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Application of Numerical Wave Models for Prediction of Wave Characteristics at Deep Sea Ports of Myanmar

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***Abstract*— *An important component of most coastal and ocean engineering projects is an accurate assessment of wave climate at the project site. Wave penetration inside harbors has been one the main issues that port planners and engineers have to deal with in recent years. Realistic wind wave condition in a coastal area, and in and around harbor can be obtained by predicting the wind wave conditions in a large area where the waves are generated. In this research, the numerical wave simulations were carried at two potential sites for deep sea port in Myanmar. Two types of numerical wave models: Phase-averaged model, SWAN (Simulating* Waves *Nearshore), and Phase-resolving model, BOUSS (Boussinesq-type equations) were employed to predict the wave characteristics for interested area. The detailed characteristics of wave parameters were determined by two numerical wave models and the results were compared for selected points. From their results, phase-resolving models would be used in small scale area and more preferred because of their ability to calculate accurately diffraction, shoaling, refractions and nonlinearity, especially for calculating specific processes in and around harbors. On the other hand, phase-averaged model could be more suitable for large scale area, where local wave generation is dominant, because of their reliability and time saving processing.*

***Keywords*— *Deep Sea Port, Myanmar, Numerical wave model, Phase-averaged model, Phase-resolving model.*

I. INTRODUCTION

Knowledge of wave conditions in and around harbours is practical interest for harbour authorities since waves affect the stability of entrance channels and the safety of ships [1]. Typical applications include determination of safe conditions for the loading/unloading of ships, optimization of harbour layouts for both win-generated and long-period infra-gravity waves, design of coastal structures, and the evaluation of the impact of coastal structures on adjacent shorelines.The computation of these wave conditions is often based on offshore wave data, which are transformed to a number of locations in the harbour. In this transformation the effects of refraction, diffraction and reflection against quays are important. In somewhat larger harbour areas also the effect of local wave generation may contribute significantly to the wave agitation [2].

The function of a harbour is to provide safe anchorage for vessels and to facilitate smooth transfer of cargo between ships and adjoined land. Assured harbour tranquillity is not only essential for safe anchorage, but it is also important for efficient port operation [3]. Part of the management system, the efficient harbour management is also very important. Thus, the ability for predicting and analysing wave behaviour near/in the harbour is needed for loading/unloading of cargos and for preventing excessive motion of the moored ships, especially in extreme wind wave conditions [4].

To prevent the adverse effects of marine environment on port operations, the aforementioned port element need to be protected against action of short- and long-period waves, currents, and siltation. Lack of protection may not only cause damage to vessels and quay installations, but, most importantly, interfere with port operations, causing delays, and economic losses. Insufficient protection of the harbour against waves and currents can cause interruption of vessel loading/uploading operations. In the viewpoint of port operation, the relationship between ship motion and cargo handling works as well falls in the judgment of harbour serenity. Thus establishing statistics of the wave climate outside the harbour and transforming it to inner harbour is a fundamental task.

Physical modelling studies are expensive and time demanding, which poses limitations on the number of cases to be tested [5]. For example, the scale of the model may not be sufficiently large to represent all the features of the prototype. Besides the scale, wave patterns in the laboratory model may be modified by the boundaries of the tank. Thus, numerical wave propagation models seem to be the most suitable tools for analysis and optimization of wave characteristics [4]. Numerical models are used to express the physical concepts of the phenomena for hindcasting and forecasting of wave parameters that help in the design of the coastal structures [6]. Due to the initiation of powerful computers and development of several numerical techniques, solving coastal problems using numerical models are found to be very reliable, cost effective and time saving tools [6].

A number of mathematical models have been developed to simulate the propagation and transformation of waves in coastal regions and harbours [7]. The different models are based on different assumptions, which limit the types of problems to which they can be applied. Therefore one or more than one type of model should be selected to make the best or most efficient representation of the problem being considered.

For several coastal and offshore activities, the information on waves during monsoon is of prime importance for Myanmar. As in-situ measurements are difficult to get during monsoons, a good model can provide the required wave information for

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any practical application, subject to the accuracy of winds. Therefore, it is instantly necessary to conduct detailed study on waves especially for deep sea port projects in order to meet the needs of design, construction, and safe operation of ports [4].

In this research, SWAN is used to test capabilities of phase-resolving model in an environment where significant effects of refraction, reflection and/or diffraction are expected. The information about performance of SWAN and its ability to correctly represent physical phenomena particularly concerning refraction and diffraction would be provided from the systematic analysis of conditions [8]. Realistic wind wave condition in a coastal area, and in and around harbour can be obtained by predicting the wind wave conditions in a large area where the waves are generated [9]. In this extensive area, the prediction is practically only possible in a phase-averaged sense [10]. In this sense, the energy spectra of the wave are modelled, while the phases are assumed to be uniformly distributed [3].

Coastal waters are waters that are shallow enough to affect the waves, adjacent to a coast, possibly with small shoals or islands, headlands, tidal flats, reefs, estuaries, harbours or other features, with time-varying water levels and ambient currents. The non-linear Boussinesq equations are available when waves enter water that is so shallow that the linear wave theory no longer holds. These equations implicitly include shoaling, refraction, diffraction and reflections and also nonlinear wave–wave interactions. Even depth-induced breaking can be included [11]. According to [3], since the phase information is lost in a phase-averaged model like SWAN, in small scale such as a harbour, phase-resolving models such as the mild-slope equation and Boussinesq-type equations are widely used and more preferred because their ability to calculate accurately diffraction, shoaling, refractions and nonlinearity, especially for calculating a specific processes such as harbour oscillations.

This research article covers five sections. The importance of wave for coastal structures and port operations, advantages and types of numerical wave model are briefly introduced in section 1. In section 2, the detailed description of SWAN and BOUSS are presented. The data and methodology are illustrated in section 3. The characteristics of wave parameters were determined by two numerical wave models and the results were compared for selected points in the fourth section. And the last section, section 5, deals with the conclusion and recommendations.

II. Model Description

A. SWAN Model

For describing the wave propagation in the near-shore were performed simulation with the SWAN (acronym for **S**imulating Waves Nearshore), a spectral phase averaging wave model designed to obtain realistic estimates of wave parameters in coastal areas from given wind, bottom, and current conditions (Holthuijsen et al.2001) [12,13].

In the SWAN model, for the control equation for wave description, the dynamic spectrum balance equation is adopted based on the theory of linear and random surface gravity waves. In the flow field, the random waves are presented in two-dimensional dynamic spectral density rather than two-dimensional energy spectral density [14]. Therefore the model is based on the wave action balance equation (or energy balance in the absence of currents) with sources and sinks [15]. The evolution of the wave spectrum is described by the spectral action balance equation.

For Spherical coordinates [14],

$$\frac{\partial}{\partial t}N + \frac{\partial}{\partial \lambda}c_{\lambda}N + (\cos\varphi)^{-1}\frac{\partial}{\partial \varphi}c_{\varphi}\cos\varphi N + \frac{\partial}{\partial \sigma}c_{\sigma}N + \frac{\partial}{\partial \theta}c_{\theta}N = \frac{S}{\sigma} \quad (1)$$

Φ is latitude and λ is longitude.

where $N(\sigma, \theta; x, y, t)$ is the action density as a function of intrinsic frequency σ, direction θ, horizontal coordinates x and y, and time t. The first term on the left-hand side represents the local rate of change of action density in time, the second term represents propagation of wave action in geographical space with velocities c_x and c_y in x and y directions. The third term represents shifting of the relative frequency due to variations in depths and currents with propagation velocity c_σ in σ space. The fourth term represents depth and current-induced refraction with propagation velocity c_θ in θ space. The expressions for all of propagation velocities are taken from linear wave theory [13].

The term at the right-hand side of the wave action balance equation is the source term of energy density representing wave generation, energy dissipation and non-linear wave-wave interaction [14].

$$S(\sigma,\theta) = S_{in} + S_{ds} + S_{nl} \quad (2)$$

B. Boussinesq Model

Boussinesq equations are vertically integrated for wave propagation in the two-dimensional horizontal plane with different assumptions made for the variation of fluid motion over the water depth. The equations are depth-integrated equations for the conservation of mass and momentum, and for nonlinear wave propagation in shallow and intermediate water depths. It is a comprehensive numerical model for simulating the propagation and transformation of waves in coastal regions and harbours based on a time-domain solution of Boussinesq-type equations [16]. The fully nonlinear equations are particularly useful for simulating highly asymmetric waves in shallow water, wave-induced currents, wave setup close to the shoreline, and wave-current interaction [17]. The modified equations can simulate most of the hydrodynamic phenomena of interest in coastal regions and harbour basins including [7]:

a. Shoaling
b. Refraction
c. Diffraction
d. Full/partial reflection and transmission
e. Bottom fraction
f. Nonlinear wave-wave interaction
g. Wave breaking and run-up
h. Wave-induced currents, and

i. Wave-current interaction.

The Boussinesq equations for slowly varying depth are (Peregrine, 1967) [18]:

$$\eta_t + \nabla.(hu) = 0, \quad u_t + g\nabla\eta = 0 \tag{3}$$

$$u_t + (u.\nabla)u + g\nabla\eta = (1+\beta)\frac{h}{2}\nabla[\nabla.(hu_t)] + \beta\frac{gh}{2}\nabla[\nabla.(h\nabla\eta)] - (1+\beta)\frac{h^2}{6}\nabla(\nabla.u_t) - \beta\frac{gh^2}{6}\nabla(\nabla^2\eta) \tag{4}$$

where $u = (u,v)$ is the two-dimensional depth-averaged velocity vector, η is the surface displacement, $h = h(x,y)$ is the varying water depth as measured from the still water level, and g is the gravitational acceleration. The subscript t stands for partial differentiation with respect to time and ∇ for the two-dimensional horizontal gradient operator.
β is dispersion coefficient. ($\beta = 1/5$).

III. DATA AND METHODOLOGY

A. *Study Area*

The study area is defined from 8° N to 22° N Latitude and 80° E to 100° E Longitude. Fig.1 is showing the larger domain and the location of smaller areas for nested run. The dimension of larger domain is about 1540 km in North-South direction and 2200 km in East-West direction. Total grid number of 840 x 1200 with 1' resolution. The west and south boundaries are considered as open boundaries and the north and east boundaries are closed boundaries for simulations. There are two nested area to predict wave characteristics: area one is at west coast and area two is at southern coast of Myanmar.

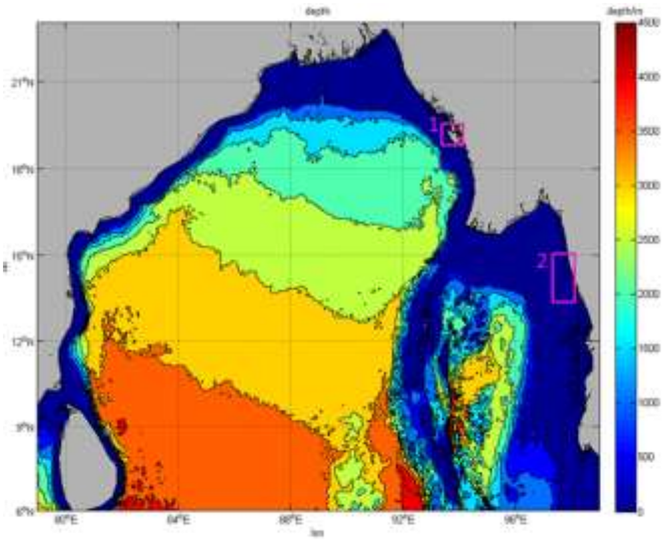

Fig. 1. Domain and nested areas in modelling system with ETOPO1 bathymetry data

B. *Bathymetry Data*

The model used bathymetry data derived from the ETOPO1 (Earth Topography and Ocean Bathymetry Database, resolution of 0.01667° x 0.01667°). It is 1 Arc-Minute Global Relief Model developed in August 2008 by the National Geophysical Data Center (NGDC), National Oceanic and Atmospheric Administration (NOAA).

C. *Wind Data*

The reanalyzed NCEP (National Centers for Environmental Prediction) wind data in the form of *U* and *V* velocity components was used. It was obtained from the NOAA (National Oceanic and Atmospheric Administration) FTP server stored in GRiB2 files per month and available as 1.25° x 1° resolution for every 3 hours interval. To get the same spatial resolution with water depth data, it was changed to 1 Arc-Minute (0.01667° x 0.01667°) and used as input wind field for SWAN model.

D. *SWAN Model Set-up*

The SWAN model was adopted for numerical simulation with the nesting method to obtain fine solution. The idea of nesting is to compute the waves for a larger region first and then for smaller regions. A nested SWAN run can be carried out with the boundary conditions obtained from a larger area SWAN run such as computational grid for the smaller area bounded by the larger area.

The spectral resolution of 25 frequencies (minimum 0.0418 Hz and maximum 1.0 Hz) and 24 directions (between 0°-360°) are set for simulation in SWAN model.

The SWAN Cycle III version 40.51 was used for wave simulations. The model was implemented in the two-dimensional and non-stationary mode with spherical coordinates. Moreover, the physical phenomena such as third generation mode, computation of quadruplet wave-wave interactions, cumulative steepness method for whitecapping, and dissipation by depth-induced wave breaking and friction were activated [14]. The backward space backward time (BSBT) numerical propagation scheme was chosen for simulation. The computational time step during computation was 1 hour and output request was with the time step of every 3 hours for larger domain and 1 hour for smaller nested areas. The maximum mean wind speeds of the monsoon season always occur in June along Myanmar coastline according to the background study. Therefore, the selected time for this simulation is June 2016.

E. *Boussinesq Model Set-up*

The deep water waves were transformed to harbor front by using the results from nested SWAN run and waves entering into inner harbor were estimated by using Boussinesq Wave model (BOUSS). Phase resolving model requires post processing tools in order to obtain parameters as wave heights and wave periods [4]. Fig. 2 shows the difference between the surface elevation and a wave height [19].

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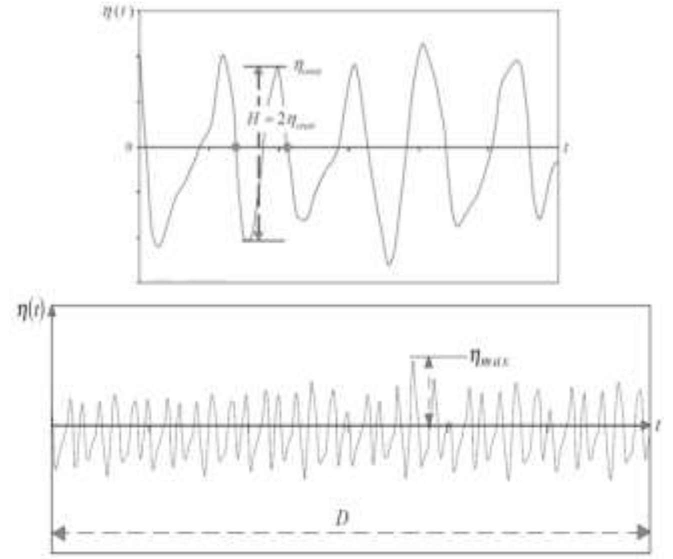


Fig. 2. Relation between wave height and water surface elevation in a duration D [19]

Realistic wind wave conditions were obtained by performing simulations of a spectral-phase averaging code SWAN in nested areas, i.e. from a large domain to the harbor regions. The resulting parameters from the nested SWAN run simulation in the harbor were then taken as an input signal for a phase-resolving model.

The smaller area computational domain was discretized as a rectangular grid with grid sizes $\Delta x = 10\ m$ and $\Delta y = 10\ m$, in the x and y directions, respectively, and $\Delta t = 0.2\ s$ in phase-resolving model BOUSS.

IV. RESULTS AND DISCUSION

The results from nested simulation of SWAN were used as the initial data for Boussinesq Model (BOUSS). In this research, two smaller areas within the larger domain were selected and the simulations were carried out by using nesting method. The main reason is to get better and more accurate results for smaller regions with smaller time steps. The numerical simulations at the Kyauk Pyu deep sea port (west coast) and Dawei deep sea port (south coast) have been performed. The results from both models were compared and analysed.

A. Nested Area (1)

Kyauk Pyu Deep Sea Port Area (West Coast)

The smaller area (1) for nested SWAN simulation is defined from 19° 15' N to 19° 30' N Latitude and 93° 30' E to 93° 45' E Longitude. The dimension of nested model domain is about 27.50 km x 27.50 km. Total grid number of 15 x 15 with 1' resolution. There are three selected points in this area as shown detailed in Fig. 3. Location and water depth of selected points are listed in Table I.

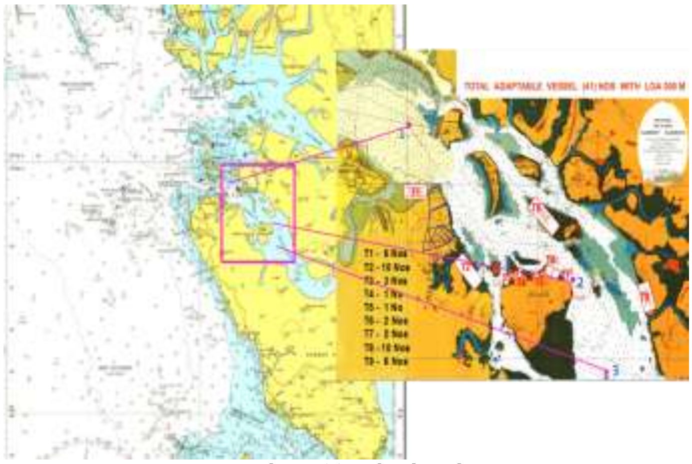


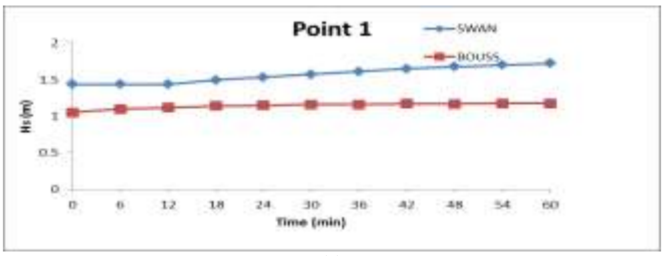
Fig. 3. Nested area (1) with selected points.

The simulation was carried out by using the results from larger domain as boundary condition for smaller nested area. Nested SWAN run were simulated for the time from 20160609.06:00:00 to 20160610.18:00:00, because maximum significant wave height and wave period were occurred at that duration in the previous simulation. The resulting parameters from the nested SWAN run were then taken as an input signal for BOUSS. For BOUSS wave model, the simulation were carried out for 1 hour (20160610 09:00:00 - 20160610 10:00:00) on 10th June 2016 because maximum significant wave heights H_s were occurred at that time according to the results from nested SWAN simulation.

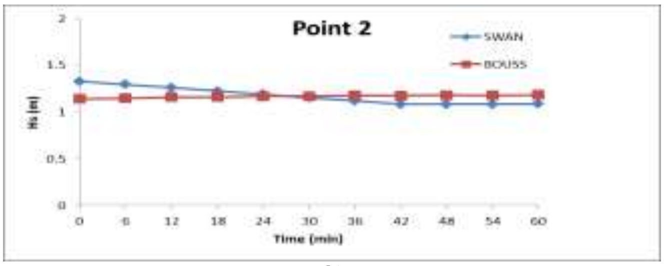
TABLE I. Location and water depth of selected points in nested area (1)

Points	Latitude (° ')	Longitude (° ')	Water depth (m)
1	19° 26.5'	93° 35'	25
2	19° 23'	93° 42'	20
3	19° 20'	93° 46'	15

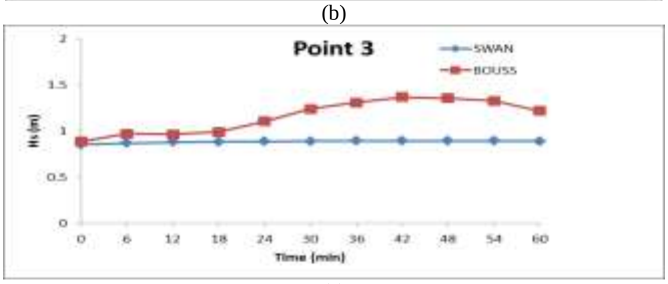
The H_s obtained from nested SWAN run was about 1.5 m but it was found 1 m from BOUSS for point (1). For point (2), H_s from both models results were very similar and about 1.2 m at that time. Point (3) is the inner most point of the harbor and the magnitude of H_s from SWAN were 0.8 m and very stable. But those from BOUSS were larger and unstable. It could be the effect of the reflection, diffraction, and/or nonlinear interactions inside harbor. The results of H_s from both models were shown in Fig. 4 (a), (b), and (c) for all 3 points in nested area (1).



(a)

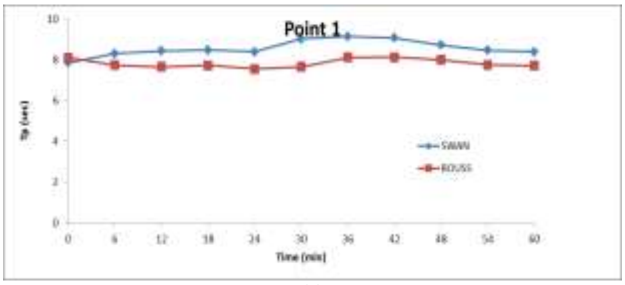


(b)

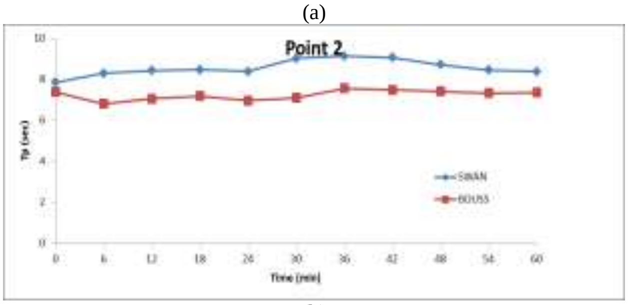


(c)

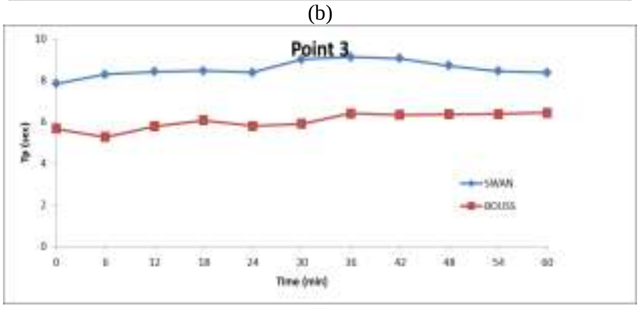
Fig. 1. Comparison of significant wave height between SWAN & BOUSS for points (1), (2), and (3) in nested area (1).



(a)



(b)



(c)

Fig. 5. Comparison of wave period between SWAN & BOUSS for points (1), (2), and (3) in nested area (1).

Comparison of wave period for all 3 points could be seen in Fig. 5 (a), (b), and (c) respectively. Wave period at point (1) from both model results were about 8 s. For point (2), the values from SWAN were about 8 s and those from BOUSS were about 7 s. The largest difference of wave period could be seen in point (3). In here also, the differences between two models results inside the harbor were larger than the other points.

B. Nested Area (2)

Dawei Deep Sea Port Area (South Coast)

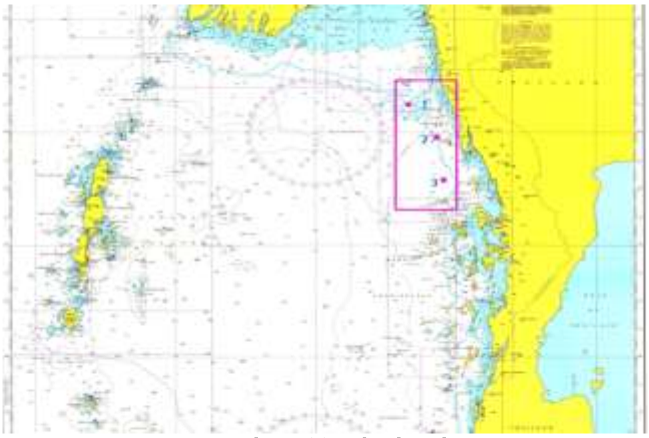


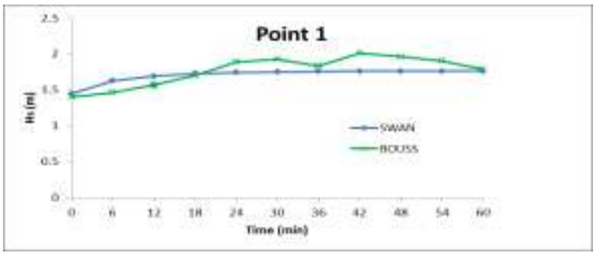
Fig. 6. Nested area (2) with selected points.

For nested area (2), the computational domain is 12° 45' to 15° N Latitude and 97° to 98° E Longitude as shown in Fig.6. The dimension is about 247 km x110 km and grid number of 135 x 60. Table II shows the location and water depth of three selected points for nested area (2).

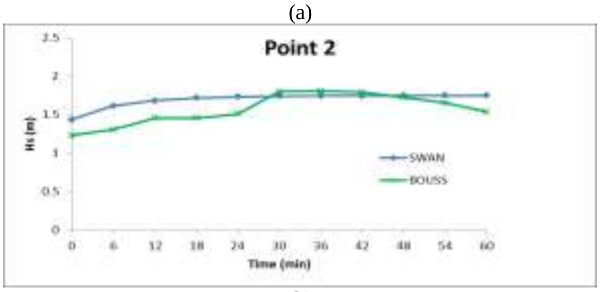
TABLE III. Location and water depth of selected points in nested area (2)

Points	Latitude (° ')	Longitude (° ')	Water depth (m)
1	14° 40'	97° 20'	37
2	14°	97° 45'	40
3	13° 16'	97° 55'	54

For the selected points from Fig. 6, the H_s obtained from nested SWAN run was about 1.5 m and it was found more or less 1.5 m from BOUSS at all three points. The results from BOUSS were a little varies during simulation. The results of H_s from both models were shown in Fig. 7 (a), (b), and (c) for all 3 points in nested area (2).



(a)



(b)

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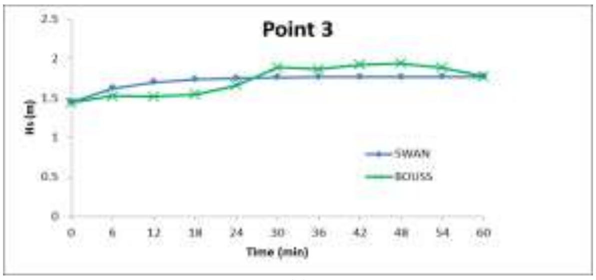
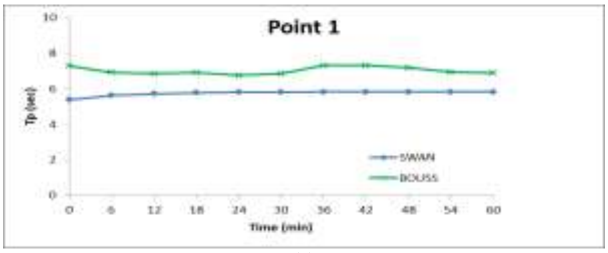
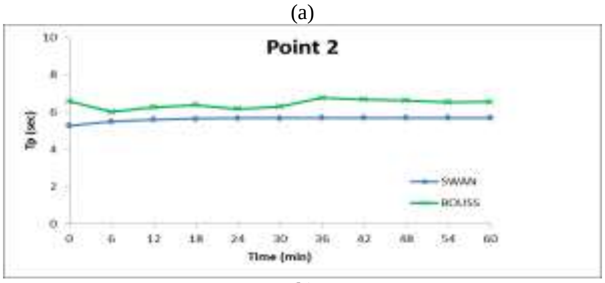


(c)

Fig. 6. Comparison of significant wave height between SWAN & BOUSS for points (1), (2), and (3) in nested area (2).



(a)



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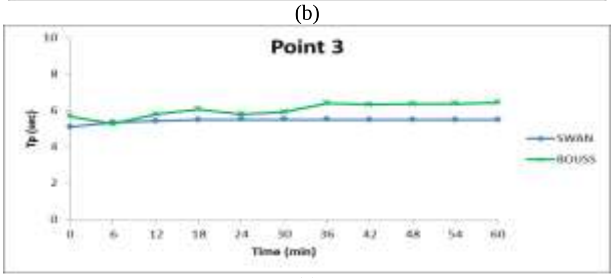

(c)

Fig. 7. Comparison of wave period between SWAN & BOUSS for points (1), (2), and (3) in nested area (2).

Wave period comparison for all 3 points could be seen in Fig.7 (a), (b), and (c) respectively. Wave period from SWAN model results were less than those from BOUSS. In general, the results from both models gave the same behavior for significant wave heights and also for wave periods. The small values of differences that could be observed were the effects of reflection and/or diffraction especially near the coastline and at shallower water depth. The simulated values from SWAN were very stable because the prediction would be practically possible in a phase-averaged sense in the deep water area.

V. Conclusion and Recommendations

In this article, a method for predicting and analyzing wave parameters in and around harbor is proposed. This can be done by combining the result of phase-averaging model SWAN with the phase-resolving model BOUSS. These simulations tools can be applied to any harbor. As a study case, two deep sea ports along Myanmar coastline were chosen for testing these simulations.

In practice, spectral and phase resolving models are often used in studies to compute the wave conditions in the entrance channel and, in and around harbor area. In such applications each model is used to compute specific effects, where the phase-resolving models are used to compute diffraction, refraction and reflection effects, and while the phase-averaged models are used to compute the effects of local wave generation. Combining the results of both model types requires a sophisticated approach and may easily lead to incorrect predictions of the wave conditions in and around the harbor [20].

Wave characteristics are mainly determined through field measurements, numerical simulation, physical models and analytical solutions. Each method has its own advantages and disadvantages [21]. The purpose of this research is to determinate under which wave and harbor geometry conditions, SWAN could be used and in which cases a phase resolving model is required. From the results, phase-resolving models are important in the case of ports since effect of diffraction and refraction are predominant near in and around harbor.

Spectral wave energy models such as SWAN are widely used to make predictions of waves in deep and shallow water, incorporating the effects of wave interactions and transformations such as refraction, diffraction and breaking. To calculate nearshore processes such as wave run-up on a wave-by-wave basis, phase-resolving shallow-water and Boussinesq-type models are more useful. However, these models are more computationally expensive and cannot be used in deep water. Therefore, a convenient solution is to use the output from a spectral energy analysis to create a wave input for a shallow-water Boussinesq-type analysis in the nearshore.

As numerical models are more flexible and many runs can be made easily, they can provide information that can be used as input for a physical model design. Physical modeling studies are expensive and time demanding, which poses limitations on the number of cases to be tested. But those modeling also should be done for important coastal structures before construction. Moreover, for accuracy, data validation of the models should be compared with measured data.

Myanmar's coastline can roughly be divided into a North-Western stretch located in the Bay of Bengal, and a Southern stretch located in the Andaman Sea. In general, the Southern stretch is substantially better suited for deep sea port development because of the mild wave climate of Andaman Sea. The Andaman Sea is sheltered by the Andaman Islands, causing a milder wave climate compared to the unsheltered Bay of Bengal, which is favorable for navigation.

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