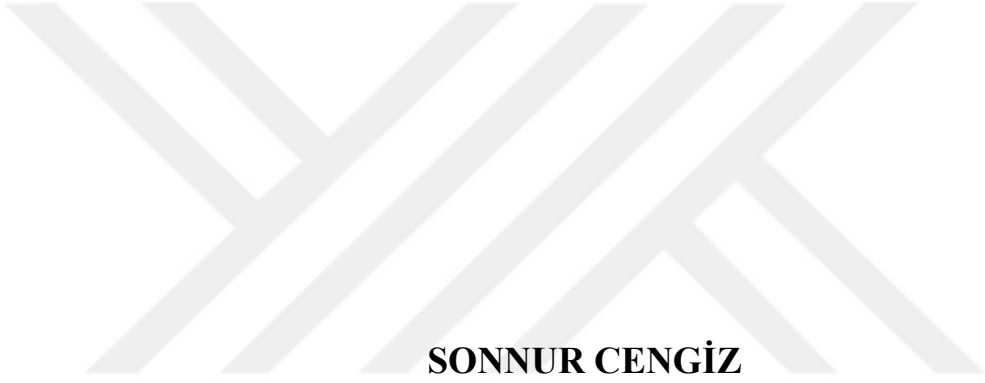


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GEBZE TECHNICAL UNIVERSITY
GRADUATE SCHOOL

SIMULATION OF ENERGY DISSIPATION IN WAVE BREAKING
BY A BOUSSINESQ MODEL



SONNUR CENGİZ

A THESIS OF MASTER OF SCIENCE
DEPARTMENT OF CIVIL ENGINEERING

ADVISOR: DOÇ. DR. BURAK AYDOĞAN

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LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

BOUSSINESQ MODELİ İLE DALGA KIRILMASINDA
ENERJİ DAĞILIMININ SİMÜLASYONU

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YÜKSEK LİSANS TEZİ
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ABSTRACT

For coastal engineering, it is very important to properly handle wave breaking. Wave breaking, coastal erosion, damage to coastal structures, is an important phenomenon for port operators to understand. As the waves approach the shore, they become shallow, the wave forms change, and wave breaking is seen. The wave breaks by losing its energy during breaking. Wave breakings have different physical processes, and these processes are still not fully explained today.

Various calculation and simulation methods are used to explain wave breaking. MIKE21 BW and Simulating Waves till Shore (SWASH) are among these programs. Within the scope of this study, the wave breaking energy that occurs during wave breaking was simulated by using MIKE21 BW and SWASH program. MIKE21 BW incorporates two modules capable of performing one-dimensional and two-dimensional solutions. These modules solve Boussinesq-type equations by employing an improved linear dispersion formulation. The SWASH wave model provides simulation using nonlinear shallow water equations that incorporate non-hydrostatic pressure and certain transport equations. The SWASH wave simulation program enables the simulation of non-hydrostatic, free-surface, and rotating flow phenomena in one and two dimensions. DUCK94 datasets consist of base bathymetries, tide data, wave spectrum data. AYGEM experimental data consist of surface profiles taken from six different wave gauges during the experiment. Two different bases are formed in bathymetry with slope characteristics. The installation and measurement points of the DUCK94 and AYGEM experimental models were created in such a way that they are identical to the experimental setups.

For the DUCK94 and AYGEM experiments, the breaking parameters and accuracy changes of the models were examined. The models were compared with the data observed from the experiments and their calibration was provided. The effects of breaking parameters on wave breaking energy are given comparatively. DUCK94 experimental models were examined for cases where breaking parameters were not present, and the relationship between the presence of breaking parameters and the simulation capabilities of the programs was questioned.

Keywords: Boussinesq Equation, Wave Breaking, MIK21 BW, SWASH.

ÖZET

Kıyı mühendisliği için dalga kırılmasını uygun şekilde ele almak çok önemlidir. Dalga kırılması, kıyı erozyonu, kıyı yapılarının zarar görmesi, liman işletmelerinin anlaması gereken önemli bir olgudur. Dalgalar kıyıya yaklaştıkça sığlaşır, dalga şekilleri değişir ve dalga kırılması görülür. Dalga, kırılma sırasında enerjisini kaybederek kırılır. Dalga kırılmalarının farklı fiziksel süreçleri vardır ve bu süreçler bugün hala tam olarak açıklanamamıştır.

Dalga kırılmasını açıklamak için çeşitli hesaplama ve simülasyon yöntemleri kullanılır. MIKE21 BW ve Simulating Waves till Shore (SWASH) bu programlar arasındadır. Bu çalışma kapsamında, dalga kırılması sırasında ortaya çıkan dalga kırılma enerjisi, MIKE21 BW ve SWASH programı kullanılarak simüle edilmiştir. MIKE21 BW, tek boyutlu ve iki boyutlu çözümler gerçekleştirebilen iki modül içerir. Bu modüller, geliştirilmiş bir doğrusal dağılım formülasyonu kullanarak Boussinesq tipi denklemleri çözer. SWASH (Kıyıya Kadar Dalgaları Simüle Etme) dalga modeli, hidrostatik olmayan basıncı ve belirli taşıma denklemlerini içeren doğrusal olmayan sığ su denklemlerini kullanarak simülasyon sağlar. SWASH dalga simülasyon programı, hidrostatik olmayan, serbest yüzeyli ve dönen akış olaylarının bir ve iki boyutta simülasyonunu sağlar. DUCK94 veri kümeleri baz batimetrikler, gelgit verileri, dalga spektrumu verilerinden oluşur. AYGM deney verileri, deney sırasında altı farklı dalga ölçerden alınan su yüzey profillerinden oluşmaktadır. Batimetride eğim karakteristiğine sahip iki farklı taban oluşur. DUCK94 ve AYGM deney modellerinin kurulum ve ölçüm noktaları, deney düzenekleri ile aynı olacak şekilde oluşturulmuştur.

DUCK94 ve AYGM deneyleri için modellerin kırılma parametreleri ve doğruluk değişimleri incelenmiştir. Modeller, deneylerden gözlemlenen verilerle karşılaştırılmış ve kalibrasyonları sağlanmıştır. Kırılma parametrelerinin dalga kırılma enerjisi üzerindeki etkileri karşılaştırmalı olarak verilmiştir. Kırılma parametrelerinin bulunmadığı durumlar için DUCK94 deney modelleri incelenmiş, kırılma parametrelerinin varlığı ile programların simülasyon yetenekleri arasındaki ilişki sorgulanmıştır.

Anahtar Kelimeler: Boussinesq Denklemi, Dalga Kırılması, MIK21 BW, SWASH.

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LIST OF SYMBOLS AND ABBREVIATIONS

H_s	: Significant wave height
η	: Wave profile
a	: Wave amplitude
k	: Wave number
w	: Angular frequency
L	: Wave length
T	: Wave period
d	: Water depth
K_s	: Shoaling coefficient
C_{g0}	: Deep water group velocity
C_g	: Nearshore group velocity
d_0	: The shallow water depth at the deep-water boundary
d_1	: Refracted wave water depth
α_0	: Angle with wave and costline
α	: Angle made by the refracted wave fronts with the coastline
c_0	: Deep water wave celerity
c_1	: Refracted wave celerity
b	: The distance between wave orthogonals
K_r	: Refraction coefficient
H_y	: Reflected wave height
K_y	: Reflection coefficient
ξ_0	: Offshore breaking parameter
ξ_b	: Inshore breaking parameter
Ψ_1	: Boussinesq dispersion term in x direction
Ψ_2	: Boussinesq dispersion term in y direction
B	: Boussinesq dispersion factor
n	: Porosity term
C	: Chezy resistance number
a'	: Resistance coefficient for laminar flow in porous media
b'	: Resistance coefficient for turbulent flow in porous media
ξ	: Water surface level above datum
δ	: Thickness of the surface roller
C_x	: Roller celerity components in x direction
C_y	: Roller celerity components in y direction
f_v	: Roller celerity factor
p_n	: Hydrostatic pressure
p_{nh}	: Nonhydrostatic pressure
τ_{xx}	: Turbulent stress in x – x plane
τ_{xz}	: Turbulent stress in x – z plane
τ_{zz}	: Turbulent stress in z – z plane
$\gamma(z)$	: Porosity
ϵ	: Minimum value of γ
b	: Constant shape factor
α	: Initial breaker index
β	: Final breaker index

AYGM : Altyapı Yatırımları Genel Müdürlüğü
DUCK94 : DUCK nearshore experiment
IBA : Initial breaking angle
FBA : Final breaking angle
NSWE : Nonlinear Shallow Water Equation
WG : Wave gauge



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1. INTRODUCTION

1.1. Aim and Content of the Study

Understanding the wave transformation processes that occur in coastal areas is crucial for coastal management. Structures to be built in coastal areas, arrangement of coastline structure, design of breakwaters, port planning and other issues are managed through the analysis and modeling of wave processes in coastal areas. To perform these patterns, it is important to know the wave characteristics of the region. One of the most effective ways to understand wave processes in a region is to conduct field measurements. However, field measurements may not always be appropriate, but can also be a costly solution. For this reason, many wave modeling systems have been developed from the past to the present. These modeling systems allow wave modeling in coastal areas using various parameters such as bottom bathymetry, statistical properties of waves, wind, bottom friction.

Modeling systems perform wave modeling using different wave equations and various approaches. Due to differences in modeling systems, the outputs of the created models may vary. When conducting wave modeling, it is important to carefully study the model inputs. Parameters such as the bottom topography on which the wave will travel, the water level, tidal characteristics, and bottom friction are very important inputs for wave modeling. Apart from these input parameters, it is also very important to define the wave breaking parameters in the model. Parameters with low error levels can be defined by default for each model, but not every parameter may give the best results under all model conditions.

This study aims to simulate the energy propagation process that occurs during wave breaking using MIKE21 BW and SWASH programs. The simulations will be carried out by focusing on the wave breaking process, using the experimental data obtained from the field measurements made in the DUCK94 and AYGEM experiments.

In Chapter 1, Boussinesq and the Nonlinear Shallow Water Equations (NSWE) are introduced. The development of these equations is examined and studies on wave energy propagation are discussed. The definition of waves and wave transformation processes were explained.

In Chapter 2, the MIKE21 BW using the Boussinesq wave model and the SWASH numerical modeling systems using the Nonlinear Shallow Water Equations are introduced. The equations used by the models and the process of building the model are presented.

In Chapter 3, the DUCK94 dataset and the AYGM experimental dataset used in this study are given together with the experimental setups and bathymetry systems. Model applications based on experimental data in MIKE21 BW and SWASH are described.

In Chapter 4, the calibration and default model results are presented and compared with the data obtained from the experiments.

In Chapter 5, conclusions are drawn from the model results obtained and the performance of the models is evaluated. This work was accompanied by descriptions of potential future developments and improvements that could be carried out.

1.2. Literature Review

There are two different approaches to modeling the movement of water at shallow depths and wave formation, which are broadly based on similar foundations: the Nonlinear Shallow Water Equations (NSWE) and the Boussinesq equations. Both equations can be used with numerical solution methods to obtain practical applications for the given problem. These equations are based on the assumption that moving water is incompressible and neglect rotational effects. They are commonly used to investigate hydrodynamic wave problems, especially phenomena such as wave propagation, breaking, and interaction.

The Boussinesq approach can be used to incorporate dispersion effects and process slightly smaller wavelengths by extending the shallow water equations. Boussinesq (1872) derived the Boussinesq equations by adding dispersive effects to the NSWE for waves propagating on a horizontal bottom, which in turn included low-order dispersive elements to form the first form of equations based on the concept of a horizontal base. The original equation had poor dispersion properties and nonlinearity, as well as considering fixed depths [Madsen and Fuhrman, 2010]. Throughout history, new forms of Boussinesq equations have been developed.

Peregrine (1967) published a more advanced set of Boussinesq equations, which described the nonlinear behavior of irregular short waves at varied depths using averaged velocities. These equations are currently known as the classical Boussinesq equations.

To present date, many Boussinesq equations have been derived for various purposes. A variety of dependent variables can be selected to derive different forms of the equation, and typical velocity variables include surface velocity, bottom velocity, depth-averaged velocity, and depth-integrated velocity. On the other hand, since the terms nonlinear and distributive are of higher order, they can be manipulated by calling the linear long-wave equation [Hamm et al., 1993].

Madsen et al. (1991) presented a discussion of the various forms of Boussinesq equations and concluded that the accuracy of the embedded linear distribution relation, phase celerity, and group velocity largely depends on the form of Boussinesq equations, with the exception of very small wave numbers (h/L_0 less than 0.05). The phase celerity and group velocity parameters for linear waves at water depths up to and beyond the deepwater boundary have been significantly improved by the new equations. These equations are expressed in two horizontal dimensions with respect to surface elevation and velocity components integrated with depth. The system of equations that allows the determination of the coefficient B in deeper waters should be used depending on the obtained linear distribution properties.

Madsen and Sorensen (1992) extended the the Boussinesq equations to include terms proportional to the lower slope required for the shallow behavior of the equations. In the standard Boussinesq equations, if the h/L_0 ratio exceeds 0.12, the shoaling distortion increases rapidly. Therefore, it must be concluded that the accuracy of the phase velocity in a varying bathymetry generally provides a very optimistic measure of the range of practical application of the equation. On the contrary, the new equations offer accurate simulation of irregular wave trains propagating from deep to shallow waters, providing good precision in both shoaling and linear distribution for h/L_0 up to 0.50.

Madsen and Sorensen (1992) used an example to test the applicability of their model to linear shoaling. A 700 meter long waterway with a flat and sloping bottom was chosen. A continuous depth of 13 meters is available for the first 10 meters from the sea border. Between 10 and 650 m, a slope of 1/50 is given. Finally, between 650 and

700 meters, the bottom flattens again, with a still water depth of 0.2 meters. A sinusoidal wave with period of 4 s is produced at the sea boundary, while a sponge layer is applied at the coastal boundary. A spatial grid of 0.2 m and a time step of 0.01 s were used in the model simulation.

For ordinary Boussinesq equations where Boussinesq dispersion factor $B = 0$, it can be understood that significant errors arise for h/L_o greater than 0.10, while $B = 1/15$ has an obvious effect and offers a perfect match to the first-order Stokes theory form for h/L_o up to 0.50. Derivatives and higher derivatives of water depth, wave number, and wave amplitude are not considered because they are assumed to be slow-changing functions of x . The momentum equation does not take into account the Boussinesq components proportional to h_x . Unfortunately, these parameters have been shown to have a large influence on the shoaling properties and their effects are cumulative [Madsen and Sorensen, 1992].

Nwogu (1993) derived a new form of the Boussinesq equations, used the velocity at any point on the water's surface as input instead of the commonly used depth-averaged velocity. In this case, the equations improve the properties of linear distribution and allow to make solutions over a wider range of water depths.

Beji and Nadaoka (1996) made corrections to the Boussinesq equations derived by Madsen and Sorensen (1992)'s and Nwogu (1993)'s equation in order to improve the accuracy of depth-varying terms and create a more accurate mathematical basis for these equations.

Orszaghova et al. (2010) solved the Boussinesq and NSW equations as hybrids. They validated the resulting equation using data from three different experiments.

The NSW describe wave motion in shallow waters. They are used to illuminate numerous wave interactions in shallow waters and help to understand the various phenomena in this particular environment. NSW gives more accurate results, especially in inland and central coastal areas, where nonlinear effects are more pronounced, while it gives weaker solutions as it moves further into deeper waters [Broccini et al., 2008].

Elgar and Guza (1985) shed light on nonlinear wave dynamics by considering the dual-spectrum state of gravitational waves. In doing so, they contributed to the elucidation of nonlinear interactions in shallow waters.

Janssen et al. (2006) derived the development equations for weak nonlinear, omnidirectional, and multi-frequency waves moving from deep to shallow waters, thus facilitating the understanding of nonlinear waves.

Broccini et al. (2008) observed the modeling of coastal currents using NSWs. Applying the Reynolds equations in depth to NSWs, they developed two-dimensional depth-averaging models.

Liu et al. (2009) used both linear and nonlinear shallow-water equations for tsunami prediction and showed that NSW gave better results at shallower water depths.

Kennedy et al. (2000) used the Boussinesq wave equations to simulate wave transformation, breaking, and run up. They described the development of a surf zone model using the extended Boussinesq equations of Nwogu (1993) and the fully linearized Boussinesq equations of [Wei et al., 1995]. In this model, a modified eddy viscosity formulation was used to introduce wave breaking. In addition, they defined a slot technique for the representation of a moving shoreline. During these studies, model was compared with 1D laboratory experiments in which regular and irregular wave breaking conditions were examined. Errors such as overestimation of wave heights were observed in the model results.

Wu and Nepf (2002) investigated the effects of wave directivity on wave breaking criteria and energy losses through laboratory experiments. Wave breaking conditions were created using a technique to create two-dimensional, spatially focused, and spatially diffracted waves. The energy loss due to breaking was also found to increase with greater spatial focus.

Tian et al. (2010) simulated the energy dissipation that occurs during two-dimensional wave breaking using the eddy viscosity model. They considered wave breaking in terms of both time and length and proposed an approach that relates wave energy and wave dissipation rates to wave steepness.

Carini et al. (2015) made estimates about the rates of energy loss due to wave breaking in coastal areas based on thermal images. For these estimates, they used wave roller lengths. Using the wave roller model of Duncan (1981) in conjunction with wave slope estimates, they calculated the rate at which wave energy is lost.

Aydogan and Kobayashi (2014) used the Boussinesq equations to generate positive and negative solitary waves in a laboratory experiment with a regularly increasing base

slope. They numerically modelled this experiment, which is based on the measurement of wave velocities, with InterFoam. When they compared the model results with the data obtained from the experimental results, they determined that the numerical model was capable of realistic modeling, but differences in the baseline conditions could lead to differences in the model results.

Saprykina et al. (2022) investigated energy losses during wave breaking for spilling and plunging breakers using field experiments and numerical models. In this study, phase resolving Boussinesq model and phase averaged SWAN model were used. The results show frequency dependent in energy loss at the 2nd and 3rd harmonics for the spilling and plunging wave breakers in both models. In the SWAN models used with the Stochastic Parametric model based on the Boussinesq equations (SPB) approximations, it was observed that the energy loss coefficients for the plunging breaking waves depended on the quadratically on frequency. On the other hand, in SWAN models used with the Lumped Triad Approximation (LTA) approach, frequency dependent energy loss was observed for plunge breakers.

Zhang et al. (2018) modeled six different laboratory experiments conducted on beaches with and without bars. The goal was to validate the SWASH model's ability to simulate various wave conditions. Models were not calibrated and were set with default parameters. As a result, it was found that the measurements and model results obtained from the experiments were parallel. The study concluded that SWASH can accurately calculate long coastal currents without calibration.

Yang et al. (2021) experimentally validated a generalized second order 3D theory to link nonlinear wave propagation from a numerical model to a physical model. For this purpose, they used the MIKE21 BW program. The second order model was validated using oblique regular waves, unidirectional irregular waves, and multidirectional irregular waves in both a flat bonding pool and a concave-convex bonding pool.

Bai and Shi (2012) used wave simulation in the MIKE21 BW program for a Wave Energy Converter (WEC) to be placed in the Chengshantou wave field. Based on the model results, they determined the wave properties in this area.

Panigrani et al. (2015) used the Boussinesq wave model to simulate inner harbor wave agitation. They used the wave model WAM to obtain offshore wave data, which they then analyzed and brought it close to shore. The Boussinesq wave model is used to predict wave disturbances in harbor basin and dock settlements.

At first, wave breaking was tried to be solved with NSW. According to NSW, the front face of the wave would be completely perpendicular before the wave underwent break. However, since this can also be seen in flat bathymetry, NSW could not model the location of the wave break completely accurately [Schaffer et al., 1993].

Since the Boussinesq equations have frequency dispersion, they can be applied in a wide wave spectrum and in a wider coastal region. Because of the frequency dispersion, the Boussinesq equations could not directly model wave refraction in shallow waters. Therefore, the Boussinesq equations have been extended to include wave breaking and energy dissipation [Madsen et al., 1997].

The concept of surface rollers a physical approach, was presented by Deigaard (1989). According to this approach, wave breaking begins when the local water surface profile reaches a certain slope. Based on Deigaard (1989) 's concept of surface rollers Schaffer et al. (1993) extended the Boussinesq equation with the concept of surface rollers.

1.3. Wave Properties

Waves are fluctuations in the water level that are accompanied by local currents, accelerations, and pressure fluctuations. The wind drives back against the force of gravity, which tries to raise the level of still water to create gravitational waves. These waves make up the majority of the total wave energy available due to their prevalence. Wave heights from gravity and wind are rarely greater than 10 meters, and their duration ranges from 1 to 30 seconds [Kamphuis, 2000].

The orbital motion of water molecules produces waves. The wave profile is represented by a sine (or cosine) curve by the simplest method (linear waves) [AYGM, 2016].

Figure 1.1 shows basic wave definitions. The highest points are the wave crests, and the lowest points are the wave troughs. The vertical distance between a wave crest and a wave trough is the wave height (H). The horizontal distance between two wave crests in the wave profile is the wavelength (L). The time it takes for a wave to repeat itself once is the wave period (T) and is measured in seconds, minutes, or hours. Frequency (f) is used to represent the distance traveled by waves in one second and is measured in hertz. Here, d represents the sea depth from the still water level (SWL) and z represents the bottom level. C represents the wave propagation velocity.

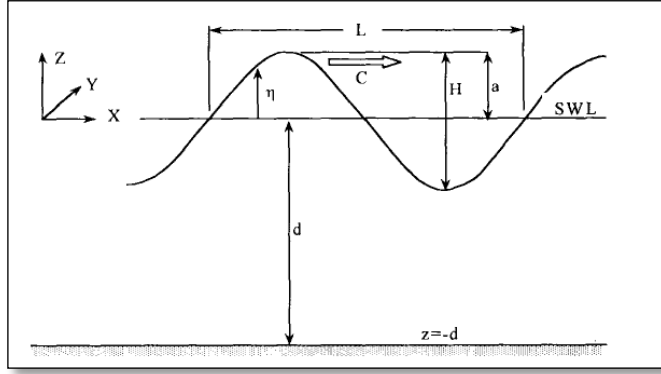


Figure 1.1: Basic wave definition [Kamphuis, 2000]

The η is the wave profile seen in the figure represents the vertical displacement wave profile of the free water surface starting from the still water level. η is wave profile, described by equation 1.1.

$$\eta = a \cdot \sin(kx - \omega t) = a \cdot \sin\left(\frac{2\pi}{L}x - \frac{2\pi}{T}t\right) \quad (1.1)$$

a is wave amplitude, k is wave number, ω is angular wave frequency, L is wave length and T is wave period.

There are different classifications of sea waves. The d/L ratio is one of them. Here, d is water depth measurement. According to this criterion: where $d/L > 0.5$, this wave is a deep water wave. When $d/L < 0.05$, this wave is a shallow water wave. Waves with values within these two ranges are referred to as transition or transition zone waves. In equation 1.2, the wavelength equation is given.

$$L = \frac{g \cdot T^2}{2 \cdot \pi} \cdot \tanh\left[\frac{2 \cdot \pi \cdot d}{L}\right] \quad (1.2)$$

1.4. Wave Transformation

1.4.1. Shoaling

When a deep water wave approaches a gently sloping coastal topography, the wavelength and phase velocity decrease accordingly. As the water depth decreases, the group velocity of the wave also decreases. The decrease in water depth causes the phase velocity and group velocity to be closer to each other, resulting in less dispersion behavior of the waves. During shallowing, the wave approaches the shore perpendicularly, and no change in the wave period can be observed in this process. Shoaling coefficient, K_s can be calculated as shown in equation 1.3 [Holthuijsen, 2010].

$$K_s = \left(\frac{C_{g0}}{C_g} \right)^{\frac{1}{2}} \quad (1.3)$$

C_{g0} is deep water group velocity and C_g is near shore group velocity.

1.4.2. Wave Refraction

Unlike shallowing, in the case of refraction, changes in wave directions are observed due to the changing slopes of the seabed. Due to varying sea slopes, wave speeds and heights also differ as a result of these variable ocean conditions.

Bottom currents can affect the wave direction and intensity, resulting in further changes in the wave pattern. Wave refraction not only affects the wave height but also determines the angle at which the wave will break. The general formula of wave diffraction according to Snell's Law is given by equation 1.4.

$$\frac{\sin \alpha_1}{\sin \alpha_0} = \frac{\sin \alpha_1}{\sin \alpha_0} = \frac{L_1}{L_0} = \frac{c_1}{c_0} = \frac{\tanh(2\pi d_0/L_0)}{\tanh(2\pi d_1/L_1)} = \tanh\left(\frac{2\pi d_1}{L_1}\right) \quad (1.4)$$

d_0 and d_1 are shallow water depth and refracted wave depth. α_0 and α_1 are the angle with wave and coastline and the angle made by the refracted wave fronts with the coastline. c_0 and c_1 are deep water wave celerity and refracted wave celerity.

In areas with complex bottom contours, the refraction coefficients K_r are determined using graphs, while the refraction coefficient for parallel contours is calculated using equation 1.5.

$$K_r = \sqrt{\frac{b_0}{b}} = \sqrt{\frac{\cos \alpha_0}{\cos \alpha}} \quad (1.5)$$

1.4.3. Wave Diffraction

Wave diffraction occurs primarily as a result of the interaction between the waves reaching the harbor and the wave breaker. It is generally believed that after diffraction, the wavelength of the waves decreases [Kankal, 2010].

1.4.4. Wave Reflection

Change the direction of a wavefront at an interface between two different environments so that the coast returns to the seaside. In this case, when a wave from the open sea encounters an obstacle, it is not completely damped. The incoming wave exhibits a return behavior with its undissipated energy [Kömürcü, 1998]. The equation for the reflection coefficient, K_y is given in equation 1.6.

$$K_y = \frac{H_y}{H} \quad (1.6)$$

Here H_y is reflected wave height and H is incoming wave height.

1.4.5. Wave Breaking

Waves originating from deep waters become shallower as they approach the shore, which causes the wave height to increase. However, when the wave steepness reaches the critical value, the wave breaks. When a wave is broken, a large amount of wave energy is converted into turbulent kinetic energy. There are geometric, kinematic and dynamic criteria in wave breaking. Geometric breaking criteria refer to standards that evaluate wave breaking based on the geometric properties of the wave [Perlin et al., 2013]

A kinematic criterion states that wave breaking occurs when the horizontal particle velocity at the wave crest exceeds the wave phase velocity [Craciunescu et al., 2019].

According to the dynamic criterion, the wave breaking is evaluated according to the dynamic characteristics of the flow influenced by the wave. When the maximum vertical accelerations of wave particles on a free surface, gravitational acceleration is equal to wave breaking.

The type of wave breaking depends on the slope of the seafloor and the wave height. There are three main types of wave breaking: spilling, plunging, and surging. Battjes (1974) presented the breaking parameter in the form given in equation 1.7 and equation 1.8.

$$\xi_0 = \frac{s}{\sqrt{\frac{H_0}{L_0}}} \quad (1.7)$$

$$\xi_b = \frac{s}{\sqrt{\frac{H_b}{L_0}}} \quad (1.8)$$

ξ_0 and ξ_b are offshore and inshore breaking parameters. s is seabed slope. H_0 represents deep water wave height and H_b represents deep wave height where the wave break.

In **Table 1.1**, the distinctions of breaking types are defined according to the numerical ranges of breaking parameters.

Table 1.1: Wave breaking type.

Breaking type	ξ_0	ξ_b
Spilling	$\xi_0 < 0.5$	$\xi_b < 0.4$
Plunging	$0.5 < \xi_0 < 3.3$	$0.4 < \xi_b < 2$
Surging	$3.3 < \xi_0$	$2 < \xi_b$

2. METHODOLOGY

2.1. MIKE21 BW

The MIKE21 BW includes two modules that can realize one-dimensional and two-dimensional solutions. These modules solve Boussinesq-type equations using an improved linear distribution formulation. These equations, derived primarily by Madsen et al. (1991) and Madsen and Sørensen (1992) are known as the Boussinesq equations. In classical equations, the h/L_0 ratio can be defined up to 0.22, while in these equations, the h/L_0 ratio can be defined in a wide range up to 0.50. The surf zone was expanded as defined by Madsen et al. (1991) [DHI, 2023a].

MIKE21 BW, two-dimensional models, utilize the following improved Boussinesq equations given in equation 2.1.

Continuity:

$$\eta \frac{\partial z}{\partial t} + \frac{\partial B}{\partial x} + \frac{\partial Q}{\partial s} = 0 \quad (2.1)$$

X momentum:

$$\begin{aligned} & n \frac{\partial P}{\partial t} + \frac{\partial}{\partial x} \left(\frac{P^2}{h} \right) + \frac{\partial}{\partial y} \left(\frac{PQ}{h} \right) + \frac{\partial R_{xx}}{\partial x} + \frac{\partial R_{xy}}{\partial y} + F_x + \\ & n^2 gh \frac{\partial \xi}{\partial x} + n^2 P \left[a' + \frac{b' \sqrt{P^2 + Q^2}}{h} \right] + \frac{gP \sqrt{P^2 + Q^2}}{h^2 C^2} + n \Psi_1 = 0 \end{aligned} \quad (2.2)$$

Y momentum:

$$\begin{aligned} & n \frac{\partial Q}{\partial t} + \frac{\partial}{\partial y} \left(\frac{Q^2}{h} \right) + \frac{\partial}{\partial x} \left(\frac{PQ}{h} \right) + \frac{\partial R_{yy}}{\partial y} + \frac{\partial R_{xy}}{\partial x} + F_y + \\ & n^2 gh \frac{\partial \xi}{\partial y} + n^2 Q \left[a' + b' \frac{\sqrt{P^2 + Q^2}}{h} \right] + \frac{gQ \sqrt{P^2 + Q^2}}{h^2 C^2} + n \Psi_2 = 0 \end{aligned} \quad (2.3)$$

Boussinesq dispersion terms Ψ_1 and Ψ_2 are defined;

$$\begin{aligned}\Psi_1 \equiv & -\left(B + \frac{1}{3}\right) d^2(P_{xxt} + Q_{xyt}) - nBg d^3(\xi_{xxx} + \xi_{xyy}) \\ & -ddx \left[\frac{1}{3} P_{xt} + \frac{1}{6} Q_{yt} + nBg d(2\xi_{xx} + \xi_{yy}) \right] \\ & -ddy \left[\frac{1}{6} Q_{xt} + nBg d\xi_{xy} \right]\end{aligned}\quad (2.4)$$

$$\begin{aligned}\Psi_2 \equiv & -\left(B + \frac{1}{3}\right) d^2(Q_{yyt} + P_{xyt}) - nBg d^3(\xi_{yyy} + \xi_{xxy}) \\ & -ddy \left[\frac{1}{3} Q_{yt} + \frac{1}{6} P_{xt} + nBg d(2\xi_{yy} + \xi_{xx}) \right] \\ & -ddx \left[\frac{1}{6} P_{yt} + nBg d\xi_{xy} \right]\end{aligned}\quad (2.5)$$

P and Q are flux density in x direction and y direction. B is Boussinesq dispersion factor. F_x and F_y horizontal stress term in x and y direction. n is porosity. C is Chezy resistance number, $m^{0.5}/s$. a' is resistance coefficient for laminar flow in porous media. b' is resistance coefficient for turbulent flow in porous media. ξ is water surface level above datum.

The MIKE21 BW is used to simulate waves propagating from deep water to shallow water. This model includes wave breaking and takes into account the surf zone, which encompasses the moving shoreline conditions. MIKE21 BW can be used to solve a variety of engineering problems that occur in coastal, harbor and shallow water environments. Some of these problems are: shoaling, refraction, breaking, wave diffraction, bottom friction, moving shoreline, partial reflection, transmission, nonlinear wave-wave interaction, frequency propagation, directional propagation.

Phenomena such as wave grouping, surf beats, generation of bound subharmonics and superharmonics, and near-resonant triple interactions can also be calculated using MIKE21 BW. MIKE21 BW can be used to model these phenomena, allowing for more complex wave interactions and detailed simulations. The flexibility of MIKE21 BW provides users with a wide scope of research to solve a variety of engineering problems.

The Boussinesq equations are solved using an indirect finite difference method by the 2DH module (two horizontal space coordinates), in which the variables are defined on

a stepped rectangular grid in space. Otherwise, these equations are defined on a structured or unstructured grid, where the variables are defined traditional Galerkin finite element method is solved by the 1DH module (a horizontal space coordinate). The MIKE21 BW consists of three main sections: basic parameters, calibration and output.

2.1.1. Basic Parameters in MIKE21 BW

In the Basic Parameters section, the main input parameters for the simulation are defined. These parameters include: module type, bathymetry file, equation type, numerical solver type (2D only), boundary condition, simulation period. These parameters serve as the primary input information for configuring the simulation in MIKE21 BW and allow users to define the key features and conditions of the model. In general, one-dimensional models and two-dimensional models should use deep-water terms when considering wave diffraction and the presence of moving shorelines. As seen in the model interface, in this case, the linear distribution factor $B = 1/15 = 0.06667$ should be used in the equation.

2.1.2. Calibration Section in MIKE21 BW

In the calibration section, the goal is to achieve the best fit between the application results of the model and the observed data. Users can make fine adjustments by adjusting certain parameters in the calibration section. This section includes components that affect the accuracy of the model, such as bathymetric parameters (2D), boundary data (2D), surface height (2D), internal wave generation, bottom friction, eddy viscosity, filtration, wave breaking, moving shoreline, porosity layers, and sponge layers.

Wave, filter, porosity, and sponge layer files are created using MIKE tools and used as input. Filters are used to eliminate high-frequency instabilities during rise and fall and to dampen wave energy in areas where surface wave cannot be resolved. Porosity is used to model partial reflection and/or conduction through structures by assigning permeability values. Sponge (or absorbent) layers can be used as effective numerical wave absorbers in Boussinesq wave simulations. These layers, for example, apply radiation boundary conditions at the boundaries of the model and can be used to absorb

wave energy emitted from the field. In Boussinesq wave simulations, the width of the sponge layer should be one or two wavelengths. The sponge layer is defined in coastal areas and behind the place where the inland wave is identified to prevent wave radiation. The sponge layer coefficient is obtained from the [DHI, 2023b], depending on the number of grid points covered by the sponge layer.

2.1.2.1. Surface Roller Concept

The incorporation of wave breaking in the MIKE 21 BW is based on the concept of surface rollers. When the local slope of the water surface exceeds a predetermined angle, wave breaking is considered to have occurred, and in this case, the geometry of the surface wave is determined. An additional transfer momentum factor resulting from the asymmetrical vertical distribution of horizontal velocity is used to account for the effect of the breakers. The concept of surface roller for wave breaking, which is also used in MIKE21 BW, was introduced in the works of [Schaffer et al. 1993] and [Madsen et al. 1997].

Schaffer et al. (1993) reported that the critical angle of breaking defined as ϕ in his study undergoes a change from the initial angle of breaking ϕ_B to the angle ϕ_0 . The reason for this change is that the wave refraction that occurs in the inner surf area transitions to a bore-style stage. Because of this transition exponential decay of $\tan\phi$ was chosen. The change of roller depending on time and breaking angle is given in equation 2.6.

$$\tan \phi = \tan \phi_0 + (\tan \phi_B - \tan \phi_0) \exp \left[-\ln 2 \frac{t - t_B}{t^*} \right] \quad (2.6)$$

Roller are determined by three parameters, $\tan\phi_B$, $\tan\phi_0$, and t^* . t^* is the timescale for the development of rollers. Depending on these three parameters, the model can be calibrated. In general, $\phi_B \approx 20^\circ$ and $\phi_0 \approx 10^\circ$ are accepted.

In the surface roller approach, the roller is considered as the volume of water carried by the wave velocity. As a result of this approach, it is assumed that it causes a vertical distribution of horizontal particle velocity [Madsen et al., 1997]. Surface roller concept and cross section of breaking wave and assumed vertical profile of the horizontal particle velocity components given in **Figure 2.1**.

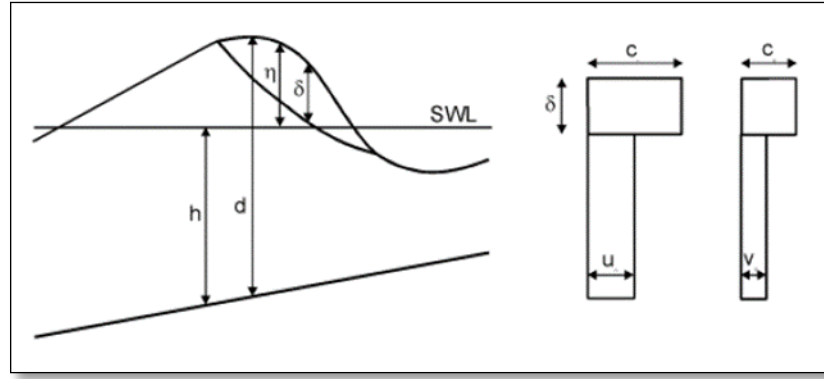


Figure 2.1: Surface roller concept [DHI, 2023a]

This velocity profile is considered valid in the case of wave breaking resulting in the following modified version of Boussinesq's equations given in equation 2.7, equation 2.8, equation 2.9.

$$\frac{\partial \eta}{\partial t} + \frac{\partial P}{\partial x} + \frac{\partial Q}{\partial y} = 0 \quad (2.7)$$

$$\frac{\partial P}{\partial t} + \frac{\partial}{\partial x} \left(\frac{P^2}{d} \right) + \frac{\partial}{\partial y} \left(\frac{PQ}{d} \right) + \frac{\partial R_{xx}}{\partial x} + \frac{\partial R_{xy}}{\partial y} + gd \frac{\partial \eta}{\partial x} + \psi_x + \frac{\tau_x}{\rho} = 0 \quad (2.8)$$

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial y} \left(\frac{Q^2}{d} \right) + \frac{\partial}{\partial x} \left(\frac{PQ}{d} \right) + \frac{\partial R_{yy}}{\partial y} + \frac{\partial R_{xy}}{\partial x} + gd \frac{\partial \eta}{\partial y} + \psi_y + \frac{\tau_y}{\rho} = 0 \quad (2.9)$$

The extreme momentum caused by the unequal velocity distribution brought about by the presence of a roller is considered with R_{xx} , R_{xy} , and R_{yy} . R_{xx} , R_{xy} , and R_{yy} was given in equation 2.10, equation 2.11 and equation 2.12.

$$R_{xx} = \frac{\delta}{1 - \frac{\delta}{d}} \left(C_x - \frac{P}{d} \right)^2 \quad (2.10)$$

$$R_{xy} = \frac{\delta}{1 - \frac{\delta}{d}} \left(C_x - \frac{P}{d} \right) \left(C_y - \frac{Q}{d} \right) \quad (2.11)$$

$$R_{yy} = \frac{\delta}{1 - \frac{\delta}{d}} \left(C_y - \frac{Q}{d} \right)^2 \quad (2.12)$$

$\delta = \delta(t, x, y)$ is thickness of the surface roller. C_x , C_y are roller celerity componenets in x and y direction.

The parameters set by the roller concept for wave breaking are as follows:

Roller Form Factor: This parameter represents the shape or form of the roller. It defines the relationship between the roller height and the length of the wave crest.

Type of Roller Celerity: Refers to the speed of propagation of the roller. Depending on the specific characteristics of the waves and the breaking process, different types of roller celerities can be considered. The direction of the roller can be determined interactively according to the instantaneous wave field (Type 1) or set to a predefined wave direction (Type 3). The first method (Type 1) can sometimes lead to stability problems, so the second type is usually recommended.

Roller Celerity Factor: This factor determines the relationship between roller celerity and wave celerity. It affects the timing and extent of wave breaking. Roller celerity factor given in Equation 2.13 and Equation 2.14.

$$(c_x, c_y) = (c \cos \theta, c \sin \theta) \quad (2.13)$$

$$c = f_v \sqrt{gh} \quad (2.14)$$

f_v is roller celerity factor. The value of f_v can range between 1 and 1.3. When $f_v = 1$, it is used to model linear shallow water theory in areas outside the surf zone, providing better results. On the other hand, when $f_v = 1.3$, it yields better results within the surf zone. In the MIKE21 BW program, the default value of f_v is set to 1.3.

Initial Breaking Angle (IBA): Represents the angle at which the wave crest begins to break. It shows the beginning of wave breaking and the transition from regular waves to broken waves. In the MIKE21 BW program, the default value for the IBA is 20 degrees. However, this value can be adjusted in the range from 10 to 40 degrees.

Final Breaking Angle (FBA): This parameter defines the maximum angle at which the wave crest is broken. It determines the degree of wave breaking and the resulting turbulence and energy distribution. In the MIKE21 BW program, the default value for the FBA is 10 degrees. This value can be adjusted in the range from 5 to 30 degrees.

Half Time Cut-Off Roller: This parameter specifies the amount of time during which the roller is considered significant. It determines the time frame in which the effects of

the roller on the wave transformation are taken into account. It must be equal to $T_p/5$.

Wave Direction: Indicates the direction of wave propagation. The roller concept takes the wave direction into account when determining the breaking characteristics and the corresponding parameters.

2.1.3. Output Section

In the output section, there are options to produce simulation outputs in different formats. Through graphical representations such as time series graphs, contour maps, or spatial profiles, users can see and analyze data. In addition, MIKE21 BW offers export options so that the results can be shared with additional analysis or other stakeholders and exported in a variety of formats. In the output section, you will find deterministic parameters, phase average parameters, wave disturbance parameters (2D), and hot start parameters (2D).

2.2. SWASH

The SWASH wave model provides simulation using NSWE that include non-hydrostatic pressure and specific transport equations. The SWASH wave simulation program provides simulation of non-hydrostatic, free-surface, and rotating flow phenomena in one and two dimensions. Delft University of Technology created and continues to maintain the numerical simulation SWASH. The study from (Stelling and Zijlema, 2000; Stelling and Duinmeijer, 2003; Zijlema and Stelling, 2005; Zijlema and Stelling, 2008; Smit et al. 2013; Zijlema, 2020) served as the foundation for the development of SWASH's open source code. The SWASH program allows you to surf under different wave conditions with varying interaction characteristics and wave transformation in surf zones. The SWASH program can simulate rapid and complex changes such as tsunamis, river floods, and flood waves. The SWASH program is designed to simulate intensity-based flows and large-scale ocean circulation, including tidal processes and storm surges in coastal seas, estuaries, lakes, and rivers. This model, known as the wave flow model, can be used in coastal areas up to the shoreline. The basic idea of the SWASH code is to offer an effective and reliable model for shallow water flows and surface waves in complex situations across a wide range of temporal and spatial dimensions. To ensure that mass and momentum are fully

conserved at a fractional level, SWASH uses a staggered grid structure based on a second order finite difference approximation. This makes it possible to monitor the area where the waves are break and analyze the phenomenon of wave breaking.

2.2.1. Equations for SWASH

Zijlema et al. (2011) presented the NSWE for a three-dimensional system to be used in the non-hydrostatic SWASH model. Smit et al. (2013) provided this equation in a similar form to equation 2.15, equation 2.16 and equation 2.17 including two-dimensional cases. These equations are given for a free-surfaced, incompressible, and constant pressure fluid [Van Eeden, 2017].

$$\frac{\partial u}{\partial t} + \frac{\partial uu}{\partial x} + \frac{\partial wu}{\partial z} = -\frac{1}{\rho} \frac{\partial (p_n + p_{nh})}{\partial x} + \frac{\partial \tau_{xz}}{\partial z} \tau + \frac{\partial \tau_{xx}}{\partial z} \quad (2.15)$$

$$\frac{\partial w}{\partial t} + \frac{\partial uw}{\partial x} + \frac{\partial ww}{\partial z} = -\frac{1}{\rho} \frac{\partial p_{nh}}{\partial z} + \frac{\partial \tau_{zz}}{\partial z} \tau + \frac{\partial \tau_{zx}}{\partial x} \quad (2.16)$$

$$\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} = 0 \quad (2.17)$$

p_n and p_{nh} are hydrostatic and non-hydrostatic pressures. $u(x; z; t)$ and $w(x; z; t)$ are horizontal and vertical velocities respectively in space and time. τ_{xx} , τ_{xz} , τ_{zz} are turbulent stress terms.

3. DATA

3.1. DUCK94 Experiments

The DUCK94 experiments consist of a series of field experiments conducted by the Coastal and Hydraulics Laboratory of the U.S. Army Engineer Research and Development Center (formerly the Coastal Engineering Research Center) at the Field Research Facility (FRF) located in Duck, North Carolina, USA. These experiments aim to improve the understanding and modeling of coastal waves. The experiments involve a variety of participants and focus on summarizing environmental conditions, data collected, and data accessibility. The DUCK94 experiments focused on specific topics such as small and medium-sized sediment transport and morphology, wave shoaling, wave breaking, and splashing processes involving nearshore circulation as well as sediment movement. These issues have been studied and analyzed during experiments to improve understanding and modeling in these areas of coastal research. In this context, a total of 31 different experiments were carried out. During the experiments carried out, various measurement techniques were used to collect relevant data. These measurements included monitoring coastal morphology changes, measuring seafloor level fluctuations, making sediment measurements, monitoring flow rates, and recording pressure measurements [Birkemeier, 1996].

In this study, wave spectrum data, bottom bathymetry data and tide data of different time intervals obtained from DUCK94 experimental measurements were used. Spectrum files contain data from 15 different locations. A total of 799 different spectral values were appropriately matched with 38 bathymetry datasets based on time and date. Models were prepared taking into account in tidal changes in sea level.

The spectrum data used were obtained from July, August, September, October and November of 1994. Data distribution collected on a daily basis, with measurements taken every 3 hours, resulting in 8 hourly data points per day. The specific times at which data is collected are: 01:00, 04:00, 07:00, 10:00, 13:00, 16:00, 19:00 and 22:00. These time intervals were chosen to capture the change in wave conditions throughout the day and to provide a comprehensive representation of the wave spectrum over the specified months. Spectrum files contain spectra for 15 different locations, from the deepest to the shallowest points. These locations are numbered from 1 to 15, and each

location represents a specific depth or location throughout the profile. The spectra provide information about the wave energy distribution at each of these locations, allowing for the analysis of wave properties and their variation from the deepest to the shallowest points.

The location information of 15 different wave sensors in the experimental area is given in **Table 3.1**. The data in this table were collected on September 7, 1994 at 13:00.

Table 3.1: DUCK94 experiment wave gauge locations.

Location No.	X (m)	Z (m)
loc1	135.01	-0.31
loc2	145.42	-0.92
loc3	160.77	-0.58
loc4	169.5	-0.63
loc5	205.34	-1.04
loc6	190.2	-1.105
loc7	220.23	-1.34
loc8	240.55	-1.63
loc9	252.03	-3.15
loc10	264.7	-1.9
loc11	320.37	-2.93
loc12	370.08	-4.36
loc13	398.39	-3.71
loc14	480.34	-5.01
loc15	884.11	-7.63

The Z (m) value provided here represents the vertical distance of each wave sensor from the reference point of the seabed. This value historically varies based on the tidal fluctuations. The changes in sea level have been adjusted using daily and hourly tide data for accurate measurements.

Under TÜBİTAK Project Number 119N900, as detailed by [Aydın, 2023], wave spectra and seabed bathymetry measurements obtained from the DUCK94 experiments were corrected. The normalized data from this study has been utilized.

3.2. AYGM Experiment

The experiments were carried out in the Hydraulic Research Laboratory of the General Directorate of Infrastructure Investments of the Ministry of Transport and Infrastructure (AYGM) of the Republic of Türkiye. The experimental setup was built in an open channel 0.6 m wide, 1.2 m high and 40 m long. The top view of the canal is shown in **Figure 3.1**. Two different slope values, 1/20 and 1/10, were used for canal bed bathymetry. For the creation of a 1/20 slope bed bathymetry, the distance from the wave generator to the beginning of the bed slope was determined as 11.95 m. The length of the inclined bed plate is determined as 15.55 m. The highest point of the bed plate from ground level was 0.79 m, which was designated as the zero point. When creating a 1/10 inclined bed bathymetry, the distance measured between the wave generator and the starting point of the bearing slope is 19.19 m. The length of the inclined bed plate is 8.31 m. The highest point of the bed plate is 0.79 m, which corresponds to the zero point. In both experimental setups, a section of 27.50 m of the canal was used. The experiments were carried out with a water depth of $d = 0.79$ m.



Figure 3.1: Top view of the channel.

In the unbuilt sections of the canal, damping elements were installed to prevent wave reflections. Fluctuations on the water surface were measured using wave meters in six different locations. The locations of the wave indicators and the corresponding water depths in their respective regions are presented in **Table 3.2**.

Table 3.2: Structuring the experimental study.

Wave Gauge No.	1/20 Profile		1/10 Profile	
	Location (0+) (cm)	Depth (cm)	Location (0+) (cm)	Depth (cm)
1	90	5.1	98.5	5.6
2	163.5	8.7	143.5	10.7
3	276.2	14.4	225.0	18.9
4	527.2	26.4	324.0	29.0
5	730.5	37.5	566.0	54.2
6	1555.6	79.0	831.0	79.0

The waves were generated using a wave paddle connected to a computer system. The experiments produced monochromatic waves, bichromatic waves, and waves JONSWAP spectrum. The periods and heights of the waves were defined on the computer to create the desired wave conditions. Fluctuations on the surface of the water were converted into signals by wave gauges (WG) and transferred to the computer system, from which time series data was extracted. The front view of the wave generator is shown in **Figure 3.2**.



Figure 3.2: Front view of the wave generator.

In the 1/20 slope profile, regular waves were produced with periods ranging from 1 sec to 4.5 sec and wave heights ranging from 0.19 m to 0.22 m. **Table 3.3** gives the monochromatic waves run on the 1/20 sloping base profile.

Table 3.3: Monochromatic waves run on the 1/20 sloping base profile.

Wave No	T (s)	H (m)
1	1	0.22
2	1.08	0.22
3	1.1	0.22
4	1.2	0.22
5	1.37	0.19
6	1.4	0.22
7	1.5	0.22
8	1.86	0.15

Table 3.3 Continued: Monocromatic waves run on the 1/20 sloping base profile.

9	1.9	0.22
10	2	0.20
11	2	0.22
12	2.1	0.22
13	2.2	0.22
14	2.3	0.22
15	2.5	0.22
16	2.6	0.22
17	3.6	0.20
18	4.3	0.20
19	4.5	0.20

Waves with a lowest period of 0.98 s and a highest period of 4.49 s were used for the formation of bicromatic waves. In these waves, the wave height range is between 6 cm and 14 cm. Bicromatic waves run on the 1/20 sloping base profile given in **Table 3.4**.

Table 3.4: Bicromatic waves run on the 1/20 sloping base profile.

Wave No	T ₁ (s)	H ₁ (m)	T ₂ (s)	H ₂ (m)
1	0.98	0.12	1	0.12
2	1	0.10	2	0.10
3	1	0.12	2	0.12
4	1.1858	0.12	1.2	0.12
5	1.2	0.06	2	0.06
6	1.267	0.12	1.3	0.12
7	2	0.14	2.083	0.14
8	2.199	0.12	2.3	0.12
9	2.5	0.10	2.632	0.10
10	2.5	0.14	2.632	0.14
11	2.6	0.14	2.67	0.14
12	3	0.14	3.09	0.14
13	4.3	0.14	4.49	0.14

The gamma values used in the creation of JONSWAP spectrum waves were 3.3, 5, 7 and 10. For JONSWAP spectrum waves, waves with periods of 1.2 s, 2 s, and 3 s were produced with a wave height of 0.20 m. The period, wave height and gamma parameters of JONSWAP spectrum waves are presented in **Table 3.5**.

Table 3.5: JONSWAP spectrum waves run on the 1/20 sloping base profile.

Wave No	T (s)	H (m)	Gamma
1	1.2	0.2	3.3
2	2	0.2	3.3
3	3	0.2	3.3
4	1.2	0.2	5
5	2	0.2	5
6	3	0.2	5
7	1.2	0.2	7
8	2	0.2	7
9	3	0.2	7
10	1.2	0.2	10
11	2	0.2	10
12	3	0.2	10

At the 1/10 slope profile, 13 regular waves were produced with periods ranging from 1.2 s to 3.5 s and a wave height of 0.24 m. Monocromatic waves run on the 1/10 sloping base profile given in **Table 3.6**.

Table 3.6: Monocromatic waves run on the 1/10 sloping base profile.

Wave No	T (s)	H (m)
1	1.2	0.24
2	1.3	0.24
3	1.4	0.24
4	1.5	0.24
5	1.6	0.24
6	1.7	0.24
7	2	0.24
8	2.2	0.24
9	2.4	0.24

Table 3.6 Continued: Monocromatic waves run on the 1/10 sloping base profile.

10	2.6	0.24
11	2.8	0.24
12	3	0.24
13	3.5	0.24

The gamma values used to generate the JONSWAP spectrum waves were 3.3, 7 and 10. Waves with a period of 1.2 s and 2 s were produced at a wave height of 0.20 m and a total of 6 waves were obtained. The period, wave height and gamma values of JONSWAP spectrum waves are presented in **Table 3.7**.

Table 3.7: JONSWAP spectrum waves run on the 1/10 sloping base profile.

Wave No	T (s)	H (m)	Gamma
1	1.2	0.20	3.3
2	2	0.20	3.3
3	1.2	0.20	7
4	2	0.20	7
5	1.2	0.20	10
6	2	0.20	10

3.3. DUCK94 Model Set up with MIKE21 BW

In the modeling of the DUCK94 experiments, the test data were obtained from the part corresponding to the 9th month of the general data set. This dataset consists of 238 separate spectrum data. From this spectrum data 207 spectrum data was chosen. Initially, a 1D model setup was used to create the MIKE21 BW models. However, explosions were seen in a few models, which encouraged the choice to go ahead with 2D modeling.

3.3.1. 1D Models with MIKE21 BW

The module type was determined as 1D. The bathymetry file was created separately for each model by adding tidal variation values. Bathymetry files were created with a grid spacing of 1 m, resulting in a total of 933 grid points. When creating the bathymetry file, sponge layer sections were included, with 80 grid points at the shallowest part and 100 grid points at the deepest part. **Figure 3.3** shows the bathymetry file of the model dated September 1, 1994, at 01:00.

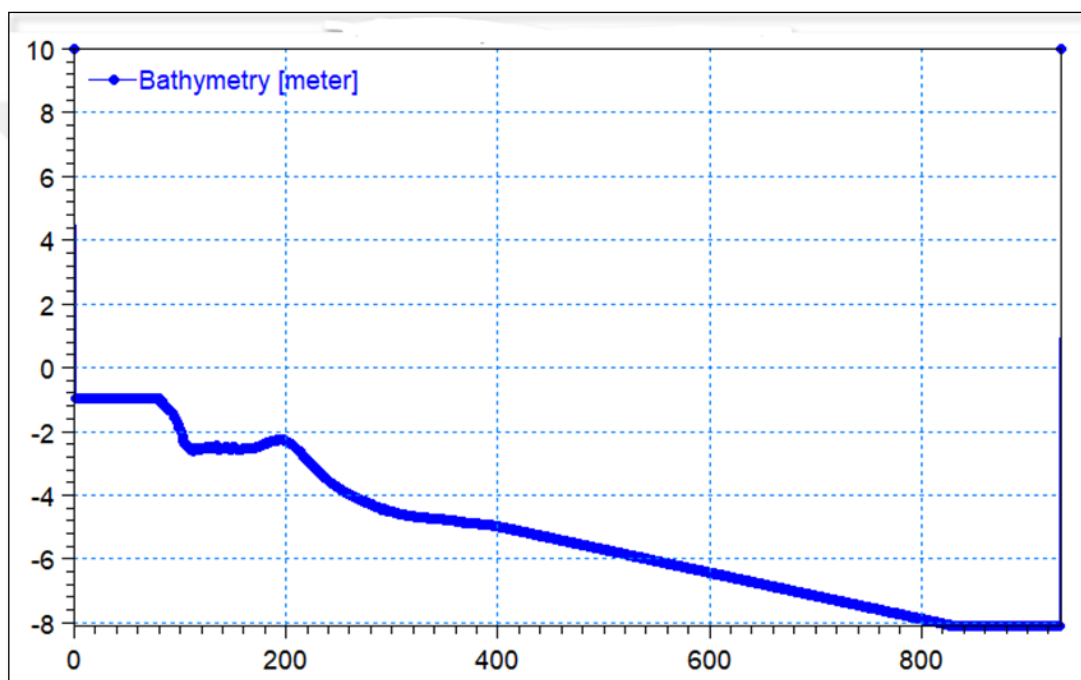


Figure 3.3: 1 September 1994, at 01:00-MIKE21 BW bathymetry.

In modeling, there are options for the classic Boussinesq type and the improved equation type. The improved Boussinesq equation type, which includes the term deep water, was chosen. In this section, the linear dispersion factor B is set to the default value of 0.667.

The time step interval is set to 0.01 s. It was determined that the simulation period had a total of 100001 time steps. The simulation duration was set to 16 minutes and 40 seconds. The Courant number was calculated as 0.0891.

The waves described in the calibration section on internal wave generation were created using the MIKE21 Toolbox. Spectrum files have been created. Experimental spectra were added to the generated frequency files. In the random wave generation section, waves were generated by defining a user-defined 1D frequency spectrum. One dimensional wave type is used. The first random number seed was set to 100. For each model, the water depth and minimum time period value in the series were determined. The minimum time period in the series is calculated as described in equation 3.1 and equation 3.2. Wave identification was made at point 830 and wave transmission was provided from the right side to the left side of the model.

$$\frac{d}{L_0} = 0.5 \quad (3.1)$$

$$L_0 = 1.56 * T^2 \quad (3.2)$$

A numerical low-pass filter was applied to implement the effects of wave-induced instabilities in the coastal area. The filter is defined at 80 grid points to cover the coastal area. A filter coefficient of 0.5 is selected for the filter. In sections where the filter is not applied, the filter coefficient is assigned as 0. **Figure 3.4** shows the 1D filter created in MIKE21 BW with 0.5 coefficient.

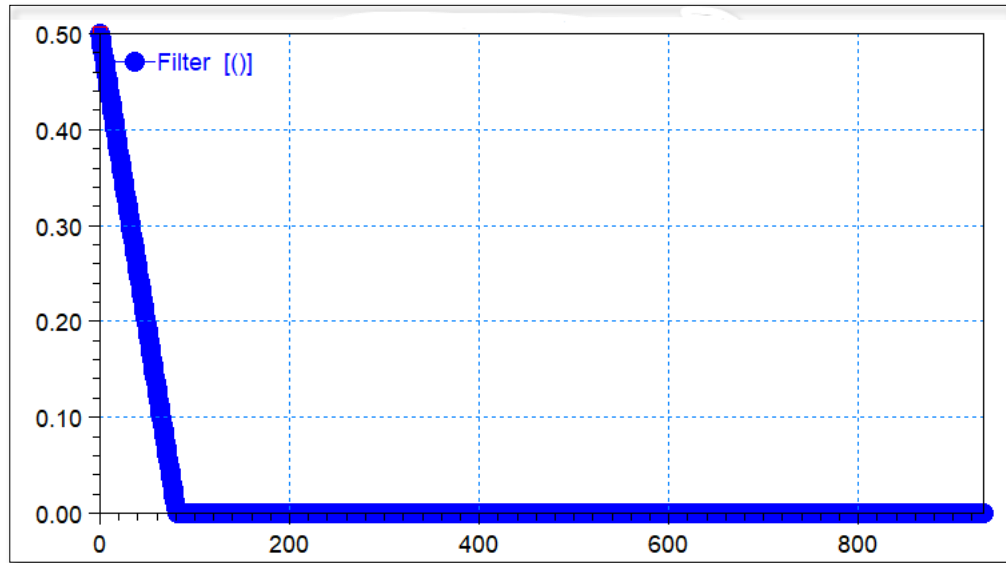


Figure 3.4: Filter with 0.5 coefficient in MIKE21 BW.

Wave breaking situation is used in the models. The wave breaking parameters were defined as the roller form factor set to the default value of 1.5. Roller celerity was prescribed using the projected wave direction approach, defined as type 3. The roller celerity factor was set to 1.3 as it provided better results in shallow water. The initial and final breaking angle values were adjusted for model calibration. The IBA values were selected as 10, 20, 30 and 40, while the FBA values were set as 5, 10, 20 and 30. These values have been used in various combinations for the models.

To create the sponge layer, 81 grid point extensions were added to the bathymetry file at the shallowest part and 102 grid point extensions at the deepest part. Sponge layer files were created using the MIKE21 Toolbox. The coefficients for the sponge layer calculation are determined according to **Equation 3.3**. In the shallowest section of 81 points, the base value is defined as 10 and the power value is 0.892. In the 102 point section on the deepest part on the right side, the base value is defined as 10 and the power value is defined as 0.92. The coefficients used to determine the sponge layer are given in **Table 3.8**.

$$C_{sponge} = \dot{a}^{(r^{i-1})}, i = 1, N_{sponge} \quad (3.3)$$

The base and power values for different sponge layer amounts are provided in the **Table 3.8**.

Table 3.8: Recommended values for sponge layer coefficients.

N_{sponge}	$\dot{a}$	r
10	5	0.50
20	7	0.70
50	10	0.85
100	10	0.92
200	10	0.95

3.3.2. 2D Models with MIKE21 BW

3.3.2.1. Bathymetry, Numerical Parameters and Simulation Period

In the MIKE21 BW program, it is recommended to use the model setup planner for the definition of bathymetry and simulation period. In the calculations for the Boussinesq equations developed here, the Δx , grid length, is determined as 1.04 m. According to [DHI, 2023b] if wave breaking and moving shoreline parameters are to be observed in a 2D system simulation, the Δx value should be between 1 and 2 m.

A Δx value of 1m was chosen as the lower limit for modeling. To define bathymetry in two dimensions, 933 grid points were specified in the x plane and 3 grid points in the y plane. Grid lengths are defined as 1m.

Bathymetric measurements from the DUCK94 experimental site were included in the grid template created for bathymetry. To make this template suitable for one-dimensional bathymetry, the y-axis at locations 1 and 3 are designated as terrain. To achieve this, in the calibration parameters, the bathymetric value and presentation place boxes of the bathymetric data section were set to 11. Sections 1 and 3 in the bathymetry part are filled with the value 11. For the definition of sponge layer in bathymetry, the deepest point was defined at 133 points and the shallowest point at 80 points, both at the same depth.

Since DUCK94 bathymetric data were not available for each date range, spectrum values were matched with the nearest bathymetric value and model definitions were made. In **Figure 3.5**, bathymetry data dated 1994-09-07 and bathymetry created in MIKE21 BW are given. In the DUCK94 experiments, tide heights varied for each model. These differences are defined in the calibration section by bathymetric parameters and shifting the reference level. The increase of bathymetry by tidal data is defined in this way to obtain the most accurate bathymetric definition for the model.

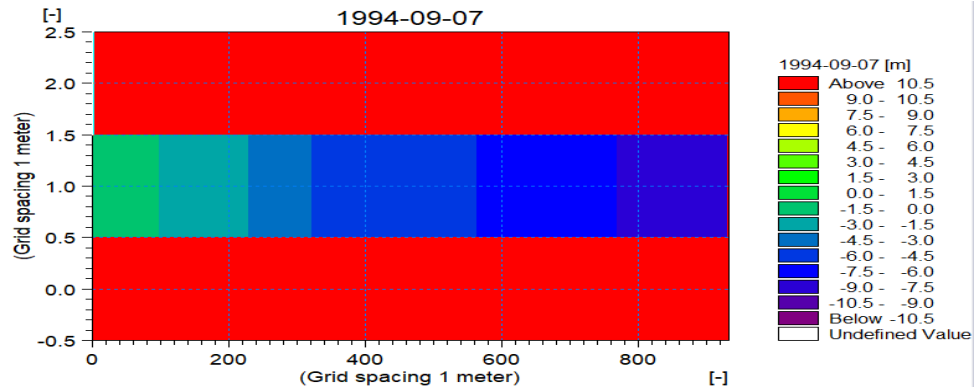


Figure 3.5: DUCK94 bathymetry at 1994-09-07 used in the MIKE21 BW.

In order to reduce the instabilities that may occur during wave breaking, sponge layer identification has been applied in the model. These definitions were made using the MIKE Toolbox and specific sections for the sponge layer were defined in the bathymetry files. These sections were typically located at the most frequent points and at the deepest points. The sponge layer is defined in a separate file, the land descriptions in the bathymetry files are marked with the number 11. Similarly, land points in both the sponge layer and bathymetry files are identified by the number 11. In the most frequently used section, 80 grid points were determined for the sponge layer, and 103 grid points were determined for the sponge layer at the deepest points. **Figure 3.6** shows the sponge layer entry created in MIKE. **Figure 3.7** shows a detailed representation of the sponge layer input used in the MIKE21 BW program from the left and right profiles, respectively.

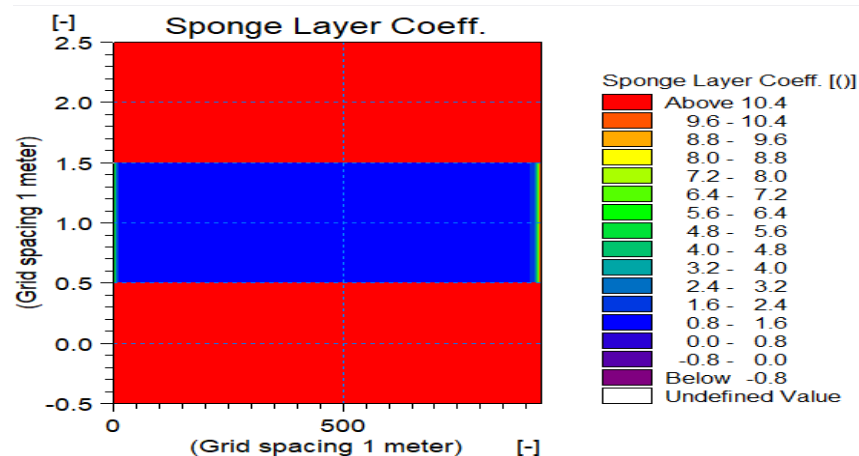


Figure 3.6: Sponge layer input used in the MIKE21 BW program.

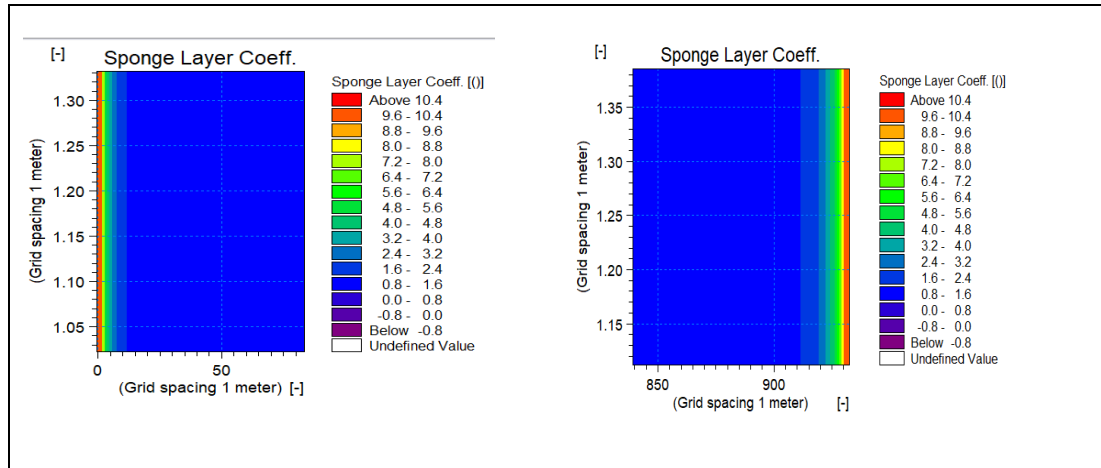


Figure 3.7: Detailed representation of the sponge layer input used in the MIKE21 BW program from the left and right profiles, respectively.

In simulations involving wave breaking and moving shorelines, it was recommended to apply a low-pass filter. These low-pass filters were prepared in a similar way to a bathymetry file covering the points where wave breaking would occur. Low-pass filters were identified along grid points starting with a constant of 0.5 and descending linearly towards the ends. In the models, linearly descending filters were applied, the 90 shallowest grid points to be covered. The detailed filter input with a constant of 0.5 used in the MIKE21 BW program is given in **Figure 3.8**.

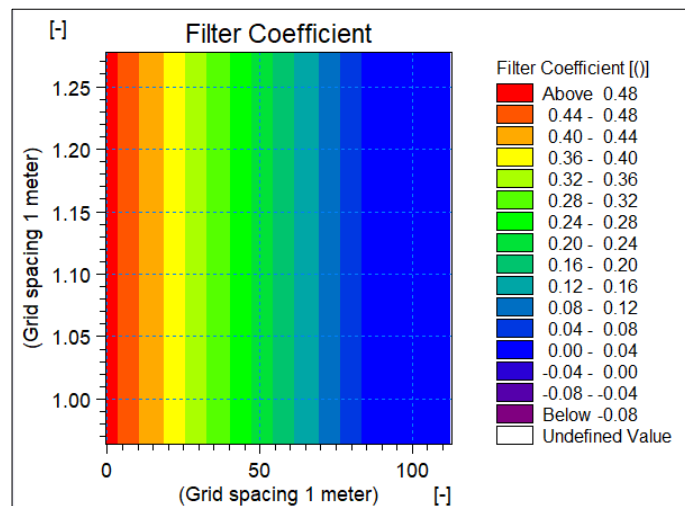


Figure 3.8: Filter input with a constant of 0.5 used in the models of the MIKE21 BW.

Using the MIKE21 Toolbox, the first step involved the preparation of wave energy spectrum files. The spectrum values obtained from the DUCK94 experiments were

integrated into these prepared spectrum files. These files were then used to create waves using random wave generation. One-dimensional user-defined spectrum files were used to generate model-based waves, and the wave type was specified as one-dimensional. In the auxiliary parameter specification section, the first random number is defined as 100. The water depth was determined by the pattern and the amount of tide. The smallest wave period value in the series is calculated by equation 3.1 and equation 3.2.

The time series was defined by 100001 time steps, each with a time interval of 0.01 seconds. In this way, wave files were defined separately for each model, providing a separate specification for each.

In MIKE21 BW, incident waves are defined as boundary conditions. In the case of incident wave formation, a layer of sponge is placed behind the wave to ensure that the wave is directional or non-directional. A sponge layer is defined behind the area where the waves are formed, preventing the outgoing waves. Therefore, in the models, it was determined that the wave formation point at the boundary coincides with the end point of the sponge layer defined at the deepest point. The wave generation points were indicated by a line perpendicular to the wave propagation plane. This definition was made by selecting the 1st and 3rd grids in the y-plane from the bathymetric grids.

The main idea in the definition of a moving shoreline is to model the impermeable beach structure as an extended permeable plane by assigning very small porosity values. In vertical sections, there is a smooth flow of water at the top, while there is a porous flow at the bottom. Adjustments need to be made to reduce instabilities in the transition between these two regimes [Madsen et al. 1997]. In equation 3.3, the vertical variation of porosity is given.

$$\gamma(z) = \begin{cases} 1, & Z_L \leq z \\ \epsilon + (1 - \epsilon)e^{\frac{b(z-Z_L)}{(Z_L-Z_B)}}, & Z_B \leq z \leq Z_L \end{cases} \quad (3.3)$$

$\gamma(z)$ is the porosity, ϵ is the minimum value of γ , b is a constant shape factor defining the exponential transition between the two flow regimes, z is the vertical coordinate, $Z_L(x, y)$ defines the physical sea bed and Z_B defines the lower limit of the porous region. Basically, ϵ should be as small as possible and b as big as possible so that the mass balance is not distorted and the flow is not disturbed in the physical domain.

The minimum porosity value should be selected as small as possible to maintain flow characteristics. However, in areas with steep bathymetry, higher porosities may be required. It is recommended to choose a pore width between 0.01 and 0.001. In the models, a pore width of 0.01 caused instabilities during wave simulations, leading to burst states. Therefore, to overcome these instabilities, pore widths were increased to 0.1.

In order to obtain output, definitions are made for 15 different locations according to network numbers. The calculation of the output is defined to cover the entire bathymetry. For time settings, it is specified that the results will be printed every 10 steps with a total of 100001 time steps. To obtain the temporal variation of the water surface, the wave heights is selected from the output elements.

3.3.3. 1D Models with SWASH

3.3.3.1. Computational Grid

Grids can be defined by user-specified location dimensions, resolution, and orientation. Grids can be uniform, linear, orthogonal, curvilinear, or an unstructured triangular mesh. The size and number of grids are determined by the user. During grid definitions, x and y coordinates are specified first. For one-dimensional models, the y-coordinate is set to zero. Next, the direction of the x-axis is defined and the lengths of the calculation grids are specified. For one-dimensional models, this value is zero in the y-direction grid length. Finally, the mesh numbers are defined for the x and y directions. The mesh numbers are one less than the grid numbers, and the mesh count in the y-direction is set to zero. Model bathymetry is initially defined on a grid-by-grid basis using the "Grid" command. Bathymetric grids in the x and y planes are defined similarly to grid definitions. Mesh definitions are made for x and y planes and grid lengths are specified in meters. Bathymetry files are read using the "Read Input Grid" command. At this point, the unit of length of the bathymetric level is defined and the direction in which the bathymetry file is to be read is specified.

3.3.3.2. Initial and Boundary Conditions

In the definition of initial conditions; constant, zero, or stable conditions can be specified. In the model definitions, a zero initial condition is defined, assuming that the water level and velocity components are initially zero.

The wave boundary condition was defined using spectrum data from the DUCK94 experiments. From the experimental data, the spectrum value at the deepest point was transferred to the spectrum files with sp1 extension. These files were then identified as boundary conditions, specifically wave boundary conditions. SP1 extension spectrum files (SPEC1D) contain wave spectrum in one dimension. These files are defined for a single location, and there are two different definitions in their content: frequencies in hertz and density of variance in m^2/Hz . These files can only contain fixed wave spectrum and are intended to be used in a single location. To be consistent with the definition of bathymetry, wave coupling is defined as western. On the east side, which is the shallow part where the wave will reach and break, a reflection boundary condition is defined, which indicates the area where the wave will be reflected.

In SWASH, a layer of sponge is defined to allow the waves to absorb energy when they leave the computational field. In the models, the sponge layer designation is indicated by 80 layers on the east side. Since the sponge layer can be identified from the wave boundary, no sponge layer has been identified behind the point where the wave occurs.

3.3.3.3. Wave Breaking

To correctly start the wave breaking process, it is necessary to trace the wave front faces, which resemble perpendicular holes. This can be controlled by the vertical velocity of the free surface. This occurs when the conditions given in Equation 3.4 in shallow water are exceeded.

$$\frac{\partial \zeta}{\partial t} > \alpha \sqrt{gh} \quad (3.4)$$

The α parameter represents the maximum local surface steepness, allowing the breaking process to be started. In SWASH, the recommended default value is 0.6,

which corresponds to a 25° angle. According to SWASH, observed that this value yielded good results for regular and irregular waves.

Another parameter that represents wave breaking is the β parameter, which defines the continuation of the wave breaking process. This parameter acts as a trimming parameter to stop the end of the wave break. It must be less than α and its default value is 0.3. The conditions for the parameter β are given in equation 3.5.

$$\frac{\partial \zeta}{\partial t} > \beta \sqrt{gh} \quad (3.5)$$

In the model definitions, these parameters, which are the α and β that manage wave breaking, will be calibrated and the parameters that achieve maximum simulation accuracy will be found.

3.3.3.4. Output Request

For a location-based result system with point entries, a list of locations is provided for the desired points with point entries. To achieve this, grid points corresponding to the locations where the wave measuring devices are located are determined in the bathymetric field from the DUCK94 experimental data. These grid points are then defined in the form of a list. The results are written in a table that captures changes in water levels through a "WATL" definition. The intervals from which the conclusions will be drawn are indicated here. The simulation process is defined by "COMPUTE", which indicates the start time, time step and end time of the simulation. The number of time steps is not defined.

3.4. AYGM Model Set up with MIKE21 BW

Bathymetry definitions were made different slope (m). Separately for $m = 1/20$ and $m = 1/10$ plane slopes. 670 points are defined in the x plane and 3 points in the y plane. Grid lengths were determined as 0.1 meters. 200 points were defined at the shallowest points where wave breaking occurred, and 195 points were defined for the sponge layer in a straight line bathymetry behind the point where the wave occurred. The terrain is located in the 1st and 3rd places in the y-plane. The terrain along the grids is defined by number 11. Since there was no change in the water level (tide) in the

experiments, the increase bathymetry was set to 0. The sponge layer is defined by the shallowest 200 points and the deepest 195 points. 210 grid points with filters were defined to cover the grids where wave breaking would occur.

The simulation period is defined differently for regular monochromatic, regular bichromatic, and irregular waves with JONSWAP spectrum. To ensure the maximum Courant number, the time step interval was defined as 0.001 seconds. For regular monochromatic waves, the number of time steps was set at 100001 steps; 300001 steps for bichromatic waves; and 600001 steps to observe the change in JONSWAP waves.

Wave files were defined using the MIKE21 Toolbox. For monochromatic and bichromatic waves, wave information was entered to generate the waves. For JONSWAP waves, the wave is defined with H_s , peak period (T_p), sigma, and gamma information. H_s , T_p , sigma and gamma parameters were obtained from the experimental setups and matched with the parameters used in the experimental setups. Using these waves defined at the model level, the wave definition is given from the point at the end of the sponge layer under the deepest boundary condition.

To obtain the output, the points defined in the output list in the model area according to the locations of the WG during the experiment were obtained as outputs in terms of water levels every 10 time steps.

3.5. AYGM Model Set up with SWASH

While creating AYGM experimental models in SWASH, seabed bathymetry files were initially created. Bathymetry files of $m = 1/20$ and $m = 1/10$ seabed slopes used in AYGM experiments were defined in SWASH files with bot extension. When defining bathymetry, the model bathymetry is extended by the length of the sponge layer. For AYGM models, a layer of sponge with a depth of 20 meters has been defined at the shallowest points where the waves reach the shore. Model grid numbers and lengths were adjusted to fit the experimental setups. Grid lengths were set at 0.1 meters. A model area of 47 meters with 469 mesh points was defined.

Wave boundary condition definitions were made using SWASH's boundary condition identification code. In this way, the definitions of JONSWAP waves and regular waves are made separately for each model. The first boundary condition for the model is set to zero.

Wave breaker α and β parameter values were defined for the models. During model calibration, different values of these parameters were used and the calibration results were examined.

WG points, which locations were determined in the experimental setup, were defined in a list. Thus, the time series of the water level from these points were obtained. In SWASH models, time steps are defined as follows: 100001 for monochromatic waves, 300001 for bichromatic waves, and 600001 for JONSWAP waves. The time step is set to 0.001 seconds.

3.6. Statistical Parameters Used in This Study

In this study, specific statistical analysis methods were used to accurately evaluate the model results. These methods include Correlation Coefficient (CC), R-squared, Root Mean Square Error (RMSE), Mean Absolute Error (MAE), Scatter Index (SI) and Bias. The results obtained from the MIKE21 BW and SWASH models were statistically compared with the results of the DUCK94 and AYGGM experimental models. These comparisons were made to evaluate the relationship between the model and the experimental results, the accuracy of the model, and the degree of similarity between the model and the observed parameters. While comparing the model results with the experimental results, error rates were measured using RMSE and MAE. The distribution of model results compared to actual data was characterized using SI and Bias. R-squared and Pearson CC were used to measure the accuracy of the models.

3.6.1. Correlation Coefficient

The Correlation Coefficient (CC) is used to measure the strength and direction of the relationship between two different sets of data. There are different correlation coefficients with varying properties depending on their use. These include Pearson's correlation coefficient, Spearman's correlation coefficient, among others, each with different characteristics. The most commonly used is the Pearson's correlation coefficient. Pearson's correlation coefficient examines the relationship between two linear series. Correlation coefficient can take values from -1 to 1. -1 represents a perfect negative correlation, while 1 represents a perfect positive correlation.

3.6.2. R-Square

The coefficient of determination, also known as R-squared, is a statistical measure that shows the rate of variance in the dependent variable that can be estimated from the independent variable in a regression model. This value ranges from 0 to 1. A value of 0 indicates that there is no relationship between the model and the predicted values, while a value of 1 indicates that the model is making excellent predictions.

3.6.3. Root Mean Square Error

Root Mean Square Error (RMSE) is a statistical measure that measures the average magnitude of errors between predicted and observed values. RMSE is calculated as the square root of the mean of the square of the differences between the predicted and observed values. This measurement is valuable in assessing the accuracy and precision of the models.

3.6.4. Mean Absolute Error

Mean Absolute Error (MAE) is a method used to measure error. It provides the average magnitude of errors between the data obtained from a model and the observed data. Models with low MAE values are considered to have high accuracy.

3.6.5. Scatter Index

In the analysis made with the scatter index, the level of irregularity in the data is measured. The lower the scatter index, the closer the two data points are to each other. A high dispersion index indicates that the data points are far apart.

3.6.6. Bias

Bias in statistical analysis indicates how much the results of the model deviate from the actual values. If a model gives good results, the bias value is low, indicating that the model results are closely aligned with the measurement results. Conversely, if the model results are poor, the bias value is high.

4. RESULTS

Calibration of the MIKE21 BW and SWASH models began by selecting a validation dataset. This dataset was selected from the 9th month data of the DUCK94 experiment, which contains the most information. The wave boundary state was determined using wave data from location point 15, which was measured at the deepest point in the experiments. In this way, installations were made with a total of 207 models for the MIKE21 BW and SWASH models.

4.1. DUCK94 Experiment Models with MIKE21 BW

4.1.1. MIKE21 BW Model Results with Default Parameters

Statistical data obtained from running the DUCK94 experiment validation set with MIKE21 BW in the default breaking parameter, IBA: 20° and FBA: 10°, are given in **Table 4.1**. According to the model results, the lowest correlation was found to be 0.687 and the highest RMSE value was found at location 1. Location 1 is the point closest to the shore and is the point most affected by wave breaking. Therefore, modeling this point, location 1, is the most difficult, and the highest deviation is expected to occur at this particular location. The correlation values approach 1 for location 15, which corresponds to the wave boundary condition. As the water depth increases, wave breaking is less likely to occur, resulting in less pattern deviation at points where the water depth is greater.

Table 4.1: Statistical results of 207 MIKE21 BW wave models with default breaking parameter in 15 different locations.

Location	CC	RSQUARE	RMSE	MAE	SI	Bias
1	0.6871	0.4721	0.2463	0.1803	0.0607	-0.0571
2	0.8335	0.6947	0.2511	0.1342	0.0538	-0.0706
3	0.8294	0.6879	0.2883	0.1617	0.0831	-0.1459
4	0.8492	0.7211	0.2758	0.1549	0.0761	-0.1402
5	0.8791	0.7728	0.2521	0.1353	0.0635	-0.1060
6	0.9145	0.8364	0.2273	0.1262	0.0517	-0.1093
7	0.9300	0.8650	0.1992	0.1062	0.0397	-0.0854
8	0.9508	0.9040	0.8791	0.0833	0.0268	0.1353
9	0.9780	0.9565	0.1388	0.0764	0.0193	-0.0597

Table 4.1 Continued: Statistical results of 207 MIKE21 BW wave models with default breaking parameter in 15 different locations.

10	0.9557	0.9133	0.2623	0.1230	0.0688	-0.0622
11	0.9747	0.9500	0.2000	0.0834	0.0400	-0.0607
12	0.9864	0.9731	0.1727	0.0786	0.0298	-0.0649
13	0.9889	0.9780	0.1670	0.0754	0.0279	-0.0574
14	0.9926	0.9853	0.1275	0.0627	0.0163	-0.0430
15	0.9956	0.9913	0.1365	0.0704	0.0186	-0.0566

The distribution of H_s for the four points closest to the shore and the shallowest depths is shown in **Figure 4.1**. As can be seen, the H_s values obtained do converge with each other, progressing from shallow to deep.

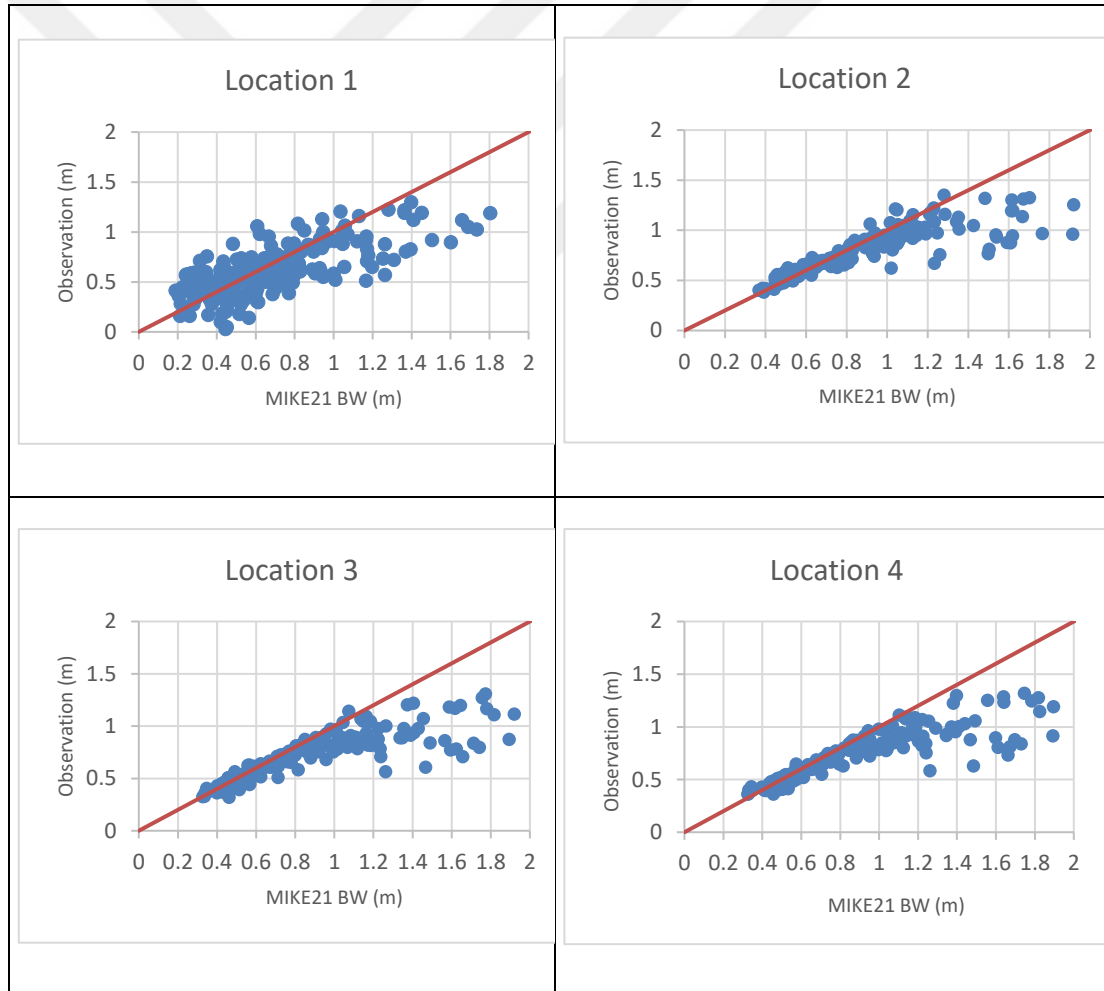


Figure 4.1: Comparison of H_s from MIKE21 BW models for 4 locations in the shallowest water in default model with observations from DUCK94 experiment.

Figure 4.2 provides distributions of models and experimental results from shallow to deep for deepest 4 locations. The connection between the increase in water depth and H_s values is evident.

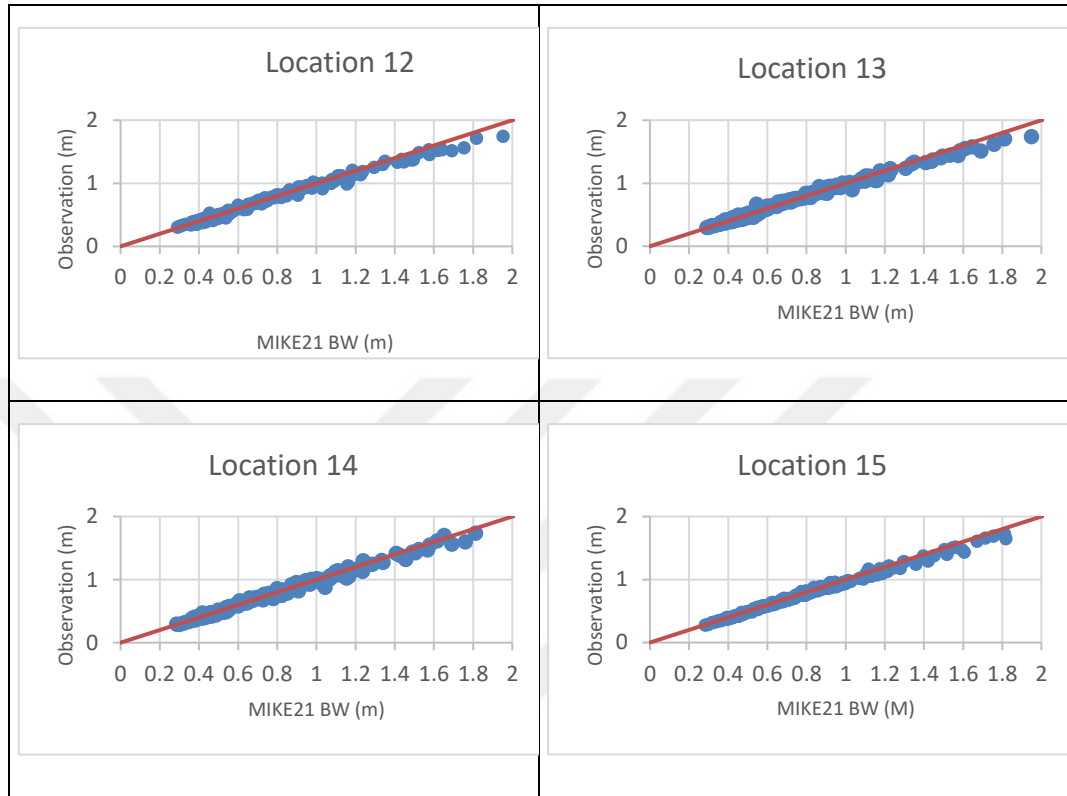


Figure 4.2: Comparison of H_s from MIKE21 BW models for 4 locations in the deepest water in the default model with observations from DUCK94 experiment.

It is possible to model in MIKE21 BW without including wave breaking. **Table 4.2** presents the statistical results of the model excluding wave breaking. As seen in these results, the correlation was found to be 0.642 and the RMSE value was found to be 0.383. Model errors are more pronounced in the sections where wave breaking occurs. As you get closer to the wave boundary condition, there is a less significant increase in error rates. As seen in this case, the MIKE21 BW can simulate energy losses even without breaking, but models that include breaking provide a more accurate representation of energy losses.

Table 4.2: Statistical results of 207 MIKE21 BW wave models with non breaking parameter.

Location	CC	RSQUARE	RMSE	MAE	SI	Bias
1	0.6420	0.4122	0.3819	0.2516	0.1459	-0.1417
2	0.7518	0.5652	0.4048	0.2073	0.1638	-0.1021
3	0.7483	0.5600	0.4440	0.2151	0.1971	-0.1559
4	0.7711	0.5946	0.4297	0.2049	0.1846	-0.1473
5	0.8190	0.6708	0.4023	0.1960	0.1618	-0.1136
6	0.8637	0.7460	0.3714	0.1775	0.1379	-0.1144
7	0.8929	0.7972	0.3358	0.1600	0.1127	-0.0921
8	0.9189	0.8444	0.8190	0.1425	0.0807	0.1960
9	0.9728	0.9464	0.1655	0.0804	0.0274	-0.0262
10	0.9486	0.8998	0.2245	0.1251	0.0504	0.0061
11	0.9760	0.9526	0.1561	0.0780	0.0244	0.0018
12	0.9839	0.9681	0.1372	0.0648	0.0188	-0.0152
13	0.9856	0.9714	0.1301	0.0619	0.0169	-0.0088
14	0.9916	0.9833	0.0950	0.0494	0.0090	-0.0050
15	0.9972	0.9943	0.0990	0.0487	0.0098	-0.0429

4.1.2. MIKE21 BW Model Results with Calibration Parameters

It has been observed that the models in the MIKE21 BW with wave breaking involved achieve higher accuracy values. When the statistical results are analyzed on a location-by-location basis, it is clear that the model results are in good agreement with the experimental results outside the surf zone. According to the results of the model, it is generally understood that wave breaking occurs mostly in coastal areas. Modeling these regions where wave breaking occurs is more difficult due to the inclusion of different wave and water motion properties associated with breaking. In order to improve the accuracy of the models, calibration procedures will be carried out taking into account this coastal zone. In the MIKE21 BW program, calibration was made with wave breaking parameters IBA and FBA.

On the MIKE21 BW, IBA is set to the default value of 20°. For IBA, the lower limit is 10° and the upper limit is 40°. The default value for the FBA is 10°, the lower bound is 5°, and the upper bound is 30°. The IBA must be higher than FBA, and the two values must not be equal. During the study, when IBA and FBA were set equally, an attempt was made to observe wave behavior, but the model did not yield any results. Different break angle values were used to run the models in various combinations: 5, 10, 20, and 30 for FBA; 10, 20, 30, 40 for IBA. These parameters were used in different

combinations, with using IBA larger than FBA. The time series obtained from the model results were analyzed in the Python program and spectrum curves were derived from these analyzes. The H_s values obtained from the spectra of the DUCK94 experiments were statistically compared with the H_s values obtained from the model results. Statistical comparison of model results and experimental results is presented in tables from between **Table 4.3** to **Table 4.11**. As can be seen, where wave breaking did not occur, there was little change in the model results run with different parameters. In location 1, the correlation coefficients ranged from 0.66 to 0.69. Since the correlation coefficients were close to each other, RMSE and MSE values were examined. Compared to other models, the model with IBA: 10° and FBA: 5° has been found to provide the most optimum results. RMSE and MAE values of 0.248 and 0.180 in the default model and 0.192 and 0.157 for the IBA: 10° and FBA: 5° model. In addition, the correlation value in this model was higher than in the default model.

Table 4.3: Statistical result of 207 sample models with IBA: 10° - FBA: 5°.

Location	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
CC	0.6965	0.8503	0.88306	0.90271	0.8917	0.9158	0.9198	0.9505	0.9708	0.9827	0.9857	0.9783	0.9877	0.9901	0.99785
RSQUARE	0.4851	0.7229	0.77979	0.81489	0.7951	0.8386	0.8461	0.9035	0.9425	0.9658	0.9716	0.9571	0.9756	0.9803	0.9957
RMSE	0.1922	0.1629	0.11361	0.10366	0.1177	0.1101	0.1225	0.1417	0.1576	0.0848	0.0904	0.113	0.0907	0.1003	0.10432
MAE	0.1572	0.1031	0.0711	0.06576	0.0701	0.0658	0.0651	0.0674	0.0859	0.0556	0.0439	0.045	0.0436	0.0489	0.05537
SI	0.0369	0.0177	0.01291	0.01075	0.0139	0.0121	0.015	0.0148	0.0248	0.0072	0.0082	0.0128	0.0082	0.0101	0.01088
Bias	0.0269	0.0588	-0.0189	-0.0133	0.0194	0.0099	0.028	0.0701	0.0337	0.0202	0.0188	0.0097	0.0146	0.0178	-0.0517

Table 4.4: Statistical result of 207 sample models with IBA: 20° - FBA: 5°.

Location	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
CC	0.6829	0.8344	0.8235	0.8495	0.8800	0.9157	0.9312	0.9509	0.9767	0.9557	0.9746	0.9859	0.9885	0.9924	0.9955
RSQUARE	0.4663	0.6962	0.6781	0.7217	0.7743	0.8385	0.8672	0.9042	0.9540	0.9133	0.9498	0.9719	0.9772	0.9849	0.9910
RMSE	0.2461	0.2400	0.2886	0.2711	0.2472	0.2221	0.1935	0.1457	0.1377	0.2559	0.1959	0.1690	0.1640	0.1243	0.1350
MAE	0.1792	0.1293	0.1611	0.1506	0.1312	0.1218	0.1019	0.0814	0.0745	0.1203	0.0809	0.0757	0.0734	0.0609	0.0686
SI	0.0606	0.0524	0.0833	0.0735	0.0611	0.0493	0.0375	0.0255	0.0190	0.0655	0.0384	0.0286	0.0269	0.0155	0.0182
Bias	-0.0605	-0.0686	-0.1439	-0.1353	-0.1003	-0.1043	-0.0803	0.1312	-0.0535	-0.0575	-0.0574	-0.0612	-0.0545	-0.0402	-0.0548

Table 4.5: Statistical result of 207 sample models with IBA: 30° - FBA: 5°.

Location	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
CC	0.6942	0.7774	0.7478	0.7724	0.8202	0.8677	0.8987	0.9221	0.9590	0.9289	0.9490	0.9849	0.9853	0.9920	0.9976
RSQUARE	0.4819	0.6044	0.5592	0.5967	0.6727	0.7530	0.8077	0.8503	0.9196	0.8628	0.9006	0.9701	0.9707	0.9840	0.9952
RMSE	0.3453	0.4209	0.5160	0.4961	0.4733	0.4396	0.3990	0.3202	0.2658	0.3296	0.2697	0.2070	0.1923	0.1418	0.1344
MAE	0.2337	0.2002	0.2584	0.2450	0.2269	0.2131	0.1892	0.1563	0.1220	0.1408	0.0967	0.0869	0.0811	0.0646	0.0677
SI	0.1192	0.1772	0.2663	0.2461	0.2240	0.1933	0.1592	0.1178	0.0706	0.1086	0.0727	0.0429	0.0370	0.0201	0.0181
Bias	-0.1370	-0.1623	-0.2427	-0.2303	-0.1972	-0.1961	-0.1695	0.2269	-0.1089	-0.0769	-0.0732	-0.0756	-0.0624	-0.0488	-0.0642

Table 4.6: Statistical result of 207 sample models with IBA: 40° - FBA: 5°.

Location	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
CC	0.6905	0.7890	0.7757	0.8013	0.8432	0.8886	0.9143	0.9359	0.9701	0.9378	0.9598	0.9853	0.9855	0.9922	0.9975
RSQUARE	0.4767	0.6225	0.6017	0.6421	0.7110	0.7897	0.8360	0.8760	0.9412	0.8795	0.9213	0.9709	0.9711	0.9845	0.9950
RMSE	0.3042	0.3467	0.4285	0.4103	0.3876	0.3559	0.3182	0.2632	0.2232	0.3155	0.2506	0.2007	0.1923	0.1400	0.1362
MAE	0.2129	0.1685	0.2238	0.2120	0.1943	0.1813	0.1584	0.1283	0.1083	0.1382	0.0946	0.0855	0.0815	0.0645	0.0682
SI	0.0926	0.1202	0.1836	0.1684	0.1503	0.1267	0.1013	0.0727	0.0498	0.0995	0.0628	0.0403	0.0370	0.0196	0.0185
Bias	0.1082	0.1344	0.2084	0.1978	-0.1651	-0.1648	-0.1390	0.1943	-0.0990	-0.0749	-0.0715	-0.0745	-0.0631	-0.0489	-0.0647

Table 4.7: Statistical result of 207 sample models with IBA: 30° - FBA: 10°.

Location	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
CC	0.6923	0.7916	0.7792	0.8014	0.8436	0.8886	0.9140	0.9355	0.9661	0.9377	0.9596	0.9855	0.9856	0.9909	0.9956
RSQUARE	0.4793	0.6266	0.6072	0.6422	0.7117	0.7896	0.8354	0.8752	0.9333	0.8793	0.9208	0.9712	0.9714	0.9818	0.9912
RMSE	0.3039	0.3479	0.4259	0.4119	0.3887	0.3577	0.3199	0.2436	0.2259	0.3160	0.2512	0.2005	0.1916	0.1423	0.1376
MAE	0.2124	0.1715	0.2206	0.2124	0.1941	0.1818	0.1586	0.1288	0.1108	0.1387	0.0947	0.0850	0.0812	0.0658	0.0708
SI	0.0924	0.1210	0.1813	0.1697	0.1511	0.1280	0.1023	0.0737	0.0510	0.0999	0.0631	0.0402	0.0367	0.0202	0.0189
Bias	-0.1116	-0.1340	-0.2052	-0.1980	-0.1647	-0.1652	-0.1390	0.1941	-0.0917	-0.0750	-0.0714	-0.0739	-0.0628	-0.0457	-0.0569

Table 4.8: Statistical result of 207 sample models with IBA: 40° - FBA: 10°.

Location	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
CC	0.6903	0.7841	0.7479	0.7733	0.8208	0.8683	0.8989	0.9225	0.9587	0.9291	0.9489	0.9852	0.9855	0.9907	0.9957
RSQUARE	0.4766	0.6148	0.5593	0.5980	0.6737	0.7539	0.8080	0.8510	0.9192	0.8632	0.9005	0.9707	0.9712	0.9815	0.9914
RMSE	0.3487	0.4077	0.5166	0.4954	0.4730	0.4368	0.3987	0.3208	0.2632	0.3288	0.2697	0.2059	0.1907	0.1432	0.1354
MAE	0.2350	0.1927	0.2590	0.2448	0.2265	0.2111	0.1888	0.1558	0.1211	0.1403	0.0965	0.0866	0.0806	0.0660	0.0703
SI	0.1216	0.1666362	0.2669	0.2454	0.2237	0.1908	0.1590	0.1174	0.0693	0.1081	0.0727	0.0424	0.0364	0.0205	0.0183
Bias	-0.1385	-0.1554	-0.2436	-0.2304	-0.1975	-0.1946	-0.1696	0.2265	-0.1057	-0.0768	-0.0732	-0.0755	-0.0623	-0.0460	-0.0565

Table 4.9: Statistical result of 207 sample models with IBA: 30° - FBA: 20°.

Location	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
CC	0.6936	0.7967	0.7740	0.7996	0.8428	0.8879	0.9136	0.9347	0.9666	0.9364	0.9585	0.9854	0.9854	0.9922	0.9957
RSQUARE	0.4810	0.6348	0.5991	0.6394	0.7102	0.7883	0.8346	0.8737	0.9344	0.8769	0.9187	0.9709	0.9710	0.9845	0.9913
RMSE	0.3056	0.3591	0.4345	0.4155	0.3921	0.3605	0.3228	0.2428	0.2264	0.3184	0.2535	0.2014	0.1926	0.1401	0.1375
MAE	0.2146	0.1805	0.2262	0.2137	0.1953	0.1828	0.1600	0.1302	0.1094	0.1391	0.0953	0.0855	0.0814	0.0642	0.0707
SI	0.0934	0.1290	0.1888	0.1726	0.1537	0.1299	0.1042	0.0754	0.0512	0.1014	0.0643	0.0406	0.0371	0.0196	0.0189
Bias	-0.1101	-0.1433	-0.2104	-0.1989	-0.1657	-0.1659	-0.1400	0.1953	-0.0939	-0.0751	-0.0714	-0.0741	-0.0625	-0.0485	-0.0569

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Table 4.10: Statistical result of 207 sample models with IBA: 40° - FBA: 20°.

Location	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
CC	0.6637	0.7814	0.7620	0.7857	0.8355	0.8807	0.9122	0.9337	0.9720	0.9457	0.9688	0.9851	0.9883	0.9936	0.9837
RSQUARE	0.4842	0.6106	0.5806	0.6172	0.6980	0.7756	0.8322	0.8717	0.9447	0.8943	0.9386	0.9705	0.9767	0.9872	0.9676
RMSE	0.3357	0.4051	0.4861	0.4660	0.4408	0.4080	0.3663	0.3455	0.2209	0.2788	0.2105	0.1722	0.1627	0.1170	0.1493
MAE	0.2283	0.1948	0.2449	0.2317	0.2129	0.2002	0.1756	0.1448	0.1095	0.1298	0.0862	0.0763	0.0729	0.0580	0.0673
SI	0.1127	0.1641	0.2363	0.2172	0.1943	0.1665	0.1342	0.0968	0.0488	0.0777	0.0443	0.0297	0.0265	0.0137	0.0223
Bias	-0.1292	-0.1516	-0.2258	-0.2132	-0.1795	-0.1793	-0.1530	0.2129	-0.0932	-0.0571	-0.0543	-0.0583	-0.0491	-0.0375	-0.0498

Table 4.11: Statistical result of 207 sample models with IBA: 40° - FBA: 30°.

Location	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
CC	0.6903	0.7848	0.7460	0.7713	0.8193	0.8669	0.8979	0.9215	0.9597	0.9277	0.9470	0.9849	0.9854	0.9921	0.9976
RSQUARE	0.4766	0.6158	0.5565	0.5949	0.6713	0.7515	0.8063	0.8492	0.9210	0.8607	0.8969	0.9701	0.9710	0.9842	0.9952
RMSE	0.3486	0.4084	0.5206	0.4994	0.4766	0.4428	0.4022	0.3493	0.2675	0.3314	0.2734	0.2082	0.1923	0.1417	0.1339
MAE	0.2350	0.1928	0.2602	0.2459	0.2278	0.2138	0.1899	0.1567	0.1216	0.1407	0.0970	0.0871	0.0810	0.0646	0.0676
SI	0.1216	0.1668	0.2711	0.2494	0.2272	0.1960	0.1617	0.1197	0.0715	0.1098	0.0747	0.0434	0.0370	0.0201	0.0179
Bias	-0.1378	-0.1556	-0.2447	-0.2314	-0.1984	-0.1971	-0.1705	0.2278	-0.1121	-0.0772	-0.0736	-0.0759	-0.0624	-0.0489	-0.0640

4.2. DUCK94 Experiment Models with SWASH

4.2.1. SWASH Model Results with Default Parameters

The statistical data obtained from the application of the SWASH model with the default breaking parameters to the validation set of the DUCK94 experiment are presented in **Table 4.12**. Breaking in SWASH is defined by the default breaking parameters $\alpha = 0.6$ and $\beta = 0.3$. According to the model results, the lowest correlation was 0.632 and the highest RMSE value was 0.243 in the location 1. As the location points converge to location 15, which is the wave boundary condition, it is clear that the experimental and model results converge.

Table 4.12: Statistical results of 207 SWASH wave models with default breaking parameters in 15 different locations.

Location	CC	RSQUARE	RMSE	MAE	SI	Bias
1	0.6323	0.3998	0.2426	0.1837	0.0589	-0.0374
2	0.8191	0.6709	0.1800	0.1054	0.0324	-0.0258
3	0.8173	0.6680	0.1918	0.1130	0.0368	-0.0735
4	0.8374	0.7012	0.1807	0.1075	0.0327	-0.0692
5	0.8667	0.7511	0.1674	0.0967	0.0280	-0.0443
6	0.9060	0.8209	0.1532	0.0964	0.0235	-0.0620
7	0.9265	0.8584	0.1364	0.0827	0.0186	-0.0456
8	0.9548	0.9116	0.1267	0.0694	0.0131	0.0967
9	0.9793	0.9589	0.1123	0.0885	0.0126	-0.0480
10	0.9737	0.9481	0.1802	0.1007	0.0325	-0.0667
11	0.9854	0.9711	0.1285	0.0875	0.0165	-0.0630
12	0.9672	0.9355	0.1602	0.0906	0.0257	-0.0599
13	0.9879	0.9759	0.1184	0.0807	0.0140	-0.0565
14	0.9933	0.9866	0.0919	0.0655	0.0084	-0.0451
15	0.9674	0.9359	0.1036	0.0818	0.0337	-0.0466

The experimental results for the distribution of the SWASH model and the H_s are given in **Figure 4.3** for the four shallowest points. It has been observed that the agreement between the model and the experiments increases as the measurement points move away from the coast. The results are most pronounced at the point closest to the shore, where wave breaking and the resulting irregularities are most pronounced.

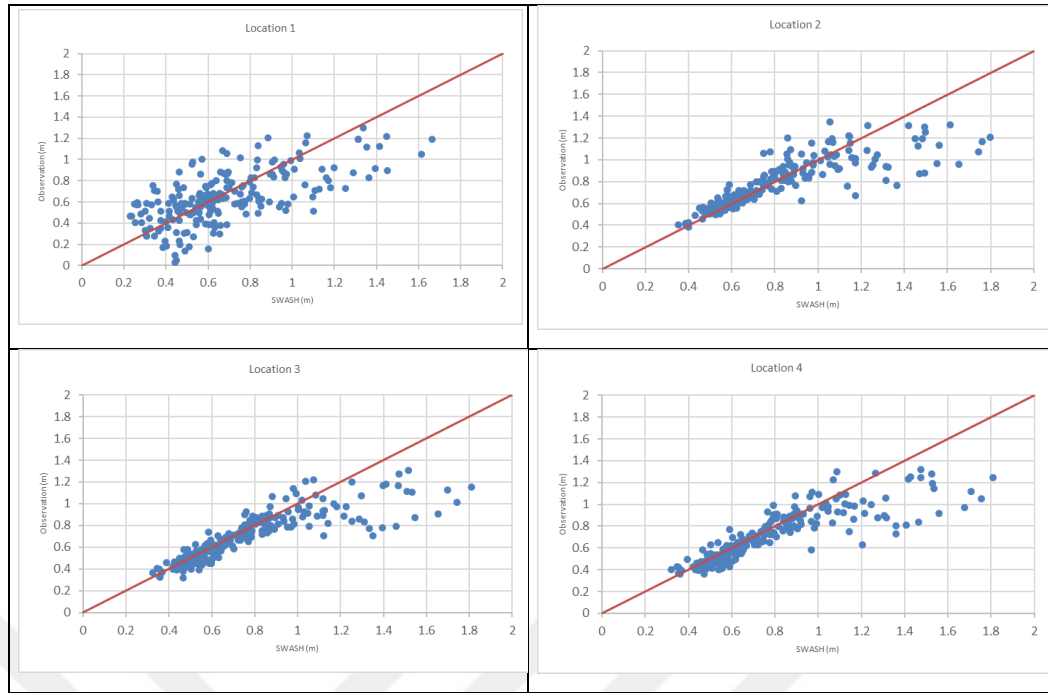


Figure 4.3: Comparison of H_s from SWASH models of 4 locations in the shallowest water in default model with observations from DUCK94 experiment.

In **Figure 4.4** and **Figure 4.5** H_s distributions are provided for the 4 deepest points, in locations 12, 13, 14, and 15.

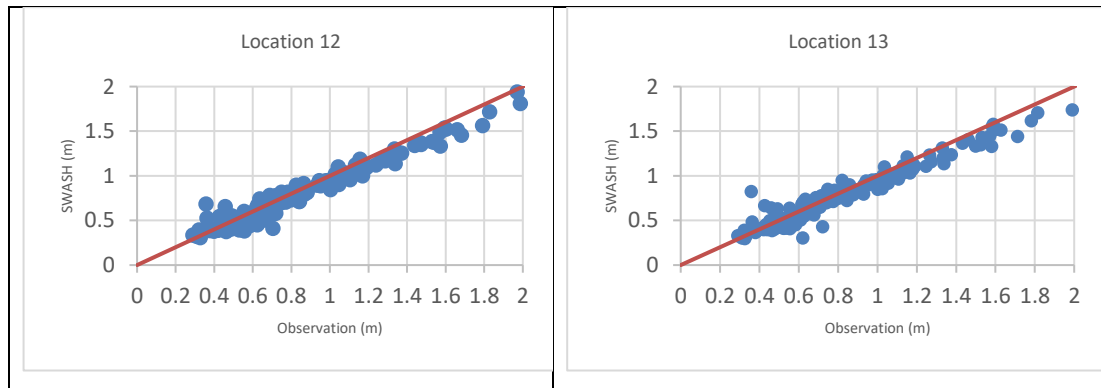


Figure 4.4: Comparison of H_s from SWASH models of location 12 and 13 in default model with observations from DUCK94 experiment.

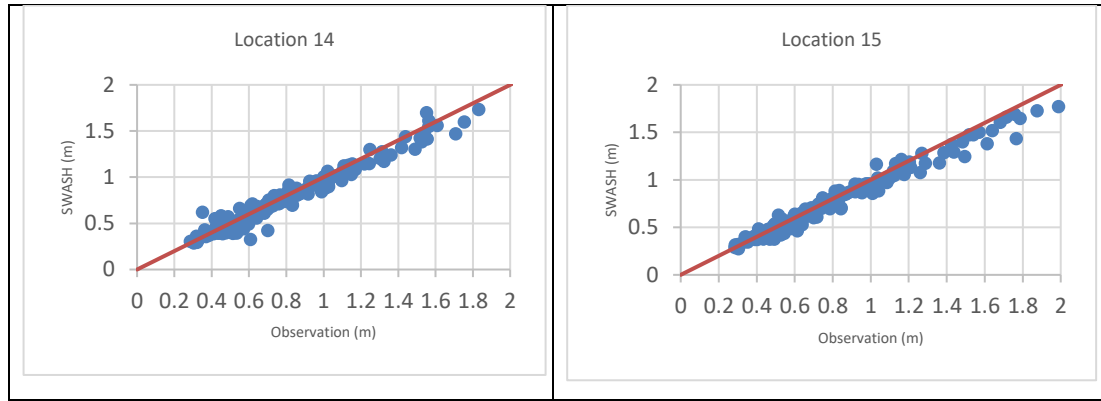


Figure 4.5: Comparison of H_s from SWASH models of location 14 and 15 in default model with observations from DUCK94 experiment.

A SWASH model can be built without including parameters that caused an error during model setup. SWASH can simulate energy distribution due to wave breaking in any situation [SWASH Team, 2023].

Table 4.13 gives statistical values of SWASH models run without breaking the parameters. A correlation coefficient of 0.590 and an RMSE of 0.936 were observed at the shallowest point, location 1. At each location where the model results were examined, the increase in errors corresponded to a decrease in correlation values. RMSE values exceeded 1 in 5 different locations. It appears that models run with wave break off in SWASH give less accurate results compared to models operated with default wave breaking settings.

Table 4.13: Statistical results of 207 SWASH wave models with non breaking parameter in 15 different locations.

	CC	RSQUARE	RMSE	MAE	SI	Bias
Location 1	0.58981	0.34788	0.93561	0.53071	0.8754	-0.469
Location 2	0.87933	0.77322	0.16447	0.09928	0.0271	0.009
Location 3	0.67995	0.46233	1.05007	0.61055	1.1026	-0.6
Location 4	0.69418	0.48189	1.04898	0.61223	1.1004	-0.601
Location 5	0.72996	0.53284	1.03402	0.59339	1.0692	-0.573
Location 6	0.77091	0.5943	1.0286	0.59959	1.058	-0.588
Location 7	0.80348	0.64558	1.00946	0.5842	1.019	-0.573
Location 8	0.82884	0.68698	0.92996	0.56014	0.9968	0.5934
Location 9	0.86208	0.74318	0.96251	0.53385	0.9264	-0.529
Location 10	0.8537	0.72881	0.90146	0.47884	0.8126	-0.459
Location 11	0.86932	0.75572	0.83256	0.45505	0.6932	-0.439
Location 12	0.84905	0.72088	0.80149	0.44116	0.6424	-0.415

Table 4.13 Continued: Statistical results of 207 SWASH wave models with non breaking parameter in 15 different locations.

Location 13	0.88456	0.78244	0.76939	0.40287	0.592	-0.389
Location 14	0.89365	0.79861	0.71874	0.36947	0.5166	-0.36
Location 15	0.8507	0.72369	0.70302	0.36785	0.4942	-0.333

4.2.2. SWASH Model Results with Calibration Parameters

As observed in the model performed in SWASH with default settings, the locations where wave breaking occurs exhibit lower correlation and higher error rates. Areas with higher model accuracy are those outside the wave breaking zone. Therefore, when performing model calibrations, the wave breaking region was taken into account. The model results were compared statistically using different values for the wave breaking parameters called α and β . α needs to be greater than β , and both values should not be equal to zero [SWASH Team, 2023]. Calibration results for some models are given in **Table 4.14** to **Table 4.18**. When the results were examined, it was observed that the values remained almost unchanged for the locations outside the wave break points. The correlation in location 1 is around 0.63. According to the results, the model with $\alpha = 0.4$ and $\beta = 0.3$ provides the most optimal result. The RMSE and MAE values for the default model in location 1 are 0.243 and 0.183, respectively, while the model selected with alpha $\alpha = 0.4$ and $\beta = 0.3$ yields RMSE and MAE values of 0.226 and 0.173, respectively.

Table 4.14: Statistical result of 207 sample models with α : 0.4 - β : 0.3.

Location	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
CC	0.6352	0.8406	0.8363	0.8547	0.8793	0.9104	0.9257	0.9540	0.9750	0.9781	0.9837	0.9657	0.9859	0.9913	0.9675
RSQUARE	0.4034	0.7067	0.6994	0.7305	0.7732	0.8287	0.8569	0.9101	0.9506	0.9567	0.9678	0.9326	0.9721	0.9826	0.9361
RMSE	0.2261	0.1481	0.1583	0.1488	0.1392	0.1292	0.1205	0.1293	0.1276	0.1244	0.0992	0.1410	0.0961	0.0810	0.1802
MAE	0.1725	0.0908	0.0952	0.0912	0.0821	0.0846	0.0753	0.0666	0.0916	0.0753	0.0718	0.0749	0.0692	0.0606	0.0777
SI	0.0511	0.0219	0.0250	0.0221	0.0194	0.0167	0.0145	0.0108	0.0163	0.0155	0.0098	0.0199	0.0092	0.0066	0.0325
Bias	-0.0177	0.0022	-0.0504	-0.0471	-0.0251	-0.0448	-0.0294	0.0821	-0.0256	-0.0397	-0.0412	-0.0394	-0.0350	-0.0250	-0.0439

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Table 4.15: Statistical result of 207 sample models with α : 0.8 - β : 0.3.

Location	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
CC	0.6377	0.8009	0.8093	0.8298	0.8612	0.9027	0.9258	0.9542	0.9810	0.9694	0.9842	0.9666	0.9879	0.9929	0.9662
RSQUARE	0.4066	0.6414	0.6549	0.6886	0.7417	0.8149	0.8571	0.9104	0.9624	0.9397	0.9687	0.9343	0.9760	0.9858	0.9335
RMSE	0.2519	0.2035	0.2108	0.1991	0.1862	0.1708	0.1520	0.1212	0.1154	0.2162	0.1594	0.1818	0.1427	0.1117	0.1836
MAE	0.1886	0.1159	0.1214	0.1152	0.1059	0.1042	0.0885	0.0741	0.0894	0.1141	0.1002	0.1026	0.0924	0.0753	0.0833
SI	0.0635	0.0414	0.0444	0.0397	0.0347	0.0292	0.0231	0.0169	0.0133	0.0468	0.0254	0.0330	0.0204	0.0125	0.0337
Bias	-0.0501	-0.0378	-0.0839	-0.0789	-0.0556	-0.0725	-0.0576	0.1059	-0.0622	-0.0792	-0.0759	-0.0713	-0.0677	-0.0535	-0.0445

Table 4.16: Statistical result of 207 sample models with α : 1.0 - β : 0.3.

Location	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
CC	0.6366	0.8043	0.8065	0.8261	0.8597	0.9015	0.9258	0.9534	0.9816	0.9659	0.9824	0.9656	0.9867	0.9918	0.9672
RSQUARE	0.4052	0.6468	0.6504	0.6824	0.7391	0.8127	0.8572	0.9090	0.9636	0.9330	0.9652	0.9323	0.9736	0.9837	0.9355
RMSE	0.2592	0.2129	0.2220	0.2115	0.1980	0.1829	0.1631	0.1297	0.1246	0.2359	0.1776	0.1957	0.1571	0.1247	0.1859
MAE	0.1919	0.1171	0.1252	0.1197	0.1098	0.1085	0.0927	0.0796	0.0940	0.1198	0.1060	0.1084	0.0971	0.0795	0.0829
SI	0.0672	0.0453	0.0493	0.0447	0.0392	0.0335	0.0266	0.0204	0.0155	0.0556	0.0315	0.0383	0.0247	0.0155	0.0346
Bias	-0.0586	-0.0442	-0.0888	-0.0845	-0.0612	-0.0787	-0.0642	0.1098	-0.0728	-0.0852	-0.0823	-0.0776	-0.0729	-0.0580	-0.0475

Table 4.17: Statistical result of 207 sample models with α : 0.6 - β : 0.2.

Location	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
CC	0.6325	0.8168	0.8180	0.8372	0.8674	0.9055	0.9252	0.9536	0.9780	0.9750	0.9851	0.9668	0.9875	0.9933	0.9683
RSQUARE	0.4000	0.6671	0.6692	0.7009	0.7524	0.8199	0.8560	0.9093	0.9565	0.9505	0.9704	0.9348	0.9752	0.9867	0.9376
RMSE	0.2318	0.1672	0.1664	0.1558	0.1458	0.1305	0.1210	0.1274	0.1127	0.1561	0.1110	0.1494	0.1051	0.0816	0.1777
MAE	0.1775	0.1050	0.0992	0.0935	0.0877	0.0841	0.0742	0.0658	0.0845	0.0874	0.0747	0.0794	0.0718	0.0581	0.0757
SI	0.0537	0.0280	0.0277	0.0243	0.0212	0.0170	0.0146	0.0113	0.0127	0.0244	0.0123	0.0223	0.0110	0.0067	0.0316
Bias	-0.0140	0.0073	-0.0395	-0.0351	-0.0121	-0.0312	-0.0181	0.0877	-0.0327	-0.0510	-0.0485	-0.0473	-0.0440	-0.0352	-0.0403

Table 4.18: Statistical result of 207 sample models with α : 0.6 - β : 0.4.

Location	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
CC	0.6357	0.8080	0.8074	0.8268	0.8604	0.9017	0.9259	0.9546	0.9803	0.9718	0.9849	0.9669	0.9877	0.9934	0.9678
RSQUARE	0.4042	0.6529	0.6519	0.6836	0.7404	0.8131	0.8572	0.9113	0.9609	0.9445	0.9700	0.9348	0.9755	0.9869	0.9366
RMSE	0.2399	0.1875	0.1940	0.1838	0.1721	0.1556	0.1380	0.1204	0.1076	0.1876	0.1355	0.1651	0.1234	0.0921	0.1829
MAE	0.1816	0.1133	0.1110	0.1051	0.0986	0.0936	0.0787	0.0669	0.0832	0.0997	0.0876	0.0904	0.0807	0.0647	0.0800
SI	0.0576	0.0352	0.0376	0.0338	0.0296	0.0242	0.0191	0.0137	0.0116	0.0352	0.0184	0.0272	0.0152	0.0085	0.0335
Bias	-0.0227	-0.0071	-0.0562	-0.0526	-0.0309	-0.0504	-0.0370	0.0986	-0.0439	-0.0641	-0.0621	-0.0590	-0.0553	-0.0425	-0.0447

4.3. AYG M Experiment Models with MIKE21 BW

In AYG M experiment models, time series were extracted from the water surface and experiments with the same parameters were created in MIKE21 BW. The time series obtained from the MIKE21 BW and AYG M experiment's results were analyzed and compared together in the Python program. In AYG M experiments, different wave parameters were handled separately for two different bed slopes.

4.3.1. Results from the Models with Base Slope $m = 1/20$

Models with a bed slope of $m = 1/20$ were used and analyzed to model waves with JONSWAP spectrum, monochromatic waves and bichromatic waves.

4.3.1.1. JONSWAP Wave Model Results

Different waves with various height and period parameters are simulated in JONSWAP models at a bed slope of $m = 1/20$. Time series values obtained from the points where WG were installed were compared with experimental measurements using the spectrum analysis method. **Table 4.19** presents the statistical results for the model and the experimental results performed with the default parameters in the MIKE21 BW program.

Table 4.19: Statistical result of default JONSWAP models for $m = 1/20$.

	CC	RSQUARE	RMSE	MAE	SI	Bias
Location 1	0.6814	0.4642	0.0236	0.0146	0.0001	-0.0016
Location 2	0.4496	0.2021	0.0218	0.0276	0.0003	-0.0131
Location 3	0.2370	0.0562	0.0326	0.0316	0.0011	-0.0316
Location 4	0.4098	0.1679	0.0763	0.0760	0.0058	-0.0760
Location 5	0.4401	0.1937	0.0520	0.0506	0.0027	-0.0506
Location 6	0.6821	0.2196	0.0279	0.0232	0.0330	-0.0025

As can be seen in **Table 4.19**, the correlation was calculated as 0.682 in location 6. This value is low for the point closest to the wave generator. The correlation value was calculated as 0.681 for location 1. At this point, the RMSE value was found to be 0.024.

The model's and observed H_s values for location 1, location 2 are presented in **Figure**

4.6. The model's and observed H_s values for location 5, and location 6 are given in **Figure 4.7**. When observed in **Figure 4.7**, the H_s values for MIKE21 BW are around 0.2 m for all locations as the given wave property. H_s values are higher than the model results. H_s values remained around 0.2 m up to location 3, but the observed H_s gradually decreases with shallower water depth.

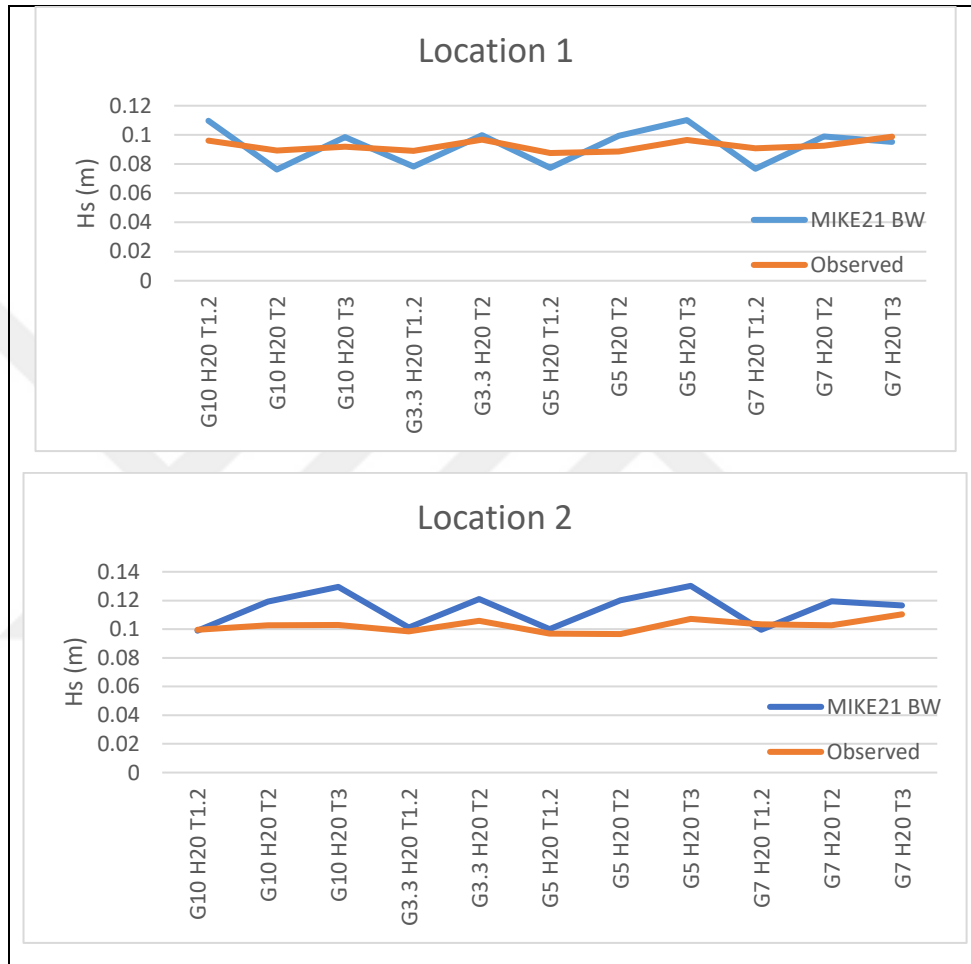


Figure 4.6: Comparison of H_s values for the shallowest two locations between the default MIKE21 BW model and the AYGm experiment results for 1/20 bottom slope.

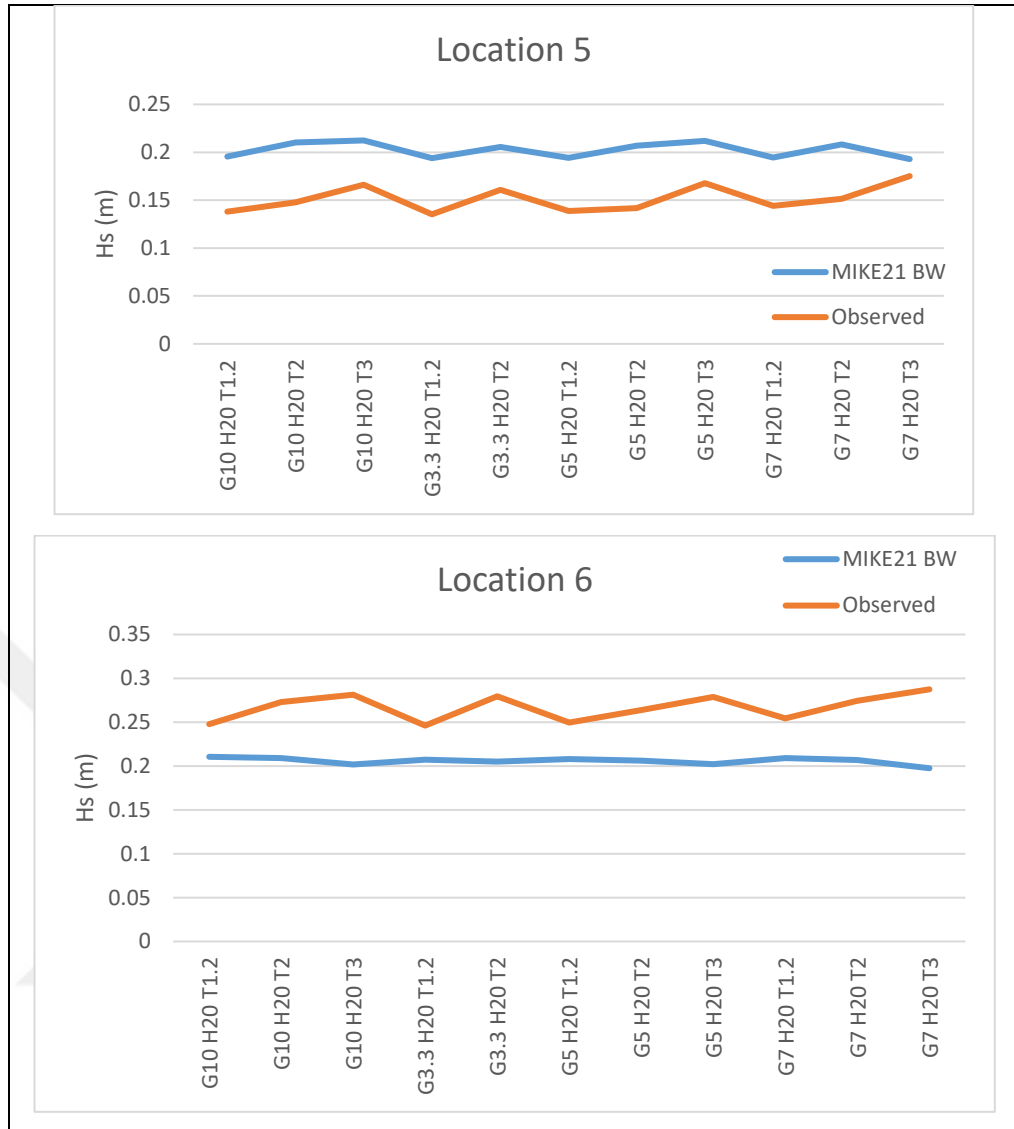


Figure 4.7: Comparison of H_s values for the deepest two locations between the default MIKE21 BW model and the AYG M experiment results for 1/20 bottom slope.

When examined according to the 2 shallowest locations, the highest correlation values were measured in the model with IBA: 10° - FBA: 5° . In this model, the correlation value calculated in location 6 reached 0.903 and the correlation values in other locations were higher than the default model. RMSE values for the 3 shallowest locations were calculated as 0.011, 0.017 and 0.016, respectively. These values were 0.024, 0.022, and 0.033 in the default model. When the results of the other models were examined, it was calculated that the model with IBA: 20° - FBA: 5° had a lower RMSE value in these locations, but the correlations were also lower. Statistical result of IBA: 10° - FBA: 5° model is given in **Table 4.20**.

Table 4.20: Statistical result of IBA: 10°- FBA: 5° JONSWAP models for $m = 1/20$.

	CC	RSQUARE	RMSE	MAE	SI	Bias
Location 1	0.8174	0.6681	0.0110	0.0102	0.0006	0.0186
Location 2	0.6606	0.4364	0.0170	0.0139	0.0005	0.0122
Location 3	0.7011	0.4916	0.0163	0.0138	0.0003	0.0041
Location 4	0.6853	0.4696	0.0387	0.0359	0.0015	-0.0359
Location 5	0.8637	0.7459	0.0215	0.0189	0.0005	-0.0189
Location 6	0.9034	0.8161	0.0105	0.0355	0.0061	0.0776

4.3.1.2. Monocromatic Wave Model Results

Regular waves running in the experiments were analyzed using the zero crossing method in the Python program and the H values were calculated. The calculated H values were compared statistically. A statistical comparison of the H values obtained from the models and experiments run with the default parameters in MIKE21 BW is given in **Table 4.21**.

Table 4.21: Statistical results of default monocromatic models for $m = 1/20$.

	CC	RSQUARE	RMSE	MAE	SI	Bias
Location 1	0.885315	0.783782	0.009288	0.007143	8.63E-05	0.002996
Location 2	0.812752	0.660566	0.01693	0.013764	0.000287	0.011607
Location 3	0.720498	0.519117	0.039013	0.035435	0.001522	0.03453
Location 4	0.439115	0.192822	0.030988	0.02517	0.00096	-0.01453
Location 5	0.70734	0.50033	0.042572	0.036868	0.001812	-0.03649
Location 6	0.875311	0.76617	0.025736	0.023882	0.000662	-0.02388

At the 6th location, close to the boundary condition, a correlation of 0.875 was calculated. The RMSE values for location 1 and location 2 are calculated as 0.009 and 0.017, respectively. After the default model, the most accurate results were obtained in location 1 with a correlation coefficient of 0.614 using the IBA: 10° - FBA: 5° model. The statistical results of the IBA: 10° - FBA: 5° model are presented in **Table 4.22**.

Table 4.22: Statistical results of IBA: 10° - FBA: 5° monocromatic models for m=1/20.

	CC	RSQUARE	RMSE	MAE	SI	Bias
Location 1	0.614266	0.377323	0.020199	0.016046	0.000408	0.015857
Location 2	0.406585	0.165311	0.033348	0.029728	0.001112	-0.02197
Location 3	0.749957	0.562436	0.064213	0.061833	0.004123	0.061833
Location 4	0.322779	0.104187	0.057674	0.051567	0.003326	0.049196
Location 5	0.571146	0.326208	0.023279	0.017612	0.000542	0.011412
Location 6	0.799228	0.638766	0.032027	0.03012	0.001026	0.03012

4.3.1.3. Bicromatic Wave Model Results

The model results of the bicromatic waves run in MIKE21 BW were obtained in time series. Model results and experimental results were analyzed by zero crossing method and H values were calculated. The statistical comparison of the H values obtained from the experimental measurements and model results is given in **Table 4.23**.

Table 4.23: Statistical result of default bicromatic models for m = 1/20.

	CC	RSQUARE	RMSE	MAE	SI	Bias
Location 1	0.8803	0.7749	0.0166	0.0126	0.0003	-0.0094
Location 2	0.7804	0.6090	0.0122	0.0116	0.0008	0.0211
Location 3	0.8259	0.6820	0.0360	0.0294	0.0026	0.0486
Location 4	0.7954	0.6327	0.0491	0.0464	0.0046	0.0617
Location 5	0.9080	0.8245	0.0496	0.0448	0.0018	-0.0147
Location 6	0.9772	0.9548	0.0218	0.0197	0.0016	0.0129

In the model results, 0.880 correlation and 0.017 RMSE value were calculated in location 1. A correlation of 0.977 and an RMSE of 0.022 were reached in location 6, which is the deepest point.

Model with IBA: 10° - FBA: 5° parameters gave the best results after the default model's results. In this model, a correlation of 0.829 and an RMSE value of 0.018 were found in location 1. The values obtained as a result of statistically comparing this model with the experimental measurements are given in **Table 4.24**.

Table 4.24: Statistical result of IBA: 10° - FBA: 5° bicromatic models for m = 1/20.

	CC	RSQUARE	RMSE	MAE	SI	Bias
Location 1	0.8290	0.6873	0.0178	0.0157	0.0003	0.0072

Table 4.24 Continued: Statistical result of IBA: 10°- FBA: 5° bicromatic models with IBA: 10°- FBA: 5° for $m = 1/20$.

Location 2	0.7255	0.8565	0.0286	0.0225	0.0002	0.0071
Location 3	0.7773	0.6042	0.0514	0.0486	0.0013	-0.0165
Location 4	0.7982	0.6371	0.0681	0.0617	0.0024	-0.0321
Location 5	0.8398	0.7052	0.0423	0.0357	0.0025	0.0417
Location 6	0.8923	0.7961	0.0401	0.0356	0.0005	-0.0143

4.3.2. Results from the Models with Base Slope $m = 1/10$

4.3.2.1. JONSWAP Wave Model Results

Waves simulated in a bathymetry with a slope of $m = 1/10$ were run on MIKE21 BW with default IBA and FBA values. The H_s values obtained from the time series and the H_s values obtained from the experimental measurements were statistically compared and the results are given in **Table 4.25**. Looking at the values in the **Table 4.25**, the correlation values are close to 1. At location 6 where the slope begins, the H_s model parameter was found to be 0.2 m in the models created with MIKE21 BW.

Table 4.25: Statistical result of default JONSWAP models for $m = 1/10$.

	CC	RSQUARE	RMSE	MAE	SI	Bias
Location 1	0.944492	0.892065	0.006316	0.005371	3.99E-05	0.005265
Location 2	0.973623	0.947941	0.007789	0.006501	6.07E-05	-0.0065
Location 3	0.96713	0.93534	0.027903	0.02619	0.000779	-0.02619
Location 4	0.984877	0.969982	0.050286	0.049806	0.002529	-0.04981
Location 5	0.982889	0.966072	0.037273	0.032767	0.001389	-0.03277
Location 6	0.98227	0.961822	0.036334	0.030672	0.00132	-0.03067

The H_s values obtained from the model results and experiment results for location 1, location 2 and location 3 are given in **Figure 4.8**. The H_s values obtained from the model results and experimental results for location 4, location 5 and location 6 are given in **Figure 4.9**.



Figure 4.8: Comparison of JONSWAP spectrum H_s of 3 locations in the shallowest water in default MIKE21 BW model and observed H_s .



Figure 4.9: Comparison of JONSWAP spectrum H_s of 3 locations in the deepest water in default MIKE21 BW model and observed H_s .

It was observed that from **Figure 4.8** and **Figure 4.9**, there was no change in the height of the model wave travelling in a straight bathymetry at location 6. In the experiment with a slope of $m = 1/10$, the wave gauge at location 6 is farther away from the wave

generator. As expected, at this point, the significant wave heights obtained in the experiment underwent a further loss of energy, resulting in a decrease in H_s values. Contrary to the observation, the H_s of the MIKE21 BW models for both bathymetry were calculated as 0.20 m for $d = 0.79$ m. For this reason, RMSE values, which were much lower in locations 1 and 2 were calculated at a higher level in locations 5 and 6. Statistical comparison of H_s values obtained from experimental measurements and MIKE21 BW model with IBA: 10° - FBA: 5° is given in **Table 4.26**. When the models working with different breaking parameters were examined, the model with IBA: 10° - FBA: 5° showed a correlation of 0.985 in location 6. Compared to the default model, this model showed higher RMSE values in location 1 and location 2, while RMSE values in other locations were significantly lower. In this model, when locations 5 and 6 were observed, the H_s values differed from the values given characteristically in the experiments. It was closer to the H_s values observed in the experiments and therefore the RMSE values were found to be lower.

Table 4.26: Statistical result of IBA: 10° - FBA: 5° JONSWAP models for $m = 1/10$.

	CC	RSQUARE	RMSE	MAE	SI	Bias
Location 1	0.9512	0.9048	0.0317	0.0311	0.0010	0.0311
Location 2	0.9751	0.9507	0.0299	0.0293	0.0009	0.0293
Location 3	0.9669	0.9348	0.0193	0.0186	0.0004	0.0186
Location 4	0.9767	0.9540	0.0093	0.0071	0.0001	-0.0071
Location 5	0.9788	0.9580	0.0091	0.0074	0.0001	-0.0073
Location 6	0.9850	0.9702	0.0099	0.0084	0.0001	-0.0079

4.3.2.2. Monochromatic Wave Model Results

A statistical comparison of the monochromatic waves operating in MIKE21 BW with the default breaking parameters and wave heights obtained from experimental measurements is given in **Table 4.27**. As can be seen, the correlation coefficient for location 1 was calculated as 0.776 and the RMSE number as 0.03 in the model results.

Table 4.27: Statistical result of default monochromatic models for $m = 1/10$.

	CC	RSQUARE	RMSE	MAE	SI	Bias
Location 1	0.7765	0.6030	0.0301	0.0245	0.0009	0.0218
Location 2	0.6667	0.4445	0.0368	0.0354	0.0014	-0.0354
Location 3	0.7207	0.5194	0.0519	0.0413	0.0027	0.0380
Location 4	0.6124	0.3750	0.0412	0.0397	0.0017	-0.0397
Location 5	0.7207	0.5194	0.0220	0.0146	0.0005	0.0001
Location 6	0.8095	0.6553	0.0216	0.0175	0.0005	0.0175

When the statistical values of the models working with different breaking parameters were examined, the correlation in location 1 increased to 0.850 for the IBA: 10° - FBA: 5° model. **Table 4.28** shows a statistical comparison of the IBA: 10° - FBA: 5° monochromatic model and the observed H values. In this models, RMSE values are calculated to be higher than the default model.

Table 4.28: Statistical result of IBA: 10° - FBA: 5° monochromatic models for $m = 1/10$.

	CC	RSQUARE	RMSE	MAE	SI	Bias
Location 1	0.8503	0.7230	0.0702	0.0658	0.0049	0.0658
Location 2	0.8422	0.7093	0.1044	0.1006	0.0109	0.1006
Location 3	0.7473	0.5585	0.0340	0.0292	0.0012	0.0110
Location 4	0.6481	0.4200	0.1108	0.1044	0.0123	0.1044
Location 5	0.8206	0.6734	0.0250	0.0209	0.0006	-0.0062
Location 6	0.8617	0.7426	0.0857	0.0791	0.0073	0.0791

4.4. AYGM Experiment Models with SWASH

4.4.1. Results from the Models with Base Slope $m = 1/20$

4.4.1.1. JONSWAP Model Results

In AYGM experiment models were run by entering parameters into SWASH and the time series of the water surface obtained from the WG points were statistically analyzed. A statistical comparison of the model created in SWASH with the default wave breaking parameters $\alpha: 0.6$ - $\beta: 0.3$ with experimental measurements is given in **Table 4.29**.

Table 4.29: Statistical comparison of $\alpha: 0.6 - \beta: 0.3$ JONSWAP model and observed H_s for $m = 1/20$.

	CC	RSQUARE	RMSE	MAE	SI	Bias
Location 1	0.8149	0.6641	0.0278	0.0246	0.0008	0.0246
Location 2	0.6677	0.4459	0.0181	0.0143	0.0003	0.0131
Location 3	0.6946	0.4825	0.0123	0.0107	0.0002	0.0024
Location 4	0.6491	0.4214	0.0387	0.0336	0.0015	-0.0336
Location 5	0.8393	0.7044	0.0272	0.0246	0.0007	-0.0167
Location 6	0.9421	0.8876	0.0838	0.0836	0.0070	0.0837

As shown in **Table 4.29**, the correlation coefficient was obtained as 0.815 at location 1. In location 6, this value is 0.942. The RMSE value is 0.028 at location 1 and 0.084 at location 6.

The H_s values obtained from the model and experimental results for location 1, location 2 are shown in **Figure 4.10** and **Figure 4.11**. The values for location 5 and location 6 are presented in **Figure 4.12**. As seen in the location 6, the H_s values in the SWASH remained at a lower level than the observed H_s values. However, it is seen that they follow the same trend in the location 6.



Figure 4.10: Comparison of H_s of location 1 in the shallowest water in default SWASH model with observed.



Figure 4.11: Comparison of H_s of location 2 in the shallowest water in default SWASH model with observed.



Figure 4.12: Comparison of H_s of 2 locations in the deepest water as time-series in default SWASH model with observed.

When comparing the results of models run with different breaking parameters, the $\alpha: 0.8 - \beta: 0.3$ model gives the best results. CC follow a similar trend to the default model, while RMSE values are lower. The statistical results of models with $\alpha: 0.8 - \beta: 0.3$ are given in **Table 4.30**.

Table 4.30: Statistical result of $\alpha: 0.8 - \beta: 0.3$ JONSWAP models for $m = 1/20$.

	CC	RSQUARE	RMSE	MAE	SI	Bias
Location 1	0.8140	0.6627	0.0265	0.0235	0.0007	0.0235
Location 2	0.6642	0.4412	0.0155	0.0121	0.0002	0.0108
Location 3	0.6835	0.4672	0.0110	0.0099	0.0001	-0.0004
Location 4	0.6231	0.3883	0.0410	0.0360	0.0017	-0.0360
Location 5	0.8372	0.7009	0.0290	0.0259	0.0008	-0.0186
Location 6	0.9448	0.8926	0.0840	0.0837	0.0070	0.0837

4.4.1.2. Monochromatic Wave Model Results

In SWASH, H values were calculated using the zero crossing method from time series obtained through experimental measurements of monochromatic waves operating at a gradient slope of $m = 1/20$. The calculated H values were compared statistically. A statistical comparison of the H values obtained from the simulated waves with the default breaking parameters in SWASH and the H values obtained from the experiments is presented in **Table 4.31**.

Table 4.31: Statistical result of $\alpha: 0.6 - \beta: 0.3$ monochromatic wave models for $m = 1/20$.

	CC	RSQUARE	RMSE	MAE	SI	Bias
Location 1	0.9482	0.8990	0.0158	0.0139	0.0003	0.0139
Location 2	0.8471	0.7175	0.0200	0.0186	0.0004	0.0179
Location 3	0.6010	0.3612	0.0504	0.0464	0.0025	0.0461
Location 4	0.4138	0.1712	0.0240	0.0202	0.0006	0.0052
Location 5	0.4834	0.2337	0.0404	0.0343	0.0016	-0.0247
Location 6	0.7412	0.5493	0.0686	0.0640	0.0047	-0.0640

As can be seen, a higher correlation and a lower RMSE value were obtained in location 1 compared to location 6. In location 6, the correlation coefficient is 0.74. When the models working with different breaking parameters were examined, a model with breaking parameters of α : 0.4 - β : 0.3 gave very close results with the default model. Especially in the shallowest location, correlation and error rates are very similar to each other. Towards deeper locations, the correlation decreases and RMSE values increase. At location 6, the correlation decreased from the default model to 0.6845, and the RMSE values were smaller in other locations except location 1. Statistical values for the model with breaking parameters α : 0.4 - β : 0.3 are presented in **Table 4.32**.

Table 4.32: Statistical result of α : 0.4 - β : 0.3 monochromatic models for $m = 1/20$.

	CC	RSQUARE	RMSE	MAE	SI	Bias
Location 1	0.9343	0.8729	0.0163	0.0149	0.0003	0.0149
Location 2	0.9263	0.8580	0.0197	0.0187	0.0004	0.0187
Location 3	0.7948	0.6316	0.0497	0.0471	0.0025	0.0471
Location 4	0.3665	0.1343	0.0349	0.0289	0.0012	0.0232
Location 5	0.4375	0.1914	0.0304	0.0249	0.0009	-0.0114
Location 6	0.6845	0.4685	0.0705	0.0655	0.0050	-0.0655

4.4.1.3. Bicromatic Wave Model Results

The bicromatic waves run in the SWASH program were statistically analyzed together with the waves observed from the experiment. The results of the statistical analysis for default model and observed values are given in **Table 4.33**.

Table 4.33: Statistical result of α : 0.6 - β : 0.3 bicromatic models for $m = 1/20$.

	CC	RSQUARE	RMSE	MAE	SI	Bias
Location 1	0.6955	0.4838	0.0257	0.0230	0.0007	0.0228
Location 2	0.6807	0.4633	0.0477	0.0432	0.0023	0.0432
Location 3	0.7061	0.4985	0.0808	0.0726	0.0065	0.0726
Location 4	0.5486	0.3009	0.1008	0.0924	0.0102	0.0924
Location 5	0.8278	0.6853	0.0613	0.0561	0.0038	0.0552
Location 6	0.9119	0.8315	0.0889	0.0876	0.0079	0.0876

As can be seen in **Table 4.33**, the CC was found to be 0.695 and the RMSE value was 0.026 in location 1. In location 6, the correlation was 0.911 and the RMSE value was 0.009. For Bicromatic models, the model with breaking parameter α : 0.4 - β : 0.3 gave the most accurate results on the location 1. This has been observed similarly for monochromatic wave models in bathymetry with a slope of 1/20. The statistical results of the α : 0.4 - β : 0.3 model are given in **Table 4.34**.

Table 4.34: Statistical result of α : 0.4 - β : 0.3 bicromatic models for $m=1/20$.

	CC	RSQUARE	RMSE	MAE	SI	Bias
Location 1	0.8774	0.7698	0.0349	0.0340	0.0012	0.0340
Location 2	0.7274	0.5291	0.0402	0.0363	0.0016	0.0363
Location 3	0.7710	0.5945	0.0605	0.0564	0.0037	0.0564
Location 4	0.5478	0.3001	0.0266	0.0244	0.0007	0.0205
Location 5	0.7212	0.5202	0.0822	0.0728	0.0068	0.0728
Location 6	0.8779	0.7707	0.0972	0.0961	0.0095	0.0961

4.4.2. Results from the Models with Base Slope $m = 1/10$

4.4.2.1. JONSWAP Wave Model Results

Jonswap models with a slope of $m = 1/10$ are created in SWASH with default breaking parameters. The statistical results obtained from the model and observed from experiment time series are given in **Table 4.35**. As can be seen in **Table 4.35**, CC were found to be 0.95 and above. The RMSE value was calculated as 0.051 at the location 1 and 0.009 at the location 6.

Table 4.35: Statistical result of α : 0.6 - β : 0.3 JONSWAP models for $m = 1/10$.

	CC	RSQUARE	RMSE	MAE	SI	Bias
Location 1	0.9582	0.9182	0.0514	0.0508	0.0026	0.0508
Location 2	0.9759	0.9524	0.0251	0.0243	0.0006	0.0243
Location 3	0.9739	0.9485	0.0179	0.0146	0.0003	-0.0096
Location 4	0.9754	0.9513	0.0147	0.0131	0.0002	-0.0054
Location 5	0.9459	0.8946	0.0096	0.0086	0.0001	-0.0056
Location 6	0.9457	0.8944	0.0061	0.0056	0.0000	-0.0004

The H_s values obtained from model results and observed values for location 1, location 2 and location 3 are shown in **Figure 4.13**, while the values for location 4, location 5, and location 6 are presented in **Figure 4.14**.



Figure 4.13: Comparison of H_s of 3 locations in the shallowest water in default SWASH model with observed.

As can be seen in **Figure 4.13**, while the observed H_s values were higher at location 1 and location 2 than the H_s values obtained from SWASH, they started to converge at location 3.



Figure 4.14: Comparison of H_s of 3 locations in the deepest water in default SWASH model with observed.

As can be seen in **Figure 4.13** and **Figure 4.14**, the observed H_s values at location 1 and location 2 were found to be higher than the H_s values obtained from SWASH. As we went from location 1 to location 6, the H_s values got closer to each other.

When the results of models run with different breaking parameters are compared, the $\alpha: 0.8 - \beta: 0.3$ model yields the most optimal results. While CC follow a similar trend to the default model, the RMSE values are lower. Statistical result of $\alpha: 0.8 - \beta: 0.3$ JONSWAP model is given in **Table 4.36**.

Table 4.36: Statistical result of $\alpha: 0.8 - \beta: 0.3$ JONSWAP models for $m = 1/10$.

	CC	RSQUARE	RMSE	MAE	SI	Bias
Location 1	0.9586	0.9189	0.0496	0.0491	0.0025	0.0491
Location 2	0.9765	0.9536	0.0212	0.0207	0.0004	0.0207
Location 3	0.9717	0.9443	0.0133	0.0114	0.0002	0.0077
Location 4	0.9746	0.9499	0.0207	0.0168	0.0004	-0.0168
Location 5	0.9610	0.9235	0.0126	0.0112	0.0002	0.0068
Location 6	0.9464	0.8956	0.0062	0.0055	0.0000	-0.0004

4.4.2.2. Monochromatic Wave Model Results

Statistical comparisons of the SWASH model results of monochromatic waves running in bathymetry at a slope of $1/10$ and the H values obtained according to experimental observations are given in **Table 4.37**. As can be seen in **Table 4.37**, the correlation value was found to be 0.881 in location 1. In location 6, this value was found to be 0.696. While the RMSE value was 0.077 in location 1, this value was calculated as 0.0575 in location 6.

Table 4.37: Statistical result of $\alpha: 0.6 - \beta: 0.3$ monochromatic models for $m = 1/10$.

	CC	RSQUARE	RMSE	MAE	SI	Bias
Location 1	0.8810	0.7762	0.0766	0.0721	0.0093	0.0921
Location 2	0.8081	0.6530	0.0775	0.0767	0.0095	0.0967
Location 3	0.8154	0.7380	0.0769	0.0782	0.0048	0.0682
Location 4	0.6365	0.4051	0.0826	0.0653	0.0020	-0.0565
Location 5	0.6552	0.5703	0.0478	0.0388	0.0023	0.0377
Location 6	0.6966	0.4853	0.0575	0.0483	0.0033	-0.0477

When the results of the model created with different wave breaking parameters were examined, the most optimal result was obtained with a model with α : 0.4 - β : 0.3 parameters. Statistical results for the models with wave breaking parameters as α : 0.4- β : 0.3 are given in **Table 4.38**.

Table 4.38: Statistical result of α : 0.4 - β : 0.3 monochromatic models for $m = 1/10$.

	CC	RSQUARE	RMSE	MAE	SI	Bias
Location 1	0.9142	0.8357	0.0551	0.0545	0.0030	0.0123
Location 2	0.8561	0.7329	0.0568	0.0504	0.0032	0.0504
Location 3	0.8295	0.6882	0.0409	0.0387	0.0017	0.0327
Location 4	0.6410	0.6855	0.1237	0.1116	0.0106	-0.0741
Location 5	0.6724	0.4521	0.0806	0.0741	0.0065	0.0545
Location 6	0.7322	0.5361	0.1042	0.0998	0.0109	-0.0998

As can be seen in **Table 4.38**, the correlation coefficient increased to 0.914 in location 1 and the RMSE value decreased to 0.0551. While the correlation value continued to be low in location 6, the correlation increased for location 6 as well.

5.CONCLUSIONS AND RECOMMENDATIONS

The main purpose of this study is to observe wave energy propagation during wave breaking processes using MIKE21 BW and SWASH programs. To achieve this, DUCK94 and AYGM experimental models were simulated in MIKE21 BW and SWASH programs and model calibrations were performed to obtain the most accurate model parameters.

In chapter 4, the results of the validation models selected for the DUCK94 experiments are given for both MIKE21 BW and SWASH. By observing the results of the validation models, a breaking parameter was selected for each program. With these selected parameters, the dataset consisting of 799 different experimental models from DUCK94 experimental data was modelled in both MIKE21 BW and SWASH.

Table 5.1 shows a statistical comparison of the H_s values calculated from the 799 MIKE21 BW selected breaking parameter IBA: 10° - FBA: 5° model and the H_s values obtained from the DUCK94 experiments. **Table 5.2** gives the statistical comparison of the waves operating with the default breaking parameter IBA: 20° - FBA: 10° in MIKE21 BW and the H_s values obtained from the DUCK94 experiments.

Table 5.1: Statistical result of 799 MIKE21 BW model for selected breaking parameter IBA: 10° - FBA: 5° .

	CC	RSQUARE	RMSE	MAE	SI	Bias
Location 1	0.8192	0.6711	0.16852	0.1130	0.0284	0.0017
Location 2	0.8631	0.7450	0.22575	0.13034	0.0200	0.0654
Location 3	0.8699	0.7567	0.14780	0.08769	0.0218	0.0052
Location 4	0.9113	0.8305	0.12283	0.07876	0.0151	0.0100
Location 5	0.9230	0.8519	0.12948	0.08438	0.0168	0.0390
Location 6	0.9313	0.8672	0.11749	0.07304	0.0138	0.0200
Location 7	0.9359	0.8760	0.11885	0.07008	0.0141	0.0267
Location 8	0.9492	0.9011	0.12298	0.0710	0.0138	0.0844
Location 9	0.9549	0.9118	0.13435	0.07789	0.0181	0.0286
Location 10	0.9731	0.9469	0.10478	0.06767	0.0110	0.0290
Location 11	0.9792	0.9589	0.11955	0.05674	0.0143	0.0378
Location 12	0.9810	0.9623	0.10547	0.05421	0.0111	0.0088
Location 13	0.9861	0.9723	0.1050	0.05196	0.011	0.0350
Location 14	0.9875	0.9752	0.10012	0.04647	0.010	0.0113
Location 15	0.9958	0.9917	0.10609	0.04404	0.0113	-0.0390

Table 5.2: Statistical result of 799 model with MIKE21 BW for default parameter IBA: 20°- FBA: 10°.

	CC	RSQUARE	RMSE	MAE	SI	Bias
Location 1	0.7465	0.5572	0.2547	0.1808	0.0649	-0.0921
Location 2	0.8573	0.7349	0.3414	0.1911	0.0661	-0.0548
Location 3	0.8422	0.7093	0.3041	0.1727	0.0925	-0.1376
Location 4	0.8886	0.7896	0.2803	0.1552	0.0786	-0.1233
Location 5	0.9076	0.8237	0.2761	0.1534	0.0762	-0.1025
Location 6	0.9149	0.8370	0.2753	0.1422	0.0758	-0.1100
Location 7	0.9193	0.8451	0.2645	0.1326	0.0700	-0.0973
Location 8	0.9308	0.8665	0.2576	0.1173	0.0583	0.1534
Location 9	0.9395	0.8826	0.2534	0.1241	0.0642	-0.0887
Location 10	0.9453	0.8935	0.2744	0.1344	0.0753	-0.0661
Location 11	0.9803	0.9610	0.1666	0.0758	0.0278	-0.0449
Location 12	0.9895	0.9791	0.1595	0.0819	0.0254	-0.0639
Location 13	0.9886	0.9774	0.1424	0.0685	0.0203	-0.0326
Location 14	0.9949	0.9899	0.1162	0.0584	0.0135	-0.0454
Location 15	0.9970	0.9940	0.1079	0.0486	0.0116	-0.0442

Examining **Table 5.1** and **Table 5.2**, it can be observed that the correlation values for the default model are lower than the model run with the calibrated parameters up to location 10. For location 1, the model generated with the calibrated breaking parameters shows a correlation of 0.819, while for the default model, the correlation remains at 0.746. In addition, RMSE values were found to be higher in the default model. The RMSE value for location 1 is 0.168 for calibrated models and 0.255 for default models. Compared to other locations on a location-by-location basis, the RMSE values for the default models are higher than for the calibrated models.

Table 5.3 provides statistical comparison of the simulations for 799 DUCK94 models in the SWASH models with calibrated breaking parameters α : 0.4 - β : 0.3. **Table 5.4** provides the statistical results of the simulations performed in the SWASH models with the default breaking parameters α : 0.6 - β : 0.3 for the 799 DUCK94 models.

Table 5.3: Statistical result of 799 model with SWASH for selected breaking parameter α : 0.4 - β : 0.3.

	CC	RSQUARE	RMSE	MAE	SI	Bias
Location 1	0.7248	0.5254	0.21097	0.145	0.0445	-0.027

Table 5.3 Continued: Statistical comparison of 799 model with SWASH for selected breaking parameter α : 0.4 - β : 0.3.

Location 2	0.8466	0.7167	0.1682	0.10956	0.0283	-0.007
Location 3	0.8645	0.7473	0.17075	0.10153	0.0292	-0.034
Location 4	0.9003	0.8106	0.14847	0.09476	0.022	-0.027
Location 5	0.9169	0.8408	0.14266	0.08958	0.0204	-0.007
Location 6	0.9259	0.8574	0.14087	0.08779	0.0198	-0.033
Location 7	0.9344	0.8731	0.13552	0.07924	0.0184	-0.031
Location 8	0.9473	0.8973	0.14695	0.07236	0.0156	0.0896
Location 9	0.9496	0.9017	0.14648	0.09117	0.0215	-0.036
Location 10	0.9632	0.9277	0.14907	0.08486	0.0222	-0.032
Location 11	0.9758	0.9522	0.1128	0.07198	0.0127	-0.013
Location 12	0.9759	0.9524	0.12125	0.0766	0.0147	-0.035
Location 13	0.9843	0.9688	0.09778	0.06172	0.0096	-0.005
Location 14	0.9894	0.9789	0.08819	0.06079	0.0078	-0.021
Location 15	0.9853	0.9708	0.13524	0.06408	0.0183	-0.036

Table 5.4: Statistical result of 799 model with SWASH for default breaking parameter α : 0.6 - β : 0.3.

	CC	RSQUARE	RMSE	MAE	SI	Bias
Location 1	0.6945	0.4824	0.2214	0.17283	0.049	-0.022
Location 2	0.8385	0.70311	0.19639	0.1237	0.0386	-0.035
Location 3	0.8574	0.7351	0.20164	0.1183	0.0407	-0.061
Location 4	0.8955	0.80183	0.1781	0.1091	0.0317	-0.051
Location 5	0.9121	0.83197	0.17219	0.1044	0.0297	-0.034
Location 6	0.9216	0.84939	0.17527	0.1035	0.0307	-0.059
Location 7	0.9294	0.86374	0.16992	0.0943	0.0289	-0.056
Location 8	0.9424	0.88811	0.16213	0.0846	0.0248	0.1044
Location 9	0.9466	0.89598	0.17907	0.1069	0.0321	-0.067
Location 10	0.9569	0.91572	0.20044	0.1073	0.0402	-0.06
Location 11	0.9787	0.95784	0.12355	0.079	0.0153	-0.037
Location 12	0.9795	0.95937	0.13719	0.0871	0.0188	-0.056
Location 13	0.9866	0.97331	0.10773	0.0685	0.0116	-0.026
Location 14	0.9925	0.98502	0.09674	0.0658	0.0094	-0.04
Location 15	0.9848	0.96984	0.14391	0.0688	0.0207	-0.04

As seen in **Table 5.3**, in location 1, the correlation for the calibrated model is 0.725 and the RMSE is 0.211. In contrast, the default models give a correlation of 0.694 and an RMSE of 0.221 in location 1. When the results of the calibrated model are compared with the results of the model with the default breaking parameters on the basis of location, it is seen that the calibrated model has a higher correlation and lower error

rates than the default model results. However, the results of the two different models are quite close to each other.

When the statistical comparisons made for 799 models in the MIKE21 BW and SWASH programs were examined, it was observed that the calibrated models gave more accurate results in the wave breaking regions than the models with default parameter and were more consistent with the results obtained from the experiments.

In a comparison based on the default model, the MIKE21 BW was 5% more correlated, but the RMSE value was 3% lower than the SWASH model. The RMSE values of the MIKE21 BW are higher than the RMSE values of SWASH for the default model. When the results of the calibrated models were evaluated, it was observed that the MIKE21 BW models experienced a significant decrease in RMSE values. The correlation coefficient for location 1 increased by 9% compared to the default model, while the RMSE value decreased by 9%. This was not the case for SWASH, where the increase in correlation was 3% and the decrease in RMSE was 1%. When comparing the default model results for location 1, MIKE21 BW returned more accurate results in terms of both correlation and errors.

In **Figure 5.1** and **Figure 5.2** the default MIKE21 BW and SWASH models and the observed H_s results are given for the 2 shallowest points. According to the results here, MIKE21 BW and SWASH overestimate at the points where the wave height increases.

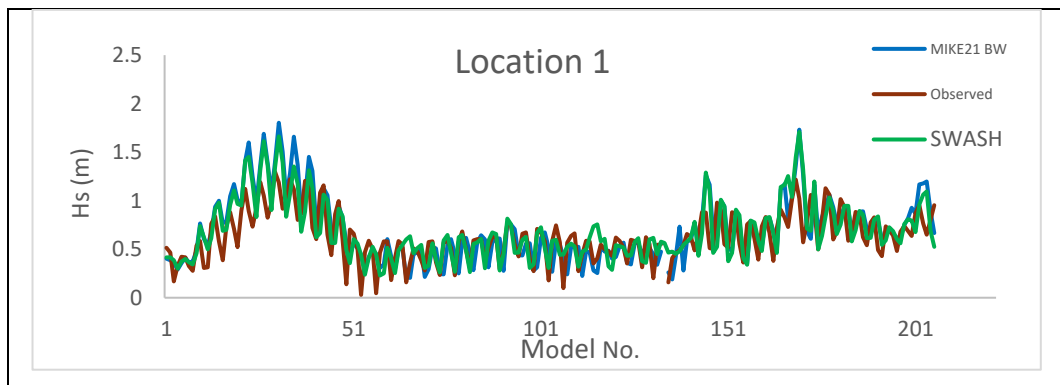


Figure 5.1: Comparison MIKE21 BW and SWASH default models with observed H_s in location 1.



Figure 5.2: Comparison MIKE21 BW and SWASH default models with observed H_s in location 2.

In **Figure 5.3**, the H_s values at the 2 deepest locations are given for MIKE21 BW, SWASH and the data observed in the experiment. Even at points where wave heights are around 3.5 m, model results approach the observed results.

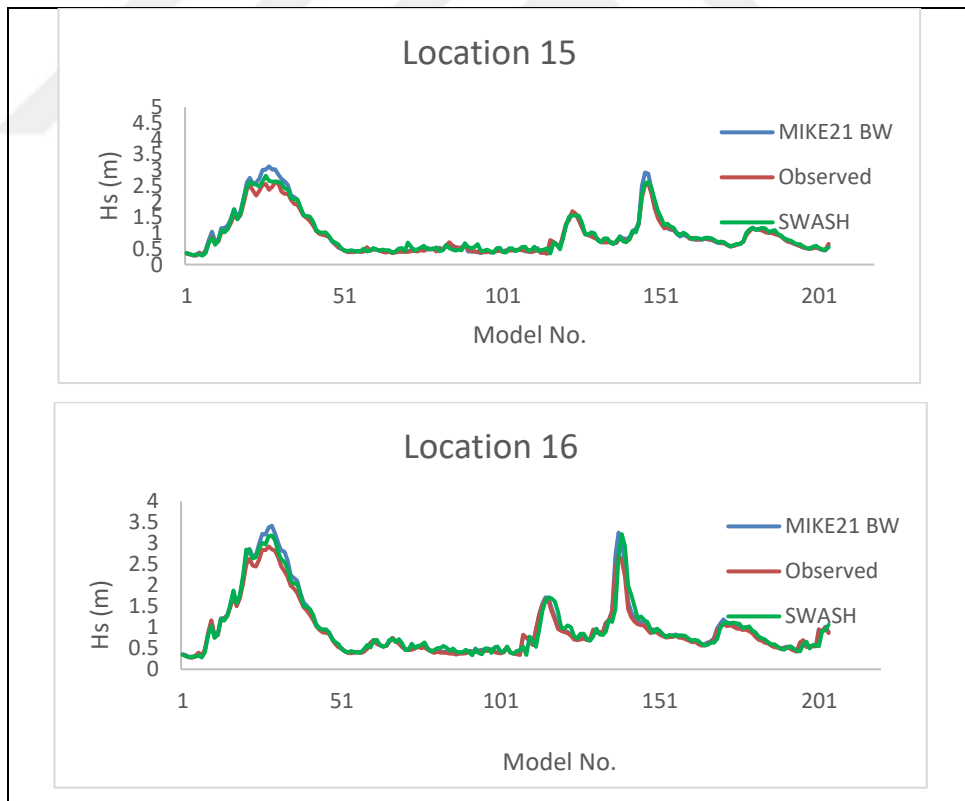


Figure 5.3: Comparison MIKE21 BW and SWASH default models with observed H_s in 2 deepest water point.

Figure 5.4 shows the comparison of the calibrated MIKE21 BW and SWASH models with the observed H_s values from the experiment for shallowest 2 points. As can be seen in the figures, MIKE21 BW was seen to converge to the observed values while SWASH continued to overestimate at the points where the wave heights increased.

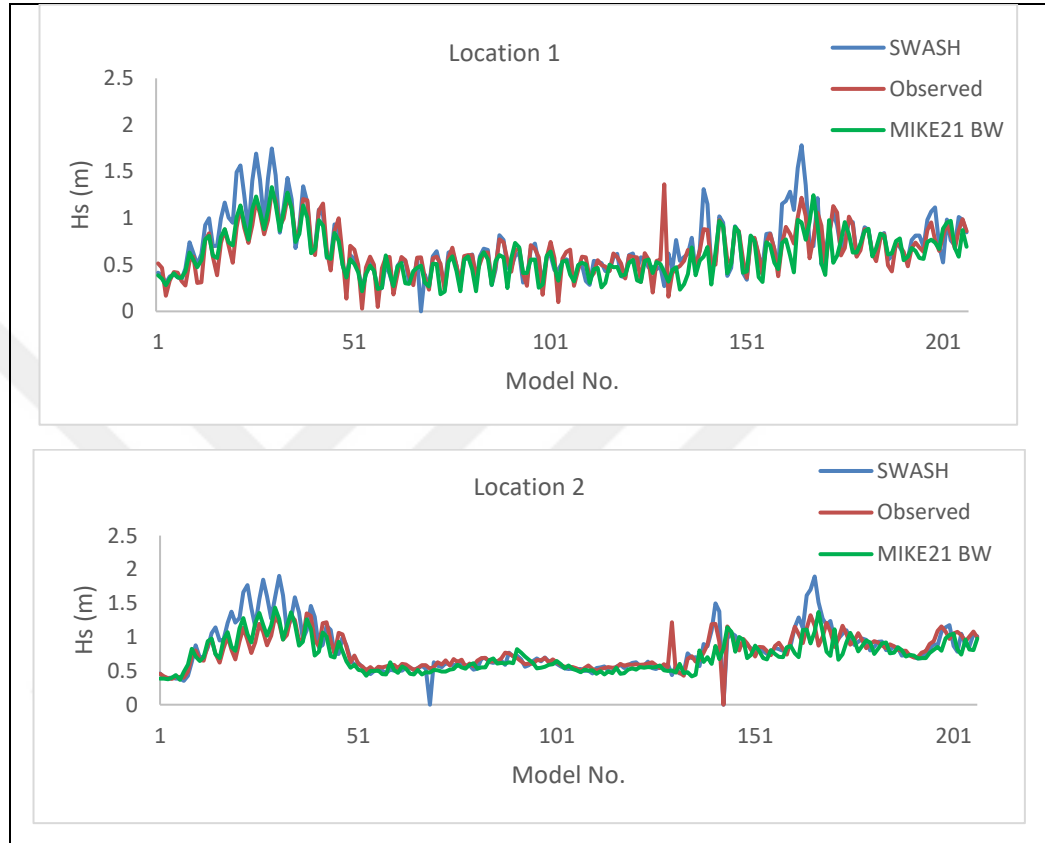


Figure 5.4: Comparison MIKE21 BW and SWASH calibrated models with observed H_s in 2 shallowest water point.

No specific validation data set was selected in the AYGM experiments. Instead, the models were studied based on running JONSWAP spectrum waves, monochromatic waves and bicromatic waves with different seabed bathymetries. The results of these models were analyzed and the breaking parameters of the models were obtained.

When examined for JONSWAP models, it is seen that models created on a seabed with a slope of $m = 1/20$ result in higher error values than models created at a slope of $m = 1/10$. On the MIKE21 BW, default JONSWAP models showed an increase in their RMSE value compared to the calibrated model. When this comparison was made for SWASH, lower RMSE values were obtained with $\alpha: 0.4$ - $\beta: 0.3$ breaking parameters. In statistical comparisons for MIKE1 BW and SWASH, it was observed that MIKE21

BW models showed more variability with calibration in bathymetry with a slope of 1/20. In 1/10 inclined bathymetry, there is not much difference between the default and calibration models. In the models made for SWASH, the calibration model and the default model, which work with both 1/20 and 1/10 inclined bathymetry, give very close results. It has been determined that the model working with calibration parameters in the JONSWAP models made in SWASH gives better results than the default model in location 1 and location2, which are the shallowest locations.

In **Figure 5.5**, the results of JONSWAP models with a default slope of $m = 1/20$ in the MIKE21 BW and SWASH models are presented, along with experimental measurements for locations 1, 2. As shown in **Figure 5.5**, the results of the MIKE21 BW and SWASH models are similar.



Figure 5.5: Comparison H_s values from experimental observation, MIKE21 BW and SWASH default JONSWAP model in location 1, 2.

In **Figure 5.6**, JONSWAP models calibrated for slope $m = 1/20$ in MIKE21 BW and SWASH are presented with experimental measurements. It can be observed that the calibrated models give very close results for both MIKE21 BW and SWASH.

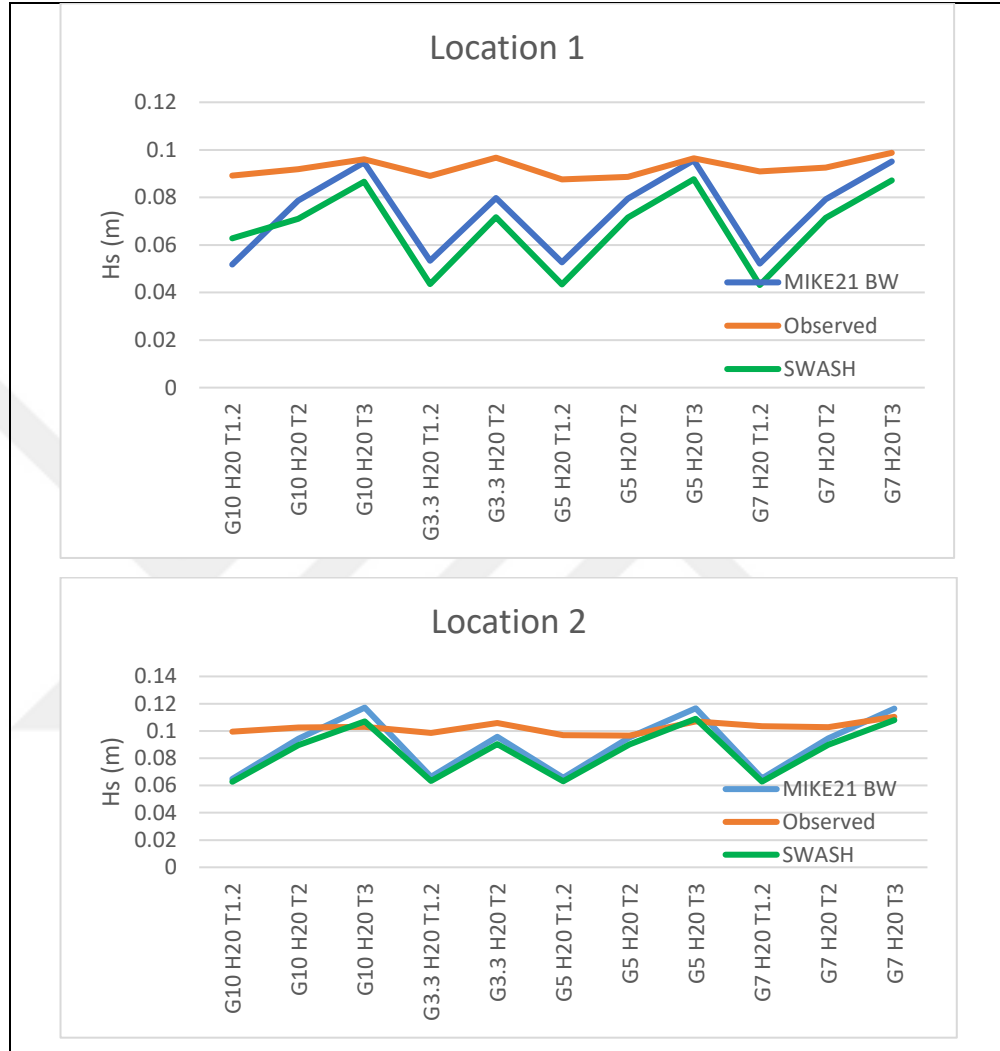


Figure 5.6: Comparison H_s values from experimental observation, MIKE21 BW and SWASH calibrated JONSWAP model in location 1, 2.

As shown in **Figure 5.5** and **Figure 5.6**, very similar results were observed for the MIKE21 BW and SWASH models in both default and calibrated models. On the contrary, the results obtained from the experiments differ from the results of the two models.

In **Figure 5.7**, a comparison of the H_s values for JONSWAP waves operating with the default parameters on a bathymetry with a slope of $m = 1/10$ is provided for the

experimental measurements in MIKE21 BW, SWASH, for location 1, location 2. As can be seen in **Figure 5.7**, MIKE21 BW has performed better modeling for this particular bathymetry, especially in location 1.

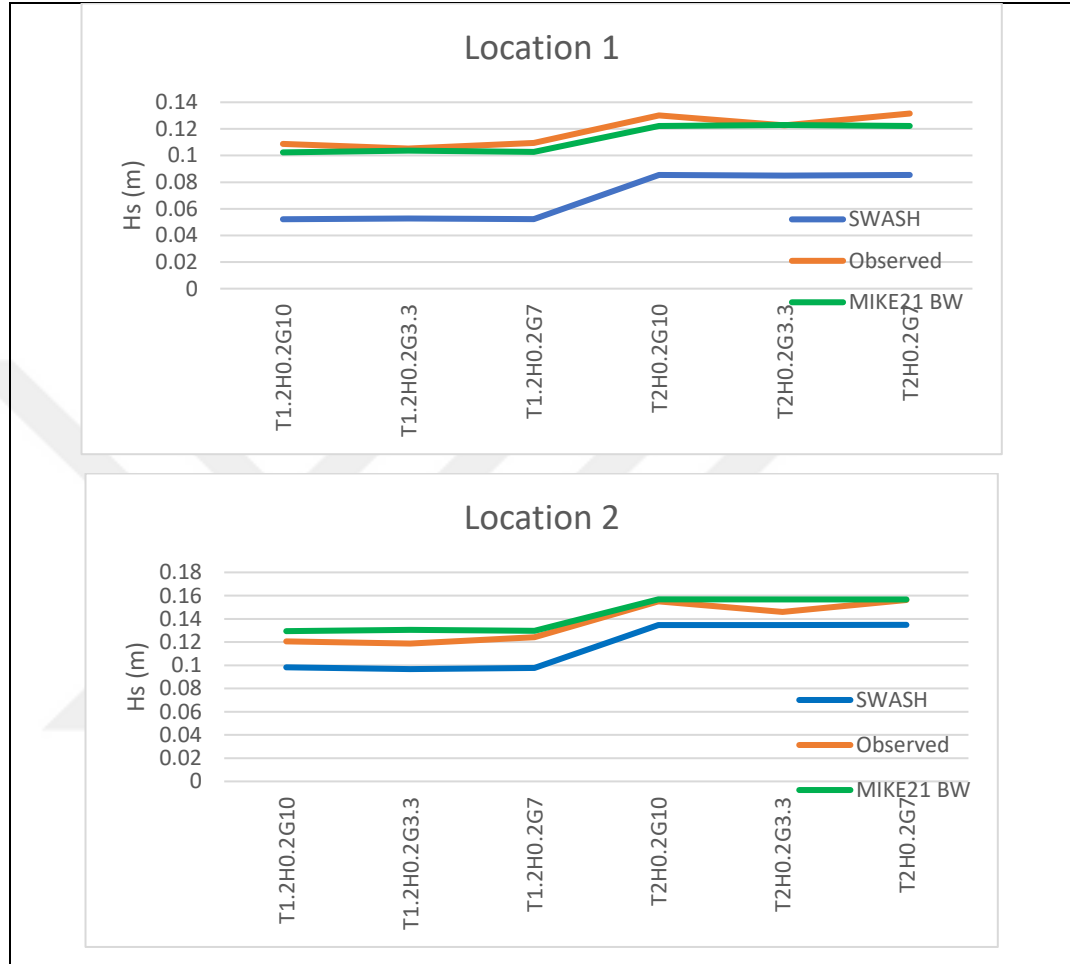


Figure 5.7: Comparison H_s values from experimental observation, MIKE21 BW and SWASH default JONSWAP model in location 1, 2.

In **Figure 5.8**, a comparison of H_s values for JONSWAP waves operating with calibrated parameters on a seabed with a slope of $m = 1/10$ is provided for the experimental measurements in MIKE21 BW and SWASH for location 1, location 2. For MIKE21 BW, the model created with calibrated parameters estranged from the experimental measurements. Therefore, although the calibration values were slightly higher in the default model, the RMSE values were calculated higher. For SWASH, the change between the calibrated model and the default model is very small.



Figure 5.8: Comparison H_s values from experimental observation, MIKE21 BW and SWASH calibrated JONSWAP model in location 1, 2.

For 1/20 and 1/10 inclined bathymetries, the monocromatic and bicromatic models showed different results than the JONSWAP spectrum wave models. For the 1/20 inclined models, the JONSWAP model for the MIKE21 BW gave more accurate results in the calibration model, while the models with default parameters gave better results in the monocromatic and bicromatic models. In the determinations made for SWASH, the wave with JONSWAP spectrum model, monocromatic and bicromatic wave models showed similar features in the 1/20 inclined bathymetry. Here, it was observed that the model with calibrated breaking parameter at the shallowest points gave a lower error.

When the results of the MIKE21 BW model for 1/10 inclined bathymetry were examined, the behavior of JONSWAP waves and monocromatic waves for the default and calibrated model was similar. While the correlation has increased, as in the JONSWAP wave model, RMSE values have also increased. In the SWASH models, the monocromatic wave models were similar to the JONSWAP wave models, and the

calibrated models achieved a lower RMSE value with a higher correlation in location 1 and location 2.

When the results obtained from the JONSWAP spectrum waves run in 1/20 inclined bathymetry are observed, it can be seen that the results of the MIKE21 BW and SWASH models are similar to each other in both the default parameter models and the calibrated models, they do not resemble the results obtained from the experiment. On the other hand, in 1/10 inclined bathymetry, the results of the MIKE21 BW and SWASH models are parallel both relative to each other and according to the model results. In models with a slope of 1/10, the correlations of the MIKE21 BW and SWASH models approach 1 for each location.

The results obtained in this way may have more than one reason. The bottom friction in the experimental setup was not taken into account when model installations were made. In the 1/20 inclined base, a wooden material with a different coefficient of friction is used in a longer area than in the 1/10 inclined base. Due to this parameter, which is not defined in the models, the model results and experimental results may have given higher error rates. Secondly, porosity is not defined in the models, and the porosity characteristic of the wave-dampening elements used in the experiments may also be the source of different results. A third reason is that erroneous measurements were taken in the 1/20 inclined experimental setup. After the experimental measurements were taken and the experiments were completed, the modeling phase was started and the experiments were not repeated.

In order to reduce the error rates of the models and to make better calibrations, it can be applied to detail the model designs and to install them with the friction coefficients of different floors and to include environmental properties such as porosity in the models. By making the models simultaneously with the experiments, repeated trials can be made according to the error rates in the models, thus minimizing the erroneous measurements caused by the experimental setup.

As can be understood from the model and observation results, the MIKE21 BW model, which works with the analysis of the Boussinesq wave equations, gives more accurate results in shallow water waves. The calibrations performed in the MIKE21 BW program were able to reduce the error rates of the models more than SWASH and the calibrations were more effective. From this point of view, it means that every physical

condition, wave conditions, boundary conditions can affect model results and model calibrations when modeling. When wave modelling, a modeling tool suitable for bathymetry slope, wave conditions and formation processes should be selected.

DUCK94 experiments and AYGM experiments were calibrated with breaking parameters and common parameters were found to give optimum results. The results of the calibrated models in the DUCK94 experiments increased the accuracy of the model at a much higher rate than in the AYGM experiments. The main reason for that there are many more models in the DUCK94 experiments than in the AYGM experiments. In addition, AYGM experiments are small-scale experiments, while DUCK94 experiments are based on real marine measurements.

Although the MIKE21 BW is operated in 2D mode, the limits to be applied to 1D mode are set and it is operated like a 1D model. SWASH was run in 1D mode. MIKE21 BW and SWASH allow modeling in 2D mode and covering larger areas. Performing model calibrations in 2D mode will better understand the fracture processes that will occur on a coastline and will allow more precise calibration.

The values of the calibration parameters obtained by making models in MIKE21, BW and SWASH with the data sets of different experiments such as DUCK94 and AYGM experiments can be observed under different wave and boundary conditions.

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PUBLICATIONS AND PRESENTATIONS FROM THE THESIS

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