e.g. De Bakker et al., 2014; Van Dongeren et al., 2007). Especially in shallow water, long wave self-self interactions dominate and generate higher harmonics that lead to steepening of the wave front and eventually to breaking De Bakker et al. (2016). Furthermore the interactions by non-linear energy transfer from infra-gravity waves back to sea-swell components seems an important mechanism (e.g. De Bakker et al., 2015; Guedes et al., 2013; Henderson et al., 2006; Thomson et al., 2006). An alternative dissipation mechanism (with some reservations) was presented by (Henderson and Bowen, 2002) who attributed the shoreline dissipation to bottom friction however (Henderson et al., 2006) showed that this is not the case. Although bottom friction may not be dominant for sandy beaches, numerical studies on coral reefs has shown the importance of dissipation by bottom friction while propagating across the reef flat (Pomeroy et al., 2012; Van Dongeren et al., 2013).

Investigating these mechanisms requires advanced methods, such as bi-spectral analysis. However the shoaling and reflection behaviour can already provide hints towards the governing dissipation mechanisms.

**Reflection**

Due to their long wave lengths infra-gravity will experience the coastline as a steep slope and consequently tend to reflect, propagating in offshore direction as a free wave. The combination of incoming and reflected waves could give rise to cross-shore quasi-standing wave patterns Guza et al. (1985). For low-frequency standing wave to occur, the dissipation of the onshore directed infra-gravity waves should be small. The reflection of infra-gravity waves is commonly quantified by the reflection coefficient $R = H_{IG,ref}/H_{IG,in}$, determined as a ratio of the reflected ($H_{IG,ref}$), offshore propagating, infra-gravity wave and the incoming ($H_{IG,in}$), onshore propagating, wave. The reflection coefficient $R$ can be related to the relative steepness, as a surf-similarity parameter for infra-gravity waves, derived by Battjes et al. (2004). This parameter is of the same form as the $\beta_b$ parameter, described in equation 2.7. Assuming that the incident infra-gravity wave height is in the same order as the local water depth, the depth at breaking $h_b$ could be replaced by the incoming infra-gravity wave height $H^*$.

$$\beta_H = \frac{h_x}{\omega} \sqrt{\frac{g}{H^*}}$$

(2.8)

Thereby $\beta_H$ is in fact a low-frequency equivalent of the conventional Iribarren number $\xi$. This parameter distinguishes breaking from non-breaking waves on a slope by a value for the relative steepness,
equation (2.9). Both surf-similarity parameters are related by a numerical constant: $\xi = \sqrt{2\pi} \beta_H$.

\[
\xi = \frac{\tan \alpha}{\sqrt{H_0/L_0}}
\]  

(2.9)

For short waves, Battjes (1974) found a relation between the reflection coefficient at the shoreline and the relative steepness, described by the Iribarren number, presented in figure 2.4. This relation is based on the value of $\xi_c \approx 2.3$ for the onset of breaking ($R = 50\%$) and can be written in terms of $\beta_H$ using equation (2.10).

\[
R = 0.1\xi^2 = 0.2\pi \beta_H^2
\]  

(2.10)

For values of $\xi < 2.5$, i.e. as long as the short waves break, this relation provides a good description of the reflection behaviour of short waves. For $\xi > 2.5$ a transition appears towards reflection coefficients of $R \sim 0.8$. Due to effects of viscosity, turbulence and permeability of the beach the theoretical value of $R = 1$ seems not realistic according to Battjes (1974).

A similar pattern is found for infra-gravity waves based on experimental data of a bi-chromatic waves on a 1:35 slope (Van Dongeren et al., 2007), field data on the beaches of Ameland and Egmond (De Bakker et al., 2014) and SWASH-modelling for different slopes (De Bakker et al., 2016). All studies found that the $\beta_H$ parameter is a strong control on the dissipation and reflection behaviour of infra-gravity waves. Although different ranges and values for the transition from breaking to reflection are concluded.

![Figure 2.4: The reflection of short waves at the shoreline as function of the Iribarren number $\xi$. The solid line represents the approximation given by $R = \min(1, 0.2\pi \beta_H^2)$ after Battjes (1974).](image)

![Figure 2.5: The reflection of infra-gravity waves at the shoreline as a function of $\beta_H$ after Van Dongeren et al. (2007) (left), De Bakker et al. (2014) (mid) and De Bakker et al. (2016) (right).](image)
Since the research on A-type, macro-tidal, rocky shore platforms is still in its infancy, this chapter will set the first steps in understanding the wave transformation processes and quantify the importance of IG-waves at these type of rocky shore platforms. Section 3.1 describes the selected site and scopes the analysis by a selection of field data for further analysis. The methodology, to convert the measured data to comparable bulk parameters, is described in 3.2, followed by the results in section 3.3. The short wave attenuation and importance of IG-waves is discussed in section 3.4. Finally, to conclude this chapter, section 3.5 will answer the first sub-research question.

3.1. Field Site Measurements
For this research the platform near Lilstock is selected from the WASP dataset. Lilstock (LST) is located near Bridgwater in the district of Somerset, in the South West of the United Kingdom (figure 3.1). The site is part of Lilstock beach, which is located on the margins of the Severn Estuary, famous for its macro-tidal environment. Waves approach the platform predominately from the WestNorthWest and are typically a combination of sea condition from the mouth of the Bristol Channel and moderate swell originating from the Celtic Sea and the North Atlantic. Field measurements at Lilstock have been conducted in December 2014 for seven tidal cycles during moderate winter storms. During the field campaign significant wave heights of 2.35 m have been recorded at the Hinkley Point wave rider, which
is located 3 km offshore of the Lilstock platform, figure 3.2. Waves were approaching from the West-NorthWest with a mean direction of 286° and a mean peak period of 6.5 s. Measured offshore wave conditions are presented in appendix C.1. The surface of the platform is characterised by gentle inclined flats oriented in NorthEast direction. The flats consist of hard sandstone blocks on top of softer mudstone layers. While the platform is submerged the blocks are unhinged by the waves, resulting in many loose bolders at the platform and a gravel beach at the cliff-toe.

The Lilstock site is selected for its wide gently sloping platform which makes it a typical example of a type A platform. Due to its width, and in combination with the macro-tidal range, the breakpoint will move across the platform during the tidal cycle, which allows to separate breaking and non-breaking waves. This is useful for calibration of the XBeach model and the analysis of the IG-wave generation mechanisms. For the measurement campaign at the platform, 15 high frequency (8 Hz) pressure transducers (PT) were bolted in a cross-shore array oriented towards the NorthNorthWest (319°), with approximately 15-20 meters spacing, figure 3.2 (right) and figure 3.4. A summary of the platform characteristics is given in table 3.1.
### 3.1. Field Site Measurements

**Table 3.1: Site characteristics.**

<table>
<thead>
<tr>
<th>Site characteristic</th>
<th>Dimension</th>
<th>Lilstock</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>[-]</td>
<td>A</td>
</tr>
<tr>
<td>Mean elevation w.r.t. OD</td>
<td>[m]</td>
<td>1.23</td>
</tr>
<tr>
<td>Platform width</td>
<td>[m]</td>
<td>290</td>
</tr>
<tr>
<td>Bed slope $\tan(\alpha)$ (foreshore / platform)</td>
<td>[-] / [°]</td>
<td>0.035 / 0.017</td>
</tr>
<tr>
<td>Orientation cross-shore array</td>
<td>[°]</td>
<td>329°</td>
</tr>
<tr>
<td>Tidal range (neap / spring)</td>
<td>[m]</td>
<td>5.4 / 10.9</td>
</tr>
<tr>
<td>Roughness indication; standard deviation of profile measured with terrestrial laser scanner (grid of 0.5m)</td>
<td>[m]</td>
<td>O(0.02 – 0.04)</td>
</tr>
</tbody>
</table>

**Classification of tidal phases**

To isolate hydrodynamic processes across the platform the tidal cycle is subdivided in three tidal phases related to sub-zones of the inter-tidal zone as presented in figure 3.4. The classification is based on the slope of the platform and its characteristics at the shoreline during the tidal phase. The first area, referred to as the high-tide phase, is defined by the steep-sloping gravel beach and vertical cliff up till the edge of the inter-tidal zone. The second area, the middle-tide phase, is defined by the gently sloping platform from the base of the cliff till the edge of the platform. Finally the low-tidal phase is defined from the edge of the platform till spring low tide. It should be stressed that this classification of the inter-tidal sub-zones should not be confused with the classification used by marine biologists to indicate certain areas in the eulittoral zone based on the overall average exposure.

**Table 3.2: Classification of intertidal sub-zones**

<table>
<thead>
<tr>
<th>Tidal phase</th>
<th>Intertidal sub-zone</th>
<th>OD [m]</th>
<th>Mean bed slope [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-tidal phase</td>
<td>Vertical cliff and steep sloping beach</td>
<td>3 - HAT</td>
<td>0.12</td>
</tr>
<tr>
<td>Middle-tidal phase</td>
<td>Gently sloping platform</td>
<td>0 - 3</td>
<td>0.02</td>
</tr>
<tr>
<td>Low-tidal phase</td>
<td>Foreshore and transition to deeper water</td>
<td>LAT - 0</td>
<td>0.04</td>
</tr>
</tbody>
</table>

![Figure 3.4: Cross-section of Lilstock platform including an indication of sub-zones, tidal phases and PT locations.](image-url)
DATA SELECTION

For the analysis of the wave transformation processes two tidal cycles are selected, presented in table 3.3. The remaining cycles will be used for validation of the calibrated numerical model without going into detail of the wave transformation processes during those measurements. The corresponding time frames of the tidal phases as defined in section 3.1 are determined based on the measured surface elevation of the most offshore PT.

Table 3.3: Data selection.

<table>
<thead>
<tr>
<th>Data selection</th>
<th>Dimension</th>
<th>Calm</th>
<th>Energetic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date</td>
<td>09-12-2014</td>
<td>11-12-2014</td>
<td></td>
</tr>
<tr>
<td>Tidal cycle number</td>
<td>[-]</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>Wave climate</td>
<td>Sea/swell</td>
<td>Sea/swell</td>
<td></td>
</tr>
<tr>
<td>Time frame tidal cycle</td>
<td>[hh:mm]</td>
<td>17:20 - 00:00</td>
<td>06:00 - 13:00</td>
</tr>
<tr>
<td>High-tidal phase</td>
<td>[hh:mm]</td>
<td>19:00 - 21:50</td>
<td>07:50 - 11:00</td>
</tr>
<tr>
<td>Middle-tidal phase (rising)</td>
<td>[hh:mm]</td>
<td>17:20 - 19:00</td>
<td>06:00 - 07:50</td>
</tr>
<tr>
<td>Mean offshore $H_s$ [m]</td>
<td>0.97</td>
<td>1.97</td>
<td></td>
</tr>
<tr>
<td>Mean offshore $T_p$ [s]</td>
<td>7.2</td>
<td>6.3</td>
<td></td>
</tr>
<tr>
<td>Mean offshore $T_z$ [s]</td>
<td>4.4</td>
<td>4.9</td>
<td></td>
</tr>
<tr>
<td>Number of bursts</td>
<td>[-]</td>
<td>24</td>
<td>24</td>
</tr>
</tbody>
</table>

3.2. POST-PROCESSING

For analysis of the wave transformation processes the measured data is processed to bulk parameters. This section elaborates on the steps taken to transform the measured signals to comparable parameters, that can be used for the analysis of wave transformation processes.

3.2.1. MEASURED DATA

The data of the pressure transducers (PT), collected by the WASP project, is presented as a surface elevation $\eta$ with respect to Ordnance Datum (ODN), the vertical datum of the British Isles. The pressure signal was continuously measured during multiple tidal cycles with a sampling rate $f_s$ of 8 Hz. To obtain the surface elevation the pressure signal is corrected for depth attenuation according to Nielsen (1989) and subsequently converted to a surface elevation time-series for each PT. To analyse the time-series the signal is split into $L$ bursts of length $l$. As described in 3.2.2 and appendix A the selected

Figure 3.5: Measured surface elevation at most offshore PT (nr. 15) in Lilstock, 2014-12-11 (left) and example of a selected burst signal with its associated detrended signal (right).
burst length will have to guarantee a wave climate in each burst that is statistically stationary to obtain reliable and representative bulk wave parameters. Each burst is subsequently detrended using a linear detrend function to remove the offset, creating a time-series with the mean value equal to zero as indicated in figure 3.5.

3.2.2. VARIANCE DENSITY SPECTRA
Bulk parameters can be derived from a variance density spectrum which is a representation of the measured data in the frequency domain. By applying a Fourier analysis the spectral density estimate of the signal can be determined, which is a presentation of the variance of the amplitude for each frequency bin. Welch’s method of overlapping segments is used to improve the spectral density estimation (SDE) and reduce noise as explained in appendix A. This method divides the detrended signal, in the time domain, into $N$, 50% overlapping, segments of length $n$ and multiplies each segment with a Hanning window. Since the frequency resolution of a SDE is determined by the length of the signal, in this case the length of the segments $n$, the improvement of the spectral density estimation by Welch averaging is in exchange of a reduction in frequency resolution. The frequency resolution can be calculated using equation (3.1),

$$\Delta f = \frac{f_s}{w}$$

with $\Delta f$ the width of each frequency bin in Hz, $f_s$ the sampling rate of 8 Hz and $w$ the length of a window in number of samples. By virtue of this method, a longer window (or segment) will increase the frequency resolution which is convenient for analysis of the low-frequency wave motions of $O(0.01 \text{Hz})$. Figure 3.6 presents different spectral densities for a different number of windows. The value of $\Delta f$ thereby indicates the lower limit of the frequency domain. The upper limit is determined by the Nyquist frequency, equal to $f_s/2 = 4 \text{Hz}$, which is well above the considered waves of interest.

**IMPLICATIONS DUE TO MACRO-TIDAL REGIME**
Due to the large tidal ranges the vertical rate of change in water level increases up to 2 m/h which influences the wave transformation process on smaller time scales compared to micro-tidal environments. Especially during rising and falling tide, the water depth at the start of a burst could differ significantly compared to the water depth at the end for the same burst. Due to depth induced breaking the macro-tidal regime will tend to affect most influence on the wave height of the energetic (short) waves. Consequently the amplitude variation of a selected burst will increase or decrease during rising or falling tide respectively, this is already observed in the raw signal of PT15 in figure 3.5.

To increase frequency resolution of the SDE the burst length should be increased, which follows from equation 3.1. However a longer burst is less likely to contain statistically stationary wave characteristics, especially in a macro-tidal environment. This complicates the selection of the representative burst length. To cope with this contradiction, three criteria have been formulated to select a burst length.
length of which the wave amplitude is minimally influenced by the tidal elevation and still allows maximum Welch averaging, while complying to a minimal frequency resolution of 0.004 Hz. Appendix A elaborates on this procedure and applies this method to the data of the most offshore PT in Lilstock for the tidal cycle with the most energetic wave conditions.

Based on the results, as presented in appendix A, a burst length of \( l = 1024 \) s (8192 samples) is selected using \( N = 7 \) windows of \( n = 256 \) s (2048 samples) overlapping by 50% (1024 samples or 128 s). With this selection a frequency resolution of \( \Delta f = 0.0039 \) Hz can be obtained which allows detailed analysis of the low-frequency motions. Furthermore the tidal elevation during each burst is 0.44 m averaged over the rising tide for the data set in Lilstock.

3.2.3. Bulk parameters

Bulk parameters like the wave height and -period describe the wave climate during a small period. These statistical parameters make it easy to compare different bursts. For analysis of the wave transformation across the platform, the measured data is used to determine bulk parameters both in spatial and temporal domains. The spatial domain is evidently represented by the amount of pressure transducers (\( P \)) situated in the cross-shore arrays of PTs as presented in figure 3.4. The temporal domain is defined by the time frames of the selected tidal cycle, presented in table 3.3, and subsequently split into \( L \) representative bursts. Together they span a matrix of \( P \times L \) in which the bulk parameters can represent the wave transformation in space and time. Each element in this domain can be denoted by an index for space (\( P \)) and time (\( L \)).

Water levels, tide and setup

Based on the measured surface elevation the mean water level \( \eta_{PL} \) for each burst at each PT can be determined. Subtracting the bed level at the considered PT from the mean water level reveals the local mean water depth during the considered burst \( h_{PL} \). Since there is no detailed tidal data available, the tidal elevation is determined using a moving window of 15 minutes applied at the water level signal measured at the most offshore PT. Thereby the determined tidal signal includes other macro scale effects like (storm) surge. It has to be mentioned that during low water, when the most offshore PT gets in the surf-zone, the tidal signal is influenced by wave induced setup. The set-up across the platform is defined with respect to the tidal elevation determined at the offshore PT. By subtracting the mean tidal elevation from the mean water level the local mean set-up across the platform \( \eta_{Setup,PL} \) can be determined.

Wave classification

In this research two wave categories are distinguished: infra-gravity waves (IG) and short waves (SH). The first contains the low-frequency motions, the latter are characterised by the high-frequency swell- and sea waves. To be able to compare bulk parameters and have a clear definition of both wave types a frequency based classification is defined. In literature different frequency ranges for IG-waves can be found, a common bandwidth is 0.005 – 0.05 Hz (e.g. De Bakker et al., 2014; Guedes et al., 2013; Henderson et al., 2006)) however others use 0.004 – 0.04 Hz (e.g. Janssen et al., 2003; Masselink, 1995). In this research IG-waves are defined in the range of 0.004 Hz – \( f_{split} \) and SH-waves by \( f_{split} – 0.4 \) Hz. The split frequency is determined by observing the individual wave spectra at the most offshore pressure transducer as explained in appendix A.2. This results in a split frequency of 0.055 Hz.

Spectral parameters

The spectral moment is a statistical characteristic which is derived from the variance density spectrum and used to express the bulk wave parameters. For a random sea-surface elevation that is treated as a stationary, Gaussian process, the \( n \)th order moment of its variance density spectrum is determined using equation (3.2).

\[
m_n = \int_0^\infty f^n E(f) df
\]
An important statistical characteristic is the zero-order moment \( m_0 \) which is equal to the variance of the sea surface elevation \( \eta^2 \). When Rayleigh distributed waves are assumed the root-mean-square wave height can be determined using equation (3.3)

\[
H_{\text{rms}} = \sqrt{8m_0}
\]  

(3.3)

The root-mean-square wave height is used to represent the wave height of each burst. This parameter is determined for the total spectrum (\( H_{\text{rms, tot}} \)), the SH-wave frequency range (\( H_{\text{rms, SH}} \)) and IG-wave frequency range (\( H_{\text{rms, IG}} \)). The choice for \( H_{\text{rms}} \) instead of \( H_s \) is based on the output of XBeach which presents the short wave energy as a value of \( H_{\text{rms}} \).

Due to the macro-tidal range, PTs are sometimes located in the shoaling zone and sometimes in the surf-zone. To separate breaking from non-breaking waves the edge of the surf-zone is identified using the breaking criterion from Miche (1944) which describes the maximum wave height at each water depth with \( \gamma = H/h \). In this research a value of \( \gamma = 0.31 \) is used which corresponds to the \( H_{\text{rms}} \) wave height as explained in appendix A.3.

The spectral parameter \( T_{m-1,0} \) is used to represent the wave period which is determined using equation (3.4).

\[
T_{m-1,0} = \frac{m_{-1}}{m_0}
\]  

(3.4)

Because the \( m_{-1} \) is used, this bulk parameter attributes more weight to the low frequency part of the spectrum instead of the high-frequency tail. Therefore this value is less sensitive to details in the measurements and the data-processing.

**Natural Variability**

Waves are characterised as a random stochastic process which can be described using bulk wave parameters derived from wave spectra. For an analysis with subsequent bursts of a fixed length (\( t_0 = 0 \) s and \( t_1 = 1024 \) s) a bandwidth around each subsequent bulk parameter can be derived depending on the selection of \( t_0 \). As described in section 3.2.2, the reliability of the variance density spectrum can be improved by Welch averaging, which improves the estimate of the stochastic variables of one single burst. However, on the scale of subsequent bursts there is no averaging involved to improve the estimate. Therefore a moving burst, with the same length of the subsequent bursts and an interval of 30 seconds, is applied to determine a quasi-continuous time-series of bulk wave parameters. This quasi-continuous signal of bulk wave parameters is compared with the bulk parameters derived for each subsequent bursts, that are used for the analysis, to define a bandwidth for each considered bulk wave parameter. Both the averaged absolute error and the averaged relative error, with respect to the bulk wave parameters of the subsequent bursts used for the analysis, are determined. This procedure is performed for all high-tidal phases for \( H_{\text{rms, SH}} \) and \( H_{\text{rms, IG}} \) and summarised as the mean of the values corresponding to the 98th percentile errors, as explained in appendix A.4. Table 3.4 summarizes the bandwidth values found for different bulk wave parameters. In practical terms the bandwidth is a useful value for the interpretation of the results and gives an idea of the natural variability of the waves. Furthermore, these bandwidths can be used as a range of accuracy for the calibration of the numerical model.

<table>
<thead>
<tr>
<th>Bandwidth for different sub-zones</th>
<th>( \epsilon_{\text{abs, SH}} ) [m]</th>
<th>( \epsilon_{\text{rel, SH}} )</th>
<th>( \epsilon_{\text{abs, IG}} ) [m]</th>
<th>( \epsilon_{\text{rel, IG}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outside surf-zone</td>
<td>0,051</td>
<td>10,9</td>
<td>0,015</td>
<td>18,1</td>
</tr>
<tr>
<td>Inside surf-zone</td>
<td>0,063</td>
<td>20,0</td>
<td>0,022</td>
<td>17,6</td>
</tr>
<tr>
<td>All PTs</td>
<td>0,053</td>
<td>12,2</td>
<td>0,017</td>
<td>18,2</td>
</tr>
</tbody>
</table>
3.3. RESULTS
The methodology to convert the measured data to bulk parameters is applied to all tidal cycles. This section describes the results with the focus on cycle three (calm conditions) and six (energetic conditions) which are jointly presented on a process based level.

3.3.1. WATER DEPTH AND SETUP
From the mean water levels at the platform the water depth and the setup across the platform are determined. The water depth is one of the major controls on the propagation of waves across the platform. Figure 3.7 shows the mean water depths at the platform in spatial and temporal domain. Due to the macro-tidal environment the water depth at the platform varies significantly over time and increases up to 2.5\text{m} and 5.5\text{m} at the most onshore and offshore PT respectively. During low tide all

![Mean depth - tide 3 and tide 6](image)

Figure 3.7: Mean water depths at the platform for the selected tidal cycles.

PTs fall dry, therefore the measurements can only describe the hydrodynamics during mid- and high tidal phases. Figure 3.8 shows the set-up across the platform as defined in 3.2.3. The mean water depth is normalized by the mean depth at breaking ($h_b$) to compare the setup effects in- and outside the surf-zone and the mean water depth at the edge of the platform ($h_e$) showing the setup across the platform. Normalising to $h_b$ results for each burst in one value that is exactly one since the depth at breaking is not interpolated but assigned to the closest PT. A clear difference between the different tides is observed with respect to the setup levels which is attributed to the difference in incident wave height. The maximum setup during the sixth tidal cycle is in the order of 0.2\text{m}, which corresponds to

![Setup vs. normalised depth and h/h_e](image)

Figure 3.8: Setup versus normalised depth for all tidal cycles measured at Lilstock. On the left the depth is normalised by the depth at breaking $h_b$, on the right the depth is normalised by the depth at the most offshore PT $h_e$. Colors indicate the chronology of the seven tidal cycles with the light blue the first tide and the darkest blue the last tide.
3.3. Results

An offshore wave height of \( H_s = 2.35 m \). Furthermore, there are some discontinuities in the order of 2\( cm \) to 5\( cm \) observed in the set-up plots of figure 3.9. A closer look reveals that these discontinuities are present both during low and high water and that their magnitude is time independent. This implies that the discontinuities originate from the measurements by the pressure transducers instead of other wave processes. This could be either due to measurement errors of the considered PT or due to errors in the measurements of the GPS location of the PT.

Figure 3.9: Setup in spatial and temporal domain for the third (left) and sixth (right) tidal cycle.

3.3.2. Wave Transformation

Figure 3.10 shows the results for three bulk wave parameters of both tidal cycles plotted in spatial and temporal domain, with horizontally the subsequent bursts (time) and vertically the cross-shore distance. The most offshore PT is selected as reference location \((x = 0)\) and positive values are in onshore direction. This presentation allows to observe the tidal influence on the wave transformation processes while wave propagate in onshore direction and at the same time relate the transformation of different bulk wave parameters to each other.

The influence of the tide is, among others, observed by different wave height of the short waves. For both tidal cycles the short wave height is larger during rising tide compared to falling tide as a consequence of wave-current interaction. This is also observed for the other tidal cycles as presented in appendix C.2.

During high-tidal phases, shoaling of the short waves can be observed while waves propagate across the platform in shore-ward direction, followed by, a decrease in short wave height due to dissipation by breaking in the surf-zone. At the same time, an increase of the spectral wave period \( T_{m-1,0} \) is observed, which is a result of the decreasing high-frequency energy and indicates that the low-frequency motions tend to dominate the platform close to the cliff-toe. The latter is confirmed by the increasing IG-wave height close the shoreline.

When comparing both cycles, it can be observed that both the spectral wave period \( T_{m-1,0} \) and IG-wave height \( H_{rms,IG} \) have higher values during the more energetic wave conditions. This indicates that the low-frequency energy increases with increasing offshore wave conditions.

Focusing on the IG-wave height, differences between the evolution during mid- and high-tidal phases can be observed. During rising and falling tide the IG-wave height tends to decrease across the platform, contrary to the high-tidal phase when IG-waves are clearly increasing in wave height. This tidal modulation of the IG-wave height is confirmed by observations at B-type platforms.

In figure 3.10 the black line indicates the outer edge of the surf-zone, which moves significantly across the platform during the tidal cycle. As a result of the large fluctuations in the water depth the point where waves start to break due to depth induced breaking varies spatially with \( > 220 m \) and \( 150 m \) for 09-Dec and 11-Dec respectively. The width of the surf-zone itself is consequently linked to the incident wave height and has an average width of \( 60 m \) and \( 130 m \) for both cycles respectively.
Figure 3.10: Bulk parameters of wave transformation for the selected tidal cycles in Lilstock. From top to bottom: (1) Wave period $T_{m-1.0}$, (2) Short wave height $H_{rms,SH}$ and (3) IG-wave height $H_{rms,IG}$. The black line in the center plots indicates the outer edge of the surf-zone based on the breaking criterion of Miche (1944) using a value of $\gamma = 0.31$.

3.3.3. INFRA-GRAVITY WAVE IMPORTANCE

In general the importance of the IG-waves increases in the inner surf-zone. To quantify the significance figure 3.11 shows the relative importance of IG-wave energy as a fraction of the total wave energy. For both cycles it holds that during the tidal cycle the relative importance increases in onshore direction with the largest rate of change in the surf-zone. To stress this, figure 3.12a shows the percentage of IG-wave energy for all tidal cycles plotted versus the normalised depth. In the shoaling zone ($h/h_b > 1$) a slight increase of the relative importance is observed up to 20% compared to the surf-zone ($h/h_b < 1$) where the relative importance increases significantly up to 55%. Besides the strong increases in the surf-zone a tidal modulation of the relative importance at the shoreline can be observed. During mid-tidal phases the increase of relative importance towards the shoreline is smaller compared to high-tidal phases. This corresponds to the results in figure 3.10 and shows that not only the absolute IG-wave height but also the relative contribution to the total wave energy is larger during high-tidal phases compared to mid-tidal phases. Quantifying this behaviour, the IG-wave height $H_{rms,IG}$ at the shoreline during mid-tide is on average 42% of IG-wave height at the shore-line during...
3.4. DISCUSSION

The result as presented in the previous section are discussed to place the findings in perspective.

3.4.1. SHORT WAVE ATTENUATION

Dissipation of short waves, due to depth induced breaking, is generally a well-studied mechanism although for rocky shore platforms this is still a hot-topic in many recent studies. Figure 3.13a shows the short wave height $H_{rms}$ across the platform versus the mean water depth for all tidal cycles. The

Figure 3.11: Percentage of IG-wave energy with respect to the energy to the total spectrum.

Figure 3.12: Infra-gravity wave importance, colors are the same as in figure 3.8.
line indicates the breaker criterion according to Miche (1944) for a theoretical value of $\gamma = 0.31$ as used in figure 3.10 to indicate the outer edge of the surf-zone. In figure 3.13a the wave height in the surf-zone is generally higher than the breaker criterion would subscribe which suggests that the value of $\gamma$ is set too low. This could be explained with the assumption of Rayleigh distributed waves ($H_{\text{max}} = 2H_s$) which is used to derive the value of $\gamma H_{\text{rms}}$, appendix A.3. For measurements at a B-type platform

\begin{figure}[h]
    \centering
    \includegraphics[width=\textwidth]{h_rms_SH_vs_h_hb.pdf}
    \caption{(a) $H_{\text{rms,SH}}$ versus the mean water depth, the lines indicate the breaker criteria. (b) $H_{\text{rms,SH}}$ versus the mean water depth normalised to the depth at breaking for $\gamma = 0.31$.}
    \label{fig:3.13}
\end{figure}

Ogawa et al. (2015) found that the maximum wave height at the platform is 1.34 times higher than $H_{m0}$, which is lower than the theoretical value of 2 and results in a value of $\gamma = 0.46$ which is close to the values of $\gamma = 0.42$ observed by Thornton and Guza (1982). Applying this value to the measured data at Lilstock still results in wave heights that exceed the breaker criterion in the inner surf-zone, figure 3.13a. Furthermore, the latter value of $\gamma = 0.46$ shows that waves start already to attenuate before the breaker criterion is met. Figure 3.13b shows the same short wave height plotted versus the mean water depth normalised by the depth at breaking. This figure shows clearly that the maximum short wave heights are well centered around the normalised depth of $h/h_b = 1$. This indicates that, although wave heights inside the surf-zone will be underestimated, the value of $\gamma = 0.31$ does give a reasonably good estimate of the initiation of breaking.

3.4.2. IG-WAVES AT A-TYPE PLATFORMS COMPARED TO OTHER STUDIES

To place the finding on the importance of IG-waves at A-type rocky shore platforms in perspective, the IG-wave heights found at Lilstock of $H_{m0,IG} = 0.34\text{m}$, for offshore conditions of $H_s = 2.35\text{m}$ and $T_p = 7.2\text{s}$, are compared to other coastal morphologies like B-type rocky shore platforms, coral reefs and dissipative sandy beaches.

With their measurements at two B-type platforms Oraka and Rothesay Bay Beetham and Kench (2011) found IG-waves at the cliff toe of 0.15m and 0.13m respectively. For Rothesay Bay offshore wave conditions of $H_s = 1.3\text{m}$ and $T = 5\text{s}$ has been measured which is comparable to conditions found for Lilstock. The relation of $H_{s,IG}$ to the offshore wave height is found to be 0.1 which is slightly lower although in the same order of magnitude compared to Lilstock. For Oraka $H_s = 0.35\text{m}$ and $T = 10\text{s}$ where measured, indicating swell conditions which makes the $H_{s,IG}$ hard to compare to Lilstock. Ogawa et al. (2015) found values of $H_{m0,IG} = 0.3\text{m}$ close to the cliff toe during high-tide conditions on their B-type platform for offshore conditions of $H_s = 2\text{m}$ and $T = 5\text{s}$, which is in the same order of magnitude as the findings for Lilstock. Compared to studies at the Ningaloo Reef by (e.g. Pomeroy et al., 2012; Van Dongeren et al., 2013), the IG-wave height at Lilstock is in the same order of magnitude although offshore conditions are indicating swell ($H_s \sim 1.6\text{m}$ and $T_p > 10\text{s}$) and are therefore not particularly comparable. Studies at dissipative beaches conducted by De Bakker et al. (2014), for two sites along
the Dutch coast, found IG-wave heights between $0.2m - 0.5m$ for Ameland and between $0.03m - 0.4m$ for Egmond. For Ameland offshore wave conditions of $H_s = 4.4m$ and $T = 7s$ have been measured and for Egmond $H_s = 3.6m$ and $T = 8s$. For both sites the wave period is similar to the energetic sixth tidal cycle of Lilstock but wave heights exceeded the offshore conditions of Lilstock. The constant of proportionality found in figure 3.12b is sightly higher compared to the value of 0.11 found by De Bakker et al. (2014), although in the same order of magnitude.

In general it can be concluded that for Lilstock the IG-wave height, close to the cliff-toe, is in the same order of magnitude to other coastal morphologies. It must be noted that the IG-wave height of the combined signal $s_i$ used, i.e. incoming plus outgoing waves. Thereby the reflection at the shoreline, which is very site dependent, is implicitly taken into account.

3.5. CONCLUSION

Based on the results presented in this chapter, an answer can be formulated to the first sub-research questions.

*What is the magnitude of infra-gravity waves at A-type macro-tidal rocky shore platform for different tidal phases and how does this compare to other morphological settings?*

During the measurements campaign at the Lilstock platform, IG-waves were measured with a wave height of $H_{rms,IG} = 0.24m$ (corresponding to $H_{m0,IG} = 0.34m$) during energetic offshore wave conditions with $H_s = 2.35m$ and $T_p = 7.2s$. Both the IG-wave height and relative importance of IG-wave energy are higher during more energetic conditions compared to calm wave conditions. The constant of proportionality between the IG-wave height at the most onshore located PT, near the cliff-toe, and offshore measured wave height is 0.14, averaged for seven tidal cycles.

The IG-waves at the cliff-toe are found to be modulated by the tide with lower values during mid-tidal phases compared to high-tidal phases, for both the absolute value of the IG-wave height and the relative contribution to the total wave energy.

Compared to other studies on infra-gravity wave transformation, the observed IG-wave height close to the cliff-toe is in the same order of magnitude compared B-type rocky shores (e.g. Beetham and Kench, 2011; Ogawa et al., 2015), other IG-wave studies at coral reefs (Pomeroy et al., 2012; Van Dongeren et al., 2013) and field studies at dissipative beaches (De Bakker et al., 2014). Although the IG-wave height seems to be in the same order of magnitude, the offshore wave conditions differ among these studies which makes it hard to draw firm conclusions.

**OTHER FINDINGS**

As a consequence of the macro-tidal environment, large fluctuation in the water depth ($2m/h$) will influence the wave conditions at shorter time scales which decreases the stationarity of the signal. Therefore, shorter burst lengths are preferred in macro-tidal environments compared to micro-tidal environments to obtain burst of stationary wave conditions and consequently representative variance density spectra.

Even when applying Welch averaging to increase the reliability of the variance density spectra of one single burst, there remains a bandwidth around the bulk wave parameters. This is investigated by applying a moving window analysis for a measured time-series, resulting in a variability of 5.3cm for $H_{rms,SH}$ (12,2%) and 1,7cm for $H_{rms,IG}$ (18,2%) based on the measurements and averaged for all high-tidal phases. Since this is not an error of the measurement itself, but depends on the moments to select a burst this is referred to as the natural variability. Furthermore discontinuities in the setup values in the centre of the space-time domain are observed in the order of $O(0.03m)$. 
NUMERICAL MODELLING

To improve predicting capabilities and increase understanding of the hydrodynamics across rocky shore platforms, numerical modelling has been conducted using the open source software XBeach. Furthermore, the numerical model will assist in the analysis of IG-wave transformation. This chapter describes the setup of the numerical model, calibration of model parameters and validation of the calibrated model using other tidal records. The model results are discussed in section 4.5 to conclude on the modelling capabilities.

4.1. XBEACH SURF-BEAT
The XBeach model has originally been developed to model the nearshore processes during extreme events, like hurricanes, and therefore includes wave breaking, surf and swash zone processes, dune erosion, overwashing and breaching (Roelvink et al., 2009). To run the numerical model, different hydrodynamic options can be used, all having their own advantages. For this research, the Surf-Beat (SB) option has been selected which is computationally fast and resolves the short wave variations and the associated low-frequency motions on the wave group scale. The Surf-Beat modus is therefore capable of computing the infra gravity waves which are of great interest for this research. Appendix B elaborates on equations and parameters used by XBeach-SB to compute the wave propagation.

4.2. MODEL SET-UP
This research takes the first step into modelling the wave transformation across rocky shore platforms therefore, some simplifications have been applied. First of all, the model is set up for a one-dimensional transect across the platform coinciding with pressure transducers. Secondly, only the hydrodynamics are considered and sediment transport at the platform is neglected. As a consequence there is no morphological feedback considered in the model.

BOUNDARY CONDITIONS
The boundary conditions required to force the XBeach-SB model consist of wave conditions and a tidal elevation. Since the focus is on near-shore processes across the platform, instead of the transformation from offshore to near-shore, both boundary conditions can be derived from the measured water level elevation at the most offshore located pressure transducer at the platform. Using the Surf-Beat modus the wave conditions should contain information of both the high frequency (> 0.055 Hz) short wave group and the incoming long wave (< 0.055 Hz). Figure 4.1 shows an example of this input and appendix B elaborates on the procedure to derive these conditions. Because the wave energy is derived from one single PT the wave direction can not be obtained, therefore normal incident waves are assumed. The tidal elevation can be obtained by averaging the measured signal with a 15 minutes moving window, which is the same method as described in paragraph 3.2.3.
4. Numerical modelling

Computational grid
During the measurement campaign of the WASP project, bathymetric surveys of the platforms have been carried out using a terrestrial laser scanner providing an elevation with respect to Ordnance Datum (OD) in Ordnance Survey (OS) coordinates. These coordinates have been used to generate a computational grid with varying cross-shore grid size based on the Courant condition, using a value of $CFL_{\text{max}} = 0.9$. The grid spacing has been determined for the most critical wave during low water resulting in a high grid-resolution varying between 1 and 3 meter. Figure 4.2 shows the measured cross-shore profiles including the grid spacing.

4.3. Calibration
Before the model can be applied to investigate the hydrodynamics and morphological behaviour of rocky shore platforms, it should be able to reproduce the measured data as described in chapter 3. This section elaborates on the procedure and subsequently presents the results of the calibrated model.

4.3.1. Procedure
The XBeach-SB model is calibrated for three model parameters influencing the computations of the hydrodynamics across the platform. To calibrate these parameters the model results are compared to the measurements from the field. The model results are therefore converted to the same bulk param-
eters as used to describe the hydrodynamics across the platform, as was described in chapter 3. For comparison, three bulk parameters are considered: the short wave height $H_{rms,SH}$, the infra-gravity wave height $H_{rms,IG}$ and the setup across the platform $h_{setup}$.

Two tidal cycles have been considered for calibration, as will be explained in 4.3.2, the other tidal cycles are used for validation of the calibrated model. The aim of the calibration is to find one set of model parameters which creates minimal errors between measurements and model results.

**Parameters for calibration**

Since this research has the emphasis on the transformation of IG-waves, the calibration of the parameters focuses on minimal errors in the IG-wave height. Because IG-waves are mainly forced by energy gradients across the short wave groups, first the short wave height should be considered. In XBeach-SB the short wave energy is dissipated by bottom friction, wave breaking and vegetation. However, the latter is not taken into account for the modelling across rocky shore platforms, therefore only the first two dissipation processes are considered for calibration.

The first dissipation mechanism depends on the time-averaged orbital velocity amplitude computed by the model and a short-wave friction coefficient $f_w$ after Jonsson (1966). The value of this dissipation term only affects the short-wave action balance and is therefore unrelated to the bed friction of the mean currents. The second dissipation mechanisms is modeled after Roelvink (1993), who described the dissipation term as a fraction of breaking waves multiplied by the dissipation per breaking event. Here the fraction of breaking depends on the parameter $\gamma$, which is the ratio of the $H_{max}$ over the instantaneous water depth. Both $f_w$ and $\gamma$ are calibrated to obtain the right amount of dissipation of the short wave energy. Appendix B elaborates in more detail on these dissipation mechanisms and the equations used to model them.

To consider the dissipation of mean currents and IG-waves by surface roughness, the bed roughness coefficient $c_f$ is considered. This coefficient determines the bed shear stress which is incorporated in the non-linear shallow water equations. The coefficient $c_f$ is depending on surface roughness, and could be determined using several formulations depending on the situation. In this research only the value of $c_f$ itself is considered, which is by default 0.003, comparable to a Chezy value of $55 m^{1/2}/s$.

**Table 4.1: Model parameters for calibration**

<table>
<thead>
<tr>
<th>Associated process</th>
<th>Parameter</th>
<th>Default</th>
<th>Coral reefs</th>
<th>Range</th>
<th>Step size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short wave bottom friction</td>
<td>$f_w$</td>
<td>0</td>
<td>0.6</td>
<td>[0 - 0.4]</td>
<td>0.05</td>
</tr>
<tr>
<td>Short wave breaking</td>
<td>$\gamma$</td>
<td>0.55</td>
<td>0.55</td>
<td>[0.3 - 0.8]</td>
<td>0.05</td>
</tr>
<tr>
<td>Bed shear stress</td>
<td>$c_f$</td>
<td>0.003</td>
<td>0.1</td>
<td>[0.003 - 0.14]</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Table 4.1 shows the default settings for XBeach-SB of the considered parameters, these values are calibrated based on several field studies on dissipative sandy beaches. Since rocky shore platforms (mainly of the B-type) share morphological similarities with coral reefs, the calibrated settings for the XBeach-SB model by Van Dongeren et al. (2013) are also presented. In the last column the ranges considered for the calibration of each parameter are presented.

**XBeach bulk parameters**

The XBeach model computes the water level $z_s$ and short wave energy $E$ at each grid point for each numerical time step. Both output variables are extracted from the set of model results as a time-series at the position of each PT. For a fair comparison the time-series are split into bursts of the same length as used for the measurements.

The output variable $z_s$ represents the surface elevation and thereby the low-frequency motions induced by the short wave group. Therefore $z_s$ can be used to determine the infra-gravity wave height for each burst. To do so, an amplitude spectrum is derived from $z_s$, following the same procedure as explained in section 3.2.2. The low-frequency part of these spectra ($0.004 Hz - 0.055 Hz$) are subsequently used to calculate the bulk wave parameter $H_{rms,IG}$, using equation (3.3). Also the mean water
level \( \bar{\eta} \) and mean water depth \( \bar{h} \) for each burst are easily obtained from the instantaneous water level output of XBeach.

The short wave height takes an extra step, since it is composed of two components. The first is derived from the energy of the short wave group \( E \) which is presented by XBeach as a time-varying \( H_{rms} \), calculated using equation (4.1).

\[
H_{rms} = \sqrt{\frac{8E}{\rho g}} \tag{4.1}
\]

The result of \( H_{rms} \) is averaged for each burst to obtain the mean wave height of the short wave groups \( \bar{H}_{rms} \). The second component is based on the high-frequency (> 0.055 Hz) part of the spectra derived from the surface elevation \( z_s \), which is used to determine \( H_{rms,hf} \) using equation (3.3). Both components are combined using equation (4.2) to obtain the short wave height \( H_{rms,SH} \).

\[
H_{rms,SH} = \sqrt{H_{rms}^2 + H_{rms,hf}^2} \tag{4.2}
\]

**Performance indicators**

To assess the model performance with respect to the measurements, indicators are defined for the short wave height \( (H_{rms,SH}) \), the infra gravity wave height \( (H_{rms,IG}) \) and the mean water depth \( (\bar{d}) \). The bulk parameters derived from the measurements \( (M) \) are compared with the bulk parameters computed with the XBeach model \( (C) \) at each PT \( (i) \) and for each burst \( (t) \). To be able to compare runs with different settings the errors in spatial and temporal domain are brought down to one characteristic value by taking the root-mean-square (in space and time) of the errors as defined by equation (4.3).

\[
\epsilon_{abs, rms} = \sqrt{\frac{1}{N} \sum_{n=1}^{N} (C_{(i,t)} - M_{(i,t)})^2} \tag{4.3}
\]

Here \( N \) is the number of elements in the considered space-time domain and \( n \) the individual elements for an error at a certain PT during a certain burst. The value of \( \epsilon_{abs, rms} \) determines an absolute error averaged in space and time and thereby indicates how well the model reproduces the measured bulk parameters for a certain set of parameters.

In analogy with equation (4.3) a relative error averaged in space and time can be defined using equation (4.4) to determine the significance of the error with respect to the value of the measured bulk parameter \( M \).

\[
\epsilon_{rel, rms} = \sqrt{\frac{1}{N} \sum_{n=1}^{N} \left( \frac{C_{(i,t)} - M_{(i,t)}}{M_{(i,t)}} \right)^2} \tag{4.4}
\]

Minimal values of \( \epsilon_{abs, rms} \) and \( \epsilon_{rel, rms} \) will define the optimal set of the calibrated parameters.

**Interaction effects**

In the shoaling zone the dissipation of short wave energy is dominated by bottom friction, therefore this area can be used to calibrate \( f_w \). In the surf-zone the short wave energy is dissipated by both bottom friction and short wave breaking. Once the dissipation of short wave energy by bottom friction is set with \( f_w \) for measurements in the shoaling-zone the measurements in the surf-zone can be used to calibrate \( \gamma \) for the dissipation by short wave breaking. Both zones will be independently assessed for the calibration of \( f_w \) and \( \gamma \) to obtain minimal errors for \( H_{rms,SH} \).

Simultaneously with the dissipation of short wave energy the mean currents, associated with the energy of the long waves \( (H_{rms,IG}) \), are reduced by a bed shear stress \( \tau_B \). The latter dissipation mechanism influences the water levels, hence the mean water depth \( (\bar{h}) \) at the platform, by the shallow water equation and thereby the short wave propagation. To cope with this interaction effect \( f_w \) and \( \gamma \) are calibrated satisfying minimal errors for \( H_{rms,IG} \) and \( \bar{h} \). In a practical sense this results in an assessment of \( f_w \) and \( c_f \) for elements outside the surf-zone and \( \gamma \) and \( c_f \) for elements inside the surf-zone.
4.3.2. Calibration results

The results of the calibration procedure are presented first for the calibration of \( f_w \), outside the surf-zone, and next for \( \gamma \) and \( c_f \), inside the surf-zone.

Outside surf-zone

For the calibration of \( f_w \) for the Lilstock site the third tidal cycle is selected. Due to the low-energetic conditions the width of the surf-zone is relatively small (60 m), resulting in a large amount of measurements located in the shoaling zone (188 elements in space and time). Averaging the errors over this number result in a high reliability of the performance indicators. Figure 4.3 shows the values of

\[ \epsilon_{\text{abs, rms}} \] and \( \epsilon_{\text{rel, rms}} \), based on model results of several combinations of parameters defined horizontally for values of \( c_f \) and vertically for \( f_w \). Together they span a surface where a minimum indicates the optimal set of model parameters. Focusing on the errors for \( H_{\text{rms,SH}} \), figure 4.3 shows a strong dependency on the value of \( f_w \), with small errors for low values of \( f_w \), versus a very weak dependency on the value of \( c_f \). This complies to the expectations since only the \( f_w \) parameter is linked to the short wave action balance. Based on the results in figure 4.3 a minimal value of \( \epsilon_{\text{rel, rms}} \) is found for a short wave friction parameter of \( f_w = 0.05 \). This value is set for Lilstock and used to calibrate \( \gamma \) and \( c_f \) based on measurements inside the surf-zone.

Inside surf-zone

To properly calibrate \( \gamma \), the sixth tidal cycle is selected. This tide is characterised by the energetic conditions and a wide surf-zone, resulting in a large number of measurements inside the surf-zone, which increases the reliability of the performance indicators. Since the third tidal cycle is used for the calibration of \( f_w \), the same procedure for the calibration of \( f_w \) is performed for the sixth cycle indicating minimal errors for the same value of \( f_w \), as presented in figure 4.3. Having set the value of
The calibration can focus on $\gamma$ and $f_w$ inside the surf-zone. Figure 4.4 shows the errors inside the surf-zone for the sixth tidal cycle measured at Lilstock (11-12-2014). Horizontally values for $c_f$ and vertically values for $\gamma$ are presented. With respect to $H_{rms,SH}$ minimal errors are observed for $\gamma = 0.4$ which improve the average result by 7 cm (20%) compared to the default settings of XBeach. Focusing on $H_{rms,IG}$ and the $\bar{h}$, the improvement for $\gamma = 0.4$ compared to $\gamma = 0.55$ is less significant, although for both error spaces the center of the concave pattern is close to a value of $\gamma = 0.4$. Furthermore, and contrary to $H_{rms,SH}$, there is a strong dependency on the value of $c_f$ for both $H_{rms,IG}$ and $\bar{h}$. For both bulk parameters a strong concave shape with minimal errors for $c_f = 0.08$ is observed. Especially for $H_{rms,IG}$ a significant improvement of $> 50\%$ is accomplished compared to the default settings of XBeach.

**Calibrated parameters**

Summarising the results of the calibration procedure the following values are selected for the XBeach-SurfBeat model: $f_w = 0.05$, $c_f = 0.08$ and $\gamma = 0.4$. Table 4.2 shows the values of the calibrated param-
Table 4.2: Calibrated parameters including errors for the sixth tidal cycle (most energetic conditions), averaged over all PTs for all tidal phases.

<table>
<thead>
<tr>
<th>Site - settings</th>
<th>Model parameters</th>
<th>(H_{rms,SH})</th>
<th>(H_{rms,IG})</th>
<th>(d)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(f_w) (c_f) (\gamma)</td>
<td>(\epsilon_{abs}) (\epsilon_{rel})</td>
<td>(\epsilon_{abs}) (\epsilon_{rel})</td>
<td>(\epsilon_{abs}) (\epsilon_{rel})</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>- - -</td>
<td>5.3 cm 12.2%</td>
<td>1.7 cm 18.2%</td>
<td>O(2)cm -</td>
</tr>
<tr>
<td>LST - calibrated</td>
<td>0.05 0.08 0.4</td>
<td>6.2 cm 11.7%</td>
<td>1.9 cm 12.5%</td>
<td>1.7 cm 1.9%</td>
</tr>
<tr>
<td>LST - default</td>
<td>0 0.003 0.55</td>
<td>13.7 cm 30.0%</td>
<td>10.8 cm 68.2%</td>
<td>3.3 cm 3.5%</td>
</tr>
<tr>
<td>LST - coral reefs</td>
<td>0.60 0.1 0.55</td>
<td>17.4 cm 21.8%</td>
<td>2.6 cm 14.7%</td>
<td>2.2 cm 3.8%</td>
</tr>
</tbody>
</table>

Comparing the obtained errors with the bandwidth, as determined in section 3.2.3, shows that the averaged errors are in the same order of magnitude as the natural variability of the wave conditions itself.

4.3.3. MODEL RESULTS

To examine the model results in more detail, figure 4.6 shows two bursts as an example for the mid- and high-tidal phases of cycle number six. Other cross-sections of tide three and six are presented in appendix C. The cross-sections show bulk wave parameters based on XBeach results of the calibrated model and the field data as described in section 3.3. To assess all bursts simultaneously, figure 4.5 shows the measured versus the computed data for the three considered bulk parameters and indicates both tidal phases using colours.

In general, the bulk wave parameters based on the field data are reasonably well reproduced by the model, as presented in figure 4.5. Based on the cross-section in figure 4.6, the model shows a good reproduction of the short wave height \(H_{rms,SH}\) both inside and outside the surf-zone. The dissipation of short waves inside the surf-zone (mid-tidal burst) is forced by \(\gamma\) and the strong dissipation gradients result in a \(H_{rms,SH}\) close to the measured short wave height. The difference between the asterisk and the line of \(H_{rms,SH}\) indicate that there is some high-frequency (>0.055Hz) energy resolved in the surface elevation signal \(z_s\). This difference increases close to the shoreline, although the magnitude remains small (<4cm).

Outside the surf-zone (high-tidal burst) the short wave height is slightly underestimated (8cm) although the modelled short wave height matches the measured short wave height at the most offshore PT. This indicates that the model is less effective in reproducing the shoaling behaviour of the short waves. With respect to the IG-wave height, the model shows a fair reproduction of the measured
Figure 4.6: Cross-sections for a burst during mid-tidal phase (left) and high-tidal phase (right) for Lilstock (2014-12-11). The XBeach results of the calibrated model are indicated by asterisks and the measured bulk parameters by triangles. The top panel shows the $H_{rms,SIH}$ at PT locations and the XBeach $H_{rms}$ for each grid point, the second row shows the $H_{rms,IG}$, the third row the $\eta_{setup}$ and bottom panel the mean water level $\eta$.

$H_{rms,IG}$ especially outside the surf-zone. Inside the surf-zone the model shows larger errors although the tendency of IG-wave growth during high-tidal phases is reproduced by the model. For the mid-tidal burst a slight decay of IG-wave height is computed by the model, which does not comply with the measurements that indicate IG-wave growth. The setup, on the other hand, is very close to the measurements with an average error of 1.5 cm and 1.3 cm for the mid-tidal and high-tidal burst respectively.

4.4. VALIDATION

Figure 4.7 presents the validation of the calibrated model with measured versus computed data of all tidal cycles for all tidal phases. The most significant improvement using calibrated setting is accomplished for the IG-wave height. The errors in figure 4.7 show the averaged absolute errors for the entire run. Interestingly, the first three tidal cycles show lower errors for the IG-waves and higher errors for the setup compared to the other tidal cycles, of which the errors for both the $H_{rms,IG}$ and $\eta_{setup}$ are of the same order. This could be explained with the interaction between the bed-shear stress and hydrostatic pressure gradients balancing the radiation stresses, appendix B.4. Since the first three tidal cycles are considerably less energetic compared to the last four the gradients in the radiations stresses are of lower magnitude. Because the bed-shear stress coefficient $c_f$ is of the same order of magnitude the pressure gradients are underestimated. This is also observed in the cross-sections of tide three, appendix C.
Figure 4.7: Validation of calibrated XBeach model for all tides measured at the Lilstock platform. Top row; default settings of XBeach. Second row; calibrated settings for Lilstock. Bottom row; errors based on the runs with calibrated settings averaged over all PTs.

**Influence of topographical roughness**

The roughness of the platform is included by parametrisation, using $f_w$ and $c_f$, and by the topographical roughness, based on the detailed bathymetry, measured using terrestrial lasers or LIDAR, as used for modelling. To investigate the influence of the topographical roughness on the wave propagation, simplifications of the bathymetry are created for modelling using the calibrated settings to parametrize the roughness. The model results are presented in appendix C.3, similar to the presentation in figure 4.7. The simplifications comprise a 20m alongshore smoothed profile and an artificial profile, constructed of three linear segments after the classification in section 3.1. Based on the modelling results it is concluded that the detailed topographical roughness is not a strong control for modelling of the wave transformation across the platform, as long as calibrated settings are used.
4. DISCUSSION AND CONCLUSION
To finalize this chapter the model performance, calibrated parameters and assumptions are briefly discussed. Despite the absence of a specific sub-research question regarding the modelling capabilities of XBeach, some findings can be concluded based on the calibration of XBeach model.

MODEL PERFORMANCE
The averaged errors resulting form the calibrated XBeach model, table 4.2, are found to be acceptable when comparing them to the averaged bandwidth of the initial field data. Decomposing the averaged error to its individual errors reveals the model performance in temporal and spatial domain. Figure 4.8 shows the individual absolute errors from which an underestimation of SH-wave height outside the surf-zone and an overestimation inside the surf-zone can be observed. In general, the individual absolute errors are < 14cm and < 6cm for the SH-waves and IG-waves respectively. Furthermore, table 4.2 presents the errors for the XBeach runs with default settings and the calibrated parameters found for coral reefs (Van Dongeren et al., 2013). The largest difference is found for the SH- and IG-waves. The default settings result in an overestimation of the SH-waves inside the surf-zone, due to the high $\gamma$ value, and an overestimation of the IG-wave height, due to the low value of $c_f$. The settings found for coral reefs result in errors in between the default settings and the calibrated parameters. The overestimation inside the surf-zone, due to $\gamma = 0.55$, is compensated by an underestimation outside the surf-zone, due to $f_w = 0.6$, resulting in more dissipation of short wave energy by bottom friction. The value for $c_f$, found for the rocky platform in Lilstock is almost similar compared to the value found for coral reefs, resulting in an error of similar magnitude.

INTERPRETATION OF CALIBRATED SETTINGS
The difference between the calibrated parameters, the default values and the values found for coral reefs can also be explained from a physical point of view, by relating them to the site characteristics.

Typical for a rocky shore platform is the extreme rough surface compared to sandy beaches, which is expected to influence the wave transformation processes. The calibration of the XBeach model parameters helps to increase understanding of the interaction of the waves with the platform roughness. First of all, the calibrated value of $f_w$ remains low, from which it is concluded that dissipation of short wave energy by bottom friction is relatively small at the platform of Lilstock. Comparing this to the value calibrated for coral reefs, the dissipation by short wave bottom friction is approximately 10 times smaller at the platform of Lilstock. On the other hand, a high friction coefficient ($c_f$) is found to attain the required bed shear stress to reproduce the measured IG-waves. Thereby the value for $c_f$ is found to be in the same order of magnitude as calibrated for coral reefs. Concluding that, the low-frequency motions and mean currents experience a rough surface, i.e. high skin friction, contrary to short waves, that hardly interact with the platform roughness.
It should be mentioned that the value of $f_w$ and $c_f$ approach the same order of magnitude. Studies on coral reefs indicate that $f_w$ should be an order of magnitude larger than $c_f$, because they dissipate energy from a different frequency of the motion Lowe et al. (2007). In this study, both are assumed independent and to substantiate this assumption figure 4.4 shows clearly that the short wave height is not affected by the value of $c_f$.

In shallow water short wave breaking can be related to the water depth although, from a physical point of view, waves start to break due to an increasing steepness, and not necessarily due to the interaction with the bottom. For the platform in Lilstock a lower value of $\gamma$ is found compared to the default value of XBeach which indicates that the critical wave steepness is reached in higher water depths compared to what is expected for sandy beaches.

**Implication of assumptions**

Some assumptions were already indicated and explained in section 4.2, here some implications are discussed. The 1D assumption is a simplification of the complex bathymetry and hydrodynamics at the platform. First of all, due to this 1D assumption, an alongshore uniform coast is assumed, which is not valid for the surface roughness. The gentle inclined flats result in steps of approximately 10 to 20 cm which could result in alongshore gradients in the wave-propagation. For the Lilstock platform the steps in bathymetry are relatively small and not expected to influence the short wave propagation.

Secondly, waves are assumed normally incident where the offshore measured waves, at the Hinkley Point wave buoy, have a direction of 286° which differs 43° with the orientation of the cross-shore array of PTs. In combination with the fact that the platform of Lilstock is located relatively offshore, compared to the neighbouring platforms, the 1D assumption with normally incident waves does not take refraction, and possible focusing, into account. Furthermore, in a 1D-XBeach SurfBeat model the short-wave action will only force the cross-shore radiation stress $S_{xx}$ which results in an overestimation of the gradients in the cross-shore radiations stress, hence in an overestimation of the IG wave motions. To compensate for this effect a higher bed-shear stress is required which could result in an overestimation of the value of $c_f$.

With respect to the boundary conditions, assumptions are made for both the tide and waves. The Lilstock platform is located at the margins of the Severn estuary where high tidal currents are observed, the wave-current interaction as a results of the tidal currents is not explicitly taken into account in the model. From the data analysis in Chapter 3, figure 3.10, the wave-current interaction is clearly visible. Since waves at the offshore PT are used as boundary condition this is implicitly taken into account at the boundary but not for the propagation.

The measured surface elevation of a pressure transducer located at the offshore edge of the platform provides a sufficient boundary condition for modelling purposes of wave transformation processes across the platform. Using the measured signal as boundary condition in combination with the calibrated model parameters the measured bulk wave parameters can be reproduced within acceptable errors.
INFRA-GRAVITY WAVE GENERATION

This chapter will use field data and the calibrated XBeach model to determine the generating mechanism of infra-gravity waves, on the A-type rocky shore platforms of Lilstock, and investigate how this process is modulated by the macro-tidal range. Section 5.1 describes the method used for the analysis of which the results are presented in section 5.2 and subsequently discussed in section 5.3. Finally, section 5.4 will formulate an answer the second sub-research question.

5.1. METHODOLOGY
To determine the governing generating mechanism a cross-correlation analysis is performed. This method can be used to determine the phase relation between two time-series. Since the two signals do not necessarily have to be collocated the evolution in spatial domain can be examined. The phase relation between the high-frequency envelope and the low-frequency wave, based on correlation coefficients, provides thereby a method to qualitatively assess the generation mechanism of infra-gravity (IG) waves. To do so, first the water level time series of a considered burst is split in high-frequency ($\eta_{hf}(t)$, > 0.055 Hz) and low-frequency ($\eta_{lf}(t)$, < 0.055 Hz) constituents using band-pass filtering. The envelope of the high-frequency component is defined using equation (5.1).

$$|A(t)| = \left| \eta_{hf}(t) + i\Gamma[\eta_{hf}] \right|_{lf}$$  \hspace{1cm} (5.1)

Where $|A(t)|$ is the high-frequency envelope and $\Gamma[.]$ denotes the Hilbert transform operator. In the case where narrow-banded spectra of the original high-frequency can be assumed, $A(t)$ can be interpreted as the envelope of the short-wave group (Janssen et al., 2003). An example of this signal is given in figure 5.1.

![Figure 5.1: Example of the bandpass filtered high-frequency signal $\eta_{hf}$ (gray line) and the corresponding low-frequency signal $\eta_{lf}$ (dashed black line). Through application of equation (5.1) the short wave envelope $|A(t)|$ (solid black line) is determined. Signal is based on the measured surface-elevation at PT15.](image-url)
CROSS-CORRELATION FUNCTION

The cross-correlation function is defined after Bendat and Piersol (1986),

\[ R_{XY}(\tau) = \frac{\langle X(t)Y(t+\tau) \rangle}{\sigma_X\sigma_Y} \]  

(5.2)

where \( R_{XY}(\tau) \) is the cross-correlation coefficient for the two harmonics \( X(t) \) and \( Y(t) \), \( \sigma_X \) and \( \sigma_Y \) are the standard deviations of \( X(t) \) and \( Y(t) \) respectively. Furthermore \( \langle \cdot \rangle \) denotes time averaging and \( \tau \) is the time shift. By dividing the correlation of \( X(t) \) and \( Y(t) \) by the standard deviations the cross-correlation coefficient is normalised ensuring \(-1 \leq R_{XY} \leq 1\). To examine the generation and propagation of IG-waves various types of cross-correlations are performed. The notation of each cross-correlation is defined by \( R_{XY}(\tau, x_i; x_r) \), which determines the collection of cross-correlation coefficients with phase-lag \( \tau \) for the signals \( X(t) \) observed at location \( i \) and signal \( Y \) simultaneously observed at the fixed reference location \( r \) (Janssen et al., 2003).

EXPECTED CROSS-CORRELATION PATTERNS

Two generating mechanisms will be investigated namely 1) the release of bound long waves (Longuet-Higgins and Stewart, 1962) and 2) the breakpoint forcing (Symonds et al., 1982). In case of the first mechanism the trough of the long wave is bound to the crest of the short wave group while propagating in onshore direction outside the surf-zone. This results in negative values of the cross-correlation coefficient \( R_{A,\eta}(\tau, x_i; x_r) \) outside the surf-zone. Once the groupiness decreases, due to short wave breaking inside the surf-zone, the long wave is no longer bound and as a consequence released from the wave group. This results in an increase of \( R_{A,\eta} \), i.e. from negative values towards zero, inside the surf-zone. The coefficient of \( R_{A,\eta} \) is generally in the order of 0.3 but significantly different from zero (Masselink, 1995). In the case of the second mechanism the long waves are locally generated by a moving breakpoint. The generation of the long wave is attributed to the time-varying setup due to a varying wave height in the wave group. Long waves at the group frequency radiate away from the forcing region in both the onshore and offshore direction. Because a larger wave will result in larger setup value at the shoreline the long wave shore-ward of the forcing region is positively correlated to the short wave envelope. The offshore propagating wave is negatively correlated due to larger setdown for higher waves. Both the onshore and offshore propagating wave have been observed by Baldock (2006) and Van Dongeren et al. (2013). Figure 5.2 shows the expected patterns for both mechanisms in which qualitatively the cross-correlation coefficients for both the onshore propagating wave and the reflected wave are presented.

Figure 5.2: Example of expected cross-correlation results for two generating mechanisms. The release of bound long wave with reference signal at \( x=0 \) (left) and the forcing by a time-varying breakpoint with reference at \( x=0 \) (right). The dotted line indicates the edge of the surf-zone.
5.2. RESULTS

This section describes the results of the cross-correlation analysis for all tidal phases. To understand the generation mechanisms of infra-gravity waves first the individual propagation of the short wave envelope and the long wave is described followed by the cross-correlation between both signals. During low-tidal phases all PTs fall dry at the platform as described in section 3.3.1, therefore the cross-correlation based on the field data is restricted to mid- and high tidal phases. To examine the generating mechanism for the low-tidal phase the XBeach model is used to extend the spatial domain. Results are presented for the sixth tidal cycle corresponding to the results in Chapter 3 and 4.

5.2.1. MID- AND HIGH-TIDAL PHASES

Two characteristic bursts for the mid- and high-tidal phases are considered. The cross-correlation results based on field data and the numerical model are presented and discussed.

PROPA TEST 1S OF SHORT WAVE ENVELOPE

Low-frequency motions are induced by gradients over the cross-shore radiations stresses, which are related to the energy of the short wave group. Therefore the cross-correlation of the squared short wave envelope, $|A(t)|^2$, is used for the analysis as a result the coefficients range from $0 \leq R_{XY} \leq 1$.

Figure 5.3: Cross-correlation of the short wave envelope $R_{AA}(\tau, i, 15)$ for mid- (left) and high-tidal (right) phases. Both based on field data and XBeach results for Lilstock (2014-12-11). The black line shows the phase difference based on the group celerity $c_g$. The vertical dotted line indicates the outer edge of the surf-zone.
Figure 5.3 shows the results in spatial domain with the most offshore PT as reference signal, denoted as $R_{AA}(\tau, i, 15)$. Both the field data and the model results show a ridge of positive correlation with increasing phase-lag ($\tau$) towards the shoreline which indicates the propagation of the short wave envelope. Once the short waves travel into the surf-zone the correlation coefficient decreases due to a decrease in groupiness, this is well observed for the mid-tidal phase. The phase-lag $\tau$ corresponding to the ridge of positive correlation is reasonably well described by time lag values corresponding to the wave group celerity $c_g$, defined by equation (5.3).

$$c_g = nc; \quad n = \frac{1}{2} \left( 1 + \frac{2kh}{\sinh(2kh)} \right); \quad c = \frac{g}{\omega} \tanh(kh)$$

with $\omega$ the radial frequency $(2\pi/T)$, $k$ the wave number $(2\pi/L)$ and $h$ the mean water depth. For the field data the phase-lag of the group celerity is computed using the value of $T_{m-1,0}$ derived from the wave spectra, measured at each PT, and presented in section 3.2.3. For the XBeach results the phase-lag of the group celerity is computed with the representative wave period $(T_{m-1,0})$ used to force the model which is constant for the entire model run, as described in section 4.2.

The computed time lag values based on the group celerity ($c_g$) are compared to the time lag values based on the shallow water limit. Figure 5.4 shows the cumulative phase-lag difference ($\Delta \tau$) across the platform based on the XBeach results. The cumulative difference varies between 1.8 and 6 seconds for mid- and high-tidal phases respectively over a cross-shore distance of 240 m. This difference shows that the short wave group propagates slightly slower than the shallow water limit of $c_g \sim \sqrt{gh}$.

Comparing the wave celerity of both bursts in figure 5.3 a decrease of the computed phase-lag is observed for high-tidal phases which corresponds to an increase of the propagation speed. This is a direct consequence of the macro-tidal range because higher water depths result in larger values of $c_g$, and consequently in a decreasing phase-lag.

Comparing the result of the field data to the XBeach model in figure 5.3 it is observed that the correlation coefficients based on the XBeach model show generally lower values compared the measurements. Furthermore the ridge of the positive correlation extends further into the surf-zone compared to the field data. This difference is attributed to the signal that is used for the analysis. For the field data the short wave envelope is derived from the surface elevation signal using equation (5.1). XBeach-SurfBeat computes only the energy of the short wave group, which is presented as a time-varying wave height using equation (4.1), without information of the individual waves. As a result the latter signal shows less variability compared to the signal of equation (5.1) when considering the short wave envelope which results in a distinct pattern of the cross-correlation coefficients. Appendix D shows a comparison between the short wave envelope according to the field data and the XBeach model.
PROPAGATION OF INFRA-GRAVITY WAVE

Figure 5.5 shows the cross-correlation coefficients of the infra-gravity wave signal across the platform. For both the field data and the XBeach results the surface elevation is de-trended and subsequently band-pass filtered in the infra-gravity frequency range (0.004 Hz – 0.055 Hz). The infra-gravity wave signal at the most offshore located PT is compared to the infra-gravity wave signal of the subsequent PTs across the platform, denoted as $R_{\eta,\eta}(\tau, i, 15)$. Both the model and the field data show correlation coefficients in the same order of magnitude and qualitatively in the same pattern. Similar to the propagation of the short wave envelope ridges of positive correlation and positive phase-lag ($\tau$) are observed which indicate the onshore propagation of the infra-gravity waves. In figure 5.5 the positive ridges are neighboured by ridges of negative correlation which reveal the neighbouring troughs. The evolution of the ridges with positive correlation, corresponding to the propagation of the infra-gravity waves, is well described by the computed phase-lags based on the group celerity ($c_g$). For both the field data and the XBeach model results this indicates that the infra-gravity wave propagates with similar phase-celerity as the short wave envelope. Especially outside the surf-zone, this suggests that the long wave is bound to the short wave group, which will be further investigated in the following section.

At the shoreline ($x = 220m$) the infra-gravity wave signal reflects resulting in an offshore directed propagating wave. In figure 5.5 this is observed as a ridge of positive correlation for both bursts and well reproduced by the XBeach model. In Chapter 6 this will be discussed in more detail, related to the reflection coefficients and the presence of a standing wave.

![Figure 5.5: Cross-correlation of infra-gravity waves $R_{\eta,\eta}(\tau, i, 15)$ for mid- (left) and high-tidal (right) phases. Layout is similar to figure 5.3.](image-url)
**Interaction between short wave envelope and infra-gravity wave**

Once established how the short wave envelope and the infra-gravity wave propagate across the platform the relation between both can be examined. Figure 5.6 presents the cross-correlation coefficients between the short wave envelope at the most offshore located PT and the infra-gravity wave propagating across the platform, denoted as $R_{\eta,A}(\tau, i, 15)$. Both the field data and the XBeach model show qualitatively the same pattern for both tidal phases. In all four, a trough of negative cross-correlation coefficients is observed which indicates that the trough of the infra-gravity wave coincides with the crest of the short wave envelope. The ridge of negative correlation persists up and till the breaker line which indicates that outside the surf-zone the infra-gravity wave is bound to the short wave group. By virtue of short wave breaking inside the surf-zone the short wave group starts to break down which reduces the interaction with the infra-gravity wave and subsequently releases the bound long wave as a free wave, propagating with $c = \sqrt{gh}$. As a result the correlation between both signals decreases inside the surf-zone, along the line of computed phase-lags corresponding to $c_g$. This pattern corresponds to the conceptual cross-correlation in figure 5.2 and indicates that, for mid- and high tidal phases, infra-gravity waves are generated as bound long waves offshore and released in the surf-zone. For a better observation of the processes inside the surf-zone the local cross-correlation is computed and presented in figure 5.7. Here the cross-correlation coefficients are computed between the short wave envelope at a single PT and the infra-gravity wave propagated across the platform, denoted as $R_{\eta,A}(\tau_1, 15)$. Both the field data and the XBeach model show the same pattern for both tidal phases.
5.2. RESULTS

Figure 5.7: Cross-correlation function between the short wave envelope and the low-frequency wave $R_{\eta,A}(\tau, i, i)$. Layout and scale are similar to figure 5.6.

wave envelope at location $i$ and the infra-gravity wave at location $i$, denoted as $R_{\eta,A}(\tau, i, i)$, which allows to investigate the changes in correlation across the platform. Again, outside the surf-zone a strong negative correlation is observed, supporting the other observations and indicating bound long waves. Inside the surf-zone, and especially for mid-tidal phases, the correlation gradually tends towards positive values which is attributed to the depth modulation of the infra-gravity waves, similar to observations of Janssen et al. (2003). Due to depth induced breaking the highest waves in the wave group break first and the smaller waves remain resulting in a deformation of the shape of the short wave envelope. Hereby the crest of the short wave envelope starts to coincides with the crest of the infra-gravity wave, i.e. the short waves ‘ride’ on the crest of the long wave and the infra-gravity wave starts to act like a filter allowing the depth saturated short waves to enter the shallow region. The positive correlation inside the surf-zone is, to a lesser extend, attributed to the slightly faster propagating free long wave with respect to the short wave group. Because the cross-shore extend is relatively short and the difference in phase celerity is rather small the latter mechanism is assumed less important.

5.2.2. LOW-TIDAL PHASE

The calibrated XBeach model is used to extend the spatial domain and investigate the infra-gravity wave generation and propagation during low tidal phases.
EXTENSION OF XBEACH MODEL

LIDAR data\(^1\) from the Plymouth Coastal Observatory is used to extend to spatial domain to a water depth of −6\(mOD\), 350\(m\) offshore of the edge of the platform. To investigate the phase-relation between the short wave envelope and the infra-gravity waves the extended model is forced using the same wave boundary conditions as used in Chapter 4. The main reason being that changing too many variables at the same time will result in incomparable cases. Therefore wave conditions of the sixth tidal cycle measured during high-tide at the most offshore located PT (outside the surf-zone) are used to the force the model. The calibrated model parameters from Chapter 4 are used and the model is run for tidal levels ranging from −3.7\(mOD\) to +4.5\(mOD\) which covers the mean tidal range.

CROSS-CORRELATION RESULTS

The extended model is validated by comparing the cross-correlation coefficients based on the extended model and the field data for high-tidal phases and evaluate whether the same qualitative pattern is observed. Appendix D shows and explains the results of the high-tidal case using the extended grid. Based on these result it can be concluded that with an extension of the bathymetry, using the same wave conditions and the same calibrated parameters, qualitatively a similar cross-correlation pattern is observed from which the same generating mechanism can be concluded. This provides a basis for analysis of the low-tidal phase.

Figure 5.8 shows various cross-correlation coefficients for the low-tidal case. In the three top-panels the same patterns are observed compared to the results presented in the previous sections. Both the short wave envelope and the long waves shows a ridge of strong positive correlation outside the surf-zone, well described by the computed phases corresponding to \(c_g\). Inside the surf-zone the correlation of the short wave envelope decreases as expected due breaking of the short waves. The propagation of the infra-gravity wave is slightly more complicated due to the boundary conditions of the model. The model is forced using a free long wave which propagates with the free wave celerity towards the shoreline, well described by the ridge of positive correlation propagating with \(\sqrt{gh}\). Simultaneously a bound long wave is generated by the short wave group which propagates with the group celerity \(c_g\). Inside the surf-zone the water depth decreases rapidly resulting in a decreasing wave celerity. This is observed by the rapidly deflecting ridge of positive correlation for both long waves which is well described by the computed phase lags. During the lowest tide presented in figure 5.8, reflection of the infra-gravity wave signal is observed, most probably due to the presence of the steep fore-shore.

The cross-correlation between the short wave envelope and the infra-gravity wave, show similar results compared to the mid- and high-tidal phases. Although the correlation coefficients are slightly weaker, a ridge of strong negative values is observed outside the surf-zone. Onshore of the breaker line a switch towards positive correlations is observed while following the computed phase-lags. To examine this shift in more detail the local cross-correlation coefficients between the two signals are computed and presented in the fifth panels. For \(\eta_{\text{tide}} = 0\) a band of negative correlation centred around \(\tau = 0\) is observed up to the breaker line indicating a bound long wave. Shore ward of the breaker line an inversion of the correlation is observed indicating that the crest of the short wave coincides with the crest of the infra-gravity wave, similar to the high-tidal phases. For \(\eta_{\text{tide}} = −3\) the results of the local cross-correlation are less clear due to lower values of the cross-correlation coefficients. Around \(\tau = 0\) a band of negative correlation is vaguely observed up to \(x = -200m\) and further shore ward the phase lag for the band of negative correlation seem to increase.

From the results of the extended model, similar patterns are observed compared to the results for the mid- high-tidal cases and the conceptual cross-correlation results. A bound long wave is observed which, although vaguely visible, is subsequently released in the surf-zone. Furthermore, and despite the fact that the waves experience a steeper slope for low-tidal phases compared to high-tidal phases, there is no convincing evidence observed of a shift in generating mechanism towards breakpoint forcing. Therefore it is concluded that the generating mechanism of infra-gravity waves is similar for all tidal phases.

\(^1\)Bathymetry dates from 2007.
5.2. RESULTS

Figure 5.8: Cross-correlation function with reference location $x = -350\, \text{m}$ for the short wave envelope $R_{AA}(\tau, i, -350)$ (top-row), the infra-gravity waves $R_{\eta\eta}(\tau, i, -350)$ (second-row), the relation between both signals $R_{\eta\eta,A}(\tau, i, -350)$ (third-row) and the local relation between both signals $R_{\eta\eta,A}(\tau, i, i)$ (fifth-row). Dotted line indicates computed phase lags based on $\sqrt{g\, h}$, solid line indicated the group celerity (Eq. 5.3).
5.3. DISCUSSION

The results in this chapter are based on the cross-correlation coefficients of the sixth tidal cycle measured in Lilstock. The results indicate that for this cycle the infra-gravity waves are generated offshore as bound long waves instead of being generated locally as free waves by breakpoint forcing. Appendix D presents the cross-correlation coefficients for the third, less energetic, tidal cycle showing qualitatively similar patterns from which the same generating mechanism can be concluded.

MODEL PERFORMANCE

The cross-correlation coefficients are determined using the field data and the results of the XBeach-SurfBeat model. As mentioned in section 5.2.1 the XBeach-SurfBeat model computes not the surface elevation of the short waves but only the energy of the short wave group. Therefore the signal of the short wave envelope based on the field data is a different signal compared to the considered short wave envelope of the XBeach model. Although the signals are interpreted, and used, to describe the same physical process, both signals are derived in a different way. This has to be taken into account while interpreting the results.

To investigate the generating mechanism for low tidal phases the XBeach model is extended using LIDAR data from 2007 which is susceptible for differences compared to the measured profile by the WASP project in 2014. Furthermore boundary conditions based on the measured surface elevation at the offshore PT during high-tide are extrapolated to larger water depths. Both introduce an error whereby the results of the extended model remain questionable. Having said that, the cross-correlation coefficients based on the XBeach model produce similar patterns compared to the field data, and do not indicate clear evidence for another generating mechanism of infra-gravity waves. Therefore the model results are believed to be sufficient for the qualitative analysis of the generating mechanism.

EXPECTED GENERATING MECHANISM BASED ON SURF-SIMILARITY

As a consequence of the macro-tidal range and the topography of the platform the water depth and the effective bed-slope change significantly during the tidal-cycle. For low-tidal phases ($-3 \leq \eta_{tide} \leq 0$) the waves experience a bed-slope that is twice as steep ($\sim 1:25$) compared to mid-tidal phases ($\sim 1:50$). Both the bed slope and the water depth are an important driver in the development of infra-gravity waves. According to Battjes et al. (2004); Van Dongeren et al. (2007) the normalised bed-slope, described by equation 2.7, is a strong control on the enhancement of sub-harmonics. This parameter captures both the bed-slope and the water depth at breaking. In a mild-sloping regime ($\beta_b < 0.1$) infra-gravity waves are typically bound long waves and subsequently released in the surf-zone as a free wave. Opposed to steep-sloping regimes ($\beta_b > 0.45$) where infra-gravity waves are generally generated as a free wave by a moving breakpoint. Taking a characteristic value of $h = 3m$ for the depth at breaking and an infra-gravity wave frequency of $0.03 Hz$ the $\beta_b$ parameters for both the fore-shore and the platform result in $\beta_{b,foreshore} = 0.38$ and $\beta_{b,platform} = 0.19$ respectively. Both values of $\beta_b$ are well within the mild- and steep-sloping regime as defined by Battjes et al. (2004); Van Dongeren et al. (2007) and do not particularly favour one regime above the other. The results of the cross-correlation show a clear pattern of bound long waves outside the surf-zone and a release of the bound long wave inside the surf-zone. For high-tidal phases ($\beta_b = 0.19$) these patterns are better visible compared to low-tidal phases ($\beta_b = 0.38$) which is probably related to the bed-slope at the point of breaking experienced by the waves during these phases. On the other hand this $\beta_b$ parameter is quite sensitive to the selection of the cross-shore extend used to determine the bed-slope. Averaged across a longer cross-shore distance, the difference in bed slope, between the fore-shore and the platform reduces and as a result both $\beta_b$ values tend towards the same value of approximately $\beta_b = 0.15$.

In nature both mechanisms responsible for the generation of infra-gravity waves occur simultaneously however, in general, one is more effective than the other. That is the reason that in this research is referred to the governing generating mechanism since, usually, one tends to dominate over the other. Based on the results for mid- and high-tidal phases it is justified to refer to the generating mechanism
as governing due to the strong correlation patterns and the value of $\beta_{b,\text{platform}} = 0.19$, which is closer to the mild-sloping regime compared to the steep-slope regime. For low-tidal the term ‘governing’ is not preferred since the cross-correlation patterns between short wave envelope and infra-gravity wave are less pronounced but still indicate bound long waves.

5.4. Conclusion
To conclude this chapter an answer is formulated to the second sub-research question:

*What is the governing generating mechanism of infra-gravity waves at rocky shore platforms and in what way is this process influenced by the macro-tidal regime?*

Based on the cross-correlation analysis using field data and the calibrated XBeach model it is concluded that infra-gravity waves are, as expected, generated as bound long waves offshore and released in the surf-zone at the rocky-shore platform of Lilstock. For all tidal phases the cross-correlation coefficients show qualitatively the same patterns, which indicates that there is no shift of the generation mechanism towards breakpoint forcing. Hence, the generation mechanism is not modulated by the macro-tidal range.
6

SHOALING AND REFLECTION

Once established how infra-gravity waves are generated the shoaling and reflection behaviour across the platform will be investigated. Section 6.1 describes the method used to split incoming from reflecting waves which is required for the analysis. Section 6.2 presents the results of the shoaling and reflection behaviour. In section 6.3 discusses the methods and the possible dissipation mechanisms. Finally, section 6.4 will formulate an answers to the third and fourth sub-research question.

6.1. METHODOLOGY

Infra-gravity waves in coastal waters are usually a combination of an incoming (onshore directed) and reflected (offshore directed) component. For a quantitative analysis of the infra-gravity wave propagation, the low-frequency signals of both the field data and the XBeach model are separated into their incoming and reflected constituents.

SEPARATION METHODS

Two different methods are considered to decompose the infra-gravity wave signal. The first method, used for the separation of the field data, was initially developed by Mansard and Funke (1980) to compute the reflections in an irregular sea state for experimental investigations. To compute the incoming and reflecting signal the method requires simultaneous measurements of the surface elevation at three positions (PTs). By comparing the three co-existing spectra the incident and reflected spectra for one of the positions are determined using a least square method. Both spectra are independently derived for each frequency component (Mansard and Funke (1980), their equations 25 and 26) and subsequently transformed to the time-domain as an incoming and reflecting surface elevation. The method assumes a horizontal bottom and requires that the PTs are in reasonable proximity to each other. The first assumption is not valid for this research since the considered PTs are on a sloping platform. Therefore a small error will be induced by using this method. Appendix E.1 elaborates further on the assumptions, shows the test results of this method and proposes a correction, using 50% overlapping bursts, to improve the estimate.

The second method, for separating the incoming and reflecting constituents, uses the kinematic relation between the surface elevation and the cross-shore orbital velocity of the long wave as developed by Guza et al. (1984), equation 6.1.

\[
\zeta_{in} = \frac{1}{2} \left( \zeta + \sqrt{\frac{h}{g}}u \right) \quad \zeta_{out} = \frac{1}{2} \left( \zeta - \sqrt{\frac{h}{g}}u \right)
\]  

(6.1)

Where \( \zeta_{in} \) and \( \zeta_{out} \) are the incoming and reflecting components, \( \zeta \) is the surface elevation of the low-frequency signal and \( u \) the cross-shore current, \( h \) is the mean water depth and \( g \) the gravitational acceleration. This method assumes that all waves propagate in shallow water which is a valid assumption in the case of infra-gravity waves at the platform, as observed in Chapter 5. In order to compare...
the results to the previous method, the improvement using 50% overlapping Hanning bursts is applied to both methods.

Contrary to the first method, the one of Mansard and Funke (1980), the method of Guza et al. (1984) is not applicable to the field data. This is because there are no velocity data available at each PT. As a result the methods are implicitly linked to the two datasets, with an overlap for the method of Mansard and Funke (1980) that is applicable for both datasets. However, the method of Mansard and Funke (1980) will induce an error due to the invalid assumption of a horizontal bottom. Therefore the method of Guza et al. (1984) is preferred.

The incoming and reflection waves are determined for both the field data and the XBeach model results. The reason why both are used for the analysis is twofold. First of all, using the XBeach model is preferred since that allows to separate the infra-gravity waves with the method of Guza et al. (1984), that is generally more reliable. Although, to validate the results of that method a comparison is required to the field data. Secondly, the model is not restricted to the PT-locations which allows to compute incoming and outgoing infra-gravity waves all across the platform. The latter is essential to compute shoreline reflection coefficients at similar water depths.

**Bulkparameters**
The original low-frequency surface elevations are first bandpass filtered $(0.004 - 0.055 Hz)$ and subsequently de-trended before either of the previous methods are applied to separate the signal. Bulk parameters are derived from the incoming and reflecting signals, following the same procedure as explained in section 3.2. To be consistent with former literature the infra-gravity wave height is computed as the $H_{m0,IG}$ for both the incoming and reflecting signals with subscripts in and ref respectively. The analysis to determine the shoaling and reflection behaviour are, unless stated otherwise, based on these values.

**Terminology**
Free wave shoaling is defined as the increase in wave height due to a conservation of energy flux while waves approach shallower water. For bound infra-gravity waves holds that the increase in wave height is not solely related to the conservation of energy flux. Due to the enhancement by incident short wave groups, bound long waves gain energy from higher frequencies (Battjes et al., 2004; Longuet-Higgins and Stewart, 1962). In this research infra-gravity wave shoaling is examined by investigating the incoming infra-gravity wave height across the platform. Thereby the increase of infra-gravity wave height is not solely the conservation of energy flux but includes other possible sources and sinks of infra-gravity wave energy. The term ‘shoaling’ is thereby not directly related to the conservation of energy flux.

### 6.2. Results

The results in this chapter present the incoming and reflecting waves based on the field data and the calibrated XBeach model. First the shoaling of the incoming infra-gravity waves are investigated in section 6.2.1. Thereafter the reflection behaviour is described in section 6.2.2.

**6.2.1. Shoaling**

Figure 6.1 shows the infra-gravity wave height of the incoming and the reflecting components for the third and sixth tidal cycle based on the XBeach results. A moving window is used to obtain a quasi-continuous pattern, instead of subsequent bursts. The results are shown up an till the depth contour of $0.75m$. To describe the shoaling the focus is for now solely on the incoming components. Section 6.2.2 discusses the reflecting components. For the high-tide a clear increase of the incoming infra-gravity wave height is observed towards the shoreline, this holds for both the calm and the energetic wave conditions. During mid-tidal phases the increase is less pronounced and tends to decrease closer to the shoreline. The growth of the incoming infra-gravity waves, in spatial and temporal domain,
6.2. RESULTS

Figure 6.1: Incoming and reflecting infragravity wave heights in spatial and temporal domain for the third (left) and sixth (right) tidal cycle, based on the XBeach results, computed using the method of Guza et al. (1984).

complies to the observations based on the field data as presented in section 3.3.2 in a way that high incoming infragravity waves are observed at the same locations as high total infragravity wave signals. For a closer look into the shoaling behaviour of the incoming infragravity waves, the cross-sections of three bursts are examined. Figure 6.2 presents the incoming infragravity wave height based on the XBeach model and the measurements for the sixth tidal cycle. It is observed that the results based on the field data (obtained with the method of Mansard and Funke (1980)) deviate from the model result (obtained with the method of Guza et al. (1984)) and mainly overestimate the incoming wave height compared to the XBeach results. This is a result of the different methods used to determine the incoming wave height and the inaccuracy of the model. Section 6.3.1 elaborates further on this. The wave heights of the incoming components are compared to theoretical limits for bound ($H \sim h^{-5/2}$) and free ($H \sim h^{-1/4}$) wave shoaling with respect to the wave height at $x = 0$, as described by Battjes et al. (2004). During high-tide (burst 11 in figure 6.2) significant increase in infragravity wave height is observed, larger than the free-wave limit, however not as high as the theoretical limit for bound wave shoaling. Only the most offshore measured infragravity wave heights, based on the field data, tend to follow the shoaling limit for bound-long waves. For mid-tide (burst 5) the increase of $H_{m0,IG, in}$ is close to the free-wave limit apart from the section close to the shoreline ($h < 2m$) where a decrease of $H_{m0,IG, in}$ is observed. For lower tidal levels, when the shore-line faces the sloping platform instead of the cliff (burst 1), solely a decrease in infragravity wave height is observed for the sixth tidal cycle. Appendix E.2 shows the results of the other tidal cycles. In general for all energetic offshore conditions (tide 4-7) holds that for mid and high-tides the shoaling is higher than the limit for free waves, and that the first burst shows a considerable decrease. Opposed to the less energetic conditions (tide 1-3) where the shoaling is for all bursts very close to the free-wave limit. From the cross-correlation analysis in Chapter 5 it is concluded that, most convincing for mid- and high-tidal phases, the infra-gravity waves are bound to the short wave group. The incoming infragravity waves are consequently expected to shoal
as a bound long wave, which is at least close to the theoretical limit of \( H \sim h^{-5/2} \). However the results in figure 6.2 show that the shoaling limit is in most cases closer to the limit for a free-wave. This suggests that infra-gravity wave energy is lost due to dissipation. It is expected that the weaker enhancement is, among others, a result of the rough surface of the platform. This assumption is substantiated by the high bed friction coefficient \( c_f \) as calibrated in chapter 4, table 4.2. Due to the extreme roughness of the platform the long waves and mean currents experience a high bed friction. Consequently, a significant amount of infra-gravity wave energy is lost by turbulence. As a result the infra-gravity wave grows less strong or even starts to decrease. Especially when the water depth is small, i.e. during mid-tidal phases, a stronger interaction between the infra-gravity waves and the platform is expected, resulting in a stronger decrease in infra-gravity wave height, as observed in figure 6.2. Section 6.3.2 investigates this assumption in more detail.

GROWTH RATE

Although the growth of the incoming infra-gravity wave at high-tide is not as strong as expected, the enhancement is at least stronger than the limit for free-wave shoaling according to Greens Law. This indicates that there is an additional forcing of the incoming infra-gravity waves for higher tidal levels, that is compliant to the observed generating mechanisms. To investigate this and generalise the shoaling behaviour, the growth rate of each incoming infra-gravity wave height is evaluated by fitting a function of the local water depth with an unknown parameter \( \alpha \) to the results of the XBeach model.

\[
H \sim h^{-\alpha}
\]  

(6.2)

This is done for the results of all tidal cycles in the shoaling zone, i.e. the cross-shore section for which holds \( h > H_{rms,SH}/0.31 \). Appendix E.2 shows the curves for \( \alpha \) that fit the incoming wave heights. The obtained values of \( \alpha \) can be related to the normalised bed-slope \( \beta_b \), as described by equation (2.7) with \( h_x \) the averaged bed-slope of the shoaling zone and \( h_b \) the depth at the edge of the surf-zone. For the mild-sloping regime \( (\beta_b < 0.1) \) it is expected that the value of \( \alpha \) tends towards 2.5 opposed to the steep-sloping regime \( (\beta_b > 0.45) \) where the value of \( \alpha \) is expected to approach 0.25, in agreement with Green's Law. Figure 6.3 shows that for increasing values of \( \beta_b \) solely low values of \( \alpha \) are observed, and that the highest values of \( \alpha \) are found for the lowest values of \( \beta_b \), as expected. However, the dependency of
the growth rate $\alpha$ on the normalised bed slope $\beta_b$ is weaker compared to the results of Van Dongeren et al. (2007). This is explained by the values of $\beta_b$ which are, for almost all cases, well in between the thresholds for the mild- and the steep-sloping regime. The averaged bed-slope varies between 0.04 and 0.02 for different tidal phases and as a consequence there is not a strong preference for either regimes. This confirms also the discussion of the results in section 5.3. The values of $\alpha$, based on the results of the calibrated XBeach model, vary approximately between 0.2 and 0.8, where for higher tidal levels the values of $\alpha$ are generally higher compared to lower tidal levels. This confirms the observations in figure 6.2 and shows that the shoaling of the incoming infra-gravity wave, described by the increase of its wave height, is found to be modulated by the tide with a stronger enhancement for high-tide compared to mid-tidal phases. For some bursts the values of $\alpha$ are even lower than the free-wave limit of $\alpha = 0.25$ which indicates dissipation of the incoming infra-gravity wave, possibly by bottom friction as will be investigated in section 6.3.2.

AMPLIFICATION FACTOR

On an aggregate level, the shoaling behaviour, in terms of growth (or decay) of the incoming infra-gravity wave height in the shoaling zone, is a combination of several processes. Therefore, this could be considered as a bulk parameter in itself. The $\alpha$-parameter describes the growth rate however it lacks on describing the actual amplification of the incoming infra-gravity wave across the shoaling zone. Therefore an amplification factor is defined as in equation 6.3,

$$A = \frac{H_{IG,in,\text{sz}}}{H_{IG,in,PT15}}$$

with $H_{IG,in,\text{sz}}$ the incoming wave height at the edge of the surf-zone, of which the location is determined using the breaking criterion of Miche (1944), and $H_{IG,in,PT15}$ the incoming infra-gravity wave height at the most offshore located PT. Thereby the value of $A$ described the amplification of the infra-gravity wave across the shoaling zone at the platform. To investigate the dependency of $A$, the amplification factor is related to the tidal level, offshore wave steepness, incident wave period and the wave height measured at the offshore PT, deshoaled to deep water. For consistency the offshore steepness is determined using the deshoaled wave height and the corresponding deep water wave length. For all scatters the correlation coefficient $r^2$ and the slope $a$ of the linear regression is determined as a measure for the dependency. The results in figure 6.4 show that for all tidal cycles the amplification factor increases slightly with higher tidal levels (a) which corresponds to the observation of the shoaling behaviour as presented in figure 6.2 and figure 6.3. Furthermore the amplification factor seems to be stronger related to the offshore wave steepness (b) and the deshoaled wave height (d) than to the wave period (c). With increasing offshore wave steepness, and increasing offshore wave height, the [Figure 6.3: Growth rate of the incoming infra-gravity wave height based on XBeach results as a function of $\beta_b$ (left) and $\eta_{\text{mean}}$ (right).]
amplification factor seems to decrease from \( \approx 2.1 \) to \( \approx 1.2 \) this dependency confirms the idea that the incoming bound long waves are enhanced less in the shoaling zone as the incident short waves are steeper (e.g. Baldock and Huntley, 2002; Battjes et al., 2004). Because steeper waves break further offshore, i.e. in relatively deeper water, this shortens the cross-shore extent of effective energy transfer to the forced waves. Hence, this decreases the amplification across the shoaling zone. Finally, the dependency of the amplification of the incoming infra-gravity wave on the offshore steepness, contributes to the suggestion of Baldock (2012). He states that the type of surf-beat that is generated, is not solely depending on the relative steepness of the forced (passive) infra-gravity wave but also on the steepness of the forcing (active) incident short waves.

### 6.2.2. Reflection

This section presents the reflection coefficients and surf-similarity parameter to investigate the reflection behaviour of infra-gravity waves on a rocky shore platform. Figure 6.1 presents also the wave height of the reflecting waves, propagating in offshore direction. The reflection coefficient is consequently defined as the ratio of the reflected infra-gravity wave height divided by the incoming infra-gravity wave height, similar to Van Dongeren et al. (2007),

\[
R(x, t) = \frac{H(x, t)^{-}/ \bar{H}(x, t)^{+}}{H(x, t)^{-}/ \bar{H}(x, t)^{+}}.
\]

Both tidal cycles show a clear tidal modulation of the infra-gravity wave reflection. The significant growth of the incoming infra-gravity wave height during high-tide, in combination with the steep cliff, result in a high reflection of the incoming wave. As opposed to the mid-tidal phases where, due a reduced growth of the incoming infra-gravity wave, in combination with a milder-slope, less infra-gravity wave energy is reflected.

**Shoreline reflection**

To investigate the tidal-modulation of the infra-gravity wave reflection in more detail figure 6.5 presents the coefficients at the shoreline as a function of the mean surface elevation. For the measurements the reflection coefficients at the most onshore located PT are considered. The reflection coefficients...
based on the XBeach model are presented for the 0.75\textit{m} depth contour. Both the field data and the model results, show a similar pattern of low and high reflection coefficients. For mean water levels of $\eta_{\text{mean}} < 3\text{m}$, the reflection coefficients are in the order of 0.35 for all tidal cycles. For higher mean water levels, the high-tidal phase, the reflection coefficients reach to approximately 0.8. This transition is attributed to the shoaling behaviour as presented in the previous sections and to the presence of the steep cliff. For $\eta_{\text{mean}} > 3.5\text{m}$ the XBeach results show a clear decrease of the reflection coefficient. This is assigned to the presence of a gravel barrier (beach) at the cliff-toe. When the shoreline faces this steep barrier, the incoming infra-gravity wave reflect almost completely resulting in high-reflection coefficients. When the water level rises further ($\eta_{\text{mean}} > 3.5\text{m}$), the 0.75\textit{m} depth contour extends on top of the gravel barrier where the shore-line faces a milder-slope and the incoming infra-gravity wave dissipates. Consequently, the reflection coefficients decrease by approximately 25%. Since the onshore located PT is placed just in front of the barrier, the field data show solely high reflection coefficients for $\eta_{\text{mean}} > 3.5\text{m}$. Furthermore, the high-permeability of the barrier is expected to absorb a large portion of the infra-gravity wave energy. It must be noted that this permeability is not taken into account in the bathymetry of the model. As a result, the reflection coefficients are overestimated by the model for the bursts that directly face this barrier.

**LOW-FREQUENCY SURF SIMILARITY**

The reflection behaviour at the shoreline can also be described using the surf-similarity parameter $\beta_H$. This parameter is of similar form as the normalised bed slope $\beta_b$ and is described with equation (2.8), after Battjes et al. (2004), as elaborated in section 2.3. For the application of $\beta_H$ the XBeach model results for Lilstock, the bed slope of the swash zone is determined similar to De Bakker et al. (2014). Therefore the empirical relation of Stockdon et al. (2006) is used, equation (6.4), using the offshore wave conditions, appendix C.1.

$$S_{IG} = 0.06(H_0L_0)^{1/2} \quad (6.4)$$

With $H_0$ the offshore wave height and $L_0$ the deep-water wave length ($L_0 = gT_0^2/2\pi$). Although this relation is originally developed based on swash measurements at dissipative beaches it is assumed to be a reasonable approximation of the swash zone. The center of the swash zone is taken as point where the mean water level of the considered burst intersects with the platform slope. Figure 6.6 shows the swash slopes $h_x$ as obtained for all tidal cycles. Since the parameter $\beta_H$ is a low-frequency equivalent of the relative steepness $\zeta$, it is important that the steepness of the infra-gravity wave is well described. Therefore the root-mean-square wave height ($H_{rms,IG}^+ = \sqrt{8m0^2}$) based on the incoming infra-gravity wave signal is used instead of the significant wave height ($H_{m0,IG}^+ \cdot$). The values of $\beta_H$ are calculated for the bulk infra-gravity frequency band (0.004 – 0.055 Hz). The radial frequency is therefore assumed...
constant for all considered bursts with the mean frequency $f = 0.0255\,Hz$. Thereby $\beta_H$ is only depending on the bed-slope and the incoming infra-gravity wave height. To evaluate the effect of the macro-tidal range the corresponding tidal elevation is indicated using colors. Figure 6.7 presents the obtained values of $\beta_H$ in relation to the corresponding reflection coefficients at the 0.75$m$ depth contour, appendix E.3 presents the same relation, with similar results, for other depth contours close to the shoreline. The line in figure 6.7 gives the theoretical relation between the surf-similarity parameter $\beta_H$ and the reflection coefficients as described by equation 2.10. The results in figure 6.7 show that the bulk reflection is reasonably well described by the relation of Battjes et al. (2004). For low-tide the data tends to follow the theoretical relation quite well. However, some scatter is observed toward higher values of $\beta_H \approx 2$. For high-tide ($\eta_{mean} > 3m$) solely high reflection coefficients are observed in order of $R \approx 0.70$. The theoretical limit of $R = 1$ is never met since there is always some dissipation at the shoreline due to effects of viscosity and turbulence. For smooth slopes a reduction factor of 0.8 is proposed, as was already described by Battjes (1974). Interesting from this presentation, compared to figure 6.5, is the insight that the reflection coefficients for mid-tidal phases correspond to low values of $\beta_H$ and are well described by $R = 0.2\pi\beta_H^2$. This suggests that for mid-tidal phases infra-gravity waves are dissipated at the shoreline by long-wave breaking and during high-tide almost all infra-gravity waves reflect. It is mentioned that the results are based on the calibrated XBeach model with a high bed shear stress, that could be of influence on the reflection behaviour. This effect is investigated in section 6.3.2.
STANDING WAVES

The high-reflection coefficients, in combination with the effective shoaling of infra-gravity waves during high-tide, provide conditions for low-frequency standing waves to occur at the platform. Interestingly this has already been observed based on the cross-correlation analysis in Chapter 5.

In case of a standing wave the observed infra-gravity wave remains at one location instead of propagating in onshore or offshore location as an progressive wave. If so, the phase relation between the infra-gravity waves observed at subsequent locations, i.e. at neighbouring PTs or grid-cells, should be zero. In a cross-correlation analysis this results in a small ridge of positive, or negative, correlation with zero phase-lag with respect to each other, expected close to the shore-line. Figure 5.5 indicates this typical chessboard-like pattern for the high-tide burst, when the shoaling is at its largest. From this pattern, both observed for the measurements and the calibrated model, in combination with the high-reflection coefficients, it can be concluded that for high-tide low-frequency standing wave are observed close to the cliff.

6.3. DISCUSSION

In this section the results are discussed. First, the two methods, used for the separation of incoming and reflection components, are compared in section 6.3.1. Thereafter, the possible dissipation mechanisms of infra-gravity waves at rocky shore platforms are discussed in section 6.3.2. Furthermore, the latter section will focus on the applicability of the \( \beta_H \) parameter.

6.3.1. COMPARISON OF METHODS

In this thesis two methods are used for the separation of the incoming and reflecting signals. To assess the validity of these methods the results based on field data and the XBeach model are compared. Simultaneously this is an assessment of the modelling capabilities of XBeach with respect to the incoming and reflecting wave heights. Figure 6.8 shows the infra-gravity wave heights of the incoming,

![Figure 6.8: The infra-gravity wave heights of separated signals based on Mansard and Funke (1980) for field data and XBeach model results. Colors indicate the chronology of the tidal cycles from light to dark.](image-url)

reflecting and the combined (incoming + reflecting) signal determined with the three-PT method of Mansard and Funke (1980) based on the field data and the calibrated model for all tidal cycles. The infra-gravity wave height of the combined signal corresponds very well to the validation of the XBeach model in Chapter 4, table 4.2, the root-mean-square error deviates only by \( 0.001m \). The incoming infra-gravity wave height shows a slight overestimation of the model compared to the field data where the reflecting signal shows a small underestimation. The spreading, in terms of \( \epsilon_{r_{\text{rms}}} \) is for both signals in the same order. Once established that the accuracy of the separated signals is similar to the accuracy of the original infra-gravity wave signal, the methods are compared. In theory the sum of the incoming and reflecting signal reproduces the original signal. Since the method developed by Mansard and
Funke (1980) derives both the incoming and reflecting spectra independently. A first check is to compare the combined signal with the original time-series. Figure 6.9 shows an example of both separated signals and a comparison between the original and combined signal indicating a reasonably good reproduction of the original signal. For the method of Guza et al. (1984) this check results in an exact reproduction of the original signal by virtue of the method. To quantify the difference between original and combined signal, both methods are applied to the XBeach results of all tidal cycles. Figure 6.10 shows the infra-gravity wave heights based on both methods indicating a strong correlation. The combined signals of both methods result in virtually identical infra-gravity wave heights with negligible errors although the separated signal are both overestimated by the method of Mansard and Funke (1980) compared to the method of Guza et al. (1984). Interesting is the overestimation of 14% for the incoming wave height, which is significantly larger compared to the other signals. This overestimation is mainly attributed to the assumption of a horizontal bed which is invalid for the platform at Lilstock.

**Implications for the calibration of $c_f$**

Assuming that the method of Guza et al. (1984) is more reliable compared to the three-PT method, it could be reasoned that the incoming infra-gravity wave used as boundary conditions of the XBeach
model, is initially also 14% too high. As a result the model, without calibrated settings, overestimates the incoming and the reflecting infra-gravity wave height at the platform. To compensate for this effect more energy should be dissipated to match the field data, resulting in a higher calibrated value of $c_f$.

Using this concept, the small overestimation of the incoming and underestimation of the reflecting signal, as observed in figure 6.8, can be explained. The higher value of $c_f$ affects both the, initial too high, boundary condition and the resulting reflecting signal. The reflected signal experiences a bottom friction that is too high and therefore be underestimated. The underestimated reflecting signal consequently decreases the combined infra-gravity wave signal. Since the calibration of the XBeach model is performed on the combined signal instead of the incoming signal, the decrease of the combined signal will subsequently require a smaller value for $c_f$. In the end a value for $c_f$ is obtained that overestimates the incoming signal which is balanced by an underestimated reflecting signal, resulting in a combined signal that has the smallest error with respect to the field data. To investigate the influence of this effect on the value of $c_f$ the model could be run using a modified, gained, incoming infra-gravity wave. Also the calibration should be performed on the incoming infra-gravity wave signal and not on the combined signal. This is appointed for further research in section 7.3.

6.3.2. DISSIPATION MECHANISMS

During the presentation of the result on infra-gravity wave shoaling and reflection, possible dissipation mechanisms are indicated. This section investigates these postulations to discuss the possible dissipation mechanisms. First the importance of dissipation by bottom friction is investigated using the XBeach model. Followed by an investigation on the assumption of long-wave breaking by discussing the interpretation of the $\beta_H$ parameter.

BOTTOM FRICTION

To investigate the assumption that the roughness is an important control on the decay of the incoming infra-gravity wave height, the XBeach model is used. Since the $c_f$ value is responsible for the bed-shear stress, changing this value allows to investigate the response of the infra-gravity growth to the roughness of the platform. Figure 6.11 presents the incoming infra-gravity waves for model results with $c_f = 0.003$. This value is selected since this makes it comparable to sandy beaches. Compar-

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Figure 6.11: Incoming infra-gravity wave height for three selected bursts during the sixth tide based on XBeach results. Results shown for $c_f = 0.003$ and $c_f = 0.08$. Dashed line indicates the edge of the surf-zone.
ing the incoming infra-gravity wave height three things are observed. First of all, the incoming wave height corresponding to $c_f = 0.003$ results, as expected, in higher absolute values compared to the infra-gravity wave height corresponding to $c_f = 0.08$. Secondly, the increase of incoming infra-gravity wave height due to less bed friction is more significant for burst 1 (48% increase at the shoreline by less friction) compared to burst 11 (33% additional increase at the shoreline due to less friction). For burst 1 the decreasing infra-gravity wave height, based on $c_f = 0.08$, transforms even to an increasing infra-gravity wave height for $c_f = 0.003$. Conform to expectations, this shows that the bed friction is a stronger control on the growth of the incoming infra-gravity waves for mid-tidal cases, i.e. shallow water at the platform, compared to high-tidal cases. Finally the incoming infra-gravity wave height of burst 1 tends to shoal as a free wave ($H \sim h^{-1/4}$) when there is only little friction applied ($c_f = 0.003$). Since, the reference location ($x = 0$) of this burst is already close to the edge of the surf-zone ($x = 20$). Hence, the long-wave is already close to a free wave at this point. As a result the increase of the wave height compared to $x = 0$ will be close to Green’s Law. To evaluate the growth rate for all bursts the $\alpha$ parameter is determined for the model results with $c_f = 0.003$. Appendix E.2 shows the results for all bursts. On average the growth rate, in terms of the $\alpha$ parameter for the shoaling zone, increases with 27% from 0.46 to 0.58 with decreasing bottom friction from $c_f = 0.08$ to $c_f = 0.003$.

Although higher values of the incoming infra-gravity wave height are observed based on the model results with less friction, the increase in infra-gravity wave height is still less than the theoretical limit for shoaling bound long waves. Therefore, the assumption that bottom friction is responsible for the lower shoaling behaviour is only partly valid. More important is that the shoaling limit for bound long waves of $H \sim h^{-5/2}$ is derived for an infinite long and very mild sloping beach (Battjes et al., 2004). The resonance between short wave group and bound long wave needs time to build up and since the observations only stretch over 220 m it is virtually impossible to reach the theoretical limit. This being said, the dissipation of infra-gravity wave energy by bottom friction is still considered as a significant dissipation mechanism for this rocky shore platform.

**LONG-WAVE BREAKING**

The reflection behaviour, as presented in section 6.2.2, suggests long-wave breaking as a dissipation mechanism for infra-gravity waves close to the shoreline during mid-tidal phases at the rocky shore platform. This confirms the research by Van Dongeren et al. (2007) that concluded long-wave breaking as a dominant dissipation mechanism for infra-gravity waves on a mild-sloping beach. It must be noted that the results in section 6.2.2 are based on the calibrated model with a significant friction

![Figure 6.12: Normalised bed slope in relation to the reflection coefficient at the 0.75m depth contour based on the XBeach model with $c_f = 0.003$.](image-url)
Figure 6.13: The difference in reflection coefficients between the $R_{cf}=0.08$ and $R_{cf}=0.003$, referred to as $\Delta R$ as a function of $\beta_H$.

The mechanism of long-wave breaking is investigated in more detail by computing the shoreline reflection and $\beta_H$ parameter for four separate frequency bands, similar to the method of De Bakker et al. (2014). For each frequency band the $\beta_H$ and $R$ are determined based on the energy within the considered frequency domain $\Delta f$. The results in figure 6.14 show that infra-gravity waves with very low frequencies ($0.004Hz - 0.014Hz$) tend to preserve their energy, resulting in higher reflection coefficients for all tidal phases. Focusing on the higher frequency ranges, the $\beta_H$ parameters and the reflection coefficients decrease rapidly with increasing frequency. Especially for high-frequencies (> 0.025Hz), that are generally more susceptible to wave breaking due to a higher wave steepness, low reflection coefficients ($R < 0.2$) are observed for mid-tidal phases.

**INTERPRETATION OF $\beta_H$**

The normalised bed-slope, or relative steepness parameters, $\beta_H$ is used qualitatively to described the reflection behaviour. Although it lacks on a quantitative interpretation of the values for $\beta_H$ which is discussed in this section. Theoretically the transition from breaking to reflection is defined by the value of $\beta_H$ from where reflection coefficients of $R = 1$ commence, i.e. the intersection between $R = 0.2\pi\beta_H^2$ and $R = 1$, however in practice the value of $R = 1$ is never met. Consequently, the transition is estimated based on the presentation of $\beta_H$ versus $R$. To investigate the transition from breaking to reflection the frequency dependent $R$ and $\beta_H$ values are combined in one plot, figure 6.15, and zoomed in on the lower range of $\beta_H$ values where the transition is expected. It is observed that the values of $\beta_H$ deviate from the theoretical relation to higher values. Similar to findings of De Bakker et al. (2014) the transi-
tion from breaking to reflection is estimated for $\hat{\beta}_{H, tr} \approx 3$. This value is larger compared to the original findings of Battjes (1974) ($\xi_{tr} = 3.16 \sim \hat{\beta}_{H, tr} = 1.26$) and the laboratory data described by Van Dongeren et al. (2007) ($\hat{\beta}_{H, tr} = 1.25$). In their paper De Bakker et al. (2014) attributed this difference, and the higher values of $\hat{\beta}_H$, to the position where the reflection was measured and the selection of $H^+$ and $T$ in a random wave field, which is less straightforward compared to the monochromatic infra-gravity cases in Van Dongeren et al. (2007).

Both reasons for the higher values of $\hat{\beta}_H$, and consequently the higher value of $\hat{\beta}_{H, tr}$, are investigated using the results of the XBeach model. Furthermore two additional reasons are proposed, related to the wave length and the critical steepness of the infra-gravity wave at the onset of breaking.

Figure 6.14: Surf-similarity parameter $\beta_H$ in relation to the reflection coefficient at the 0.75m depth contour for different frequency bands. Results are based on XBeach model with $c_f = 0.08$.

Figure 6.15: Surf-similarity parameter $\beta_H$ in relation to the reflection coefficient at the 0.75m depth contour for different frequency bands. Results are based on XBeach model with $c_f = 0.08$. 

Surf-similarity - frequency dependent
**Depth dependency** Appendix E.3 shows the results of reflection coefficients and $\beta_H$ values for other depth contours varying from 0.5m to 2.0m. The results shows that the value of $\beta_H$ is similar for all depth contours. Furthermore, for increasing depth contours the reflection coefficients decrease slightly however the reflection behaviour is similar to figure 6.7 for all depth contours, i.e. independent of the position selected to compute the reflection coefficients. This indicates that the value of $\beta_{H,ir}$ is not strongly related to the depth contour used to compute the reflection coefficients.

**Selection of $H^+$ and $T$** More important is the method used to compute the $\beta_H$ parameter for different frequency bands. As explained and derived in appendix E.3 the value of $\beta_H$ is linearly depending on the period of the infra-gravity wave by $T = 1/f$ and non-linear on the wave height by $H^{-1/2}$ or $m_0^{-1/4}$. Since the spectral moment ($m_0$) is depending on the width of the frequency domain ($\Delta f$), decreasing the width of the frequency domain by a factor four increases the value of $\beta_H$ by $\sqrt{2}$. Since decreasing the width of the frequency domain progressively increases the value of $\beta_H$ this boils down to a more fundamental problem. This dependency suggests that the infra-gravity wave steepness, defined as $H/L$, can not be derived properly using spectral parameters. In an irregular wave field, described as a Gaussian process using an amplitude spectrum with independent random phases, without quadratic phase coupling, the (relative) wave steepness is always unequally proportional to the period and the wave height. For a regular, monochromatic, wave the wave steepness is known as described by $H/L$. Therefore the relative steepness, described by $\beta_H$, is applicable for a monochromatic wave but not necessarily for an irregular wave field described by spectral parameters. Especially when the infra-gravity domain is sub-divided in smaller frequency domains. This knowledge on the dependency of $\beta_H$ helps, at least as one of the possible reasons, to explain the increasing deviation of results away from the theoretical limit as presented in figure 6.15, towards higher values of $\beta_H$. By virtue of the method used to compute $\beta_H$ for smaller frequency bins, no strong conclusions can be drawn on the $\beta_H$ value corresponding to the transition from breaking to reflection.

**Wave length** Furthermore the relation of $\xi = \sqrt{2}\pi\beta_H$ implicitly assumes a deep water wave length of $L_0 = gT^2/2\pi$ based on linear wave theory. While the relation is applied to shallow water conditions, using the incoming infra-gravity wave height $H^+$ at the shoreline, for infra-gravity waves that become non-linear close to the shoreline. As a result, the computed values for $\beta_H$ should be interpreted with great care in terms of relative steepness. To overcome this issue a first step could be to use the shallow water wave celerity $c = \sqrt{gh}$ to compute the wave length which seems more appropriate for the application.

**Infra-gravity wave steepness** Another possible way to explain the increasing deviation is, more from a physical point of view, by looking at the actual steepness of the waves. The breaking of infra-gravity waves is typically like a bore, which develops due to steepening of the front by long-wave self-self interaction (Van Dongeren et al., 2007). The wave front will probably have a similar steepness at the

![Figure 6.16: Concept of the difference in wave steepness between short waves and infra-gravity waves for the onset of breaking.](image-url)
onset of breaking for all waves however the wave length of infra-gravity waves is longer at the onset of breaking compared to the wave length of short waves at the onset of breaking. As a consequence the wave steepness \( s \), defined as the ratio of the wave height over the wave length, is lower for infra-gravity waves compared to high-frequency incident waves, indicated in figure 6.16. Following this reasoning the critical steepness for the onset of breaking could be lower for infra-gravity waves compared to short waves. Figure 6.15 shows a pattern similar to the relation of Battjes (1974) although with a large deviation from the theoretical relation. Going back to that original relation, the coefficient of 0.1 in equation 2.10 follows from a critical value of \( \xi_c \approx 2.3 \) as derived for the onset of breaking \((R = 0.5)\) for short waves. For which the reflection coefficient is written as:

\[
R_{th} = \frac{(H/L)c}{H/L} \sim m \xi^2 \quad \text{with } m \approx 0.1 \text{ for } \xi_c \approx 2.3 \quad (6.5)
\]

As reasoned above, if the critical steepness would indeed be lower for the onset of infra-gravity wave breaking, the relative steepness would increase. As a consequence a lower value of \( m \) in equation (6.5) could be derived. For these results, computed from the XBeach model with \( c_f = 0.08 \), and the methods used to determine the reflection coefficients and the values of \( \beta_H \) for different frequency bands, the lower coefficient of \( m = 0.01 \) provides a better description of the reflection behaviour as presented in figure 6.15. Although, as already discussed, the value of \( \beta_H \) is overestimated by virtue of the method used to compute it for separate frequency domains, so if the value of \( m \) would indeed be smaller due to a lower critical steepness it will probably have a value in between 0.1 and 0.01. To investigate the validity of this idea more research is required.

**OTHER DISSIPATION MECHANISMS**

The results as discussed previously indicate two mechanisms, i.e. bottom friction and long wave breaking, for dissipation of infra-gravity wave energy. However, there are other mechanisms that could contribute to the dissipation like the energy transfer from long waves back to short waves which is not accounted for in the XBeach model. Since these mechanisms are not considered in this research it is not possible to conclude on the governing dissipation mechanisms. However, it is possible to state that both the bottom friction and the long wave breaking are important drivers for the dissipation of infra-gravity waves.

### 6.4. CONCLUSION

In this chapter the infra-gravity wave signals are separated in incoming and reflecting constituents to asses both the shoaling and reflection behaviour of the infra-gravity waves. To conclude this chapter answers are formulated to the third and fourth sub-research question.

**SHOALING**

Sub-research question number three:

*How do infra-gravity waves shoal for different tidal phases and does this comply with the governing generating mechanism?*

The shoaling of infra-gravity waves across A-type rocky shore platforms, described by the wave height of the incoming infra-gravity wave, is found to be modulated by the macro tidal-range and the offshore wave conditions.

- **Tidal range:** For mid-tidal phases infra-gravity waves shoal close to the shoaling limit of free waves \( (h^{-1/4}) \). In some cases the weak enhancement leads even to a decrease of the incoming infra-gravity wave height. For high-tide, and energetic conditions, the increase of the incoming infra-gravity waves is stronger than free wave shoaling \( (h^{-1/4}) \) but not as strong as the theoretical limit for a bound-long wave \( (h^{-5/2}) \).
• **Wave conditions:** The amplification of the incoming infra-gravity wave height across the platform decreases for increasing offshore wave steepness. This is mainly attributed to the offshore wave height since the amplification is hardly affected by the wave period of the incident waves.

In Chapter 5 it is concluded that the infra-gravity waves are bound to the short wave group and not generated by breakpoint forcing. The observed shoaling behaviour for high-tide complies to the generating mechanism since the enhancement is stronger than solely free wave shoaling. The $\alpha$ values vary typically between 0.4 and 0.8 for high-tidal cases, corresponding to a $\beta_b$ value of 0.2 - 0.3. The lower growth rate is only partly explained by dissipation due to bottom friction as examined using the XBeach model.

**Reflection**

Sub-research question number four:

*How is the reflection behaviour of infra-gravity waves affected by the macro-tidal range?*

The reflection behaviour of infra-gravity waves experiences a strong modulation of the macro-tidal range on the A-type rocky shore platform of Lilstock.

• **High-tide:** Large reflection coefficients are observed ($R \approx 0.8$) since the shoreline faces the steep-cliff. This results in standing waves which have been observed as a relation of zero phase-lag close to the shoreline in the cross-correlation analysis of infra-gravity waves.

• **Mid-tidal phases:** When the shoreline faces the mild-sloping platform, lower reflection coefficients are observed ($R \approx 0.35$) which indicates strong dissipation of infra-gravity wave energy.

• **Frequency dependent:** Low-frequency infra-gravity waves ($< 0.014 \, Hz$) tend to preserve their energy resulting in high-reflection coefficients for all tidal phases. High-frequency infra-gravity waves ($> 0.025 \, Hz$) indicate a stronger dependency on the macro-tidal range with lower reflection coefficients for mid-tidal phases compared to high-tide.

The bulk reflection at the shoreline is reasonably well described by the relation of Battjes (1974) using the surf-similarity parameter $\beta_{bH}$. Although the values of $\beta_{bH}$, for an irregular wave field based on spectral parameters, for smaller frequency domains $\Delta f$, results in an overestimation of $\beta_{bH}$ proportional to $m_0^{-1/4}$.

**Dissipation**

Despite the absence of a specific sub-research question on infra-gravity wave dissipation mechanisms some conclusion are drawn.

Using the XBeach model it is found that dissipation by bottom friction is a strong control on the growth of the incoming infra-gravity wave height. Using a value of $c_f = 0.003$ a difference of 48% and 33% is observed in the infra-gravity wave height at the shoreline for mid- and high-tidal phases respectively. Concluding that the dissipation by bottom friction is significant for both tidal phases but more effective when the shoreline faces the mild sloping platform, i.e. the water depth at the platform is low.

Based on the reflection coefficients found at the 0.75m depth contour it is highly likely that for mid-tidal phases long-wave breaking is a strong control on the dissipation infra-gravity waves close to the shoreline. This confirms observations by De Bakker et al. (2014, 2016); Van Dongeren et al. (2007).
7

Conclusion, Discussion and Recommendations

This chapter will reflect on this thesis’ objective and answer the main research question. Therefore the findings in previous chapters and the answers on the sub-research questions are used.

7.1. Conclusions

In this thesis field data and a numerical model are used to investigate the transformation of infra-gravity waves on an A-type rocky shore platform. The main research question is defined:

*What is the significance of infra-gravity waves on A-type rocky shore platforms and how are the transformation processes modulated by the macro-tidal range?*

Based on a quantitative analysis of field data of the WASP project, infra-gravity waves on an A-type rocky shore platform are found to be in the same order of magnitude as other coastal morphologies, like sandy beaches, coral reefs or B-type rocky shore platforms. The maximum infra-gravity wave height of $H_{m,IG} = 0.34 \text{ m}$ was measured during energetic offshore wave conditions, with $H_s = 2.35 \text{ m}$ and $T_p = 7.2 \text{ s}$. A constant of proportionality to the offshore measured wave height of 0.14 is observed, which is in the same order of magnitude compared to values found for dissipative beaches. The field data show a strong tidal modulation of the infra-gravity wave height, with increasing importance both in spatial domain, towards the shoreline, and in temporal domain, with increasing tidal elevation. The percentage of infra-gravity wave energy, as part of the total wave energy at the platform, increases up to values of 55% at the shoreline for energetic offshore conditions.

Based on a cross-correlation analysis it is found that, for the A-type platform of Lilstock, the generation of infra-gravity waves is more similar to mild-sloping beaches opposed to B-type platforms and coral reefs. During mid- and high-tidal phases, the infra-gravity waves propagate towards the surf-zone as bound long waves, indicated by a strong negative correlation between the short wave envelope and the infra-gravity wave. Subsequently, and especially for mid-tidal phases, i.e. when the shoreline faces the mild-sloping platform and the surf-zone is wide, the bound wave is released as a free wave, indicated by a gradual shift towards positive correlation. For low-tidal phases, examined using the calibrated numerical model, the cross-correlation provides less clear results of the previous mentioned mechanism. Despite the weaker correlation, there is no convincing evidence observed of a shift in generating mechanism, towards breakpoint forcing, for lower tidal levels. As a result, it is concluded that, for all tidal phases, infra-gravity waves are predominantly generated offshore as bound long waves.

The growth of incident infra-gravity waves across the platform, during high-tide, is stronger compared to the limit for free-wave shoaling according to Green’s Law ($H \sim h^{-1/4}$). This behaviour is compliant to the expectations, since infra-gravity waves are found to be bound to the short wave group. For
mid-tidal phases a weaker enhancement is observed, which is partly attributed to the interaction of the infra-gravity waves with the rough platform surface due to dissipation by bottom friction, as investigated by modelling the propagation with different values of $c_f$. The bottom friction is found to contribute significantly to the reduced growth, and decay, of the incident infra-gravity wave height on rocky shore platforms, as opposed to the influence of bottom friction on the dissipation of infra-gravity waves on sandy beaches.

As a result of the effective shoaling of incident infra-gravity waves during high-tide, in combination with the steep-cliff faced at the shoreline, high reflection coefficients are observed of $R_{bulk} \approx 0.8$. The interaction of the incoming and reflecting waves result in low-frequency standing waves, observed as a ridge of positive or negative correlation with zero phase-lag based on a cross-correlation analysis. For mid-tidal phases, i.e. when the shoreline faces the mild-sloping platform, the shoreline reflection coefficients are considerably lower and frequency dependent. Although there are some reservations on the validity of $\beta_H$ in relation to $R$ and for smaller frequency domains, the relation between $R$ and $\beta_H$ suggests that high-frequency infra-gravity waves ($0.025 - 0.055 \text{Hz}$) tend to dissipate by long-wave breaking, where low-frequency infra-gravity waves ($0.004 - 0.014 \text{Hz}$) almost completely reflect for all tidal-phases.

In summary, the importance of infra-gravity waves on an A-type rocky shore platform increases for increasing tidal levels, owing to effective bound long wave shoaling, decreasing interaction with the rough platform surface and increasing reflection coefficient at the shoreline.

7.2. DISCUSSION
All rocky coasts with unconsolidated sediments present accentuated cliff retreat. Therefore, the rocky coast erosion is one of the most important management challenges with a high social relevance. Erosional processes are often experienced as destructive and unwanted, which is particularly the case with sea cliffs where management is commonly applied to stop cliff erosion, resulting in a modification of the cliff form (Masselink and Gehrels, 2014). However, this strategy could also cause erosion of adjacent beaches where the eroding cliff is an important source of sediment for the beach. This highlights the interconnectedness of rocky coasts with other coastal systems and the required integrated approach for these challenges. An understanding of the hydrodynamic processes responsible for the cliff retreat is therefore of vital essence.

CONTRIBUTION TO GEOMORPHIC DEVELOPMENT
The increasing importance of infra-gravity waves, owing to increasing tidal levels, is consequently augmenting the contribution of infra-gravity waves to erosion and geomorphic development of rocky shore platforms and cliff retreat. Due to large reflection coefficients for high-tide, at the location of the gravel beach, the removal of cliff-toe debris by reflecting infra-gravity waves is expected to be an important mechanism.

The periodically increase of the surface elevation by infra-gravity waves will increase the water depth and provides a mechanism to deliver more high-frequency energy to the base of the cliff. This mechanism is expected to be most important for the transition period from mid- to high-tidal phase. First of all, because the relative increase in water depth due to this mechanism is larger for smaller water depths compared to the highest water depths. Secondly, because for that particular moment the surf-zone is at its widest, which is an important control on the phase-lag between the crest of the short wave envelope and the crest of the released long wave. As explained in section 5.2.1, a gradual shift towards positive correlation is observed in the surf-zone for mid-tidal phases once the bound long wave is released. This implies that the short wave group ‘rides’ on the crest of the infra-gravity wave, which allows the saturated short waves to enter the shallow region and deliver thereby more energy to a higher portion of the cliff. For high-tide, i.e. when the surf-zone is shorter, the gradual shift to-
7.2. Discussion

Towards positive correlation is not observed because the transformation of the short wave envelope is prematurely disturbed by the presence of the cliff. Thirdly, due to the steep gravel beach, high reflection coefficients can result in low-frequency standing waves, which enhance the ‘super-elevation’ even further. However, the latter will be eased by permeability of the gravel beach which will absorb a large portion of the incoming infra-gravity energy.

Relevance to Sea Level Rise

The knowledge of increasing importance of infra-gravity waves for higher tidal levels could be used and related to the predictions for global sea level rise. Since there is no morphological feedback on short time scales, the water depths at the platform will increase as a direct consequence of the rising sea level. Due to larger water depths at the platform the duration of the high-tidal phase, i.e. when the shoreline faces the steep cliff, will increase and thereby extending the period that infra-gravity waves can dominate the platform. Since the infra-gravity wave height, and the relative importance with respect to the total wave energy, are found to increase for high-tide it could be reasoned that this may augment the contribution to erosion of the platform even further. Besides, the larger water depth could result in less interaction with the platform roughness, resulting in less dissipation and therefore a higher infra-gravity wave. Although the effect of a ‘super-elevation’ during high-tide is probably less significant for larger water depths, the process of removal of cliff-toe debris could become more important due to this effect. In summary, it is hypothesised that, as an effect of sea level rise, the relative importance of infra-gravity waves increases, which may probably contribute to the enhancement of cliff erosion.

XBeach as Hydrodynamic Model for Rocky Shore Platforms

Part of the WASP objective is to increase the predicting capabilities of the wave transformation on rocky shore platforms using numerical modelling. Therefore applications and limitations of the calibrated XBeach-SurfBeat model, as applied in this research, are briefly discussed. The calibrated model is used to assess wave transformation processes across the platform for mid- and high-tide phases at Lilstock. Without large modifications of the existing XBeach-SurfBeat model, the wave height of the short wave group and the infra-gravity wave, and the mean setup across the platform, can be reproduced with acceptable errors margins.

To apply this model for other sites, a bathymetric survey of the platform and wave boundary conditions are required. Reliable boundary conditions can be obtained from the measured surface elevation of three cross-shore located pressure transducers at the edge of the platform, or one pressure transducer in combination with a co-located ADV. Since the model parameters are calibrated specifically for the site of Lilstock, it is advised to consider the calibrated parameters with great care and if possible, recalibrate the parameters for other sites with different roughness scales.

Based on tests with simplified profiles, it is found that the roughness of the Lilstock platform can be parametrised using \( f_w \) and \( c_f \) as long as the shape of the platform, i.e. the mean water depth, is correct. This might of course be different for other platforms with larger roughness scales that also affect the transformation of the short waves and therefore requires a detailed bathymetry.

For an assessment of the hydrodynamics during the tidal phases lower than measured with the PTs, the spatial domain should be extended and offshore wave conditions should be considered to force the model. Therefore a bathymetric survey is required that extends towards, at least, the water depth at the point where offshore wave conditions are extracted. In larger water depths the dissipation by short wave bottom friction and the effective bed-stresses are considerably less significant compared to the same processes in the surf-zone. Therefore it is expected that, for the platform of Lilstock, the calibrated model parameters \( (f_w, c_f \text{ and } \gamma) \) are sufficiently reliable for application in a model with offshore wave conditions and an extended spatial domain.
In this research only the modelling capabilities of XBeach-SurfBeat are investigated since the model selection lies outside the scope of this thesis and had already been chosen by the WASP project. Although, there is a wide range of other models that could be applied. For example a phase-resolving model like XBeach Non-Hydrostatic or SWASH, which compute the surface elevation using non-linear shallow water equations, including a non-hydrostatic pressure. Focussing on the transformation of infra-gravity waves it is believed that a phase-resolving model will not significantly change the results nor lead to other conclusions since the low-frequency motions are in both models computed using the shallow water equations. However, when focussing on the transformation of the short waves it could be interesting to investigate the modelling capabilities of XBeach Non-Hydrostatic compared to the phase-averaged SurfBeat model. Although due to a high required grid resolution, and small time steps, the computation will probably be time consuming and therefore expensive.

7.3. **Recommendations**

In this study insight is obtained in the hydrodynamic processes on an A-type rocky shore platforms, although some aspects remain unclear and require more research. Therefore recommendations and opportunities for further research are indicated based on the findings in this report.

- **The effect of surface roughness** Based on the calibration for the platform of Lilstock, infra-gravity waves are found to be more susceptible to the platform roughness compared to the short waves. Since the roughness of the platform was typically parametrised, a more general relation, between the model roughness and the roughness scale measured in the field, could be obtained. It is recommended to perform a similar calibration of the XBeach-SurfBeat model for other rocky shore platforms with different roughness scales to investigate such a relation. Furthermore, it is recommended to extend the model in alongshore direction (2D) to assess the influence the spatial distribution of the roughness on the wave transformation.

- **Calibration procedure** The onshore directed infra-gravity waves, derived with the method of Mansard and Funke (1980), were used as boundary conditions for the XBeach model. However, the incoming infra-gravity waves were found to be overestimated by 14% when comparing them to the separation methods of Guza et al. (1984). The overestimation is partly attributed to the calibration procedure, which was performed for the total infra-gravity wave signal. To obtain a better estimate of the actual parametrisation of the surface roughness, it is recommended to calibrate the value of $c_f$, of future XBeach models forced with an incoming long wave, simultaneously for the combined and the incoming infra-gravity signal.

- **Implications for geomorphic development** As discussed the importance of infra-gravity waves might increases as an effect of sea level rise. Therefore it is recommended to investigate the relative contribution of infra-gravity waves, during a tidal cycle, for several sea level rise scenarios to investigate this hypothesis. Eventually the knowledge on the (infra-gravity) wave transformation across a rocky shore platform could be used to determine the erosion potential under certain conditions of future scenarios. The calibrated model for the platform of Lilstock, provides a tool to quantify the energy delivered to the base of the cliff, which could be responsible for the cliff erosion. However, the relation between the wave energy at the base of the cliff and the actual cliff retreat is still unknown, therefore this is indicated as an important topic for further research.

- **Natural variability** In this research a bandwidth around the spectral (bulk) wave parameters is determined using a moving window analysis, resulting in an averaged variability of $\pm 5.3 cm$ for the short waves. This bandwidth provided support for the calibration of the XBeach model and indicated the acceptable error margins. It is recommended to perform this analysis for field data of other coastal environments as a method to quantify the natural variability of the considered wave climate and investigate the validity of this proposed method.
• **Dissipation by non-linear interactions** The dissipation of infra-gravity waves by bottom friction and long-wave breaking are indicated as important dissipation mechanisms based on the calibrated XBeach model. However, this leaves the mechanism of dissipation by energy transfer from infra-gravity waves to higher frequencies untouched. Also because this mechanism is not included in the equations of the XBeach-SurfBeat model. Therefore it is recommended to investigate the effectiveness of energy transfer to higher frequencies as a dissipation mechanism for rocky shore platforms. This enables to conclude on the relative importance of each dissipation mechanisms.

• **Validity of normalised bed-slope** $\beta_H$ As discussed in section 6.3.2, there are some reservations on the computation and the application of the normalised bed-slope, or relative steepness, $\beta_H$ for irregular waves. First of all, it is recommended to be very careful with strong conclusions on the value of $\beta_H$ especially when this value is computed for smaller frequency domains due to the dependency by $\beta_H \sim \frac{1}{f n^4}$. Secondly, it is recommended to investigate some modifications of the relation between $\xi$ and $\beta_H$. To begin, it is proposed to use a wave steepness based on the shallow water wave length instead of the deep water wave length since that seems more appropriate for infra-gravity waves close to the shoreline. Furthermore, the amplification of the infra-gravity waves was found to increase for lower offshore short wave steepness, which lends support to the earlier proposed modification of $\beta_H$ by Baldock (2012). Both modifications are recommended for further research.

• **Critical wave steepness at the onset of breaking** Related to the previous recommendation, but also for wider applications, it is recommended to reconsider the critical wave steepness at the onset of breaking. In section 6.3.2 it is reasoned that the critical steepness at the onset of breaking, described by $H/L$, is lower for infra-gravity waves compared to short waves. However, the steepness of the wave front is expected to be more similar for both cases since it is related to the surface tension. Therefore it is proposed to investigate the shape-similarity of the wave-front at the onset of breaking.
BIBLIOGRAPHY


This appendix will elaborate on some of the techniques and assumptions which have been used for post-processing of the measured data to obtain bulk parameters as used for analysis of the wave transformation processes.

**A.1. Spectral Density Estimation**

Bulk parameters can be derived from a variance density spectrum which is a representation of the wave climate in frequency domain. This section elaborates on the steps to convert a signal from time to frequency domain and the implications due to a macro-tidal environment.

**Fourier Analysis**

A wave signal or measured time-series can be considered as the sum of a large number of harmonic wave components: a Fourier series (equation A.1). Using the technique of Fourier analysis, the values of the amplitude and phase for each frequency can be determined which can be presented as an amplitude and phase spectrum for the considered signal. This is also referred to as a spectral density estimation (SDE) of a time series.

\[
\eta(t) = \sum_{i=1}^{N} a_i \cos(2\pi f_i t + \alpha_i) \quad (A.1)
\]

With \(\eta(t)\) the water level elevation, \(N\) the amount of wave components, \(a_i\) the wave-amplitude, \(f_i\) the frequency and \(\alpha_i\) the phase. To obtain reliable and representative bulk parameters the considered signal should represent a process that is statistically stationary, which means that the statistical parameters of the waves are time-independent. Although at sea the wave records are never completely stationary, the signal length should not be too long to capture wave-climates that are approximately stationary.

The spectral resolution of the Fourier analysis is determined by the length of the signal with \(\Delta f = 1/T\) where \(\Delta f\) is the width of the frequency bin in \(Hz\) and \(T\) is the duration of the signal in seconds. Furthermore, the highest frequency that can be determined by a Fourier analysis is depending on the sampling rate (\(f_s\)) of the measurement device that converts a continues time-signal to a discrete time-signal. This frequency threshold is referred to as the Nyquist\(^1\) frequency which is by definition equal to the \(f_s/2\).

The SDE of a time-series can be determined in Matlab by using the Fast Fourier Transformation (fft) function to convert the signal from time to frequency domain. The fft-function applies a numerical algorithm that prefers a signal length which is a power of two (so: 128, 256, 512, etc.) which limits the possible lengths of the signal. Although, nowadays other values than a power of two can be used but increase computation time.

\(^1\)After Harry Nyquist (1889 - 1976)
IMPROVEMENTS BY WELCH’ METHOD
To improve the spectral density estimation and reduce noise the Welch’s method of overlapping segments is applied. Therefore a Hanning window is used which affords more influence to the center of the signal. The window function is described by a cosine function that is zero at the edge of the window and one in the center.

\[ w(n) = 0.5 \left( 1 - \cos \left( \frac{2\pi n}{N-1} \right) \right) \]  \hspace{1cm} (A.2)

Where \( w(n) \) is the window function, \( N \) the length of the window and \( n \) the number of samples in the window. Due to the window function the amplitude at the edge of the signal is attenuated to zero which results in a loss of information, to overcome this loss of information the segments are overlapped by 50% and averaged to get a more reliable spectral density estimate of the considered signal. It has to be noted that increasing the amount of windows in a burst for overlapping will decrease the length of each window and thereby increase the \( \Delta f \). So the improvement by averaging is in exchange of spectral resolution.

ERGODIC PROCESSES
If averaging of a signal over time gives the same results as averaging over an selection of the signal, the process is said to be ergodic Holthuijsen (2007). It follows that such an ergodic process is stationary. Using the variance of a signal as statistical parameter of a zero-mean (\( \mu_x = 0 \)) signal, than the variance of a ergodic process can be described using equation (A.3).

\[ \sigma^2 \approx \langle (x(t_i))^2 \rangle = \frac{1}{D} \int_0^D (x(t))^2 dt \]  \hspace{1cm} (A.3)

With \( \langle . \rangle \) denoted as averaging over selection \( i \) and \( D \) the duration of the signal. The surface elevation of random, wind-generated waves under stationary conditions happens to be such an ergodic process. However since a wave signal can never be completely stationary it can be reasoned that a wave signal can also not be completely ergodic. Follow this reasoning the variance of a segment is never completely identical to the variance of the burst. Its deviation, the relative variance of a segment with respect to the variance of the burst, can be described with (equation (A.4)).

\[ \text{Relative-variance} = \left( \frac{\sigma_n^2}{\sigma_l^2} - 1 \right) \]  \hspace{1cm} (A.4)

With \( \sigma_n \) the variance of segment \( n \) and \( \sigma_l \) the variance of the burst. Taking the time average of the absolute value of the relative variance over all segments \( N \) in the signal it can be quantified whether the signal is an ergodic process or how much it deviates from an ergodic process. This is referred to as \( E_r \) in equation (A.5).

\[ E_r = \frac{1}{N} \sum_{n=1}^{N} \left| \frac{\sigma_n^2}{\sigma_l^2} - 1 \right| \]  \hspace{1cm} (A.5)

Values of \( E_r \) equal to zero would indicate an ergodic process, and therefore stationary, since the variance of each segment is equal to the variance of the burst. On the other hand values larger than zero indicate that the process is not ergodic nor stationary and increasing values of \( E_r \) indicate less homogeneity of the considered burst. Equation (A.5) will be used to cope with the implications due to the macro-tidal environment.

IMPLICATIONS DUE TO MACRO-TIDAL ENVIRONMENT
In macro-tidal environments (\( TR > 4m \), Davies and Moses (1964)) there is a significant rate of change in water level during rising and falling tide. Resulting in a difference in water depth at the begin of a burst compared to the water depth at the end for the same burst. The variations in water depth will have most influence on the wave height of the energetic (short) waves due to depth induced breaking. Implying that if the length of a selected burst is increased for rising (or falling tide), the water depth
variation over the burst increases resulting in a decrease of stationarity of the burst because short waves at the start of the burst are more influenced by the bottom compared to short waves at the end of the burst. When a burst is split into segments, like in Welch’s method, the average wave amplitude could differ over the segments and since for each segment the spectrum density estimation is determined this could result in different estimations for the segments of the considered burst. So, to obtain a signal with a high homogeneity the selection of the burst length and the length of the segments for averaging should be such that there is minimal influence of the variation in water depth on the wave amplitude.

**SELECTION OF BURST LENGTH AND WINDOW SIZE**

Both the frequency resolution and the stationarity of the burst are important to generate representative bulk parameters for the analysis of (low-frequency) infra gravity waves. To select a representative burst length and window-size that minimize the influence of the macro-tidal environment on the bulk parameters three criteria have been formulated:

1. Since this research focuses on infra gravity waves with a lower limit of 0.004Hz the minimal required frequency resolution is set to $\Delta f = 0.004\text{Hz}$.

2. To improve the reliability of the spectral density estimate a maximum number of windows to Welch average the burst signal have to be used complying to the criterion above.

3. The combination of burst length and window size as determined by the criteria above should be as close to an ergodic process as possible to obtain a high level of stationarity for each burst.

Based on the first criterion the minimal burst length or segment length of $1/0.004 = 250\text{sec}$ is required. To comply to the preferences of the Fast Fourier transformation in Matlab a window size of 256sec is used since this is a power of two resulting in a $\Delta f = 0.0039\text{Hz}$. Using 50% overlapping windows for Welch averaging the possible burst lengths $l$ can be determined based on the amount of windows $N$ resulting in a length of $l = n((N - 1)/2 + 1)$. Three different burst lengths ($l$) have been considered to investigate the sensitivity of the burst length to the stationarity of the signal. Figure A.1 shows the stationarity calculated for measurement in Lilstock on 2014-12-11 using equation A.5 for three different burst lengths each build out of 256 second windows. It can be observed that a burst length consisting of three windows of 256 seconds results in large variations of the stationarity across the tidal cycle. Due to this inhomogeneity of stationarity a comparison between bulk parameters determined for each burst is not very reliable. Increasing the number of windows results in an increase of homogeneity across the tidal cycle, although values for stationarity decrease slightly. Furthermore if the burst length becomes too long due to a large number of windows the stationarity of the bursts decreases significantly close to the edge of the tidal cycle. This confirms the expectations as discussed.

To maximize the number of windows for a more reliable spectral density estimate and obtain a high level of stationarity for each burst which shows minimal variations across the tidal cycle, seven windows for Welch averaging are selected based on the results of figure A.1. This results in a selection for a burst length of 1024 seconds (8192 samples) using seven windows of 256 seconds (2048 samples) overlapping by 50% (1024 samples or 128 seconds). With this selection a frequency resolution of 0.0039Hz can be obtained while having a tidal elevation during each burst of 0.44$m$ averaged over the rising tide.
Figure A.1: Stationarity for different burst lengths with windows size of 256 seconds (Lilstock, 2014-12-11).

Figure A.2: Stationarity for different burst lengths due to different window sizes. All combinations have 7 windows for Welch averaging (Lilstock, 2014-12-11).

**JUSTIFICATION AND SIGNIFICANCE**

To investigate the sensitivity of the window size on the stationarity according to A.5 with a constant amount of windows for averaging an analysis has been performed varying the window size for averaging over 7 windows (figure A.2). It shows that on average the stationarity increases for longer window sizes however for window sizes of 512 seconds the stationarity decreases close to the edge of the tidal cycle which can be explained by increasing influence of the tidal signal on the wave amplitude. Furthermore for a window size of 128 seconds large variations of the stationarity are observed during the tidal cycle.

To justify the selected combination of burst length and window size the bulk parameters have been determined based on different burst lengths varying between 256 seconds (one window) and 2048 seconds (15 windows) all with window sizes of 256 seconds for Welch averaging. Figure A.3 presents the value for $H_{rms}$ at the most offshore pressure transducer at Lilstock (2014-12-11).

It shows that burst lengths with less than seven windows (blue lines) will tend to have large variations in $H_{rms}$ in the order of $O(0.1–0.2\, \text{m})$. Especially during high tide and increasing with a decreasing burst lengths. Burst lengths with more than seven windows (green lines) result in relative stable results of $H_{rms}$ with a small bandwidth in the order of $O(0.05\, \text{m})$. The selected burst length of 1024 seconds with seven windows seems, based on this figure, a good average of the results and therefore a representative combination to analyse bulk parameters.
A.2. Determine split frequency

In this research two wave categories are distinguished which have been classified based on their frequency range. Infra gravity waves are defined in the range of $0.004 - f_{\text{split}}$ Hz and short waves (or gravity waves) are defined in the range of $f_{\text{split}} - 0.4$ Hz. The lower limit for infra gravity waves and upper limit for short waves are arbitrary chosen however both values are commonly used in literature (e.g. Guedes et al., 2013; Henderson et al., 2006; Thomson et al., 2006). The value of $f_{\text{split}}$ is base on the spectral shape. If there is a significant peak in wave energy observed in the lower frequency range ($0.04 - 0.1$ Hz) the split-frequency can be determined taking the frequency of the local minimum between the low- and high-energy peaks. Else half of the peak-frequency ($f_p$) of the total spectrum is used as split-frequency according to Van Dongeren et al. (2007). This analysis has been applied to the spectra derived from the most offshore PT for all tidal cycles. To avoid influences of the wave transformation processes on the platform only the most offshore pressure transducer is considered. To obtain one value for each site (as a site characteristic) the determined values for the split frequency have been averaged over all bursts that are outside the surf-zone, where the edge of the surf-zone is based on the breaking limit of Miche (1944) (appendix A.3). This results in a split-frequency of 0.055 Hz for Lilstock. Figure A.4 gives an example of this method for two different spectra where a clear local minimum between a low- and high-frequency peak can be observed.

![Justification and significance](image) Figure A.3: Values of $H_{m0}$ at the most offshore pressure transducer for different burst lengths at (Lilstock, 2014-12-11). Blue lines indicate burst lengths smaller than 1024 seconds, the red line represents the selected combination of 1024 seconds and green lines represent longer burst lengths than 1024 seconds. All combination have a window size of 256 seconds complying to the first criterion.

![Figure A.4](image) Figure A.4: Example of two burst for determination of split frequency based on local minimum in wave spectra (spectra from Lilstock, 2014-12-11).
A.3. DERIVATION OF BREAKING LIMIT

When waves are propagating towards the coastline their wave height will increase due to shoaling. Subsequently the wave steepness will increase and when waves become too steep breaking will start. Based on Stokes theory Miche (1944) derived a relation for the limiting wave steepness, equation (A.6).

\[
\frac{H}{L}_{\text{max}} = 0.142 \tanh(kh) \quad \text{(A.6)}
\]

In shallow water \((h/L < 1/20)\) equation (A.6) reduces to:

\[
\frac{H}{L}_{\text{max}} = 0.142 \frac{2\pi h}{L} \approx 0.88 \frac{h}{L} \quad \text{(A.7)}
\]

Which is equivalent to the formulation for the breaking parameter \(\gamma\):

\[
\gamma_{\text{max}} = \frac{H_{\text{max}}}{h_b} \approx 0.88 \quad \text{(A.8)}
\]

According to the Rayleigh distribution for short wave statistics the highest wave during a storm is equal to two times the significant wave height: \(H_{\text{max}} = 2H_s\). Furthermore it can be derived from the Rayleigh distribution that the root-mean square wave height is \(\sqrt{2}/2\) times the significant wave height: \(H_{r,ms} = \sqrt{2}/2H_{ms0}\). Substituting both, equation (A.8) results in:

\[
\gamma_{H_{r,ms}} = \frac{H_{r,ms}}{h_b} = \frac{\sqrt{2}}{4} \gamma_{\text{max}} \approx 0.31 \quad \text{(A.9)}
\]

This value for the ratio of root-mean-square wave height over water depth is used to determine the edge of the surf-zone. By evaluating the value of gamma for each PT or grid point based on the instantaneous wave height and water depth the point where wave breaking commences can be indicated. Thereby breaking wave can be separated from non-breaking waves. It should be mentioned that this value of gamma assumes Rayleigh distributed waves.

A.4. NATURAL VARIABILITY

A bulk parameter is a stochastic parameters that describes the wave conditions in one value although some scatter around that single value should be considered which is referred to as the bandwidth of the bulk parameter. The bandwidth, as presented in figure A.5, is defined as a comparison between bulk wave parameters based on fixed (subsequent) bursts and a bulk parameters based on a moving burst. The value is computed using equation (A.10) where the moving burst is only compared with the fixed burst in the same domain.

\[
\epsilon_{\text{abs}}(i, t) = |B_{\text{sub}}(i) - B_{\text{mov}}(i, t)|
\]

Whit \(B_{\text{sub}}(i)\) any bulk wave parameters derived from the subsequent bursts for each PT \((i)\) and \(B_{\text{mov}}(i, t)\) a time-series of the bulk parameters derived for each step of the moving burst. To indicate the significance of the bandwidth the absolute difference is normalised by the value of the fixed burst as in equation (A.11)

\[
\epsilon_{\text{rel}}(i, t) = \frac{|B_{\text{sub}}(i) - B_{\text{mov}}(i, t)|}{B_{\text{sub}}(i)}
\]

It should be stressed that these values are not considered as an error since the bandwidth depends only on the moment in time that the surface elevation is discretized as described in section 3.2.3. The bandwidth values are presented as a box-plot in figure A.5 for the sixth tidal cycle. The considered dataset is not normally distributed which would result in a large amount of outliers when applying a whisker length of 1.5 times the quartile length. Therefore the whisker is set to the value corresponding to the 98th percentile, thereby the outliers present the top 2% of the dataset of for each PT. From
both time-series, as obtained by equation (A.10) and (A.11), the values corresponding to the 98th percentile are averaged across the surf-zone, outside the surf-zone and across the total platform resulting in three values of $\epsilon_{abs}$ and $\epsilon_{rel}$ for each tide. These values are determined for the short waves and the infra-gravity waves and presented in table A.1. To summarise these values table 3.4 in section 3.2.3 presents the mean values.

As discussed in appendix A.1 the reliability of a spectra will increase if the number of windows for Welch averaging increases. Although improving the estimate of the spectrum of one burst should not be linked the natural variability, as determined with the moving burst analysis discussed in this section. To investigate the effect of averaging with more windows on the bandwidth the same analysis is performed with 15 windows for Welch averaging. The last two columns in table A.1 give the bandwidth for all tides determines with 15 windows instead of 7 windows. On average the difference is negligible which indicates that the bandwidth around each bulk wave parameter, referred to as the natural variability, is indeed not coupled to the reliability of the spectra.
Table A.1: Bandwidth values for $H_{rms,SH}$ and $H_{rms,IG}$. For tidal cycle number two all PTs at the platform were located outside the surf-zone during the high-tidal phase, therefore no values are obtained inside the surf-zone.

<table>
<thead>
<tr>
<th>Tidal cycle</th>
<th>$\epsilon_{abs,SH,7}$ [m]</th>
<th>$\epsilon_{rel,SH,7}$ [%]</th>
<th>$\epsilon_{abs,IG,7}$ [m]</th>
<th>$\epsilon_{rel,IG,7}$ [%]</th>
<th>$\epsilon_{abs,IG,15}$ [m]</th>
<th>$\epsilon_{rel,IG,15}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PTs outside surf-zone</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>0.051</td>
<td>10.9</td>
<td>0.015</td>
<td>18.1</td>
<td>0.015</td>
<td>18.2</td>
</tr>
<tr>
<td>Tide 1</td>
<td>0.056</td>
<td>15.4</td>
<td>0.009</td>
<td>16.7</td>
<td>0.009</td>
<td>16.6</td>
</tr>
<tr>
<td>Tide 2</td>
<td>0.031</td>
<td>14.9</td>
<td>0.007</td>
<td>23.4</td>
<td>0.007</td>
<td>24.4</td>
</tr>
<tr>
<td>Tide 3</td>
<td>0.050</td>
<td>13.8</td>
<td>0.011</td>
<td>18.9</td>
<td>0.012</td>
<td>18.4</td>
</tr>
<tr>
<td>Tide 4</td>
<td>0.052</td>
<td>7.1</td>
<td>0.016</td>
<td>15.4</td>
<td>0.016</td>
<td>14.8</td>
</tr>
<tr>
<td>Tide 5</td>
<td>0.062</td>
<td>9.2</td>
<td>0.024</td>
<td>22.1</td>
<td>0.024</td>
<td>21.9</td>
</tr>
<tr>
<td>Tide 6</td>
<td>0.051</td>
<td>5.7</td>
<td>0.023</td>
<td>15.0</td>
<td>0.024</td>
<td>15.3</td>
</tr>
<tr>
<td>Tide 7</td>
<td>0.054</td>
<td>10.3</td>
<td>0.014</td>
<td>15.2</td>
<td>0.014</td>
<td>15.8</td>
</tr>
<tr>
<td>Mean</td>
<td>0.063</td>
<td>20.0</td>
<td>0.022</td>
<td>17.6</td>
<td>0.023</td>
<td>17.7</td>
</tr>
<tr>
<td>PTs inside surf-zone</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tide 1</td>
<td>0.065</td>
<td>27.4</td>
<td>0.014</td>
<td>17.7</td>
<td>0.015</td>
<td>17.1</td>
</tr>
<tr>
<td>Tide 2</td>
<td>Nvt</td>
<td>Nvt</td>
<td>Nvt</td>
<td>Nvt</td>
<td>Nvt</td>
<td>Nvt</td>
</tr>
<tr>
<td>Tide 3</td>
<td>0.069</td>
<td>27.1</td>
<td>0.018</td>
<td>19.1</td>
<td>0.019</td>
<td>18.3</td>
</tr>
<tr>
<td>Tide 4</td>
<td>0.056</td>
<td>13.9</td>
<td>0.024</td>
<td>15.1</td>
<td>0.028</td>
<td>17.1</td>
</tr>
<tr>
<td>Tide 5</td>
<td>0.070</td>
<td>17.0</td>
<td>0.035</td>
<td>23.1</td>
<td>0.033</td>
<td>22.3</td>
</tr>
<tr>
<td>Tide 6</td>
<td>0.061</td>
<td>8.9</td>
<td>0.029</td>
<td>15.4</td>
<td>0.032</td>
<td>16.1</td>
</tr>
<tr>
<td>Tide 7</td>
<td>0.056</td>
<td>17.9</td>
<td>0.023</td>
<td>15.2</td>
<td>0.022</td>
<td>16.1</td>
</tr>
<tr>
<td>Mean</td>
<td>0.053</td>
<td>12.2</td>
<td>0.017</td>
<td>18.2</td>
<td>0.017</td>
<td>18.3</td>
</tr>
<tr>
<td>All PTs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tide 1</td>
<td>0.057</td>
<td>16.2</td>
<td>0.010</td>
<td>16.8</td>
<td>0.010</td>
<td>16.7</td>
</tr>
<tr>
<td>Tide 2</td>
<td>0.031</td>
<td>14.9</td>
<td>0.007</td>
<td>23.4</td>
<td>0.007</td>
<td>24.4</td>
</tr>
<tr>
<td>Tide 3</td>
<td>0.052</td>
<td>14.7</td>
<td>0.012</td>
<td>18.9</td>
<td>0.012</td>
<td>18.4</td>
</tr>
<tr>
<td>Tide 4</td>
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<td>15.4</td>
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<td>15.4</td>
</tr>
<tr>
<td>Tide 5</td>
<td>0.064</td>
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<td>0.027</td>
<td>22.3</td>
<td>0.026</td>
<td>22.0</td>
</tr>
<tr>
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<td>0.055</td>
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<td>0.025</td>
<td>15.2</td>
<td>0.027</td>
<td>15.6</td>
</tr>
<tr>
<td>Tide 7</td>
<td>0.055</td>
<td>12.3</td>
<td>0.017</td>
<td>15.2</td>
<td>0.016</td>
<td>15.8</td>
</tr>
</tbody>
</table>
The basic equations of the XBeach model are derived from Phillips (1977) and partly based on others (e.g. Longuet-Higgins and Stewart, 1964). The SurfBeat modus (SB) of XBeach refers to the hydrodynamic model option which determines the short-wave variations on the wave group scale and resolves the low-frequency wave motions associated with them. By the variations of the short wave envelope, and the resulting gradients in the radiation stresses, a force is exerted on the water column driving the infragravity waves and unsteady currents which are resolved by the nonlinear shallow water equations.

This appendix will only elaborate on the equations that are of interest for this research, with the focus on the parameters used for calibration of the XBeach-SurfBeat model. An extensive explanation of all equations used in the XBeach model can be found in Roelvink et al. (2010).

**B.1. BOUNDARY CONDITIONS**

Boundary conditions for the XBeach-SurfBeat model forced with a measured time-series requires two components: the energy of the short wave group forced and the incoming long wave.

To obtain the short wave energy the measured signal from the most offshore pressure transducer (PT) is transformed to the frequency domain using a Fourier analysis and split into a high- and low-frequency part. For the short wave groups XBeach-SurfBeat requires a time-varying wave group energy and one representative wave period ($T_{rep}$), both can be derived from the high frequency part of the measured water level. The representative period is described with spectral moments as $T_{m-10}$ which can be derived from the high frequency part of the spectrum using equation B.1.

\[
T_{m-10} = \frac{m_{-1}}{m_0}
\]  

To obtain the energy of the short wave group the amplitude spectrum of the high frequency part is transformed back to a water level signal using an inverse Fourier transformation. Next a Hilbert transformation is applied to this high frequency water level signal to determine the short wave envelope $A(t)$ which is used to determine the energy of the short wave group $E_g(t)$ using equation (B.2).

\[
E_g(t) = \frac{1}{8} \rho g (2A(t))^2
\]

With $\rho$ the density of salt water and $g$ the gravitational acceleration. The incoming long waves can be computed using the modified method of Mansard and Funke (1980) as explained in appendix E.1.

**B.2. COMPUTATIONAL GRID**

The computational grid is based on bathymetric surveys during the WASP measuring campaign. The grid is setup with a varying cross-shore grid size defined between 1 and 3 meter to assure a high spatial resolution. The optimal grid size is based on the CFL condition which is necessary to assure stability.

---

1 Courant-Friedrichs-Lewy, 1928
and thereby convergence of the numerical scheme if it also consistent. The CFL condition is defined by equation (B.3) which states that the time required for the wave to travel from one grid point to the next one should be larger than the numerical time step.

\[ \frac{\Delta t}{\Delta x} \leq 0.9 = CFL_{\text{max}} \]  

(B.3)

With \( c \) the shallow water wave propagation speed, \( \Delta t \) is the numerical time step and \( \Delta x \) the grid size.

### B.3. Short-Wave Action Balance

In the Surf-Beat modus the short-wave motions are obtained with the wave action balance, equation (B.4), which is a time-dependent forcing of the equations used in the HISWA model (Holthuijsen et al., 1989). This equation solves the variation of short-waves envelope (wave height) on the scale of wave groups.

\[
\frac{\partial A}{\partial t} + c_{x,y,\theta} \frac{\partial A}{\partial x} + \frac{\partial A}{\partial y} + \frac{\partial A}{\partial \theta} = - \frac{D_w + D_f + D_v}{\sigma} 
\]

(B.4)

With \( A \) the wave action, \( c_{x,y,\theta} \) the propagation speed in \( x-, y- \) and directional space, \( D_{f,w,v} \) dissipation functions and \( \sigma \) the intrinsic frequency. The first term on the left hand side in equation (B.4) represents the local change of wave action. The other three terms on the left hand side represent the propagation of wave action in \( x-, y- \) and \( \theta- \) domain respectively. The right hand side represents the source term, which is in this case a function for dissipation by bottom friction, breaking and vegetation.

\[
A(x, y, t, \theta) = \frac{S_w(x, y, t, \theta)}{\sigma(x, y, t, \theta)}; \quad \sigma = \sqrt{g k \tanh kh} 
\]

(B.5)

The wave action \( (A) \) is defined as the wave energy \( (E_w) \) divided by the intrinsic frequency \( (\sigma) \), equation (B.5), which is a more relevant parameter for modeling purposes in the presence of an ambient current Holthuijsen et al. (1989). Although in XBeach the wave-current interaction is included separately by a correction terms for the wave number, therefore the intrinsic frequency \( \sigma \) is equal to the absolute radial frequency \( \omega \) based on the linear wave theory.

The dissipation term on the right hand side of equation (B.4) includes three processes: wave breaking \( (D_w) \), bottom friction \( (D_f) \) and vegetation \( (D_v) \). For this research only wave breaking and bottom friction are considered since there is no vegetation present at the rocky shore platforms.

#### Wave Breaking \( (D_w) \)

Dissipation by wave breaking is included using equation (B.6) according to Roelvink (1993). In this formula the dissipation is calculated as a fraction of the breaking waves \( (Q_b) \) multiplied with the dissipation per breaking wave.

\[
D_w = 2 \frac{\alpha}{T_{\text{rep}}} Q_b E_w \frac{H_{\text{rms}}}{h}, \quad E_w(x, y, t) = \int_0^{2\pi} S_w(x, y, t, \theta) d\theta
\]

(B.6)

With \( \alpha \) a dissipation coefficient of \( O(1) \), \( T_{\text{rep}} \) the representative wave period, \( E_w \) the short wave energy \( (S_w) \) integrated over all directional bins, \( H_{\text{rms}} \) the root-mean-square wave height which follows directly from the computed wave energy and \( h \) the water depth. The fraction of wave dissipation \( (Q_b) \) is determined by the ratio of the root-mean-square wave height \( (H_{\text{rms}}) \) and the maximum wave height \( (H_{\text{max}}) \) where \( H_{\text{max}} \) is calculated using the breaker parameter \( \gamma \) multiplied by the water depth, which is based on the instantaneous water depth \( (h) \) plus a fraction of the wave height \( (\delta H_{\text{rms}}) \).

\[
Q_b = 1 - \exp\left(-\left(\frac{H_{\text{rms}}}{H_{\text{max}}}\right)^n\right), \quad H_{\text{rms}} = \sqrt{\frac{8E_w}{\rho g}}, \quad H_{\text{max}} = \gamma (h + \delta H_{\text{rms}})
\]

(B.7)

For calibration of the wave breaking function only the \( \gamma \) parameter has been modulated. For \( \alpha \), \( \delta \) and \( n \) the default values of XBeach have been applied being 1, 0 and 10 respectively.
**B.4. Shallow Water Equations**

The dissipation by short wave bottom friction is included using equation (B.8) after Jonsson (1966).

\[
D_f = \frac{2}{3\pi} \rho f_w \left( \frac{\pi H_{rms}}{T_{m01} \sinh kh} \right)^3
\]  

(B.8)

Here \( f_w \) is the short-wave friction coefficient, this value only affects the short wave action equation and is therefore unrelated to the bed friction in the shallow water equation.

**B.4. Shallow Water Equations**

To resolve the low-frequency waves and mean currents the non-linear shallow water equations are used. In XBeach the depth-averaged Generalized Lagrangian Mean (GLM) formulation is applied in which the momentum and continuity equations are formulated in terms of the Lagrangian velocity \( \mathbf{u}^L \) Roelvink et al. (2010), equation (2.45). Important for this study is the relation between the low-frequency motions, the bed-friction term and the short wave stresses. Therefore the GLM-formulation is simplified for one-dimension to explain the interaction, equation B.9.

\[
\frac{\partial \mathbf{u}^L}{\partial t} + \mathbf{u}^L \cdot \frac{\partial \mathbf{u}^L}{\partial x} = -\frac{\tau_{bx}}{\rho h} - g \frac{\partial \eta}{\partial x} + \frac{F_x}{\rho h}
\]  

(B.9)

Where \( \mathbf{u}^L \) is the sum of the Eulerian velocity (\( \mathbf{u}^E \)) and the Stokes drift (\( \mathbf{u}^S \)), \( \tau_{bx}^E \) the bed shear stress, \( g \frac{\partial \eta}{\partial x} \) the hydrostatic pressure gradient and \( F_x/p h \) the wave stresses. From equation (B.9) it can be reasoned that the bed-friction term and hydrostatic gradient are balancing the wave stresses. So for constant wave stresses an increasing bed-shear stress will result in a smaller pressure gradient.

**Bed shear stress**

The bed shear stress associated with the mean currents and long waves is included using equation (B.10).

\[
\tau_{bx} = c_f \rho u_E \sqrt{(1.16u_{rms})^2 + (u_E + v_E)}
\]  

(B.10)

Where \( u_E \) and \( v_E \) are the Eulerian velocity in the grid cell, in \( x \) and \( y \) direction respectively, and \( u_{rms} \) the orbital velocity. The parameters \( c_f \) is the dimensionless bed friction coefficient which is a measure for the bottom roughness. XBeach has included other, more commonly used, relations like the Chezy, Manning and White-Colebrook to determine the value of the dimensionless friction coefficient although for this study the value of \( c_f \) is calibrated without using any of those relations.
C.1. OFFSHORE WAVE CONDITIONS

Figure C.1 presents the offshore wave data recorded by the Hinkley Point wave rider\(^1\). The data is recorded for 30 minute intervals and shows the tidal elevation, spectral wave height \(H_{\text{mo}}\), the peak period \((T_p)\), zero-upcrossing period \((T_z)\).

\(\text{Tide}\)

\(\text{Wave height}\)

\(\text{Wave period}\)

\(\text{Wave direction}\)

\(^{1}\)Operated by Cefas
C.2. **FIELD DATA ANALYSIS**

Figure C.2 shows the bulk wave parameters of the other tidal cycles based on the measurements in field data collected by the WASP team in December 2014. These results are in addition to the results of tide 3 and 6 as presented in section 3.3.2.

![Figure C.2: Bulk wave parameters of (from left to right) tide 1, 2, 4, 5 and 7. Layout similar to figure 3.10.](image)

C.3. **XBEEACH RESULTS**

**TIDE 3**

Figure C.3 shows the model results for three cross-sections, for different tidal phases, of the third tidal cycle. The results show a very good reproduction of the short wave height and the infra-gravity wave height. Although the setup for high-tide is underestimated with respect to the field data.

![Figure C.3: Cross-sections for a burst during mid-tidal phase (left) and high-tidal phase (right) for Lilstock (2014-12-09). Layout similar to figure 4.6.](image)
Tide 6

Figure C.4 shows the model results for three cross-sections, for different tidal phases, of the sixth tidal cycle.

Figure C.4: Cross-sections for a burst during mid-tidal phase (left) and high-tidal phase (right) for Lilstock (2014-12-11). Layout similar to figure 4.6.

Modelling with simplified bathymetry

Since the roughness is parametrised, the influence of the shape of the bathymetry is investigated using two types of simplified bathymetries. The first is a smoothed profile obtained from the terrestrial laser scanner, averaged over a 20 meter wide alongshore section. Due to averaging the topographical roughness disappears resulting in a smooth profile. The second profile is abstracted to three segments based on the classification of the three tidal-phases, section 3.1. This results in the two profiles as presented in figure C.5. Using these bathymetry all tides have been run with the calibrated settings of which the results are presented in figure C.6 and C.7. On average the errors are in the same order of magnitude compared to the detailed topography.

Figure C.5: Simplified profiles used to investigate the influence of the topographical roughness and the shape of the profile.
Figure C.6: Validation of calibrated XBeach model for a smoothed profile, obtained from the terrestrial laser scanner, averaged over a 20 meter wide alongshore section and without any topographical roughness. Layout similar to figure 4.7.

Figure C.7: Validation of calibrated XBeach model for all tides measured at the Lilstock platform. Modelled using a simplified profile constructed of three segments based on the classification of the three tidal-phases, section 3.1. Without any topographical roughness. Layout similar to figure 4.7.
This appendix presents additional results of the cross-correlation analysis from Chapter 5.

**D.1. SHORT WAVE ENVELOPE SIGNALS**

Figure D.1 presents an example of the short wave envelope signals used for the cross-correlation analysis based on the field data and the XBeach model results. The short wave envelope based on the field data show more variability and generally higher values compared to the XBeach model. This results in higher values of the cross-correlation coefficients as observed in section 5.2.1. For the XBeach model the short wave envelope shows less variability since it is a direct representation of the cross-shore energy of the short wave group. For the field data the short wave envelope is determined using equation (5.1) which takes more natural variability of the short wave group into account.

![Short wave envelope signals](image)

*Figure D.1: Example of the short wave envelope signals based on the field data and the XBeach results, used for the cross-correlation analysis.*

**D.2. MID- AND HIGH-TIDAL PHASES - TIDE 3**

In Chapter 5 the cross-correlation of the more energetic sixth tidal cycle is presented. Here the results for the third, less energetic, tidal cycle are shown from which the same propagation and generating mechanism are concluded.

**Propagation of short wave envelope**

Figure D.2 shows the propagation of the incident short wave group across the platform for three bursts ranging from mid- to high-tide. The absence of a characteristic V-shape pattern indicates no reflection and full dissipation of the incoming short waves.
Figure D.2: Cross-correlation of the short wave envelope $R_{AA}(\tau, i, 15)$ based on field data and XBeach results for third tidal cycle measured in Lilstock, (2014-12-09). The black line shows the phase difference based on the group celerity $c_g$. The vertical dotted line indicates the outer edge of the surf-zone.

**PROPAGATION OF INFRA-GRAVITY WAVE**

Figure D.3 shows the propagation of the infra-gravity waves across the platform for three bursts ranging from mid- to high-tide. The characteristic V-shape pattern indicates strong reflection of the incoming infra-gravity waves.

Figure D.3: Cross-correlation of the infra-gravity wave $R_{\eta\eta}(\tau, i, 15)$ based on field data and XBeach results for third tidal cycle measured in Lilstock, (2014-12-09). Layout is similar to figure D.2.
D.3. Validation of extended XBeach model

INTERACTION BETWEEN SHORT WAVE ENVELOPE AND INFRA-GRAVITY WAVE

Figure D.4: Cross-correlation function between the short wave envelope and the low-frequency wave $R_{\eta,i}(\tau,i,15)$. Lay-out is similar to figure D.2 although the scale of the cross-correlation coefficients is narrowed to $-0.4 \leq R_{XY} \leq 0.4$.

Figure D.5: Local cross-correlation function between the short wave envelope and the low-frequency wave $R_{\eta,i}(\tau,i,i)$. Lay-out and scale are similar to figure D.4.

D.3. Validation of extended XBeach model

Figure D.6 shows the cross-correlation results for the high-tidal phases of the extended XBeach model. The short wave envelope is very well described by the group celerity as presented in the top row. The
Figure D.6: Cross-correlation function for high-tidal phases based on extended XBeach model. Top panel shows the cross-correlation of the short wave group, mid-panel the cross-correlation of the infra-gravity waves, bottom panel the cross-correlation function between the short wave envelope and the infra-gravity wave. Dashed line shows the computed phase lags for $\sqrt{gh}$ and the solid line for $c_g$.

cross-correlation of the long waves show a remarkable pattern. Two waves are observed which is explained by the boundary conditions of the model. The first is the free wave used to force the model, propagating with the shallow water celerity of $c = \sqrt{gh}$ (dashed line), indicated by the ridge of strong positive correlation from $x = -350$ m to $x = 220$ m. The second long wave slowly develops as a bound wave generated by the short wave group and not present at the boundary. The best representation of this wave is found for $\eta = 3$ m since for this burst the least reflection is observed which disturbs the pattern. This is the bound long wave which becomes visible approximately from $x = 0$ and propagates with the group celerity $c_g$ (solid line). It could be argued that this second wave is a sign of a locally generated long wave by break point forcing although since the development of this long wave start already far from the breaker line ($\approx 150$ m) this would be highly unlikely. Furthermore the cross-correlation between the short wave envelope and the long waves shows a clear band of negative correlation, extending towards the shoreline, complying to the presence of a bound long wave. Concluding that the extended XBeach model is capable of showing qualitatively similar cross-correlation patterns from which the same generating mechanism would be concluded compared to the field data. It seems therefore valid to use this model for the investigation of the generating mechanisms during low-tidal phases.
SHOALING AND REFLECTION

This appendix shows additional information and results for the analysis of shoaling and shoreline reflection from Chapter 6.

E.1. MODIFIED MANSARD AND FUNKE

For the separation of measured infra-gravity wave signal a three-point method developed by Mansard and Funke (1980) is used. This method shows similarities to the method of Gaillard et al. (1980) which was simultaneously developed. To investigate the validity of this method an artificial wave signal, with a frequency of 0.03Hz in shallow water, is examined. A probe spacing of 15m is used to separate the incoming and reflecting wave which is similar to the PT-spacing used for the field measurements. Figure E.1 shows the artificial signal and the separated signals. At the begin, center and end of both the incoming and reflecting signal an offset is observed which is not expected since only a single harmonic is examined. Given this offset a correction is proposed to improve the estimate and reduce the offset at the edge of the separated signals. First the original measured surface elevation of three neighboring PTs is split in 50% overlapping bursts of the similar lengths (1024s) and bandpass filtered for the infra-gravity band (0.004Hz – 0.055Hz). Using the method described by Mansard and Funke (1980) the

![Artificial signal - 0.03Hz](image)

![Separated signals](image)

Figure E.1: Artificial infra-gravity wave signal used to examine the method developed by Mansard and Funke (1980).
incoming and reflecting signal are derived. Next, the separated signals of each overlapping burst are multiplied with a Hanning window (Equation A.2) to reduce the offset at the edges. By adding each Hanning windowed burst it to the previous bursts a seamless transition is created from one burst to another. Figure E.2 shows how such a continuous signal is build. The continuous incoming signal, obtained with this correction, is also used as one of the boundary conditions to force the XBeach model (Chapter 4). For the analysis in Chapter 6 the continuous signal is split into subsequent bursts. The initial offset at the beginning and end of each burst is now reduced as shown in figure E.3. In the center the corrected signal is equal to the separated signal without correction and at the edges the initial offset is reduced.

**Probe spacing**

According to Mansard and Funke (1980) there is a critical combination of probe spacing for which the reflection analysis will be invalid. This is when the distance between the first and the second probe is equal to half the considered wave length and the distance between the first and the third to a multiple of that. Based on experiments with monochromatic waves they recommend in their paper on a certain probe spacing:

- $X_{1,2} = L/10$;
• $l/6 < X_{1,3} < L/3$; and
• $X_{1,3} \neq L/5$ and $X_{1,3} \neq 3L/10$

Furthermore they indicate that the probes should be located at a distance of one wave length, corresponding to the peak period of the waves, from the reflecting structure. For the measurements at Lilstock the distance between the PTs is approximately $15m – 20m$, varying on the considered triplet. These distances do not comply to all recommendations although the spacing is at least such that the maximum distance ($X_{1,3}$) is always smaller than half the considered wave length.

**Horizontal Bottom**

The method of Mansard and Funke (1980) assumes a horizontal bottom although in this research the PTs were located on the sloping platform which induces a small error. Figure E.4 shows the resolved incoming signal with the method of Mansard and Funke (1980) for PT13. Forward means using PT12 and PT11 (so in onshore direction) and backward means using PT14 and PT15 (in offshore direction). For both cases the onshore propagating wave is presented. Since both methods determine the onshore propagating wave for PT13 a similar wave is expected. However, using the backward method (PT13,14,15) has a larger mean water depth since it is sloping to deeper water compared to the forward method (PT13,12,11) sloping to shallower water. As a result a different solution is obtained. It is observed that the method corresponding to a lower water depth results in smaller wave amplitudes compared to the method corresponding to a larger water depth. Comparing the forward method for PT13 (PT13,12,11) to the backward method for PT11 (PT11,12,13) results in exactly the same wave although with a small phase-lag as shown in the bottom plot of figure E.4.

![Incoming signal - at the same PT](image)

![Incoming signal - at different PTs (same triplet)](image)

*Figure E.4: Incoming signals based on the forward and backward applied method.*
E.2. INFRA-GRAVITY WAVE SHOALING

Figure E.5: From top to bottom: Tide 1, 2 and 3 - clam offshore wave conditions.
Figure E.6: From top to bottom: Tide 4, 5 and 7 - energetic offshore wave condition.
INFLUENCE OF BOTTOM FRICTION

Figure E.7: From top to bottom: Tide 1, 2 and 3 - calm offshore wave conditions. Comparison between $c_f = 0.08$ and $c_f = 0.003$ including curves based on $\alpha$-values that fit $H \sim h^{-\alpha}$.
Figure E.8: From top to bottom: Tide 4, 5 and 7 - energetic offshore wave condition. Comparison between $c_f = 0.08$ and $c_f = 0.003$ including curves based on $\alpha$-values that fit $H \sim h^{-\alpha}$.
INFLUENCE OF BOTTOM FRICTION ON GROWTH RATE

Figure E.9 shows the influence of the bottom friction on the growth rate. Due to less friction the incoming infra-gravity waves dissipate less energy, as a consequence the growth rate $\alpha$ will increase.

![Figure E.9: Growth rate of the incoming infra-gravity wave height based on XBeach results as a function of $\beta_b$ for $c_f = 0.08$ (left) and $c_f = 0.003$ (right).](image)

E.3. INFRA-GRAVITY WAVE REFLECTION

DEPTH DEPENDENCY

Figure E.10 shows the relation between the reflection coefficient and the surf-similarity parameter ($\beta_H$) for different water depth contours varying between 0.5m and 2.0m. With increasing water depth the reflection coefficients seem to decrease slightly, although in general it can be concluded that for all depth contours qualitatively the same patterns is observed.

![Figure E.10: $\beta_H$ in relation to $R$ at varying depth contours based on the XBeach model.](image)
REMARKS ON $\beta_H$ FOR SEPARATE FREQUENCY DOMAINS

There are some remarks on computing the $\beta_H$ parameter for different frequency bands. To understand the dependency of $\beta_H$ on its variables, both the frequency and the wave height will be discussed using equation (E.1).

$$\beta_H = \frac{h_x}{2\pi f_h} \sqrt{\frac{g}{H^+}}$$

(E.1)

First of all the frequency used to compute the value of $\beta_H$ for different frequency bands is the mean frequency ($f_h$) of a considered frequency band, indicated in figure E.11. Secondly the wave height is the root-mean-square wave height, $H_i^+ = \sqrt{8m_{0i}^+}$ with $m_{0i}^+$ as defined by equation (E.2).

$$m_{0i}^+ = \int_{f_i}^{f_{i+1}} E^+(f) df$$

(E.2)

This means that $\beta_H$ is linearly depending on the period of the infra-gravity wave ($T = 1/f$) and non-linear ($m_0^{-1/4}$ or $H^{-1/2}$) on the integral of the variance density spectrum within each frequency domain, combining them results in:

$$\beta_H \sim \frac{1}{f m_0^{1/4}}$$

(E.3)

Since the value of $m_0$ is coupled to the frequency domain by equation E.3, the dependency of $\beta_H$ is visualised using a fictional uniform distributed variance density spectrum, as indicated in figure E.11, to evaluate $\beta_H$ for different frequency domains. The influence is computed with respect to the value of $\beta_{H0}$, which indicates the value of $\beta_H$ for the entire infra-gravity domain from $f_1$ to $f_2$. Figure E.12 shows that for a decreasing frequency domain $\Delta f$, i.e. a decreasing domain for integration, $\beta_H$ increases with respect to $\beta_{H0}$. So, separating the frequency domain in four segments of approximately the same size, as done in section 6.3.2, results in an increase of $\sqrt{g/H^+}$ with 41%. Depending on the considered frequency domain, $\beta_{Hi}$ could be four times larger compared to $\beta_{H0}$ of the entire infra-gravity domain.

Since $\beta_H$ represents the relative steepness of the infra-gravity wave the question remains whether the actual steepness of the infra-gravity wave increases with the same value or that this is solely the result of the method. Therefore the results based on the computation of $\beta_H$ for separate frequency should be considered with great care.

Figure E.13 presents the reflection coefficients and surf-similarity $\beta_H$ for different frequency bands,
Influence of $\Delta f$ and $H_{rms}^+$ on $\beta_H$

Figure E.12: Dependency of $\beta_H$ on the domain of integration. Left; normalised to $\beta_{H0}$ to indicate the combined effect of $\Delta f$ and $m_0$. Right: normalised by $\beta_{H0} f_i / f_h$ to isolate the effect of a larger domain for integration, independent of the frequency $f_i$ used to compute $\beta_H$.

each indicated with an other symbol. The value of $\beta_H$ is computed using equation (E.1). Figure E.13 is a combination of the separate frequencies of figure 6.14, in Chapter 6.

Surf-similarity - frequency dependent

Figure E.13: Combination of figure 6.14. Surf-similarity parameter $\beta_H$ in relation to the reflection coefficient $R$ at the shoreline for different frequency bands.
This appendix presents the preliminary model results for the platform of Hartland Quay (cover image of this report). This site is one of the selected WASP sites and was initially selected to investigate the transformation of infra-gravity waves. During the course of this research it was decided to focus only on Lilstock for the transformation of infra-gravity waves therefore these results were no longer necessary. However, these results are already taking a step forward to the parametrization of the surface roughness for other rocky shore platform. Therefore they are included in this report.

F.1. Site Description
The platform of Hartland Quay (HLQ) is located on the Atlantic coast of Devon, south of Hartland point and north of Bude, in Cornwall. Hartland Quay experiences some of the roughest seas in winter and

![Bidford Bay wave data](image)

*Figure F1: Offshore wave data for Hartland Quay (Bidford Bay wave buoy).*
due to its West facing coastline it receives mainly normally incident waves with a high contribution of swell waves. The latter is useful for calibration of the numerical model since the angle of incidence coincides well with the orientation of the cross-shore array, presented in figure F.2, reducing the occurrence of long-shore radiation stresses. The tidal range at Hartland Quay is smaller compared to Lilstock but still classified as a macro-tidal environment. The platform surface is characterized by a classic, steep inclined, washboard morphology where harder sandstone units interbedded with softer mudstone projects above the platform surface during low water.

At Hartland Quay the measurements have been conducted at the end of October in 2014 for 11 tidal cycles. Maximum significant wave heights of 2 m were recorded at the Bidford wave buoy with a mean peak period of 10.2 s and a mean wave direction of 286°. For hydrodynamic measurements 12PTs are bolted on the platform. Figure F.1 shows the offshore wave conditions recorded at the Bidford Bay wave buoy for Hartland Quay.

\[\text{Operated by the Channel Coastal Observatory}\]
To setup the XBeach-SurfBeat model the same procedure has been followed compared to the model setup for Lilstock. Waves and tidal boundary conditions are determined using the same methods and measured surface elevations. The model is setup for the second, fifth and eight tidal cycle. The Hartland Quay platform consists of large cross-shore oriented ridges which makes it hard to select a profile for 1D modelling. Figure E3 presents two profiles: the crest of the Norther Ridge and the neighboring trench. The PTs where mounted halfway on the face of the Norther Ridge. Both profiles have been used to setup the XBeach-SurfBeat model and for a first attempt the Northern Ridge results in the best reproduction of the measurements. Therefore the crest of the Northern Ridge has been selected as 1D profile for the calibration of the XBeach-SurfBeat model. The calibration procedure as described in section 4.3 has been followed and results in values of $f_w = 0.2$, $c_f = 0.08$ and $\gamma = 0.7$. Model results for the eight tidal cycle are presented in figure E3.
**Validation**

For Hartland Quay a the bottom friction parameter $c_f$ is similar compared to Lilstock and a slightly higher value of $f_w$ is obtained. Furthermore a higher $\gamma$ is found compared to Lilstock, which can be related to the selected profile. The profile used for the XBeach model is the Notheren Ridge resulting in a very small water depth, hence a high $\gamma$ is required to reproduce the short wave height inside the surf-zone. Large errors are obtained for the infra-gravity wave height and the setup, with an small overestimation during high tide but mainly an large under estimation during lower tide. It is suggested that the transformation of the short waves interacts differently with steep inclined ridges than the low-frequency motions. To investigate this alongshore variability of the surface roughness, 2D modelling is recommended for further research.

*Figure F.4: Results of calibrated XBeach-SurfBeat model for all tides measured and modelled of Hartland Quay. For all bursts (top) and high-tide only (bottom).*