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Modification first-guess SWAN &
Bench mark tests for SWAN

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Modification *first-guess* SWAN &
Bench mark tests for SWAN

R.C. Ris
C.M.G. Somers
PREFACE

This report has been written as part of the TCRAND project of the Dutch Ministry of Public Works and Coastal Management. In the report two topics - that are both related to the numerical wave model SWAN - are described. For reasons of readability, these two topics have been treated separately in this report and are divided into two parts (PART I and PART II). Each part has its own 'page of contents' and can be read as a separate report.

The subject of PART I is the modification of the formulation of the first-guess of SWAN with the purpose to improve the model performance.

PART II deals with the development of the bench mark tests for the SWAN model.
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TITLE: Modification first-guess SWAN & Benchmark tests for SWAN

ABSTRACT:

The present report consists of two parts. The subject of PART I is the modification of the formulation of the first-guess of SWAN with the purpose to improve the model performance (with respect to model convergence). PART II deals with the development of benchmark tests for the SWAN model.

PART I In a number of studies it has been found that the iterative procedure of SWAN tends to converge rather slowly. To accelerate this iteration process, a so-called first-guess in the iterative calculations has been introduced. This first-guess consists of the best possible estimate of the final solution. Although the introduction of the first-guess has considerably speeded up the iteration process in many cases, it has recently been shown that for cases with relatively high wind speeds, the first-guess significantly deviates from the final solution. The objective of the present study is to improve the agreement between the first-guess and the final solution of the third-generation mode of SWAN (and thus the convergence speed) for relatively high wind speeds. The effect of the modified first-guess on model convergence is investigated in idealised situations and in the complex field case of the Westerschelde estuary.

PART II The numerical wave model SWAN is presently specified as the new standard for nearshore wave modelling and coastal protection studies. The reliability of model results of SWAN in practical applications depends on how well the model has performed in validation and verification test cases (in both idealised situations and in laboratory and field cases). The purpose of this study is to make a large number of test cases - that are presently available - accessible for SWAN users. To this end, benchmark tests for SWAN have been developed in this study. The benchmark tests allow a user to perform many SWAN computations in idealised, laboratory or field situations and to generate prescribed output plots (where model results are compared with solutions of linear wave theory or with observations). The benchmark test are such structured that the entire procedure (pre- and post-processing and computations) is automatically arranged by only a small number of control (batch) files. The benchmark tests are suitable for IBM-compatible computers and for Unix machines.


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4.2 Listing of computations that have been performed in the Westerschelde estuary.
# List of Symbols

**Roman letters**

- \( c \): phase velocity of the waves
- \( C_d \): drag coefficient
- \( d \): water depth
- \( E \): wave energy
- \( E_{\text{tot}} \): total wave energy
- \( E^* \): non-dimensional wave energy
- \( f \): frequency
- \( f_m \): mean frequency
- \( f_m^* \): non-dimensional mean frequency
- \( f_p \): peak frequency
- \( f_p^* \): non-dimensional peak frequency
- \( f_{\text{low}}, f_{\text{min}} \): lowest discrete frequency in SWAN in Hz
- \( g \): acceleration of gravity
- \( H_s \): significant wave height (defined as \( H_s=4\sqrt{m_0} \))
- \( H_{s,\text{PM}} \): significant wave height according to Pierson and Moskowitz (1964)
- \( H_{s,\text{gen}2} \): significant wave height using second-generation mode of SWAN
- \( H_{s,\text{gen}3} \): significant wave height using third-generation mode of SWAN
- \( m0, m1 \): zero-order moment and first order moment of the energy density spectrum
- \( S_{\text{in}} \): wind input source term
- \( T_{\text{m01}} \): mean wave period
- \( T_p \): peak period
- \( U_{10} \): wind speed at 10 m height
- \( U_* \): friction velocity
- \( U_{10}^* \): adapted wind speed in terms of \( U_* \)
- \( x, y \): \( x, y \)-co-ordinate
- \( X \): fetch
- \( X^* \): non-dimensional fetch

**Greek symbols**

- \( \rho_a \): density of air
- \( \rho_w \): density of water
- \( \sigma \): radian frequency
- \( \sigma_\theta \): standard deviation in directional-space
- \( \sigma_\sigma \): standard deviation in frequency-space
- \( \bar{\sigma} \): mean frequency cf. WAM (Komen et al., 1994)
- \( \sigma_{\text{PM}} \): Pierson-Moskowitz frequency for fully developed spectra
- \( \sigma_{\text{PM}}^* \): non-dimensional Pierson-Moskowitz frequency for fully developed spectra
- \( \gamma_0 \): peak enhancement factor
- \( \theta \): mean wave direction (Cartesian convention)
- \( \theta_\psi \): mean wind direction (Cartesian convention)
- \( \theta_0 \): incident mean wave direction (Cartesian convention) at up-wave boundary
- \( \Delta x, \Delta y \): increment in \( x \)- and \( y \)-direction, respectively
- \( \Delta f, \Delta \theta \): increment in frequency- and directional-space, respectively
1 Introduction

1.1 General

To obtain realistic estimates of random, short-crested wind-generated waves in coastal waters (which may include estuaries, tidal inlets, barrier islands with tidal flats, channels etc.), the SWAN model can be used. The processes of wind generation, dissipation and nonlinear wave-wave interactions in SWAN are represented explicitly with state-of-the-art third-generation formulations. To avoid excessive computing time and to achieve a robust model in practical applications, fully implicit propagation schemes have been implemented according to a so called ‘iterative four sweep technique’ (see Holthuijsen et al., 1993). The SWAN model has successfully been validated and verified in several laboratory and (complex) field cases (see e.g. Ris et al., 1998). At present the SWAN model is used by about 150 institutes - all over the world - which apply the model as a research tool (to improve the understanding of wave modelling in coastal waters) or in consultancy projects.

With the implementation of the ‘iterative four sweep technique’ the wave computations are unconditionally stable and are carried out iteratively. Criteria to terminate the iteration can in principle be chosen arbitrarily. The following criteria are presently used as defaults in SWAN: the computations are terminated if in more than 97% of the water-covered grid points the change in significant wave height $H_s$ between two successive iterations is less than 3% or 0.03 m and the change in intrinsic mean wave period $T_{m01}$ between two successive iterations is less than 3% or 0.3 s.

1.2 Definition of the problem

In 1995 it has already been found by Dunsbergen (see Dunsbergen, 1995) that the SWAN model tends to converge rather slowly in the Friesche Zeegat and that the criteria to terminate the computations are not adequate. In order to accelerate the iteration process, an initial guess (a so called first-guess) in the iterative spectral calculations has been introduced. This first-guess consists of a best possible estimate of the final solution (when using the third-generation mode of SWAN) in the first - and only the first - iteration based on the formulations of the second-generation model DOLPHIN-B (Holthuijsen and De Boer, 1988).

The introduction of the first-guess has considerably speed up the iteration process in many cases, however, it has recently been shown that for cases with relatively high wind speeds, the first-guess significantly deviates from the final solution (see WL Delft Hydraulics, 1999). As a result, a large number of iterations were required to obtain model convergence. It appeared that this deviation between the first-guess and the third-generation mode for high wind speeds was due to the type of wind forcing in the formulations for the wind input. The second-generation formulations are driven by the wind speed $U_{10}$, whereas the third-generation formulations are driven by the friction velocity $U_*$. For low wind speeds
(\(U_{10} < 20 \text{ m/s, say}\)) the agreement between the first-guess and the third-generation mode is reasonable, but for higher wind speeds the wind forcing can differ by a factor of about 2 (obviously resulting in different wave conditions).

To improve the agreement between the first-guess and third-generation mode of SWAN (and thus the convergence speed) for high wind speeds, the wind forcing of the second-generation formulations (i.e. the first-guess) may be reformulated in terms of friction velocity \(U_*\).

### 1.3 Objectives of the study

Since it is expected that the modification of the wind forcing of the second-generation mode will improve the performance of SWAN - in particular that of model convergence - , the Dutch Ministry of Public Works and Coastal Management commissioned WL | DELFT HYDRAULICS to carry out a study to improve the first-guess of SWAN and to investigate the effect of the modified first-guess on wave growth and on model convergence.

### 1.4 General approach

To realise the above mentioned objectives, the following activities were carried out in the present study:

1. calculation of (non-dimensional) fetch-limited growth curves using the second- and third-generation mode of SWAN to determine the differences between these two modes of SWAN;
2. modification of the wind-forcing term in the second-generation formulations in order to improve the agreement between the first-guess and the third-generation mode of SWAN in the situation of fetch-limited wave growth;
3. calibration of the adapted second-generation formulations using the growth curves of Kahma and Calkoen (1992) and Pierson-Moskowitz (1964);
4. investigate the effect of the modified first-guess on model convergence in:
   - in a highly schematised one-dimensional situation (fetch-limited, deep water for a wind speed of 10 m/s, 20 m/s, 30 m/s, and 40 m/s);
   - a typical case of the complex situation of the Westerschelde estuary.

The versions of the SWAN model used for this study are SWAN CYCLE 2, version 30.75 and version 40.00. (It has been verified that the model results obtained with version 30.75 and version 40.00 are identical (at least in the situation of wave growth in deep water).)

### 1.5 Outline of the report

This report is organised as follows. The theory of the second-generation formulations are given in Chapter 2. In this Chapter the proposed adaptations of the wind-forcing and the modifications to the source code are also described. In Chapter 3 the effects of the modifications of the first-guess are studied in fetch-limited (deep water) wave growth
situations. The adapted \textit{first-guess} is validated and tuned to fit the data of the observations. The effect of the modified \textit{first-guess} on model convergence is investigated in Chapter 4 where computations have been carried out in a idealised case (fetch limited with a fetch of 25 km) and the complex field case of the Westerschelde estuary. A discussion with conclusions and recommendations is given in Chapter 5.

The project was carried out between March 1, 1999 and July 1, 1999 at WL|Delft Hydraulics as project H3515. The work was performed by dr R.C. Ris. We would like to thank dr N. Booij, dr L.H. Holthuijsen and J.J. Haagsma of Delft University of Technology (the Netherlands) for their advice and help during the project.
2 Modification of first-guess in SWAN

2.1 Introduction

To initialise the iteration process of SWAN the second-generation formulations of the DOLPHIN-B model (see Holthuijsen and De Boer, 1988) are used in SWAN. Their wind input source term $S_{in}$ reads:

$$
S_{in} = \begin{cases} 
A + BE & \text{if } E < E_{lim} \text{ and } |\theta - \theta_w| < \pi/2 \\
0 & \text{if } E > E_{lim} \text{ and } |\theta - \theta_w| < \pi/2 
\end{cases}
$$

(2.1)

where $S_{in}$ represent input by wind, $A$ and $B$ are a linear and an exponential growth term, respectively, $E$ is the spectral energy density, $E_{lim}$ is a limiting spectrum and $\theta$ and $\theta_w$ are the wave direction and the mean wind direction, respectively. The linear wave growth term $A$ only contributes to the spectrum at the initial stage of wave growth and becomes negligible compared to the term $BE$ if some energy is present. This linear growth term is therefore not considered in this study.

The exponential growth term factor $B$ is due to Snyder et al. (1981), rescaled in terms of $U_{10}$, as adapted by Holthuijsen and De Boer (1988) and Holthuijsen et al. (1996):

$$
B = \max \left[ 0, \beta_1 \frac{5}{2\pi} \frac{\rho_a}{\rho_w} \frac{k}{\sigma} \left[ U_{10} - \frac{k}{\sigma} \cos(\theta - \theta_w) - \beta_2 \right] \right] \sigma
$$

(2.2)

in which $\rho_a$ and $\rho_w$ are the densities of air and water, respectively, and where the coefficients $\beta_1$ and $\beta_2$ have been tuned for the DOLPHIN-B model ($\beta_1=0.59$ and $\beta_2=0.12$).

The limiting Pierson-Moskowitz (1964) spectrum, has been reformulated in terms of wave number with a $\cos^2$-directional distribution centered around the local wind direction $\theta_w$:

$$
E_{lim}(\sigma, \theta) = \begin{cases} 
\alpha \frac{k^{-3}}{2c_g} \exp \left( \frac{-5}{4} \left( \frac{\sigma}{\sigma_{PM}} \right)^4 \right) \frac{2}{\pi} \cos^2(\theta - \theta_w) & \text{for } |\theta - \theta_w| < \pi/2 \\
0 & \text{for } |\theta - \theta_w| \geq \pi/2 
\end{cases}
$$

(2.3)

where $\alpha$ is a proportionality factor that depends on the total dimensionless wave energy of the wind sea part of the spectrum (it is equal to 0.0081 for fully developed seas in deep water) and $\sigma_{PM}$ is the Pierson-Moskowitz (1964) frequency. In deep water $\sigma_{PM}$ is equal to $2\pi (0.13g/U_{10})$. Note that since the present study concentrates on deep water situations, only the deep water limiting spectrum is considered here (depth effects - which are considered by Holthuijsen and De Boer (1988) - are not considered here).
When comparing the exponential growth term factor $B$ of the second-generation formulations (see Eq. 2.2) with the growth term $B$ of the third-generation formulations of SWAN, which reads:

$$B = \max \left[ 0, \ 0.25 \frac{\rho_a}{\rho_w} \left[ 28 U_* \frac{k}{\sigma} \cos (\theta - \theta_w) - 1 \right] \right] \sigma \quad (2.4)$$

it is seen that the second-generation formulations are formulated in $U_{10}$ whereas the third-generation formulations are formulated in terms of $U_*$ (as adapted by Komen et al. (1984) using the wind speed $U_{10}$).

The friction velocity $U_*$ is related through a non-linear expression to the wind speed $U_{10}$. Using the expression of Wu (1982), the friction velocity $U_*$ can be calculated by:

$$U_*^2 = \begin{cases} 
1.2875 \times 10^{-3} \times U_{10}^2 & \text{for } U_{10} < 7.5 \text{ m/s} \\
(0.8 + 0.065 s / m \times U_{10}) \times 10^{-3} \times U_{10}^2 & \text{for } U_{10} \geq 7.5 \text{ m/s} 
\end{cases} \quad (2.5)$$

For low wind speeds the agreement between the wind-forcing in terms of $U_{10}$ and $U_*$ is reasonable, however, for high wind speeds ($U_{10} > 15$ m/s, say) the forcing by $U_{10}$ is significantly lower, resulting in a significant smaller significant wave heights.

It is noted here, that the peak frequency of the second-generation spectrum is in agreement with that of the third-generation mode of SWAN since it is directly based on the Pierson-Moskowitz frequency $\sigma_{PM}$.

### 2.2 Re-formulation of wind speed for first-guess

In order to improve the agreement between the model results of the second-generation and the third-generation mode of SWAN, the wind speed $U_{10}$ of the second-generation formulations should be re-formulated in terms of the friction velocity $U_*$. In literature, several expressions are available to re-formulate $U_{10}$ in terms of $U_*$. Komen et al. (1984) reformulated the growth term $B$ of Snyder (1981) in terms of $U_*$ using the expression of Wu (1982):

$$U'_{10} = 28 U_* = 28 U_{10} \sqrt{(0.8 + 0.065 s / m \times U_{10}) \times 10^{-3}} \quad (2.6)$$

where $U'_{10}$ is the adapted wind speed in terms of $U_*$. Bouws (1986) also adapted the wind speed $U_{10}$ in terms of friction velocity $U_*$ in order to bring model results in better agreement with observations at Lake Marker. Bouws used the following relation:

$$U'_{10} = U_{10} \sqrt{\frac{C_d(U_{10})}{C_d(U_{10} = 15 \text{ m/s})}} = U_{10} \sqrt{(0.8 + 0.065 s / m \times U_{10}) \times 10^{-3}} \quad (2.7)$$
Using the expression of Bouws (1986), the adapted wind speed $U'_{10}$ (left hand side of equation 2.7) is lower than $U_{10}$ for $U_{10} < 15$ m/s and higher for $U_{10} > 15$ m/s.

The adapted wind speeds (according to equations 2.6 and 2.7) with respect to the wind speed $U_{10}$ are illustrated in fig. 2.1. It is seen that for wind speeds $U_{10} < 15$ m/s the adapted wind speeds (and thus the wind forcing) are roughly of the same order, but that for higher wind speeds $U_{10} > 15$ m/s the adapted wind speed is significantly larger. The effect of both formulations (see equations 2.6 and 2.7) on wave growth have been investigated in this study.

While the present study was going on, it appeared that the directional distribution of the energy density spectrum of the limiting spectrum has also a significant effect on the model convergence. The directional distribution of the limiting spectrum is determined by the function $D(\theta)$:

$$E_{\text{lim}}(\sigma, \theta) = E_{\text{lim}}(\sigma) D(\theta)$$

(2.8)

where:

$$D(\theta) = \delta \cos^n(\theta - \theta_w) \quad \text{for} \quad |\theta - \theta_w| < \pi / 2$$

(2.9)

in which $\delta$, $\cos^n(\theta - \theta_w)$ are coefficients that are equal $\delta = 2 / \pi$ and $n = 2$ (see also Eq. 2.3). These coefficients determine the width of the directional spectrum and can optionally be changed (see Section 3).

2.3 Modification to the source code

To re-formulate the wind speed in terms of friction velocity, a number of modifications to the source code of SWAN have been made. The modifications concern the subroutine WNDPAR (in which the directional distribution of the limiting spectrum is determined and the subroutine WINDP1 (in which the wind speed $U_{10}$ is calculated). Both subroutines are stored in the file SWANCOM3.F. At each modified or new source code line the string ‘32.06’ has been added starting in column 75. The modifications are made according to the ‘SWAN programming protocol’ (see for further information the internet home page of SWAN http://swan.ct.tudelft.nl

To re-formulate the wind speed in terms of friction velocity, the following code lines have been added to the subroutine WINDP1:

```fortran
OPTION = 1
IF ( OPTION .EQ. 1 ) THEN
  WIND10 = WIND10 * SQRT( (0.8 + 0.065 * WIND10) * 0.001 ) / ((0.8 + 0.065 * 15. ) * 0.001 )
ELSE
  WIND10 = 28. * WIND10
ENDIF
```

To change the directional distribution of the energy spectrum for the first and only the first iteration, the following code lines have been added to the subroutine WNDPAR:

```fortran
...
The new and modified source code has been checked to see whether the modifications have correctly been implemented and on the presence of possible errors. The validation of the actual source code, however, has been carried out in the following three sections. In Chapter 3, the effect of the adapted wind-forcing is studied by non-dimensional wave growth curves and the coefficients - if necessary - are calibrated. In Chapter 4 the effect of the modified first-guess on model convergence is investigated.
3 Fetch-limited wave growth (deep water, 1D-situation)

3.1 Introduction

To investigate the effects of a the adapted first-guess on fetch-limited wave growth in SWAN using the second-generation and the third-generation mode of SWAN, dimensionless wave growth curves are considered. Following the SWAMP II test case (see the SWAMP group, 1985), the wave conditions - in terms of significant wave height, peak frequency and mean frequency - are computed along a section with a constant uniform wind blowing normally off a long and straight coastline. To reduce the required total computing time for a typical computation and to reduce two-dimensional wave propagation effects, the computations have been carried out with the one-dimensional mode of SWAN.

The SWAN model results are compared using the following non-dimensional variables:

\[ X^* = \frac{g X}{U_*^2}, \quad E^* = \frac{g^2 E_{\text{tot}}}{U_*^4}, \quad f_p^* = \frac{f_p U_*}{g}, \quad f_m^* = \frac{f_m U_*}{g} \quad (3.1) \]

in which \( X^* \) is the dimensionless fetch, \( X \) is the fetch (the distance from the coast in upwind direction), \( U_* \) is the friction velocity according to Wu (1982), \( E^* \) is the dimensionless total energy, \( E_{\text{tot}} \) is the total energy, \( f_p^* \) is the dimensionless peak frequency, \( f_m^* \) is a mean frequency defined as \( (T_m)_{\text{ref}} \) and \( f_m^* \) is the dimensionless mean frequency. The total energy \( E_{\text{tot}} \) is related to the significant wave height according to: \( E_{\text{tot}} = H_s^2/16 \).

The SWAN results are compared with the observations compiled by Kahma and Calkoen (1992), Wilson (1965) and Pierson-Moskowitz (1964).

3.2 Model schematisation

In the computations the spatial step in the direction of wave propagation varies between \( \Delta x = 10 \text{ m} \) for the short fetches (\( X < 10^3 \text{ m} \)) up to \( \Delta x = 50 \text{ km} \) for long fetches (\( X > 10^4 \text{ m} \)). The directional resolution is \( \Delta \theta = 10^\circ \) and the frequency resolution is \( \Delta f = 0.1 f \). The wave computations have been carried out using the default mode of SWAN.

The computations are terminated if in more than 100% of the water-covered grid points the change in significant wave height \( H_s \) between two successive iterations is less than 1.e-5% or 1.e-5 m and the change in intrinsic mean wave period \( T_m \) between two successive iterations is less than 1.e-5% or 1.e-5 s. The maximum number of iterations has been set equal 25 for this case. This rather strict criterion has been use to ensure that model convergence is obtained for all test cases (this has been verified for all cases).
The wave computations have been carried out for three different wind speeds \( (U_{10} = 10 \text{ m/s}, U_{10} = 20 \text{ m/s} \text{ and } U_{10} = 30 \text{ m/s}) \).

### 3.3 Model results

The model results are presented in figures which show the non-dimensional wave growth curves (see e.g. Fig 3.1 to 3.8). The top left panel and the top right panel represent the computed non-dimensional wave energy \( E^* \) and the non-dimensional peak frequency \( f_p^* \) as a function of non-dimensional fetch \( X^* \). The bottom left panel shows the computed non-dimensional mean frequency \( f_m^* \) as a function of \( X^* \). These results are compared with the observations compiled by Kahma and Calkoen (1992), Wilson (1965) and Pierson-Moskowitz (1964). Note that in the bottom left panel the SWAN results are in terms of mean frequency \( f_m^* \) whereas the data of the observations are in terms of peak frequency \( f_p^* \) (since no information is available of the observed mean frequency). In the bottom right panel the computed directional distribution of the wave energy is plotted as a function of non-dimensional fetch \( X^* \).

Figure 3.1 shows the growth curves using the standard third-generation mode of SWAN (including the first-guess). It is seen that the model results for different wind speeds \( (U_{10} = 10 \text{ m/s}, 20 \text{ m/s} \text{ and } 30 \text{ m/s}) \) scale fairly well using the friction velocity \( U_r \). The agreement between the data of Kahma and Calkoen (1992) and the Pierson-Moskowitz values is good. Note that the computed directional distribution of the energy spectrum (bottom right panel) varies considerably along the fetch (between \( 10^1 < X^* < 10^2 \)) and that its average value is rather high (about 38°) compared to field observations (which are of the order of 30°).

To investigate the growth curves using second-generation formulation (i.e. the first-guess) the same computations have been carried out with the second-generation formulations in SWAN activated. It is clearly seen from Fig. 3.2 that - as expected - these model results scale rather poorly in terms of friction velocity \( U_r \) and that the agreement between the data of Kahma and Calkoen (1992) and Pierson-Moskowitz (1964) is generally poor for the three wind speeds considered. The dimensionless significant wave height for fully developed conditions as computed by the second-generation model of SWAN are significantly overestimated for low wind speeds \( (U_{10} = 10 \text{ m/s}) \) and significantly underestimated for the higher wind speeds \( (U_{10} > 20 \text{ m/s}) \) compared to the data of Pierson-Moskowitz (1964) and the significant wave heights as computed using the third-generation mode of SWAN (see Fig. 3.1). The Pierson-Moskowitz values of the significant wave height \( H_{s,PM} \) and the absolute and relative differences between the significant wave height of the second- and third-generation mode are listed in Table 3.1. Note that the significant wave height for fully developed conditions according to Pierson-Moskowitz (1964) is computed by the non-dimensional total energy \( E^* \) according to Komen et al. (1984; \( E^* = 1100 \) for fully developed conditions).

It is striking that the difference between the computed directional distribution of the energy spectrum with the third-generation and the second-generation mode is rather large (compare bottom right panel of Fig. 3.1 (third-generation mode) and Fig. 3.2 (second-generation mode)). The absolute differences in the directional distribution are about 10°.
Table 3.1 Absolute and relative differences in significant wave height at fully developed conditions ($X^2 > 10^5$) using the third-generation and the second-generation mode of SWAN.

<table>
<thead>
<tr>
<th>$U_{10}$</th>
<th>$H_s,pm$ (m)</th>
<th>$H_s,gen3$ (m)</th>
<th>$H_s,gen2$ (m)</th>
<th>$\Delta H_s (= H_s,gen3 - H_s,gen2)$ (m)</th>
<th>$\Delta H_s / H_s,gen3$ (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1.95</td>
<td>1.90</td>
<td>2.45</td>
<td>-0.55</td>
<td>-29%</td>
</tr>
<tr>
<td>20</td>
<td>11.44</td>
<td>11.13</td>
<td>9.80</td>
<td>1.33</td>
<td>11%</td>
</tr>
<tr>
<td>30</td>
<td>33.33</td>
<td>33.20</td>
<td>21.70</td>
<td>11.5</td>
<td>34%</td>
</tr>
</tbody>
</table>

To improve the agreement - in terms of significant wave height and the peak frequency - between the second-generation mode and the third-generation mode of SWAN and the data of Kahma and Calkoen (1992) and the Pierson-Moskowitz values, the expressions according to Equations 2.6 and 2.7 have been implemented in SWAN. The computations with the second-generation mode of SWAN, as described here above, have been repeated with these modifications. The dimensionless growth curves using the adapted wind speed according to the expression of Komen et al. (1984) are shown in Fig. 3.3 and presented in Table 3.2 (see column 4). It is seen that the significant wave height and peak frequency are significantly overpredicted and underpredicted compared to the results of the third-generation mode for all wind speeds. The second-generation growth curves, however, now do scale better with $U_*$ (compare with results of Fig. 3.2).

The model results as computed with an adapted wind speed using the expression as suggested by Bouws (1986), are shown in Fig. 3.4 and Table 3.2 (see column 5). The agreement between the non-dimensional growth curves and the data of Kahma and Calkoen (1992) and the Pierson-Moskowitz values is good. The differences in terms of significant wave height and peak frequency between the data of Kahma and Calkoen (1992) and Pierson-Moskowitz (1964) are hardly visible on the scale of the figure. Consequently, the agreement between the model results of the second-generation mode and the third-generation mode of SWAN is by this adapted wind speed also better, both for wave growth conditions as for fully developed conditions (compare second and fifth column of Table 3.2).

<table>
<thead>
<tr>
<th>$U_{10}$</th>
<th>$H_s,gen3$ (m)</th>
<th>$H_s,gen2$ (m)</th>
<th>$H_s,gen2$ (m)</th>
<th>$H_s,gen2$ (m)</th>
<th>$\left( U_{10} = U_{10} \right)$</th>
<th>$\left( U_{10} = U_{10} \right)$</th>
<th>$\left( U_{10} = U_{10} \right)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1.90</td>
<td>2.45</td>
<td>2.78</td>
<td>2.00</td>
<td>11.90</td>
<td>9.80</td>
<td>16.12</td>
</tr>
<tr>
<td>20</td>
<td>11.13</td>
<td>9.80</td>
<td>16.12</td>
<td>11.60</td>
<td>33.20</td>
<td>21.70</td>
<td>45.00</td>
</tr>
</tbody>
</table>

Since the agreement between the model results of the second-generation mode with the adapted wind speed as suggested by Bouws (1986) and the third-generation mode is fairly reasonable and the data of Kahma and Calkoen (1992) and of Pierson-Moskowitz (1964) is good, the expression as suggested by Bouws (1986) will be used in this study to improve the first-guess. (It is noted here that the agreement between the model results obtained with the adapted formulation as suggested by Komen et al. (1984) and the data may be improved...
by re-tuning a number of coefficients in the wind input formulation of Komen et al. (1984). This is, however, beyond the scope of this study.)

To investigate whether the adapted first-guess does not affect the final solution of the third-generation mode of SWAN, additional computations have been carried out with the third-generation formulations activated. The results of these computations are shown in Fig. 3.5. It is seen that the model results presented in Fig. 3.1 are identical to those presented in Fig. 3.5 indicating that the adapted first-guess does not affect the final solution.

Although the model results of the first-guess with the adapted wind speed according to Bouws (1986) correspond well with the data of Kahma and Calkoen (1992) and Pierson-Moskowitz (1964), it is seen that the agreement between the computed directional distribution using the second-generation mode and the third-generation mode of SWAN is poor (see bottom right panel of Fig. 3.5 where in addition the directional distribution of the second-generation mode of SWAN has been plotted as well). The differences in the computed directional spreading are about $10^\circ$. To improve the agreement with respect to the directional distribution of the first-guess, the directional distribution of the second-generation formulations need to be adapted as well. This has been achieved by changing the values of the coefficients $\delta_i$ and $n$ in the expression of Eq. 2.9 on condition that:

$$\int_{-\pi/2}^{+\pi/2} \delta_i \cos^n(\theta - \theta_w) d\theta = 1 \quad \text{for} \quad |\theta - \theta_w| < \pi / 2 \quad (3.2)$$

On the basis of model results of several computations with different values of $n$ and $\delta_i$ (results not shown here), it has been found that the agreement between the directional distribution of the first-guess and the third-generation mode of SWAN is fairly reasonable if these variables are set equal $n=0.6$ and $\delta_i=0.434917$ (courtesy to JI. Haagsma of Delft University of Technology, the Netherlands, for providing us with the values of $n$ and $\delta_i$). These values correspond to a directional distribution of about $37^\circ$ (which is roughly equal to the directional distribution of the third-generation mode of SWAN).

To see if the SWAN model still reproduces the growth curves properly with this adapted directional distribution, computations have been carried out with these adapted coefficients $n$ and $\delta_i$. The results of the second-generation computations are presented in Fig. 3.6. In addition, the directional distribution of the third-generation mode (for $U_{10} = 20 \text{ m/s only}$) has also been plotted in the bottom right panel (thick line) to show that the agreement between the directional distribution of the first-guess and the third-generation mode is reasonable for fetches $X > 10^5$, say.

Again, it has been verified that the adapted first-guess (wind speed and directional distribution) does not affect the final solution of the third-generation mode of SWAN (see Figure 3.7).

From a separate study it has been found that the limiter which is used in SWAN affects model convergence (see WL | DELFT HYDRAULICS, 1999). It has been shown in that study
that if the distribution of the limiter over the frequencies was multiplied by $f/f_m$ (in which $f_m$ is a mean frequency) that the iteration process was accelerated.

In addition, it is investigated in the present study whether fetch-limited wave growth is still properly simulated if this adapted limiter is used. The results of these computations are shown in Fig. 3.8. It is seen that the wave growth curves for wave growth at very short fetches ($X^* < 10^5$) and wave growth conditions ($10^5 < X^* < 10^6$) are well reproduced by the application of the adapted limiter. The significant wave height and peak frequency for fully developed wave conditions ($X^* > 10^6$) are, however, significantly lower and higher, respectively, compared to the data of Pierson-Moskowitz (1964). A possible explanation for this observed model behaviour has been not be found and requires a detailed analysis regarding the adapted limiter. Such an analysis is beyond the scope of this study and therefore not considered here.

In this section it has been shown that with the adapted wind speed $U_{10}$ (as suggested by Bouws, 1986) and the new values of the coefficients $n$ and $\delta$, the first-guess is in better agreement with the third-generation mode of the SWAN model and the data of Kahma and Calkoen (1992) and the Pierson-Moskowitz (1964) data. In the next Chapter, the effect of the improved first-guess on model convergence is investigated in an idealised case and the field situation of the Westerschelde estuary.
4 Effect of adapted first-guess on model convergence

4.1 Introduction

It is expected that the adapted first-guess will speed up the iteration process of SWAN. To investigate and demonstrate this, model convergence has been studied in the idealised situation of fetch-limited wave growth along a section of 25 km (see also WL | DELFT HYDRAULICS, 1999) and in the complex two-dimensional situation of the Westerschelde estuary (WL | DELFT HYDRAULICS, 1999).

4.2 Deep water wave growth (one-dimensional situation)

4.2.1 Model schematisation

To investigate the effect of the adapted first-guess, wave computations have been performed along a curve of 25 km with the one-dimensional mode of SWAN. The resolution in geographical space has been taken equal $\Delta x=100$ m. In the computations, a frequency resolution of $\Delta f = 0.1 f$ is used between 0.04 Hz and 1 Hz. The computations have been carried out with a directional resolution of $\Delta \theta = 10^\circ$. The criterion that has been used to terminate the computations is the same as that in Section 3, however, the total number of iterations varies per cases (i.e., 1, 2, 5, 10, 15, 25 and 50 iterations).

In the computations, the wind speed has been varied (i.e. $U_{10}=10$ m/s, $U_{10}=20$ m/s, $U_{10}=30$ m/s and $U_{10}=40$ m/s).

To study the effect of the adapted first-guess on model convergence, output is requested at the iteration levels as specified here above along the 25 km curve and an output location at $x = 12.5$ km.

All computations have been carried out using the third-generation mode of SWAN, but with different options for the first-guess. The effect of the (adapted) first-guess on model convergence is studied in the following cases:
### Table 4.1
Listing of computations that have been performed for the one-dimensional case.

<table>
<thead>
<tr>
<th>Case</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><strong>standard first-guess</strong></td>
</tr>
<tr>
<td>2</td>
<td>adapted <em>first-guess</em>: Wind speed $U'<em>{10} = U</em>{10}(C_d(U_{10})/(C_d(15 \text{ m/s})))^{0.5}$</td>
</tr>
<tr>
<td>3</td>
<td>adapted <em>first-guess</em>: Wind speed $U'<em>{10} = U</em>{10}(C_d(U_{10})/(C_d(15 \text{ m/s})))^{0.5}$ and directional distribution equal $(\cos^{0.6})$</td>
</tr>
<tr>
<td>4</td>
<td>adapted first-guess: Wind speed $U'<em>{10} = U</em>{10}(C_d(U_{10})/(C_d(15 \text{ m/s})))^{0.5}$ and directional distribution equal $(\cos^{0.6})$ and adapted distribution of limiter $f/f_m$</td>
</tr>
</tbody>
</table>

### 4.2.2 Model results

The model results using the standard *first-guess* and the third-generation mode of SWAN for the four different wind speeds are shown in Figures 4.2.1 to 4.2.4. Figure 4.2.4.e shows the computed evolution of the significant wave height as a function of the number of iterations for the wind speeds of 10 m/s, 20 m/s, 30 m/s and 40 m/s, respectively. As expected (from the dimensionless growth curves of Fig. 3.2), the significant wave height at the first iterations (i.e. the *first-guess*) is slightly overestimated for the low wind speed of $U_{10}=10$ m/s and significantly underestimated for the higher wind speeds ($U_{10} > 20$ m/s). The SWAN model results clearly show an overshoot in the significant wave height ($H_s$) as a function of the iteration level, which is more pronounced for lower than for higher wind speeds. Note that the directional distribution (see Figures 4.2.1.a, 4.2.2.a, 4.2.3.a and 4.2.4.a) as computed by the *first-guess* is about $10^6$ smaller than the final solution of the third-generation mode. (It is noted that the results presented in this report for $U_{10}=10$ m/s, 20 m/s, 30 m/s are identical to those of test cases 14, 15 and 16 as presented in WL | DELFT HYDRAULICS, 1999.)

Changing the wind speed of the *first-guess* - in terms of $U_*$ rather than $U_{10}$ - improves the estimation of the significant wave height in the first-iteration considerably (see Figures 4.2.5.d, 4.2.6.d, 4.2.7.d and 4.2.8.d). Now, the significant wave height is nearly identical to that of the final solution (at iteration level 50) for all selected wind speeds. However, it is striking to see that although the agreement in significant wave height (and in addition the mean wave period) between the *first-guess* and the final solution is better, the model convergence has not been improved for the high wind speeds. Figure 4.2.8.e shows that with the adapted wind speed even more iterations are required to obtain model convergence for the high wind speeds compared to the standard SWAN. It appeared that this model behaviour can be ascribed to the mismatch of the directional distribution of the energy spectrum as computed by the *first-guess* and the final solution of SWAN.

A detailed analysis (carried out for a number of test cases of fetch-limited wave growth; see Chapter 3) has shown that the directional distribution of the energy spectrum of the *first-guess* differs significantly from that of the third-generation mode (see Fig. 3.5) and that the agreement can be improved if the values of the coefficients $n$ and $\delta_n$ in equation 3.2 are chosen equal $n=0.6$ and $\delta_n=0.434917$ (see Fig. 3.6). This is also evident from the bottom panel of Figures 4.2.5.a, 4.2.6.a, 4.2.7.a and 4.2.8.a where it is seen that the directional
distribution of the first-guess largely deviates from the final solution using third-generation formulations.

The results of computations with the adapted directional distribution (i.e. $\cos^{0.6}$-distribution), are presented in Figures 4.2.9 to 4.2.12. From the bottom panel of Figures 4.2.9.a to 4.2.12.a it is now seen that the agreement between the directional distribution of the first-guess and the final solution is fairly good for the low wind speeds and that it reasonable for the higher wind speeds (differences of only a few degrees). The overshoot in significant wave height as function of the iteration level, has significantly been reduced for all wind speeds considered and is not visible any more for wind speeds $U_{10} < 30$ m/s, as is evident from Fig. 4.2.12.e.

From these results it is concluded that the overshoot in the significant wave height is due to the mismatch between the directional distribution of the energy spectrum as computed by the first-guess and the final solution of the third-generation mode of SWAN.

In addition, wave computations have also been made with the adapted limiter in which the distribution of the limiter has been adjusted by: $\text{limiter} = \text{limiter}^*$ if $\theta_m$. The computed wave evolution (in terms of significant wave height, mean wave period, mean wave direction and directional distribution of the energy spectrum) is shown in Figures 4.2.13.a, 4.2.14.a, 4.2.15.a and 4.2.16.a. Generally, the agreement between these results and those as computed without the adapted limiter (see Figures 4.2.9.a to 4.2.12.a) is reasonable, except for the mean wave direction which tends to slightly oscillate if the adapted limiter is applied, presumably because the growth of high frequency wave components at relatively large side angles with respect to the mean direction of the peak of the spectrum is slightly released by the adapted limiter. As is evident from Fig. 4.2.16.c, the model convergence is significantly accelerated by the use of the adapted limiter for all wind speeds considered.

### 4.3 Model convergence in the Westerschelde (two-dimensional situation)

The complex field case of the Westerschelde estuary is used to study the effect of the adapted first-guess on model convergence in SWAN. The field conditions and the model schematisation are (nearly) identical to those described in WL | DELFT HYDRAULICS (1999). For reasons of readability, however, the field conditions and model schematisation are described here again.

#### 4.3.1 Model schematisation

The bathymetry of the Westerschelde estuary with the output curve and output location (at which model convergence is investigated) is shown in Fig. 4.3.1. The wave conditions considered in this study consist of incident swell from NW-direction penetrating into the Westerschelde estuary with a super-imposed wind sea that is generated by a local wind. The wind velocity is taken equal $U_{10} = 30$ m/s blowing from the Northerly direction (direction equal 280°; Cartesian convention). The wind field (and the water level) are assumed to be uniform over the computational grid.
The incident swell at the up-wave boundary is represented by a JONSWAP-type spectrum with a significant wave height of $H_s = 3.5$ m, a peak period of $T_p = 12$ s and a mean incident wave direction of $325^\circ$ (Cartesian convention). The coefficient $MS$ of directional spread (see SWAN user manual; Ris et al., 1997) has been taken equal 6, which corresponds to a directional spread of the waves of about $21^\circ$. To avoid the effect of the erroneous lateral boundaries on the wave conditions, wave boundary conditions have also been specified at the lateral boundaries.

The computations have been carried out with the stationary mode of SWAN using a regular rectangular computational grid. It covers an area of 30 km x 15 km. The spatial step in $x$- and $y$-direction have been chosen equal $\Delta x = 200$ m and $\Delta y = 200$ m, respectively. The computations are carried out with a directional resolution of $\Delta \theta = 10^\circ$. The spectral grid in frequency space is defined by a minimum and maximum frequency of $f_{\text{low}} = 0.04$ Hz and $f_{\text{high}} = 1$ Hz, respectively (with $\Delta f = 0.1^*f$ and MSC = 34). The computations have been terminated using the same criterion as specified in specified in Section 3.2.

To study the effect of the adapted first-guess on model convergence in the Westerschelde estuary, output is requested along an output curve and at one output location in the inner area at several iteration levels (i.e., 1, 2, 5, 10, 15, 25, and 50 iterations).

The following computations have been performed to study the effect of the (adapted) first-guess on model convergence:

<table>
<thead>
<tr>
<th>Case</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>standard first-guess with MDC = 36</td>
</tr>
<tr>
<td>2</td>
<td><strong>standard first-guess</strong> with MDC = 40</td>
</tr>
<tr>
<td>3</td>
<td>adapted first-guess: Wind speed $U'<em>{10} = U</em>{10}(C_d(U_{10})/C_d(15 \text{ m/s}))^{0.5}$ and directional distribution equal $(\cos^{0.6})$</td>
</tr>
<tr>
<td>4</td>
<td>adapted first-guess: Wind speed $U'<em>{10} = U</em>{10}(C_d(U_{10})/C_d(15 \text{ m/s}))^{0.5}$ and directional distribution equal $(\cos^{0.6})$ and adapted distribution of limiter $f/f_m$</td>
</tr>
<tr>
<td>5</td>
<td>as case 4 but for $U_{10} = 15$ m/s and $U'_{10} = 40$ m/s (with and without adapted limiter)</td>
</tr>
<tr>
<td>6</td>
<td>as case 5 but with second-generation formulations (with and without adapted limiter)</td>
</tr>
</tbody>
</table>

Table 4.2 Listing of computations that have been performed in the Westerschelde estuary.

A listing of the SWAN input file for case 1 in given in Appendix A.

### 4.3.2 Model results

The computed wave parameters along the specified curve using the third-generation mode of SWAN (with the default first guess) are shown in Fig. 4.3.2. The model convergence behaviour of SWAN at the output location deep inside the Westerschelde estuary is shown in Fig. 4.3.4. These results clearly demonstrate that - at least - 30 iterations are required to obtain model convergence.
During the study it was found that the two-dimensional wave spectra (results not shown here) showed a gap in the directional distribution of the wave spectrum. Such a gap may occur if the orientation of the computational grid coincides with a spectral direction (which obviously appeared to be the case in this study). The occurrence of such a gap can be avoided by rotating the computational grid a few degrees or by changing the total number of spectral directions (i.e. changing the value of the coefficient MDC; see SWAN-manual, Ris et al., 1997). In the present study the total number of spectral directions has been increased from MDC=36 to MDC=40.

To investigate the effect of this adapted resolution in directional space on the model results in the Westerschelde estuary, the computation as described here above has been repeated. The model results along the output curve have been plotted in Fig. 4.3.3 whereas in Fig. 4.3.4 the evolution of the significant wave height has been plotted. The results shown in Fig. 4.3.4 show that with the adapted number of spectral directions the SWAN model tends to converge more rapidly (model convergence has been obtained after 24 iterations, say) and that the significant wave height at iteration level 50 is slightly higher (obviously because the gap in the directional wave spectrum is not present with MDC=40). The directional resolution MDC=40 has been used in the remainder of this study.

Figures 4.3.5 and 4.3.7 show the model results that have been obtained with the adapted \textit{first-guess} (both wind speed and directional distribution of the energy spectrum). The results presented in Fig. 4.3.7 clearly show that with the adapted \textit{first-guess} model convergence is obtained within 17 iterations (i.e. a reduction of 7 iterations compared to the non-adapted \textit{first-guess}).

In addition to the application of the modified \textit{first-guess}, computations have also been performed with the adapted limiter (see for details Section 4.2.2). Results are shown in Figures 4.3.6 and 4.3.7. With the use of the adapted limiter it is seen that SWAN converges more rapidly (particularly for the mean wave direction and the directional spreading of the waves) compared to the results obtained with the default limiter (compare Fig. 4.3.5 and 4.3.6). The effect on the evolution of the significant wave height as a function of iteration level is also present. Now only 14 iterations are required to obtain model convergence. Although the convergence speed has been accelerated with the adapted limiter in this field case, it has been found in Chapter 3 that with the adapted limiter fetch-limited wave growth is not properly computed (see Fig. 3.8).

Figure 4.3.8 illustrates the difference in model convergence speed at the specified output location using the default and the adapted \textit{first-guess} for three different wind speeds (i.e. $U_{10}=15$ m/s, $U_{10}=30$ m/s and $U_{10}=40$ m/s). These results are as expected considering the formulation of the adapted wind speed (see Eq. 2.7). For a wind speed of 15 m/s the results between the computations with and without the adapted \textit{first-guess} should be (nearly) the same (small differences are present since the directional distribution has also been adapted). For higher wind speeds ($U_{10}>15$ m/s) the significant wave height of the adapted \textit{first-guess} is significantly higher than those as computed with the default \textit{first-guess}.

In addition, computations have been made for the same situations as described here above but now with second-generation formulations activated in SWAN and using the default and
the adapted first-guess. It is striking to see that also with second-generation formulations in SWAN (with no limitations on the change of energy density per iteration) about 10 iterations are required to obtain model convergence for the three wind speeds considered, as is evident from Fig. 4.3.9. This indicates that for the complex field case of the Westerschelde estuary - where strong refraction, wave growth by wind and highly non-linear processes such as depth-induced wave breaking and quadruplet wave-wave interactions play an important role - the numerical procedure of SWAN (i.e. the iterative four sweep technique) requires at least about 10 to 15 iterations in presence of winds.
5 Conclusions and recommendations

5.1 Conclusions

The following conclusions can be drawn from this study:

Fetch-limited deep water wave growth:

- The dimensionless wave growth curves from SWAN using third-generation formulations, scale well with the friction velocity $U_*$ of Wu (1982) and show a good agreement between the data of Kahma and Calkoen (1992) and Pierson-Moskowitz (1964).

- Wave growth curves obtained with the (standard) second-generation mode of SWAN scale poorly with the friction velocity $U_*$ of Wu (1982) (and thus also with the model results obtained with the third-generation mode of SWAN) and show a poor agreement with the data of Kahma and Calkoen (1992) and Pierson-Moskowitz (1964). Moreover, it has been found that the directional distribution of the energy spectrum as computed by the second- and third generation mode of SWAN differ significantly (about $10^\circ$).

This poor agreement between the second- and third-generation mode of SWAN is considered as unrealistic and is very inconvenient for users who apply the SWAN model in practical applications (in second- or in third-generation mode). It generally also increases the number of iterations required to obtain model convergence (see this study).

- The agreement between the second- and third-generation mode is fairly reasonable if the wind speed $U_{10}$ is adapted according to the formulation as suggested by Bouws (1986) but is generally poor if the formulation of Komen et al. (1984) is used. The agreement between the directional distribution of the energy spectrum as computed by the second- and third-generation mode has been improved by changing the coefficients of the directional distribution function (see Eq. 3.2) in the first and only the first iterations (i.e. the first-guess).

Model convergence (wave growth in idealised case and Westerschelde estuary):

- It has been found that the overshoot in the significant wave height as function of iteration level can be ascribed to mismatch of the directional distribution of the energy spectrum between the first-guess and the third-generation mode. Adapting the directional distribution of the first-guess improves the model convergence significantly (at least in the fetch-limited deep water cases considered in this study).

- The speed of model convergence has been accelerated significantly with the adapted first-guess in the fetch-limited cases (see e.g. Fig. 4.2.12.e). The relatively large overshoot has been reduced for all wind speeds considered.
• It has been found that the adapted first-guess also improves the speed of model convergence in the complex field case of the Westerschelde estuary for moderate wind speeds but that its effect is limited for relatively high wind speeds (the number of iterations required for model convergence is roughly the same as with the standard first-guess). However, the model converges more gradually which is more attractive from an operational use of the model.

Additional computations using the second-generation mode of SWAN have shown that at least 10 iterations are required to obtain model convergence in this complex case. The third-generation mode of SWAN obviously needs more iterations than the second-generation mode for this case (due to e.g. the third-generation formulations and the application of the limiter). These results thus suggest that the numerical procedure of SWAN requires at least about 12 to 15 iterations to obtain model convergence in the Westerschelde case.

• Although the fetch-limited wave growth curves could not be reproduced in detail with the adapted limiter, it has been shown that the adapted limiter further improves model convergence in the fetch-limited case (Fig. 4.2.16.c) and the Westerschelde estuary case (see Fig. 4.3.7) compared to the adapted first-guess only.

5.2 Recommendations

On the basis of the results presented in this study it is recommended:

• In the present study the first-guess of the wind sea has been improved. The first-guess of the swell part of the spectrum has, however, not be taken into account in this study. A good estimate of this swell part of the spectrum, however, may also improve the model convergence but it requires retuning of the first-guess with respect to dissipation term of the second-generation mode of SWAN. It is recommended to investigate to what extent this first-guess of the swell part can be improved.

• to change the coefficients of the directional distribution function (i.e. the coefficients $\delta_i$ and $n$ of Eq. 2.9) if changes made to the present source terms for the third-generation mode of SWAN lead to a different directional distribution of the energy spectrum.
References


Ris, R.C., 1997: Spectral modelling of wind waves in coastal areas, Ph.D.-dissertation, Delft University of Technology, Department of Civil Engineering, The Netherlands


WL | DELFT HYDRAULICS, 1998: Validation of wave propagation on curvilinear grids in SWAN, N. Doorn and R.C. Ris, Report H3306.20, the Netherlands

WL | DELFT HYDRAULICS, 1999: Effects of a self-scaling cut-off frequency on wave growth in SWAN, R.C. Ris and K.J. Bos, Report 3396, the Netherlands

Appendices
A The Westerschelde estuary: SWAN input file

$---------------HEADING-----------------------------$
$ PROJ 'Westerschelde' '01'
$--------------- MODEL INPUT ----------------------$
$ SET LEVEL=6. DEPMIN=.05 MAXERR=3 POWER=-1
$ CGRID 9500. 381100. -15. 30000. 15000. 300 150 CIRCLE 36 0.04 1. 34
$ INP BOTTOM REG 8889.3862 381139.3803, -15, 156 381, 200. 40. EXC -1.00E5
READ BOTTOM 1. 'new_bott.xyz' IDLA=3 NHEDF=0 FREE
$ BOU STAT UP Y JON VAR 0 3.5 PEAK 12. 325. 16. &
7500 3.5 PEAK 12. 325. 16.
BOU STAT LOW X JON PAR 3.5 PEAK 12. 325. 16.
BOU STAT LOW Y JON VAR 0 3.5 PEAK 12. 325. 16. &
7500 3.5 PEAK 12. 325. 16.
$ WIND 30. 280.
$ GEN3
TRIAD
FRIC
$ NUM ACCUR 1e-5 1e-5 1e-5 99.5 50
$----------------------------------------------$
$ PLOT 'COMPGRID' FILE 'casel.plt' 'Hs' 'SIGN' ISO HS VEC TRANS 0.1 2 LOC
PLOT 'COMPGRID' FILE 'casel.plt' 'TM01' ISO TM01
PLOT 'COMPGRID' FILE 'casel.plt' 'DEPTH' ISO DEP
$ TABLE 'COMPGRID' NOHEAD 'casel.tbl' XP YP DEP
CURVE 'curvel' 14500.00 388064.75 500 39000.00 381499.99
TABLE 'curvel' NOHEAD 'casel.cr' XP DEP HS TM01 TM02 RTP DIR DISPR
$ TEST 0 0 POINTS 125 0 S1D 'casel.src'
POOL
COMPUTE
STOP
Figures
Wind speed $U_{10}$ versus the adapted wind speed $U_{10}$ according to Komen et al. (1984) and as suggested by Bouws (1986).
Fetch limited wave growth (deep water)
Third-generation formulations (standard option: GEN3)

SWAN 30.75

WL | delft hydraulics

H3515  Fig. 3.1
Fetch limited wave growth (deep water)
Second-generation formulations (standard option: GEN2)

SWAN 30.75

WL | delft hydraulics

H3515 | Fig. 3.2
Fetch limited wave growth (deep water)
Second-generation formulations with adapted first-guess.
Wind speed: $U_{10} = 28 C_d^{0.5}, U_{10} = 28 U^*$

---

**SWAN 30.75**

**WL | delft hydraulics**
Fetch limited wave growth (deep water)
Second-generation formulations with adapted first guess.
Wind speed: $U_{10} = U_{10} \left( \frac{C_d(U_{10})}{C_d(U_{10}=15 \text{ m/s})} \right)^{0.5}$

---

**SWAN 30.75**

**H3515**

**Fig. 3.4**
Fetch limited wave growth (deep water)
Third-generation formulations with adapted first guess.
Wind speed: $U'_{10} = U_{10} \left( \frac{C_d(U_{10})}{C_d(U_{10}=15 \text{ m/s})} \right)^{0.5}$

**SWAN 30.75**

**H3515**  Fig. 3.5
Fetch limited wave growth (deep water)
Second-generation formulations with adapted wind speed
and adapted directional distribution ($\cos^{0.6}$)

**Pierson-Moskowitz (1964)**
**Kahma and Calkoen (1992)**
**Wilson (1965)**

**$U_{10} = 10$ m/s**
**$U_{10} = 20$ m/s**
**$U_{10} = 30$ m/s**

**Third-generation mode SWAN**

Note: the SWAN results are in terms of $f_m$ and the data of the observations are in terms of $f_p$ in this panel.
Fetch limited wave growth (deep water)
Third-generation formulations with adapted first guess:
Wind speed and directional distribution ($\cos^{0.6}$)

SWAN 30.75

H3515  Fig. 3.7
Third-generation formulations with adapted first guess

Fetch limited wave growth (deep water)

Note: The SWAN results are in terms of $t^d$ and the data of the observations are in terms of $t^d$ in this panel.
Model convergence behaviour using third-generation formulations
Standard computation with first-guess (default)

SWAN-1D  \( U_{10} = 10 \text{ m/s} \)

WL | delft hydraulics

H3515 Fig. 4.2.1.a
Frequency spectra at 3 locations
Standard computation with first-guess (default)
Significant wave height at 12.5 km
Standard computation with first-guess (default)

SWAN-1D
U_{10}=10 m/s

WL | delft hydraulics

H3515 Fig. 4.2.1.d
Model convergence behaviour using third-generation formulations
Standard computation with first-guess (default)

WL | delft hydraulics

SWAN-1D  U_{10}=20 \text{ m/s}

H3515  Fig. 4.2.2.a
Frequency spectra at 3 locations
Standard computation with first-guess (default)

SWAN-1D  \( U_{10} = 20 \text{ m/s} \)

H3515  Fig. 4.2.2.b

WL | delft hydraulics
Source terms at x = 12.5 km
Standard computation with first-guess (default)
Significant wave height at 12.5 km
Standard computation with first-guess (default)

SWAN-1D
$U_{10}=20$ m/s

H3515
Fig. 4.2.2.d
Model convergence behaviour using third-generation formulations
Standard computation with first-guess (default)

<table>
<thead>
<tr>
<th>SWAN-1D</th>
<th>U₁₀=30 m/s</th>
</tr>
</thead>
</table>

WL | delft hydraulics

H3515 | Fig. 4.2.3.a
Frequency spectra at 3 locations
Standard computation with first-guess (default)

SWAN-1D  U_{10}=30 \, \text{m/s}

WL | delft hydraulics

H3515  Fig. 4.2.3.b
Source terms at x = 12.5 km
Standard computation with first-guess (default)

SWAN-1D  U_{10}=30 \text{ m/s}

WL | delft hydraulics

H3515  Fig. 4.2.3.c
Significant wave height at 12.5 km
Standard computation with first-guess (default)

SWAN-1D
U_{10}=30 \text{ m/s}

H3515
Fig. 4.2.3.d
Model convergence behaviour using third-generation formulations
Standard computation with first-guess (default)

SWAN-1D
$U_{10}=40$ m/s

WL | delft hydraulics

H3515
Fig. 4.2.4.a
Frequency spectra at 3 locations
Standard computation with first-guess (default)

SWAN-1D  $U_{10}=40$ m/s

WL | delft hydraulics
Source terms at x = 12.5 km
Standard computation with first-guess (default)

SWAN-1D  \( U_{10} = 40 \text{ m/s} \)

WL | delft hydraulics

H3515  Fig. 4.2.4.c
Significant wave height at 12.5 km
Standard computation with first-guess (default)

SWAN-1D
$U_{10} = 40 \text{ m/s}$

WL | delft hydraulics

H3515 | Fig. 4.2.4.d
Significant wave height at 12.5 km
Wind speed: \( U_0 = 10 \) m/s, \( U_0 = 20 \) m/s, \( U_0 = 30 \) m/s, \( U_0 = 40 \) m/s

Standard computation with first-guess (default)

- \( U_10 = 40 \) m/s
- \( U_10 = 30 \) m/s
- \( U_10 = 20 \) m/s
- \( U_10 = 10 \) m/s

number of iterations (•)
Model convergence behaviour using third-generation formulations
Adapted first guess: $U_{10} = U_{10}(C_d(U_{10})/C_d(15 \text{ m/s}))^{0.6}$
Frequency spectra at 3 locations
Adapted first guess: $U_{10} = U_{10}(C_d(U_{10})/C_d(15 \text{ m/s}))^{0.5}$

SWAN-1D  $U_{10}=10 \text{ m/s}$

H3515  Fig. 4.2.5.b
Source terms at x = 12.5 km
Adapted first guess: $U_{10} = U_{10}(C_d(U_{10})/C_d(15 \text{ m/s}))^{0.5}$

SWAN-1D

$U_{10}=10 \text{ m/s}$

WL | delft hydraulics

H3515 Fig. 4.2.5.c
Significant wave height at 12.5 km
Adapted first guess: $U_{10} = U_{10}(C_0(U_{10})/C_0(15 \text{ m/s}))^{0.5}$

SWAN-1D | $U_{10} = 10 \text{ m/s}$

H3515 | Fig. 4.2.5.d
Model convergence behaviour using third-generation formulations
Adapted first guess: $U_{10} = U_{10}(C_d(U_{10})/C_d(15\ m/s))^{0.5}$

SWAN-1D  $U_{10}=20\ m/s$

WL | delft hydraulics

H3515  Fig. 4.2.6.a
Frequency spectra at 3 locations
Adapted first guess: $U_{10} = U_{10}(C_d(U_{10})/C_d(15 \text{ m/s}))^{0.5}$

SWAN-1D | $U_{10}=20$ m/s
---|---

WL | delft hydraulics

H3515 | Fig. 4.2.6.b
Source terms at $x = 12.5$ km
Adapted first guess: $U_{10} = U_{10}(C_d(U_{10})/C_d(15 \text{ m/s}))^{0.5}$
Significant wave height at 12.5 km
Adapted first guess: $U_{10} = U_{100} (C_d(U_{100})/C_d(15 \text{ m/s}))^{0.5}$
Model convergence behaviour using third-generation formulations
Adapted first guess: \( U'_{10} = U_{10}(C_d(U_{10})/C_d(15 \text{ m/s}))^{0.5} \)

SWAN-1D  \( U_{10}=30 \text{ m/s} \)

H3515  Fig. 4.2.7.a
Frequency spectra at 3 locations
Adapted first guess: $U_{10} = U_{10}(C_d(U_{10})/C_d(15 \text{ m/s}))^{0.5}$

<table>
<thead>
<tr>
<th>SWAN-1D</th>
<th>$U_{10}=30 \text{ m/s}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>H3515</td>
<td>Fig. 4.2.7.b</td>
</tr>
</tbody>
</table>

WL | delft hydraulics
Source terms at x = 12.5 km
Adapted first guess: $U_{10} = U_{10}(C_a(U_{10})/C_d(15 \text{ m/s}))^{0.5}$
Significant wave height at 12.5 km
Adapted first guess: $H_s = Hs0 \cdot \sqrt{u_0/(Cg(cGcG))}^{0.5}$
Model convergence behaviour using third-generation formulations
Adapted first guess: \( U_{10} = U_{10}(C_d(U_{10})/C_d(15 \text{ m/s}))^{0.5} \)

SWAN-1D
U_{10}=40 \text{ m/s}

WL | delft hydraulics

H3515 | Fig. 4.2.8.a
Frequency spectra at 3 locations
Adapted first guess: $U_{10} = U_{10}(C_d(U_{10})/C_d(15 \text{ m/s}))^{0.5}$

**SWAN-1D**

$U_{10}=40 \text{ m/s}$

**H3515**

Fig. 4.2.8.b
Source terms at x = 12.5 km
Adapted first guess: $U_{10} = U_{10}(C_d(U_{10})/C_d(15 \text{ m/s}))^{0.5}$

SWAN-1D $U_{10}=40 \text{ m/s}$
Model convergence behaviour using third-generation formulations
Adapted first guess: $U_{10} = U_{10}(C_{f0}(U_{10}/C_{f0}(15 \text{ m/s}))^{0.5}$
and adapted directional distribution: $\cos^{0.5}$

<table>
<thead>
<tr>
<th>SWAN-1D</th>
<th>$U_{10}=10 \text{ m/s}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>H3515</td>
<td>Fig. 4.2.9.a</td>
</tr>
</tbody>
</table>
Frequency spectra at 3 locations
Adapted first guess: $U_{10} = U_{10} (C_d U_{10}) / C_d (15 \text{ m/s})^{0.5}$
and adapted directional distribution: $\cos^{0.6}$

**Graphs:**
- $x = 0 \text{ km}$
- $x = 12.5 \text{ km}$
- $x = 25 \text{ km}$
Source terms at x = 12.5 km
Adapted first guess: $U_{10} = U_{10}(C_d(U_{10})/C_d(15 \text{ m/s}))^{0.5}$
and adapted directional distribution: $\cos^{0.5}$

<table>
<thead>
<tr>
<th>SWAN-1D</th>
<th>$U_{10} = 10 \text{ m/s}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>H3515</td>
<td>Fig. 4.2.9.c</td>
</tr>
</tbody>
</table>
Significant wave height at 12.5 km
Adapting first guess: $U_0 = U_{0c} (C_{U0} / C_{U0})^{0.5}$ and adapted directional distribution: cos $\psi$.3

WL | delft hydraulics

H3515

Fig 429d

SWAN-1D

$U_{0c} = 10 \text{ m/s}$

$H_\text{m}$

number of iterations (-)
Model convergence behaviour using third-generation formulations
Adapted first guess: $U_{10} = U_{10} \left( \frac{C_d(U_{10})}{C_d(15 \text{ m/s})} \right)^{0.5}$
and adapted directional distribution: $\cos \theta^{0.5}$

SWAN-1D  $U_{10} = 20 \text{ m/s}$

WL | delft hydraulics

H3515  Fig. 4.2.10.a
Frequency spectra at 3 locations
Adapted first guess: $U_{10} = U_{10}(C_d(U_{10})/C_d(15\text{ m/s}))^{0.5}$
and adapted directional distribution: $\cos^{0.6}$

SWAN-1D $U_{10}=20\text{ m/s}$

WL | delft hydraulics
Source terms at x = 12.5 km
Adapted first guess: \( U'_{10} = U_{10}C_d(U_{10}/C_d(15\text{ m/s}))^{0.5} \)
and adapted directional distribution: \( \cos^{0.6} \)

SWAN-1D\hline
\hline
U_{10}=20\text{ m/s}\hline

<table>
<thead>
<tr>
<th>WL</th>
<th>delft hydraulics</th>
</tr>
</thead>
<tbody>
<tr>
<td>H3515</td>
<td>Fig. 4.2.10.c</td>
</tr>
</tbody>
</table>
Significant wave height at 12.5 km
Adapted first guess: $U_{10} = \frac{C_d(U_{10}/C_d(15 \text{ m/s}))^{0.5}}{0.8}$
and adapted directional distribution: $\cos$
Model convergence behaviour using third-generation formulations
Adapted first guess: \( U_{10} = U_{10}(C_d(U_{10})/C_d(15 \text{ m/s}))^{0.5} \)
and adapted directional distribution: \( \cos^{0.6} \)

SWAN-1D | \( U_{10} = 30 \text{ m/s} \)
H3515 | Fig. 4.2.11.a
Frequency spectra at 3 locations
Adapted first guess: \( U_{10} = U_{10}(C_\alpha(U_{10})/C_d(15 \text{ m/s}))^{0.5} \)
and adapted directional distribution: \( \cos^{0.8} \)

SWAN-1D | \( U_{10} = 30 \text{ m/s} \)

H3515 | Fig. 4.2.11.b
Source terms at x = 12.5 km
Adapted first guess: \( U_{10} = U_{10}(C_d(U_{10})/C_g(15 \text{ m/s}))^{0.5} \)
and adapted directional distribution: \( \cos^{0.5} \)

<table>
<thead>
<tr>
<th>SWAN-1D</th>
<th>( U_{10} = 30 \text{ m/s} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>H3515</td>
<td>Fig. 4.2.11.c</td>
</tr>
</tbody>
</table>

WL | delft hydraulics
Model convergence behaviour using third-generation formulations

Adapted first guess: \( U_{10} = U_{10}(C_d(U_{10})/C_d(15 \text{ m/s}))^{0.5} \)

and adapted directional distribution: \( \cos^{0.6} \)

SWAN-1D  \( U_{10}=40 \text{ m/s} \)

H3515  Fig. 4.2.12.a
Frequency spectra at 3 locations
Adapted first guess: \( U'_{10} = U_{10} \left( C_0 \left( U_{10} / C_0 (15 \text{ m/s}) \right)^{0.5} \right) \)
and adapted directional distribution: \( \cos^{0.8} \)

<table>
<thead>
<tr>
<th>SWAN-1D</th>
<th>( U_{10} = 40 \text{ m/s} )</th>
</tr>
</thead>
</table>

WL | delft hydraulics

H3515 | Fig. 4.2.12.b
Source terms at x = 12.5 km
Adapted first guess: $U_{10} = U_{10}(C_d(U_{10})/C_d(15 \text{ m/s}))^{0.5}$
and adapted directional distribution: $\cos^{0.6}$

SWAN-1D  $U_{10}=40$ m/s

WL | delft hydraulics

H3515  Fig. 4.2.12.c
Significant wave height at 12.5 km
Adapted first guess: \( U_{10} = U_{10}(C_d(U_{10})/C_d(15 \text{ m/s}))^{0.5} \)
and adapted directional distribution: \( \cos^{0.6} \)

<table>
<thead>
<tr>
<th>SWAN-1D</th>
<th>( U_{10} = 40 \text{ m/s} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>H3515</td>
<td>Fig. 4.2.12.d</td>
</tr>
</tbody>
</table>

**WL | delft hydraulics**
Adapted wave height at 12.5 km

Adapted first-guess: $U_0 = U_{10}/(U_{10}/U_{15})^{0.5}$

- $U_{10} = 40$ m/s
- $U_{10} = 30$ m/s
- $U_{10} = 20$ m/s
- $U_{10} = 10$ m/s

Wind speed: $U_0 = 10$ m/s, $U_0 = 20$ m/s, $U_0 = 30$ m/s, $U_0 = 40$ m/s

- Standard computation
- Adapted first-guess (wind speed)
- Adapted first-guess (wind speed and directional distribution)

Number of iterations (\(\cdot\))
Model convergence behaviour using third-generation formulations
Adapted first-guess (wind speed and directional distribution)
and adapted limiter.

SWAN-1D  U_{10}=10 \text{ m/s}

H3515  Fig. 4.2.13.a
Model convergence behaviour using third-generation formulations
Adapted first-guess (wind speed and directional distribution)
and adapted limiter.

SWAN-1D  U_{10} = 20 m/s

WL | delft hydraulics

H3515  Fig. 4.2.14.a
Model convergence behaviour using third-generation formulations
Adapted first-guess (wind speed and directional distribution)
and adapted limiter.

SWAN-1D  \( U_{10}=30 \, \text{m/s} \)

H3515  Fig. 4.2.15.a
Adapted first guess (wind speed and directional distribution) and adopted limit.

Significant wave height at 12.5 km

\[ H(m) \]

0.00  0.50  1.00  1.50  2.00  2.50  3.00  3.50  4.00
0  1  2  3  4  5  6  7  8  9  10  11  12  13  14  15  16  17  18  19  20  21  22  23  24  25  26  27  28  29  30  31  32  33  34  35  36  37  38  39  40  41  42  43  44  45  46  47  48  49  50

---

calculated iterations (-)

---

H3515

SWAN-1D

Fig. 4.2.15b

U_0=30 m/s
Model convergence behaviour using third-generation formulations
Adapted first-guess (wind speed and directional distribution)
and adapted limiter.

SWAN-1D  U_{10}=40 \, m/s

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H3515  Fig. 4.2.16.a
Significant wave height at 12.5 km
Adapted first-guess (wind speed and directional distribution)
and adapted limiter.
Adapted first-guess (wind speed)
Adapted first-guess (wind speed and cos-distribution)
Standard computation
Adapted first-guess (wind speed and cos-distribution) and limiter

Significant wave height at 12.5 km
Adapted first-guess and limiter
Wind speed: \( U_{10} = 10 \) m/s, \( U_{10} = 20 \) m/s, \( U_{10} = 30 \) m/s, \( U_{10} = 40 \) m/s

\( U_{10} = 40 \) m/s
\( U_{10} = 30 \) m/s
\( U_{10} = 20 \) m/s
\( U_{10} = 10 \) m/s

number of iterations (-)
Model convergence behaviour using third-generation formulations

Standard computation (standard option: GEN3)
Number of spectral directions MDC=36

SWAN 40.00 U_{10}=30 m/s

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H3515 Fig. 4.3.2
Model convergence behaviour using third-generation formulations
Standard computation (standard option: GEN3)
Number of spectral directions MDC=40

SWAN 40.00  U_{10}=30 m/s

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H3515  Fig. 4.3.3
Model convergence in the Westerschelde estuary at grid point (35, 40) as a function of iteration level.
Model convergence behaviour using third-generation formulations
Computations with an adapted first-guess

SWAN 40.01  U_{10}=30 m/s

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H3515  Fig. 4.3.5
Model convergence behaviour using third-generation formulations
Computations with an adapted first-guess
and adapted limiter (U_10)
Model convergence in the Westerschelde estuary at grid point (135,40) as a function of iteration level. Adapted: first-guess, limiter

SWAN 40.01 $U_{10}=30 \text{ m/s}$

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H3515 Fig. 4.3.7
Model convergence in the Westerschelde estuary at grid point (135,40) as a function of iteration level. Adapted: first-guess
Model convergence in the Westerschelde estuary at grid point (135,40) as a function of iteration level.

- Third-generation mode (default)
- Second-generation mode (default)
- Third-generation mode (with adapted first-guess)
- Second-generation mode (adapted)

$U_{10} = 40$ m/s
$U_{10} = 30$ m/s
$U_{10} = 15$ m/s

Number of iterations (-)
PART II

Bench mark tests for SWAN
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2.4 Listing of directory structure of the benchmark tests for SWAN.
### List of Symbols

**Roman letters**
- $c_g$  group velocity
- $d$  water depth
- $E$  wave energy
- $E_{tot}$  total wave energy
- $E^*$  non-dimensional wave energy
- $f$  frequency
- $f_m$  mean frequency
- $f_m^*$  non-dimensional mean frequency
- $f_p$  peak frequency
- $f_p^*$  non-dimensional peak frequency
- $f_{low}, f_{min}$  lowest discrete frequency in SWAN in Hz
- $g$  acceleration of gravity
- $H_s$  significant wave height (defined as $H_s = 4 \sqrt{m_0}$)
- $H_i$  incident significant wave height
- $t$  time
- $T_{m01}$  mean wave period
- $T_p$  peak period
- $U_{10}$  wind speed at 10 m height
- $U_*$  friction velocity
- $x, y$  $x$-, $y$- co-ordinate
- $X$  fetch
- $X^*$  non-dimensional fetch

**Greek symbols**
- $\sigma$  radian frequency
- $\sigma_\theta$  standard deviation in directional-space
- $\sigma_\phi$  standard deviation in frequency-space
- $\sigma_{Pkld}$  Pierson-Moskowitz frequency for fully developed spectra
- $\sigma_{low}$  lowest discrete frequency in SWAN in radians
- $\sigma_{high}$  highest discrete frequency in SWAN in radians
- $\gamma_0$  peak enhancement factor
- $\theta$  mean wave direction (Cartesian convention)
- $\theta_m$  mean wind direction (Cartesian convention)
- $\theta_i, \theta_i$  incident mean wave direction (Cartesian convention) at up-wave boundary
- $\Delta x, \Delta y$  increment in $x$- and $y$-direction, respectively
- $\Delta f, \Delta \theta$  increment in frequency- and directional-space, respectively
I Introduction

1.1 General

The numerical wave model SWAN is presently considered as the new standard for nearshore wave modelling and coastal protection studies. Since the model has been released under public domain, many institutes, universities and consultancy companies apply the SWAN model in their projects. The model was developed at Delft University of Technology, Delft (the Netherlands), and which is also the focal point for improvements and further enhancements (see e.g. Booij et al., 1999).

The reliability of model results of SWAN in practical applications depends on how well the model has performed in (prescribed) validation and verification test cases (which may comprise idealised, laboratory and field cases). The general purpose of the model validation is to investigate and optimise the performance of the numerical schemes and of the representation of various physical processes of generation and dissipation of SWAN. Wave propagation and transformation are therefore considered in idealised cases (with and without currents). Model results can be compared with analytical solutions from linear wave theory and with field or laboratory observations. In such cases, model coefficients can be tuned to achieve the best agreement between the model results and observations. The verification of the SWAN model consists of the application in field situations with an increasing complexity in two-dimensional bathymetry and added presence of wind and currents. Here model results are compared with field observations.

The model validation and verification is presently mainly being carried out by Delft University of Technology (the Netherlands). They have many test cases (a number of these tests are described in e.g. Booij et al., 1999 and Ris et al., 1999 ) that are used to:

1. Verify the proper implementation of the formulations for the physical processes that are implemented in SWAN.
2. Determine the numerical accuracy and robustness of the SWAN model.
3. Verify the input and output commands of SWAN.
4. Validate and verify the performance of the SWAN model in idealised, laboratory and field cases (with added winds and currents).

Although all test cases are frequently used by Delft University of Technology, they are not well accessible to other SWAN users, because the input- and data-files (e.g. data of observations) are very limited documented and structured (with respect to the file names and the directory structure). Moreover, the pre- and post-processing tools that are required, are only limited documented.

In order to make the test cases accessible for all SWAN users, the Dutch Ministry of Public Works and Coastal Management (RIKZ) commissioned WL | DELFT HYDRAULICS to develop 'bench mark tests for SWAN'.
1.2 Objectives of the study

The purpose of the present study is to make a large number of test cases accessible for all SWAN users by establishing bench mark tests for SWAN. The bench mark tests should be organised and structured in such a way that users can run the bench mark tests in many cases and compare model results with analytical solutions (according to linear theory) or with laboratory or field observations. It should also be possible to compare the model result of a new release (which will be SWAN CYCLE 2, version 40.00; to be released mid-1999) with that of the previous release of the SWAN model (i.e. SWAN CYCLE 2, version 30.75).

The most common way to evaluate the performance of SWAN is to present the model results in plots (which can easily be interpreted by a user). To that end, model results in terms of integral wave parameters and one-dimensional wave spectra are plotted in a prescribed format and compared with analytical solutions or observations. To limit the required actions of the SWAN users as much as possible, the set-up of the SWAN bench mark tests should be such that also this post-processing part is carried out automatically. The latter is a point of concern since the format of the output of one- (and two-) dimensional wave spectra of SWAN version 40.00 is such that some post-processing is required.

Most of the (present) SWAN users apply the SWAN model on an IBM-compatible computer or a Unix-machine. The structure and files of the bench mark tests that have been developed in this study are such that the bench mark tests are suitable for use on an IBM-compatible computer and on a Unix-machine.

1.3 Outline of the report

The outline of this report is as follows. In Chapter 2 the structure the bench mark tests for SWAN is presented and discussed. In Chapter 3 a description is given of how to implement the bench mark tests for SWAN on your computer system. A discussion with conclusions and recommendations is given in Chapter 4.

The project was carried out at WL | DELFT HYDRAULICS as project H3515 between March 1, 1999 and July 1, 1999. The work was performed by dr R.C. Ris and C.M.G. Somers.
2 Structure of bench mark tests of SWAN

2.1 Introduction

Since it is the intention that many SWAN users will use the bench mark tests for SWAN, it is important to have a structure (i.e. with respect to directories, file names, pre- and post-processing programs, etc.) that:

1. Can easily be downloaded from the SWAN homepage.
2. Can be installed on a computer system with only little effort.
3. Is robust and simple to use (i.e. batch file oriented, plots are to be automatically produced).
4. Requires almost no maintenance (after having been installed on your computer).
5. New cases can easily be added to the bench mark tests.
6. Is platform independent (i.e. it should at perform well on both an IBM-compatible computer and a Unix machine).

The structure of the present bench mark tests of SWAN have been developed such that it satisfies these objectives. In the following sections the selection of the file names and names of the test cases, the directory structure and the pre- and post-processing's programs have been described.

2.2 Selection of file names and test cases

2.2.1 File names and extensions

The bench mark tests contain many files (input, output and additional files). With respect to the maintenance of the bench mark tests it has been decided to use as much as possible the same convention of names of input and output file extensions (for SWAN and the other pre- and post-processing's programs) as used by Delft University of Technology. To this end the following extensions have been used for the SWAN input files:

* .SWN   SWAN input file
* .BOT   data file with bottom depth
* .LEV   data file with water levels
* .CUR   data file with current velocities
* .WND   data file with wind velocities
* .BND   data file with 1d- or 2d- wave spectra (to be used as input spectrum at upwave boundaries)
* .NST   data file of nested computations (to be used as input for the nested computation)
The convention of the extension of the SWAN output files that has been used, is the following:

*PRT PRINT file with information regarding the computation
*PLT standard output file in HPGL-format of SWAN
*TAB data file obtained using the TABLE option (table format output)
*BLK data file obtained using the BLOCK option (block format output)
*SP1 data of one-dimensional wave spectra at a location
*SP2 data of two-dimensional wave spectra at a location
*SPC data of one- or two-dimensional wave spectra which need to be converted (only for the latest release SWAN version 40.00).

To enable users to carry out the post-processing automatically, a number of post-processing programs are present that convert output data of SWAN into a different format (or the data is for instance scaled with wind speed to obtain dimensionless parameters). These programs require generally an input file with some information. The input files for the post-processing programs can be recognised by the use of the extension *.INP.

The graphical post-processing procedure is also carried out automatically (using the OGRAPH.EXE program, developed at Delft University of Technology, the Netherlands). This OGRAPH.EXE program requires an input file (in which the commands that generate the plot are listed) and data in a prescribed format. The extension of the input file of the program is:

*OPG OGRAPH input file (with information of the graphical representation of the plot).

The name of the output file of the graphical post-processing program always starts with the following three characters:

PLFXXX standard HPGL output file of for test case ‘xxx’

As described in the introduction (see Section 1), three different types of test cases have been distinguished, i.e.:

1. Academic situations. These academic situations represent idealised situations in which model results can be compared with solutions of linear wave theory (e.g. depth- and current induced shoaling and refraction).
2. Laboratory situations. These situations refer to laboratory experiments (e.g. flume or basin) where specific physical processes were the subject of interest. In these situations detailed observations are often available. The laboratory test cases are generally used to validate the SWAN model (e.g. triad wave-wave formulations).
3. Field situations. Which comprise generally complex field cases (with added winds and currents) where observations are available. These cases are used to verify the SWAN model.
The names of the test cases have been chosen 8 characters long starting with the index ‘A’, ‘L’ or ‘F’ for the academic, the laboratory and the field cases, respectively. The next two characters (characters 2 and 3) of the file name represent the head and sub serial number of the test case considered. The last 5 characters have been reserved for a brief indication of the (physical) test case. For instance, test case A23SHOAL is the third case of the second academic test case (i.e., case ‘A23’) in which (depth-induced) shoaling is tested. L21WAVBR is the first case of the second laboratory test in which (depth-induced) breaking is tested. The directory structure of the bench mark tests largely follows these identification names of the test cases.

2.2.2 Test cases (and names) for the bench mark tests

The names of the files and the directories of all the test cases have been selected such that they are unique (in their kind) and that users of the bench mark tests can easily determine to which test case is referred.

With respect to test cases which represent idealised situations, and for most of which a comparison can be made with solutions according to linear wave theory, the following test cases - indicated with index A - have been added to the bench mark tests:

<table>
<thead>
<tr>
<th>Case</th>
<th>Purpose of test:</th>
</tr>
</thead>
<tbody>
<tr>
<td>A11REFRA</td>
<td>Depth-induced refraction and shoaling</td>
</tr>
<tr>
<td>A12REFRA</td>
<td>Depth-induced refraction and shoaling but computational grid 10° rotated</td>
</tr>
<tr>
<td>A21SHOAL</td>
<td>Depth-induced shoaling (with a $\cos^2$-directional distribution)</td>
</tr>
<tr>
<td>A22SHOAL</td>
<td>Depth-induced shoaling (with a $\cos^{500}$-directional distribution)</td>
</tr>
<tr>
<td>A23SHOAL</td>
<td>Depth-induced shoaling (with a $\cos^{500}$-directional distribution with SWAN-1D)</td>
</tr>
<tr>
<td>A31CURFO</td>
<td>Current-induced shoaling (following current)</td>
</tr>
<tr>
<td>A32CUPRO</td>
<td>Current-induced shoaling (opposing current)</td>
</tr>
<tr>
<td>A33CURSL</td>
<td>Current-induced refraction and shoaling (slanting current, incident wave direction 120°)</td>
</tr>
<tr>
<td>A34CURSL</td>
<td>Current-induced refraction and shoaling (slanting current, incident wave direction 60°)</td>
</tr>
<tr>
<td>A35CURBL</td>
<td>Current-induced blocking (wave blocking using implicit scheme in frequency space)</td>
</tr>
<tr>
<td>A36CURBL</td>
<td>Current-induced blocking (wave blocking using explicit scheme in frequency space)</td>
</tr>
<tr>
<td>A41WAVFR</td>
<td>Bottom friction formulations</td>
</tr>
<tr>
<td>A51CURVI</td>
<td>Depth-induced shoaling on three different curvi-linear grids</td>
</tr>
<tr>
<td>A52CURVI</td>
<td>Depth-induced refraction and shoaling on three different curvi-linear grids</td>
</tr>
<tr>
<td>A53CURVI</td>
<td>2D-wave-induced set-up module on three different curvi-linear grids</td>
</tr>
<tr>
<td>A61OBSTA</td>
<td>Wave propagation through obstacles</td>
</tr>
</tbody>
</table>

Table 2.1 Listing of all directories of the bench mark tests that are related to academic test cases.

A number of laboratory test cases are available to validate the SWAN model. The following laboratory cases - indicated with index L - have been added to the bench mark tests:
<table>
<thead>
<tr>
<th>Case</th>
<th>Purpose of test:</th>
</tr>
</thead>
<tbody>
<tr>
<td>L11WAVBR</td>
<td>Depth-induced breaking, mildly breaking (experiment of Battjes and Janssen, 1978)</td>
</tr>
<tr>
<td>L12WAVBR</td>
<td>Depth-induced breaking, violent breaking (experiment of Battjes and Janssen, 1978)</td>
</tr>
<tr>
<td>L21TRIAD</td>
<td>Triad wave-wave interactions (experiment of Beji and Battjes, 1993)</td>
</tr>
<tr>
<td>L31SETUP</td>
<td>Wave-induced set-up (experiment of Boers, 1996)</td>
</tr>
<tr>
<td>L41CURBL</td>
<td>Current-induced wave blocking (experiment of Lai et al., 1989)</td>
</tr>
<tr>
<td>L51HISWA</td>
<td>Wave propagation and transformation over a submerged bar (the HISWA-basin; Dingemans et al., 1989)</td>
</tr>
<tr>
<td>L61BARRI</td>
<td>Barrier Island: wave propagation and transformation using a regular and two different curvi-linear grids (Holthuijsen et al., 1993)</td>
</tr>
</tbody>
</table>

Table 2.2 Listing of all directories of the benchmark tests that are related to laboratory test cases.

The following realistic field cases - indicated with index F - have been added to the benchmark tests in order to verify wave propagation and wave transformation in the SWAN model:

<table>
<thead>
<tr>
<th>Case</th>
<th>Purpose of test:</th>
</tr>
</thead>
<tbody>
<tr>
<td>F11GRWSW</td>
<td>Depth-limited wave growth (SWAN results are compared with data of Young and Verhagen, 1996; Holthuijsen, 1980 and Bretschneider, 1973)</td>
</tr>
<tr>
<td>F21GRWDP</td>
<td>Fetch-limited deep water wave growth using <em>third-generation</em> formulations and $U_{10} = 10$ m/s (SWAN results are compared with data of Wilson, 1965; Pierson-Moskowitz, 1964 and Kahma and Calkoen, 1992)</td>
</tr>
<tr>
<td>F22GRWDP</td>
<td>As case F11GRWDP but with $U_{10} = 20$ m/s</td>
</tr>
<tr>
<td>F23GRWDP</td>
<td>As case F11GRWDP but with $U_{10} = 30$ m/s</td>
</tr>
<tr>
<td>F24GRWDP</td>
<td>Fetch-limited deep water wave growth using <em>second-generation</em> formulations and $U_{10} = 10$ m/s (SWAN results are compared with data of Wilson, 1965; Pierson-Moskowitz, 1964 and Kahma and Calkoen, 1992)</td>
</tr>
<tr>
<td>F25GRWDP</td>
<td>As case F24GRWDP but with $U_{10} = 20$ m/s</td>
</tr>
<tr>
<td>F26GRWDP</td>
<td>As case F24GRWDP but with $U_{10} = 30$ m/s</td>
</tr>
<tr>
<td>F27GRWDP</td>
<td>Model convergence in case of fetch-limited wave growth in deep water</td>
</tr>
<tr>
<td>F31HARIN</td>
<td>Wave propagation and transformation in the Haringvliet estuary, the Netherlands (Andorka Gal, 1995)</td>
</tr>
<tr>
<td>F41LAKGR</td>
<td>Wave growth in shallow lake of Lake George, Australia (Young and Verhagen, 1996a and 1996b)</td>
</tr>
<tr>
<td>F51FRIES</td>
<td>Wave propagation and transformation in the tidal inlet of the Friesche Zeeag, the Netherlands (Dunsbergen, 1995a and 1995b)</td>
</tr>
<tr>
<td>F61WESTR</td>
<td>Wave propagation and transformation in the Westerschelde estuary, the Netherlands (Andorka Gal and Roelse, 1997)</td>
</tr>
<tr>
<td>F62WESTR</td>
<td>Wave propagation and transformation on curvi-linear grids in the Westerschelde estuary, the Netherlands (Andorka Gal and Roelse, 1997)</td>
</tr>
<tr>
<td>F71MEDSE</td>
<td>Non-stationary wave computations in the Mediterranean Sea ('Gorbush storm'; Holthuijsen et al., 1996)</td>
</tr>
</tbody>
</table>

Table 2.3 Listing of all directories of the benchmark tests that are related to field cases.
2.3 Pre- and (graphical) post-processing programs

A number of pre- and post-processing programs are available in order to be able to fully automatically perform the bench mark tests.

The pre-processing programs consist of the program CONVBND.EXE only. This program converts the format of the one- and two-dimensional wave spectra that is being used for input wave spectra and up-wave boundaries of SWAN version 30.75 into that of SWAN version 40.00 (and updates). The reason that this conversion of 1d- and 2d spectra is required is that the format of the spectral files of version 40.00 has been changed compared to that of version 30.75.

Generally, two type of post-processing programs can be distinguished, i.e., post-processing programs that are related to data conversion (i.e. converting the output data of SWAN in a specific format) and to the graphical post-processing tools to make the plots.

The following post-processing programs are available with respect to data conversion:

CONVDP.EXE  This program converts wave data (as computed by SWAN version 30.75 and 40.00 and updates) into dimensionless data by using the friction velocity $U_r$ (according to Wu, 1982). The program is used for the tests cases that are related to fetch-limited (deep water) wave growth (cases F21 to F26);

CONVSH.EXE  This program converts wave data (as computed by SWAN version 30.75 and 40.00 and updates) into dimensionless data by using the wind speed $U_{10}$. This program is activated for the test case that is related to depth-limited wave growth (case F11);

CONVRT1D.EXE This program converts the format of the one-dimensional wave spectra (as computed by SWAN version 40.00 and updates) into a format that is appropriate for the graphical post-processing’s program (see below). This program is only used for SWAN version 40.00 (since the output format of version 30.75 is already in the right format for the post-processing programs). This program is activated in all test cases in which wave spectra are presented;

The following post-processing programs are available for the purpose of the graphical presentation of the model results:

OPGRAPH.EXE  The purpose of this program is to make graphs of 1d functions (see OGRAPH manual of Delft University of Technology, the Netherlands). It has the great advantage in contrast with other post-processing programs such as spreadsheets that it can be run in batch (i.e. without interference by a user) and that it is platform independent (since it is a FORTRAN77 program). The program produces HPGL plots which can easily be visualised or printed by a HPGL view- and plot program such as PRINTGL;

PRINTGL.EXE  With the program PRINTGL.EXE it is possible to visualise and plot the HPGL-files that have been made by the OGRAPH program. It is noted that this program can only be used on an IBM-compatible computer (not on Unix).
Although the PRINTGL.EXE is shareware, a user of the PRINTGL.EXE program should be aware of the following conditions with respect to its use:

PrintGL/D (c) Copyright Ravitz Software Inc. 1990, 1993
PrintGL/D is distributed as shareware. If you use PrintGL/D beyond evaluation you must purchase a registered copy for $50 from Ravitz Software Inc. See "License and Registration" in PRINTGL.DOC for more information.

Ravitz Software Inc.
P.O. Box 25068
Lexington, KY 40524-5068
USA

2.4 General directory structure of bench mark tests

In this section the directory structure that has been developed for the bench mark tests for SWAN, is described. The complete directory structure consist of only three levels:

1. Main directory of the bench mark tests (level I);
2. Directories in which the most common data is stored (level II);
3. Sub-directories with data and input files for the bench mark tests (level III).

The main directory is called TESTBANK, which corresponds to directory level I (it is noted that the name of this (and only this) main directory may be chosen arbitrarily). This main directory TESTBANK contains a number of subdirectories, which are indicated with level II (see Table 2.4). These subdirectories at level II contain all the files that are required to automatically carry out the pre-processing, the SWAN computations (with SWAN version 30.75 and 40.00) and the post-processing. Generally, four type of subdirectories can be distinguished at the second subdirectory level:

1. subdirectories who's name starts with the following characters: SWAN contain files that are directly related to SWAN (i.e., SWAN executable, central directories in which all model results of SWAN are stored);
2. subdirectory PROGS contains all the additional executables that are required to automatically carry out all the pre- and post-processing procedures;
3. the subdirectories SYS_PC and SYS_UNIX (for use on an IBM-compatible computer or a Unix system, respectively) contain all the batch files with which the computations and postprocessing procedures of the bench mark tests can be executed;
4. the subdirectories with the names starting with 'A', 'L' and 'F' contain all the subdirectories and files for the three different type of test cases, i.e.: the academic situations, the laboratory situations and the (complex) field situations, respectively.

The subdirectories at the third level (level III) of the main directories SWANPRECOMP, SWANCOMP and PROGS contain only source code (and subsequent makefile for Unix applications) of related programs. The subdirectories BATDIR and BINDIR contain the batch
files (with extension *.BAT) which should copied by a user to a so called BAT- or BIN-directory on PC or UNIX, respectively. Within all these *.BAT files a number of lines may need to be adapted (depending on your path-structure; see for more information Section 3.4). The directories with the names starting with ‘A’, ‘L’ and ‘F’ contain each four subdirectories, i.e.:

1. PRECOMP
2. COMPUTED
3. DATA
4. PLOTS

in which all the files for a particular test case have been stored. A complete overview of the directory structure at the levels II and III are given in Table 2.4.

The directory structure of the bench mark tests for SWAN is the following:
<table>
<thead>
<tr>
<th>Level II</th>
<th>Level III</th>
</tr>
</thead>
<tbody>
<tr>
<td>\SWANDOCS</td>
<td>Description of contents of subdirectory</td>
</tr>
<tr>
<td>\SWANPRT</td>
<td>Documents related to the bench mark tests for SWAN</td>
</tr>
<tr>
<td>\SWANPLOTS</td>
<td>Central directory in which all <em>print</em> files (*.PRT) of SWAN are stored</td>
</tr>
<tr>
<td>\SWANERR</td>
<td>Central directory in which all <em>plot</em> files (*.PLT) files are stored</td>
</tr>
<tr>
<td>\SWANPRECOMP</td>
<td>Central directory in which all <em>error</em> files (*.ERF) files are stored</td>
</tr>
<tr>
<td>\SWANPAS</td>
<td>Directory with <strong>executable SWANPRE.exe</strong> of SWAN version 30.75</td>
</tr>
<tr>
<td>\SWANPAS</td>
<td>Directory with the <strong>source code</strong> of SWAN version 30.75</td>
</tr>
<tr>
<td>\SWANCOMP</td>
<td>Directory with <strong>executable SWANCOMP.exe</strong> of SWAN version 40.00</td>
</tr>
<tr>
<td>\SWANCOMP</td>
<td>Directory with the <strong>source code</strong> of SWAN version 40.00</td>
</tr>
<tr>
<td>\SWANCOMP</td>
<td>Directory with the manual of SWAN version 40.00</td>
</tr>
<tr>
<td>\SWANCOMP</td>
<td>Directory with executables of all additional programs</td>
</tr>
<tr>
<td>\CONVDP</td>
<td>Source code of program CONVDP.EXE</td>
</tr>
<tr>
<td>\CONVSH</td>
<td>Source code of program CONVSILEXE</td>
</tr>
<tr>
<td>\CONVRTID</td>
<td>Source code of program CONVRTID.EXE</td>
</tr>
<tr>
<td>\OPGRAPH</td>
<td>Source code of program OPGRAPH.EXE (generates on the basis of *.OPG input</td>
</tr>
<tr>
<td></td>
<td>file the HPGL-plot with name PLF*)</td>
</tr>
<tr>
<td>\CONVIND</td>
<td>Source code of program CONVIND.EXE</td>
</tr>
<tr>
<td>\PRINTGL</td>
<td>Executable PRINTGL.EXE of the HPGL-viewer for PC-use</td>
</tr>
<tr>
<td>\SYS_PC</td>
<td>Central directory from which the batch files to perform SWAN computations</td>
</tr>
<tr>
<td></td>
<td>and generate plots can be executed for PC-applications</td>
</tr>
<tr>
<td>\BATDIR</td>
<td>Batch files which should be adapted for personal use and which should be</td>
</tr>
<tr>
<td></td>
<td>copied to the directory C/BAT</td>
</tr>
<tr>
<td>\SYS_UNIX</td>
<td>Central directory from which the batch files to perform SWAN computations</td>
</tr>
<tr>
<td></td>
<td>and generate plots can be executed for UNIX-applications</td>
</tr>
<tr>
<td></td>
<td>Batch files which should be adapted for personal use and which should be</td>
</tr>
<tr>
<td></td>
<td>copied to the directory BIN on Unix</td>
</tr>
<tr>
<td>\A11XXXXX</td>
<td>Test cases in idealised situations</td>
</tr>
<tr>
<td>\PRECOMP</td>
<td>All SWAN input files (*.SWN, *.LEV, *.BOT, *.CUR) for SWANPRE.exe</td>
</tr>
<tr>
<td>\COMPUTED</td>
<td>All SWAN input files (*.SWN, *.LEV, *.BOT, *.CUR) for SWANCOMP.exe</td>
</tr>
<tr>
<td>\DATA</td>
<td>Data of solutions according to linear wave theory</td>
</tr>
<tr>
<td>\PLOTS</td>
<td>Input files (*.OPG) for the program OPGRAPH.EXE and location where plots</td>
</tr>
<tr>
<td></td>
<td>are stored</td>
</tr>
<tr>
<td>\L11XXXXX</td>
<td>Laboratory test cases</td>
</tr>
<tr>
<td>\PRECOMP</td>
<td>All SWAN input files (*.SWN, *.LEV, *.BOT, *.CUR) for SWANPRE.exe</td>
</tr>
<tr>
<td>\COMPUTED</td>
<td>All SWAN input files (*.SWN, *.LEV, *.BOT, *.CUR) for SWANCOMP.EXE</td>
</tr>
<tr>
<td>\DATA</td>
<td>Data of laboratory observations</td>
</tr>
<tr>
<td>\PLOTS</td>
<td>Input files (*.OPG) for the program OPGRAPH.EXE and location where all plots</td>
</tr>
<tr>
<td></td>
<td>(PLF*) are stored</td>
</tr>
<tr>
<td>\F11XXXXX</td>
<td>Realistic field cases</td>
</tr>
<tr>
<td>\PRECOMP</td>
<td>All SWAN input files (*.SWN, *.LEV, *.BOT, *.CUR) for SWANPRE.exe</td>
</tr>
<tr>
<td>\COMPUTED</td>
<td>All SWAN input files (*.SWN, *.LEV, *.BOT, *.CUR) for SWANCOMP.EXE</td>
</tr>
<tr>
<td>\DATA</td>
<td>Data of field observations</td>
</tr>
<tr>
<td>\PLOTS</td>
<td>Input files (*.OPG) for the program OPGRAPH.EXE and location where plots</td>
</tr>
<tr>
<td></td>
<td>are stored</td>
</tr>
</tbody>
</table>

Table 2.4 Listing of directory structure of the bench mark tests for SWAN.
3 How to install and activate the bench mark tests on a computer system

3.1 Introduction

The complete bench mark tests for SWAN are available on the SWAN home page (http://swan.ct.tudelft.nl) and can be downloaded from this home page. In this Chapter the procedure for installation the bench mark tests on your computer system (IBM-compatible computer or Unix system) is described.

3.2 Computer dependent commands

When installing the bench mark tests on your computer it should be realised that a number of frequently used commands in the files differ with respect to the computer system that is used (i.e. an IBM-compatible computer or a Unix machine). To avoid any difficulties when installing or modifying the bench mark tests, the following differences should be a point of concern:

- Under a Unix system a distinction is made between lower case and upper case characters. In order to avoid any difficulties with system dependent commands with respect to characters, all the present file and directory names are all in lower case characters. It is therefore strongly recommended that all new file names (after e.g. compilation and renaming) and directory names are in lower case characters.
- To indicate that a comment line is present in a batch file on an IBM-compatible computer, a user should start this line with: 'REM .....' whereas on a Unix system the user should use the command: '#'....'
- The command line on an IBM-compatible computer uses a '\' whereas on a Unix system a '/' is used. The files of the bench mark tests and the additional (FORTRAN77) programs are such that after initialisation of all files on a particular computer system (i.e. an IBM-compatible or a Unix system) the difference between the command line '\' and '/' is automatically taken care of.
- Ensure that on an IBM-type computer all 'read only' file attributes are cleared (or removed) to avoid problems with the opening, writing and closing of (data) files;
- Ensure that on a Unix machine the status of all executables and batch-files (*.BAT files in the directory /BIN; see below) are changed by using the Unix-command: CHMOD +X.

3.3 Downloading the bench mark tests

The complete set of bench mark tests of SWAN can be downloaded from the SWAN home page. To download the files, a FTP program (i.e. file transfer protocol program) should be used to transfer the complete directory structure as listed in Table 2.4 to your computer system. It is recommended to download the complete bench mark tests, but a user may chose to download only the (complete) directories of the academic, the laboratory or the
field cases (see Table 2.1, 2.2 and 2.3, respectively). The data should be transferred using the ASCII-transfer option. In order to minimise the required changes to make the benchmark tests operational on your computer, it is advised to store the directory TESTBANK on the C-drive if you are using an IBM-compatible type computer (i.e. C:\TESTBANK) or your local host-directory if you are using a Unix system (i.e. /USER/TESTBANK). If all files are located in an other directory than described here above, a number of changes have to be made in several files (see Section 3.4).

3.4 Preparing the benchmark tests: path- and file names

Depending on your computer system, the following procedures are required after having downloaded all directories and files for an IBM-compatible computer and a Unix machine, respectively:

On an IBM-compatible computer

1. Ensure that there exist a directory C:BAT on your computer and that this directory is added to your path according to: \texttt{PATH= \%PATH\%:C:BAT;}
2. If you have installed the TESTBANK in a directory different than that described in Section 3.3, you have to change the path names in all the *.BAT files in the directory \texttt{TESTBANK\SYS\PC\BAT\DIRECTORY}. To this end, change the present path name \texttt{C:\TESTBANK} that is included in the *.BAT files into the name of the location of the path in which you have installed your TESTBANK directory. The modifications concern the files:
   - \texttt{CONVDP.BAT}
   - \texttt{CONRT1D.BAT}
   - \texttt{CONVSH.BAT}
   - \texttt{OPG.BAT}
   - \texttt{PRHP.BAT} (note that this file is \textit{not} available for Unix type machines)
   - \texttt{VUHP.BAT} (note that this file is \textit{not} available for Unix type machines)
   - \texttt{SWANCOMP.BAT}
   - \texttt{SWANPREC.BAT}
   - The file \texttt{CLEAR.BAT} does not need to be changed.

3. Copy subsequently all the (modified) *.BAT files to the directory C:BAT on your computer.

4. In order to perform computations with SWAN and with the pre- and postprocessing programs, it is required to compile (and link) a number of programs. The programs (to be compiled and linked) should be stored - with a specific file name - in prescribed directories. The compilation procedures are restricted to the following directories and programs:
   - Directory \texttt{TESTBANK\SWANCOMP\PROG}: compile and link - following the implementation document of SWAN, all relevant SWAN files of the most recent version 40.00 and ensure that the executable is named: \texttt{SWANCOMP.EXE}. Note that a minimum pool size of 12,500,000 is required (corresponding to 50 Mb internal memory) and that it is assumed that a user is aware of the modifications that have to be made in the computer dependent files of SWAN (reference is made to the
implementation document of SWAN). The executable SWANCOMP.EXE should be
copied to the directory TESTBANK\SWANCOMP

- Directory TESTBANK\SWANPRECOMP\PROG: compile and link - following the
  implementation document of SWAN, all relevant SWAN files of the previous version
  (i.e. version 30.75) and ensure that the executable is named: SWANPREC.EXE. Note
  that a minimum pool size of 12.500.000 is required (corresponding to 50 Mb
  internal memory) and that it is assumed that a user is aware of the modifications
  that have to made in the computer dependent files of SWAN (reference is made to
  the implementation document of SWAN). This executable SWANPREC.EXE should be
  copied to the directory TESTBANK\SWANPRECOMP

- Directory TESTBANK\PROGS: compile and link all programs listed in the directories
  and ensure that all the executable (with a name as listed here below) are stored in
  the directory TESTBANK\PROGS:

<table>
<thead>
<tr>
<th>n°</th>
<th>Directory</th>
<th>Name of executable</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CONVBND</td>
<td>CONVBND.EXE</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>CONVDP</td>
<td>CONVDP.EXE</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>CONVSH</td>
<td>CONVSH.EXE</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>CONVRTID</td>
<td>CONVRTID.EXE</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>OPGGRAPH</td>
<td>OPGGRAPH.EXE</td>
<td></td>
</tr>
</tbody>
</table>
|    |           |                    | Change DIRCH2="\" into DIRCH2="\" on line 96 and 137 in the file OCPIDS.F for PC-
  application (see also readme.txt file) |
| 6  | PRINTGL   | PRINTGL.EXE        | Only executable is available |

Note that the source code of the file PRINTGL.EXE in the directory PRINTGL is not
available but only the executable. This executable should also be present in the
directory TESTBANK\PROGS. Moreover, note that the files in the directories
CONVRTID and OPGGRAPH contain more than one *.FOR file.

End of modifications for IBM-compatible computers!

**On a Unix system**

1. Ensure that there exist a directory: /BIN
2. If you have installed the TESTBANK in a directory different than that as described in
   Section 3.3, you have to change the path in all the files in the directory
   TESTBANK/SYS_UNIX/BIN_DIRECTORY. Change the present path name
   /URIS/TESTBANK that is included in all the files (in the BIN_DIRECTORY) into the name
   of the location of the path in which you have installed your testbank directory. The
   modifications concern the files:
   - CONVDP.BAT
   - CONVRTID.BAT
   - CONVSH.BAT
   - OPG.BAT
   - SWANCOMP (note: no extension of .BAT !)
   - SWANPREC (note: no extension of .BAT !)

The file CLEAR.BAT does not need to be changed.

Ensure that the status of all the files in the directory SYS_UNIX/BIN_DIRECTORY is
changed by using Unix-command: `CHMOD +X *.`. Copy subsequently all the
(modified) files to the directory /BIN.
3. In order to perform computations with SWAN and with the pre- and postprocessing programs, it is required to compile (and link) a number of programs. The programs should be stored - with a specific file name - in given directories. The compilation procedures are restricted to the following directories and programs:

- Directory **TESTBANK/SWANCOMP/PROG**: compile and link - following the implementation document of SWAN, all relevant SWAN files of the most recent version 40.00 and ensure that the executable is named: SWANCOMP.EXE. Note that a minimum pool size of 12.500.000 is required (corresponding to 50 Mb internal memory) and that it is assumed that a user is aware of the modifications that have to made in the computer dependent files of SWAN (reference is made to the implementation document of SWAN). The executable SWANCOMP.EXE should be copied to the directory **TESTBANK/SWANCOMP**.

- Directory **TESTBANK/SWANPRECOMP/PROG**: compile and link - following the implementation document of SWAN, all relevant SWAN files of the previous version (i.e. version 30.75) and ensure that the executable is named: SWANPREC.EXE. Note that a minimum pool size of 12.500.000 is required (corresponding to 50 Mb internal memory) and that it is assumed that a user is aware of the modifications that have to made in the computer dependent files of SWAN (reference is made to the implementation document of SWAN). This executable SWANPREC.EXE should be copied to the directory **TESTBANK/SWANPRECOMP**.

- Directory **TESTBANK/PROGS**: compile and link all programs listed in the directories and ensure that all the executable (with a name as listed here below) are stored in the directory **TESTBANK/PROGS**.

<table>
<thead>
<tr>
<th>n°</th>
<th>Directory</th>
<th>Name of executable</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CONVBND</td>
<td>CONVBND.EXE</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>CONVDP</td>
<td>CONVDP.EXE</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>CONVSH</td>
<td>CONVSH.EXE</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>CONVRT1D</td>
<td>CONVRT1D.EXE</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>OPGRAPEH</td>
<td>OPGRAPEH.EXE</td>
<td>Change DIRCH2=&quot;&quot; into DIRCH2=&quot;/&quot; on line 96 and 137 in the file OCPIDS.F for UNIX application (see also readme.txt file)</td>
</tr>
<tr>
<td>6</td>
<td>PRINTGL</td>
<td>PRINTGL.EXE</td>
<td>This executable is for a dos-envivronment and cannot be used on a Unix machine!</td>
</tr>
</tbody>
</table>

Note that the files in the directories CONVRT1D and OPGRAPGH contain more than one *.FOR file. Ensure that the status of all the executables in the directory **TESTBANK/PROGS** is changed by using the Unix-command: **CHMOD +X *.EXE**

End of modifications for Unix machines!

### 3.5 Testing the modifications (with respect to the path- and file names)

The modifications as described in Section 3.4 are required in order to install the bench mark tests on your computer. In order to verify whether the installation procedure (compiling different programs, copying files to prescribed directories etc.) has successfully been completed and that from any directory the executables can be activated, it is advised to carry out the following testing procedures:
On an IBM-compatible computer

Change to the directory L41CURBL. Then change subsequently to the following directories and carry out the following scripts:

1. Change to directory COMPUTED and execute: SWANCOMP L41CURBC. Now the present version 40.00 of SWAN should be activated to compute the specified case. To test the post-processing program CONVRT1D.EXE execute: CONVRT1D L41CURBC. An output file with the extension L41CURBC.SPI should be produced.

2. Change to directory PRECOMPUTED and execute: SWANPREC L41CURBP. Now version 30.75 of SWAN should be activated to compute the specified case. (Note that the file with the one-dimensional wave does not have to be converted.)

3. Change to directory PLOTS and execute: OPG L41CURB1 and OPG L41CURB2. Two output files with the file names: PLFL41A and PLFL41B should have been produced (by the program OPGRAFHEXE). On an IBM-compatible computer these PLFL-files can be visualised by executing: VUHP PLFL41A and VUHP PLFL41B or printed by PRHP PLFL41A and PRHP PLFL41B (check the destination of the printer port in the file PRHP.BAT).

In addition to these tests, it is recommended to also check whether the programs CONVSH.EXE and CONVDP.EXE can be activated. To this end execute: CONVSH and CONVDP and check if the program responds (it should show '* .INP FILE NOT FOUND').

On a Unix system

Change to the directory L41CURBL. Then change subsequently to the following directories and carry out the following scripts:

1. Change to directory COMPUTED and execute: SWANCOMP L41CURBC. Now the present version 40.00 of SWAN should be activated to compute the specified case. To test the post-processing program CONVRT1D.EXE execute: CONVRT1D.BAT L41CURBC. An output file with the extension L41CURBC.SPI should be produced.

2. Change to directory PRECOMPUTED and execute: SWANPREC L41CURBP. Now version 30.75 of SWAN should be activated to compute the specified case, (Note that the file with the one-dimensional wave does not have to be converted).

Change to directory PLOTS and execute: OPG.BAT L41CURB1 and OPG.BAT L41CURB2. Two output files with the file names: PLFL41A and PLFL41B should have been produced (by the program OPGRAFHEXE). As described in Section 3.4, the HPGL-files (PLFL41A and PLFL41B) cannot be visualised on a Unix machine since the HPGL-viewer of the bench mark test (i.e. file PRINTGL.EXE) is only for a DOS-environment. To visualise the plots, a user should transfer all the plot files (PLF* and *.PLT) of the directory SWAN plots from the Unix machine to a local IBM-type computer. Then on the IBM-compatible computer the HPGL-plot files can be visualised by executing: VUHP PLFL41A and VUHP PLFL41B.

In addition to these tests, it is recommended to also check whether the programs CONVSH.EXE and CONVDP.EXE can be activated. To this end execute: CONVSH.BAT and CONVDP.BAT and check if the program responds (it should show '* .INP FILE NOT FOUND').
It is noted that when the plots, that have been generated by the program OPGGRAPH.EXE, are visualised on your computer with the program PRINTGL.EXE that all lines, symbols, text etc., are represented in:

a) black, if the data concerns the pre-computed option (version 30.75);
b) blue, if the data concerns the computed option (version 40.00);
c) red, if the data concerns observations (laboratory and field) or analytical solutions.

If the installation procedure has successfully been tested, the bench mark tests can be used for validating and verifying purposes of SWAN.

3.6 Activating the bench mark tests

The bench mark tests can be activated in different manners. Generally, the execution of all the files is controlled by a limited number of batch files that are stored in the directory TESTBANKSYS_PC (if an IBM-compatible system is used) or TESTBANKSYS_UNIX (if a Unix machine is used). The names of the batch files have been chosen such that they simply represent the action that will be undertaken:

Batch files to perform computations with the new version of SWAN (e.g. version 40.00):
RUNCOMPA.BAT compute all academic test cases with the present SWAN version
RUNCOMPL.BAT compute all laboratory test cases with the present SWAN version
RUNCOMPF.BAT compute all field test cases with the present SWAN version
RUNCOMPPALL.BAT activate in sequence the three batch files: RUNCOMPA.BAT, RUNCOMPL.BAT and RUNCOMPF.BAT

Batch files to perform computations with the present version of SWAN (i.e. version 30.75):
RUNPRECA.BAT compute all academic test cases with the previous SWAN version.
RUNPRECA.BAT compute all laboratory test cases with the previous SWAN version
RUNPRECA.BAT compute all field test cases with the previous SWAN version
RUNPRECALL.BAT activate in sequence the three batch files: RUNPRECA.BAT, RUNPRECL.BAT and RUNPRECF.BAT

By activating one of the above batch files, all the output generated by SWAN is copied to prescribed directories such that a user will have a general view of the model results. This concerns the following files:

- *.PRT print files generated by SWAN are copied to the directory SWANPRT
- *.ERP and *.ERF files generated by SWAN are copied to the directory SWANERR

If all computations have been carried out successfully and the output data of the computations with the 'precomputed' and 'computed' version of SWAN have been stored in the directories COMPUTED and PRECOMP, the post-processing part of the bench mark tests can be activated. This can be achieved by executing:
PLOTA.BAT generate output plots (i.e. plot files with name PLF*) for all academic test cases and copy all the files to the directory SWANPLOTS. All the *.PLT plot files generated by SWAN are also copied to the directory SWANPLOTS;

PLOTL.BAT generate output plots (i.e. plot files with name PLF*) for all laboratory test cases and copy all the files to the directory SWANPLOTS. All the *.PLT plot files generated by SWAN are also copied to the directory SWANPLOTS;

PLOTF.BAT generate output plots (i.e. plot files with name PLF*) for all field test cases and copy all the files to the directory SWANPLOTS. All the *.PLT plot files generated by SWAN are also copied to the directory SWANPLOTS;

PLOTALL.BAT activate in sequence the three batch files: PLOTA.BAT, PLOTL.BAT and PLOTF.BAT.

By copying all relevant files of all the test cases to central directories, i.e. copying the:

1. PLF* and *.PLT files to the SWANPLOTS directory;
2. *.PRT files to the SWANPRT directory;
3. *.ERF and *.ERP-files to the SWANERR directory,

a user can easily check the model results of all the test cases. This can be achieved by considering the size of the *.PRT files in the directory SWANPRT, the presence of *.ERF or *.ERP files in the directory SWANERR or by visualisation of all the plot files that have been generated. On an IBM-type computer the HPGL plots can be viewed by using VUHP PLF* or printed to a local printer by executing: PRHP PLF*. 
4 Conclusions and recommendations

4.1 Conclusions

In the present study bench mark tests for the shallow water wave model SWAN cycle 2, version 40 (and updates) have been developed. The bench mark tests for SWAN presently contain a large number of academic, laboratory and (complex) field cases in which the model results of SWAN version 40.00 are compared with solutions according to linear wave theory or with laboratory and field observations. In addition, model results of version 40.00 and version 30.75 can mutually be compared (in order to determine if the performance of the latest version of SWAN has been improved compared to that of the previous SWAN version). The model results are presented in plots, which are automatically generated. The plots (with a prescribed format) clearly show the model results obtained with the previous and present version of SWAN and the solutions according to linear wave theory or the observations.

The bench mark tests for SWAN can be simply downloaded from the SWAN homepage on a local computer system (i.e. an IBM-compatible computer or a Unix machine) and can be installed on a computer with only little effort. It is simple in use since it is batch-file oriented (i.e. computations and plots are automatically produced after executing a number of simple batch-files).

A description of each test case has been given in an accompanied document (see Appendix A: ‘Standard bench mark tests for the shallow water wave model SWAN cycle 2, version 40.00’ of this document). In this document the following items have been described for each test case separately:

1. purpose of the test case;
2. description of the situation considered;
3. test case description (i.e. what are the specifications for SWAN);
4. analytical solutions or observations that have been used to demonstrate the performance of SWAN;
5. model commands that have been activated in SWAN;
6. model results as they have been plotted in the figures;
7. references where additional information of the test case can be found.

4.2 Recommendations

With respect to the bench mark tests it is recommended to:

- In the present study a large number of most frequently used options and commands (with respect to SWAN commands and input-, and output commands) have been tested. However, still many options and commands of SWAN that have not been considered in
the present study. These options and commands are generally not frequently used by SWAN users, but it is recommended to test these options in additional cases;

- add some statistical analyses to the bench mark tests such that a user can directly obtain information on how well the SWAN model performs (in terms of for instance the Bias, Scatter Index, rms, etc.);

- extend the bench mark tests with additional test cases for which observations are available. The following test cases may be considered:

  **Stationary mode SWAN:**
  1. wave propagation and transformation in the field case of the ‘Norderneyer Seegat’ in Germany;
  2. wave growth in the field cases of ‘IJsselmeer’ and ‘Markermeer’ (two lakes in the Netherlands);
  3. wave propagation and transformation in the Petten field case (the Netherlands).
  4. propagation through obstacles.

  **Non-stationary mode SWAN:**
  1. wave propagation and transformation in the field case of ‘Lake George’ (Australia) but now with SWAN applied as a non-stationary wave model;
  2. swell wave propagation using the non-stationary version of SWAN and with a higher order scheme for wave propagation in geographical space;
  3. time-limited (deep water) wave growth.

- to update a number of files in the precomputed directory if the successor of SWAN version 40.00 and updates is submitted to the bench mark tests. The reason for this is that a number of SWAN-commands that are presently used in the SWAN input file and the boundary file (*.BND) in the pre-computed directory differ from those in the directory computed. Note that these modifications have also to be made if a new command is introduced in SWAN.
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wl | delft hydraulics

Rotterdamseweg 185
postbus 177
2600 MH Delft
telefoon 015 285 85 85
telefax 015 285 85 82
e-mail info@wl-delft.nl
internet www.wl-delft.nl

Rotterdamseweg 185
p.o. box 177
2600 MH Delft
The Netherlands
telephone +31 15 285 85 85
telefax +31 15 285 85 82
e-mail info@wl-delft.nl
internet www.wl-delft.nl