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SKYLLA: Wave motion in and on coastal structures

Verification of kinematics of waves breaking on an offshore bar

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List of symbols

$A_j$  Fourier components of the free surface  \( \text{(m)} \)

$B_j$  Fourier components of the stream function  \( \text{(m/s)} \)

$c$  wave celerity  \( \text{(m/s)} \)

$h$  mean water depth  \( \text{(m)} \)

$k$  wave number  \( \text{(m}^{-1}) \)

$N$  number of Fourier components  \( \text{(-)} \)

$t$  time  \( \text{(s)} \)

$u$  horizontal velocity  \( \text{(m/s)} \)

$w$  vertical velocity  \( \text{(m/s)} \)

$x$  horizontal coordinate  \( \text{(m)} \)

$z$  vertical coordinate, $z = 0$ at the mean water surface  \( \text{(m)} \)

$\eta$  surface elevation  \( \text{(m)} \)
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1 Introduction

1.1 Framework for the development of the model SKYLLA

The development of the numerical model SKYLLA\(^1\) started within the framework of the European research project "MAST-G6 Coastal Structures". The objective was to develop a physical-based numerical formulation for water motion on a smooth slope as well as on and in permeable structures. This formulation led to the development of the numerical model SKYLLA. Due to the inspiring results obtained in this European project, The Road and Hydraulic Engineering Division of the Dutch Ministry of Transport and Public Works were prepared to lead the continuation of the development (see contract DWW 743). This further development, outside the European MAST-project, commenced in 1993. The research mainly concerns the following tasks:

1) Boundary conditions
2) Rubble-mound structures and porous flow
3) Downward slopes and overtopping
4) Treatment of turbulence
5) Treatment of air-entrapment
6) Treatment of roughness

The planning of those tasks is described in detail in Klein Breteler and Petit (1993). This report does not describe activities to extend the model but it is a verification of the numerical model using dedicated physical model tests. It verifies the model after completion of Task 1. Activities for Task 1 are described in Petit et al. (1994), activities for Task 2 are described in Van Gent et al. (1994).

1.2 Considerations for the development of SKYLLA

Numerous coastal structures are studied using small-scale physical models. However, physical modelling can be affected by scale effects. Due to scale effects, various phenomena under prototype conditions may differ from those under conditions present in small-scale physical models. In physical models variations in the lay-out of structures are often relatively laborious compared to numerical models. These problems, as well as the complexity of measurements in breaking waves, can be overcome by numerical modelling of the breaking waves on and in coastal structures. So, on the one hand the development of a numerical model as a research tool is very important; on the other hand, there are disadvantages such as the simplification and discretisation of the involved physical processes.

Existing one-dimensional models use simplified formulations of, for instance, the free surface. For many applications these simplifications are undesirable. The development of a three-dimensional model in the near future, able to simulate the complete breaking of a wave seems unrealistic. Therefore, it was decided to develop a two-dimensional (vertical) numerical model that can simulate breaking waves on various types of coastal structures,

\(^{1}\) The model SKYLLA is named after the sea monster from the Greek mythology, once a mistress of Poseidon, living on a rock and eating shipwrecked sailors.
first for wave motion on smooth impermeable slopes and later for wave motion on and in permeable structures. A proper representation of the wave impact will not be included yet.

1.3 Description of the numerical model SKYLLA

The studies performed in the European MAST-project resulted in the research tool SKYLLA which is, able to simulate breaking waves on impermeable smooth slopes. These studies are described in Broekens and Petit (1992) and Petit and Van den Bosch (1992) and are summarized by Van der Meer et al. (1992). A summary is given below.

The model uses Navier-Stokes equations in two dimensions with a constant turbulence viscosity. The technique for solving these Navier-Stokes equations in two dimensions is based on the "Volume of Fluid method", see Nichols and Hirt (1980). The fluid is considered to be incompressible. The model uses a staggered, non-equidistant grid where for each cell the fluid fraction can vary between zero (empty) and one (full) (Eulerian approach).

The model uses a complex description of the free surface based on an adapted flux-method known as "FLAIR", see Ashgriz and Poo (1991) and is capable of simulating free surfaces that can become multiple-connected while air-entrapment can be dealt with. Those two aspects are both essential for the simulation of plunging waves. The entrapped air is modelled as if it were vacuum.

The model includes the option to model the smooth impermeable slope with "no-slip" or with "free slip". The choice of the grid does not depend on the lay-out of the slope.

In the previous phase of the development of SKYLLA, incident waves as prescribed by the method by Rienecker and Fenton (1981) were implemented. Both the left-hand and the right-hand side boundary are weakly reflecting, enabling reflected waves to leave the computational domain with an acceptable small disturbance of the wave motion in the computational domain.

1.4 Required activities

The numerical model SKYLLA enables computations of breaking waves on various types of coastal structures. Although the simulations with the model indicate that many complex phenomena can be dealt with, such verifications are only qualitative; they show flow patterns that look familiar but the accuracy of the model is still unknown. Therefore, verification of the numerical results has been performed on and impermeable slope with an, on first sight, relatively orderly wave motion. The verification of a computation with a smooth impermeable slope is described in this report. The complexity of the performed test case lies in the large length-to-depth ratio along which the wave motion has to propagate. A small systematic error in the modelling of a wave may cause relatively large deviations in the simulated breaking process because the waves have to propagate over a significant large distance to reach the position where they actually break. This phenomenon causes much larger differences for computations with a large length-to-depth ratio. For computations of breaking waves on steep slopes this phenomenon is less important. In addition, both sides of the computational domain are open which provides an additional difficulty.
1.5 Outline

The physical model tests used to verify the numerical model results are described in Chapter 2. To verify whether the incident wave that is generated in the numerical model corresponds to the flow conditions in the wave flume, the model which provides this incident wave is verified in Chapter 3. The verification of the numerical model with the results of the physical model tests, is described in Chapter 4. The conclusions and recommendations in Chapter 5 will complete this study.
2 Physical model tests

2.1 Description of physical model tests

Physical model test were performed in the SCHELDT-flume ("Scheldegoot") of DELFT HYDRAULICS. This channel has a length of 45 m, a width of 1.0 m and a depth of 1.2 m. The side walls of the flume consist of glass windows. Within the framework of the so called "Access to Large Installations" programme of the Commission of the European Communities, tests were performed to study the kinematics of waves breaking partially on an offshore bar, see Luth et al. (1994). Additional measurements were carried out using the same experimental set-up to be able to verify the wave kinematics with numerical model results.

An offshore bar was modelled as an impermeable upward slope of 1:20 with a length of 12 m followed by a horizontal section of 4.0 m and a downward slope 1:10 with a length of 6.0 m. The still water depth with respect to the toe of the structure was 0.80 m, so the still-water depth on top of the bar was 0.20 m. At the back an active wave absorber was applied. The wave generator was compensated for reflections. Figure 1 shows a sketch of the experimental set-up.

![Experimental set-up](image)

Figure 1 Experimental set-up

Regular waves with a height of 0.29 m and a wave period of 1.8 s were used here (second order wave generation). No re-circulation of water from behind the bar towards the front side of the bar was included. The wave reflection in front of the bar was 2% or less and may be considered negligible. Surface elevations were measured with wave gauges at several cross-sections. Because surface elevations were required at all cross-sections, a film was used to record them. Surface elevations above the downward slope were not recorded. The camera, however, could not record the surface elevations for the whole area of interest at the same time. Therefore, more camera positions were used (15). The camera recorded surface elevations at one particular position for a number of wave periods after which the camera was moved to the next position. Because the tests were carried out with regular waves, the recorded surface elevations could be attached to the recorded surface elevations...
from another position of a time-interval of a round number of wave periods later. The surface elevations and the area with much entrapped air were registered after analysis of the film. The recorded surface elevations were digitalized for further analysis.

Horizontal and vertical components of the velocity were simultaneously measured with two-component Laser-Doppler Velocity meters. The instruments recorded the signal for ten minutes at each position. After this, recording was stopped after which the instrument was moved to another position without stopping wave generation. Because in every recording the time starts at zero, some appropriate measurement signal had to be used for phase synchronization of all signals. A pressure gauge positioned on the slope recorded the same phenomenon at exactly the same moment of time in every recording. Therefore, the signal of the pressure gauge was used as a reference to synchronize all other signals. As reference points in time the zero-upward crossings were used. In order to check this synchronization method, the recording of the surface elevation at $x = 0.2$ m during one wave period was selected from 14 different files and plotted in Figure A1 in Appendix A. As can be seen, the differences between the 14 lines are very small which confirms that the synchronization method works properly.

Velocities measured at four cross-sections in several vertical positions in each cross-section were used for verification of the numerical model, see Figure 2. One of the cross-sections was positioned 0.5 m in front of the 1:20 slope. This is the cross-section at which the computational domain starts in the numerical model (0.0 m). The second cross-section was positioned in an area where the waves did not break yet (5.0 m). The third cross-section was positioned in the area where breaking took place (9.0 m). The last cross-section was positioned in the area after breaking, where severe turbulence and relatively more air-entrainment occurs (12.0 m).

![SKYLLA: VERIFICATION VELOCITIES](image)

Figure 2 Rays in which velocities have been measured for verification of the numerical model
2.2 Results of physical model tests

The results of the wave gauges were analyzed. The recording of the surface elevations at $x = -0.8\, m$, $x = 0.0\, m$ and $x = 0.3\, m$ were compared in Figure A2 in Appendix A. Although the distance between the locations is small and the bottom in this area is horizontal, significant differences between the registrations were observed. Both the wave height and the wave shape changes. Moreover, none of the recordings seems to be symmetric. It seems that these differences are caused by some small free waves having frequencies higher than the frequency of the main wave. Another explanation could be that the 1:20 slope starting at $x = 0.5\, m$ affects the wave motion also in front of the slope. Because the ratio of the wave height and the water depth is rather low and because the slope is very gentle, this explanation is questionable. A third explanation could be that the undertow affects the wave motion near the front of the slope. A net transport occurs in the section of the vertical where the free surface fluctuates. In the case of a closed flume (no re-circulation), this net transport in the upper part of the vertical is compensated for by a net transport in the lower part of the vertical (undertow). Although this phenomenon may contribute to the differences it does not explain the asymmetry of the waves.

In the following the phenomenon of free higher harmonics is briefly explained. The natural wave shape depends on the water depth, the wave height and the wave period. In many circumstances the natural wave shape is not sinusoidal, but may be regarded as a superposition of a sine wave and some (bound) higher harmonics. If these bound higher harmonics are not accounted for in the wave board motion, then the natural wave will be generated together with free higher harmonics. At the wave board, the phases of the free and bound higher harmonics are exactly opposite. However, since the free and bound higher harmonics propagate at different speeds, phase lags between these waves occur depending on the distance to the wave board. These phase lags cause, in turn, differences in local wave heights and asymmetry of water level recordings.

In the model tests the wave board generated second-order waves which means that free third-order (or higher) waves are generated in the flume. Due to the breaking process also second-order and third-order waves are generated which may have affected the wave motion near the analyzed cross-sections. The amplitude of the third-order wave generated near the wave board is much smaller than the first and second-order waves and therefore, the differences in local wave heights can only be rather small due to these third-order waves. However, still the phenomenon of higher order waves is supposed to contribute to the observed asymmetry and variation in wave height at the different locations in the flume.

Figure 3 shows some measured surface elevations in the whole area of interest. The envelope of the surface elevations is also shown. It is clearly shown that at the place the 1:20 slope begins the maximum surface elevations increase. The wave height decreases before the breaking process starts at roughly $x = 7.0\, m$. Behind $x = 8.0\, m$ air is entrapped.

Results of the velocity measurements will be shown directly in comparison with the numerical model results (Appendix C). It appeared that the measured velocities in the first two cross-sections, before breaking, were very periodic. In the third cross-section where the waves break, the measured velocities are less periodic but still the characteristics of the signals are similar. In the last cross-section, after breaking, the measured velocities are not periodic and therefore less suitable for comparison with numerical model results.
Figure 3  Envelope of the measured surface elevations.
3 Supply of incident wave conditions

3.1 RF-WAVE as incident wave supplier

Most applications of SKYLLA will contain a left boundary from which periodic gravity waves enter the computation area. At this boundary the water motion should be supplied as a boundary condition. Since for most applications the position of the left boundary will be such that non-disturbed waves (at least non-breaking) will occur at this boundary, a theory for periodic gravity waves propagating over a horizontal bottom may be applied. Such a method, based on the computation method by Rienecker and Fenton (1981) has been implemented and described in Petit et al. (1994). Here, it will be verified whether the method is applicable for the present purpose or that measured data must be used to form incident waves.

3.2 Description of RF-WAVE

The computer program RF-WAVE made by G. Klopman of DELFT HYDRAULICS is able to compute the water motion in a periodic gravity wave propagating in a uniform current over a horizontal bottom. The program is based on a Fourier approximation method of Rienecker and Fenton (1981). A brief introduction is given here.

A set of non-linear equations is solved by using a Fourier approximation in such a way that, apart from the assumption of potential flow theory, the only approximation follows from the fact that the number of Fourier components is finite. Other methods usually contain more approximations.

Based on its broad applicability and its accuracy RF-WAVE is regarded to be an accurate computation method. In the following a brief introduction is given.

The flow field \((u, w)\) in periodic water waves on a horizontal bottom can be described by a stream function \(\Psi(x, z, t)\) of the following form:

\[
\Psi = (c + B_0)(z + h) + \sum_{l=1}^{N} \left( B_l \frac{\sinh jk(z + h)}{\cosh (jk h)} \cos jk(ct - x) \right)
\]

\[
u = -\frac{\partial \Psi}{\partial z}
\]

\[
w = -\frac{\partial \Psi}{\partial x}
\]

where

- \(B_l\) Fourier components of the stream function
- \(c\) wave celerity
- \(h\) mean water depth
- \(k\) wave number
- \(N\) number of Fourier components
- \(t\) time

\(\text{m/s}\) \(\text{m/s}\) \(\text{m}\) \(\text{m}^{-1}\) \((-)\) \(\text{s}\)
u horizontal velocity (m/s)
w vertical velocity (m/s)
x horizontal coordinate (m)
z vertical coordinate, \( z = 0 \) at the mean water surface (m)

The surface elevation is described by:

\[
\eta(x,t) = \sum_{j=1}^{N} A_j \cos jk(ct - x)
\]  

(2)

where

\( A_j \) Fourier components of the free surface (m)
\( \eta \) surface elevation (m)

The program computes both the surface elevation and the stream function Fourier components for a periodic gravity wave propagating on a uniform current over a horizontal bottom. It applies the non-linear free surface boundary conditions in a number of free-surface points distributed uniformly over half a wavelength. This results in a system of non-linear equations, with the surface point elevations and the stream function Fourier components as unknowns. The resulting system of equations is solved using Newton's method. The program allows for the specification of an arbitrary mean velocity at any elevation, or of an arbitrary mass transport.

This solution has been implemented in the model SKYLLA because for most applications the position of the left boundary will be such that non-disturbed waves (at least non-breaking) will occur at this boundary so that the applied theory is valid.

As the described approach does not account for reflected waves which will occur in most applications of SKYLLA, the solution must be adapted. The adapted input signal is described in Petit et al. (1994).

In the following section a verification of RF-WAVE as a supplier of incident waves in SKYLLA is performed by comparing results of RF-WAVE computations with measurement data in the cross-section at the beginning of the slope.

### 3.3 Verification of RF-WAVE as incident wave supplier

The surface elevation is recorded at several locations and the horizontal and vertical components of the local water velocities are registered at several locations in a series of levels above the bottom. The measurement data at \( x = 0.0 \) m are used for the validation because at this location the bottom is still horizontal.

The comparisons concern the following aspects of the water motion:

- the surface elevation as a function of time
- the profile of the horizontal velocity under the trough and the crest of the wave
Since the surface elevation as a function of time is not symmetric, the definition of the crest and the trough of the wave requires special attention. In this study, the crest and trough of the wave are defined as the points in time in the middle between the zero-crossings of the surface elevation.

The following input is used for the RF-WAVE calculation:

- **water depth**: 0.80 m
- **wave period**: 1.80 s
- **wave height**: 0.29 m
- **mass transport velocity**: 0.00 m/s
- **number of Fourier components**: 32
- **maximum relative error**: 1E-08
- **water density**: 1000.00 kg/m³
- **gravitational acceleration**: 9.81 m/s²

Output velocities have been generated at several elevations with respect to **swl**: 0.000, -0.050, -0.100, -0.150, -0.200, -0.250, -0.300, -0.350, -0.400, -0.450, -0.500, -0.550, -0.600, -0.650, -0.700, -0.750 and -0.799 m.

The measured and calculated surface elevations as functions of time are plotted in Figure A3 in Appendix A. In this figure the measured signal has been shifted slightly in order to make the average elevation in one wave period equal to zero. Both signals agree fairly good. The small differences include the asymmetry of the measured wave and the slightly lower measured crest. Both aspects are probably caused by the occurrence of free higher harmonics, as mentioned earlier.

The measured and calculated profiles of the horizontal velocity under the crest and the trough of the wave are plotted in Figure 4. As mentioned earlier undertow occurred. This phenomenon is included in RF-WAVE. However, due to the assumption of potential flow theory the velocity profile of this undertow is constant. In practice the velocity profile is not constant but smaller velocities occur near the bottom and higher velocities more upward in the vertical. This is the reason that the predicted RF-WAVE velocities near the bottom in the direction of the wave propagation are too low and the absolute velocities in the opposite direction too large. More upward in the velocity profile, RF-WAVE predicts too large velocities in the direction of the wave propagation and too small (absolute) velocities in the opposite direction. This explains the observed differences in Figure 4 with respect to the shapes of the velocity profiles. Also the results of the crest velocities minus the trough velocities are higher for the measured data than for those computed. This may be due to the fact that the waves in the flume were somewhat higher than those in the RF-WAVE computation.
Figure 4 Comparison of measured velocity profiles and calculated profiles by RF-WAVE
4 Verification with physical model tests

4.1 Verification of surface elevations

In section 2.1 a description of the tests has been given. Regular waves with a height of 0.29 m and a wave period of 1.8 s were used. No re-circulation of water from behind the bar towards the front side of the bar was included. This resulted in a zero net transport over the bar. In the case that the rear side would be open, then a net transport over the bar occurs. In the computation only the sections with the upward and horizontal slopes were modelled. The incident wave boundary was positioned 0.5 m in front of the upward slope (1:20), the outflow boundary was positioned at the end of the horizontal section at the crest of the bar. Because the weakly reflecting boundaries allow for a net transport over the bar, a difference occurs in the comparison: the test did not show a net transport of the bar whereas the computations did. The velocity of the net transport over the bar is about 0.05 m/s.

For the viscosity a low value was chosen: 0.001 m²/s. Because the treatment at the surface required a higher viscosity to arrive at a stable computation, the value was chosen here to be 0.008 m²/s. A sensitivity analysis according to Section 4.3 was performed to study the influence of the viscosity.

Figure B1 shows surface elevations at two points in time which cover exactly two wave periods. The figure shows that the computations are not perfectly periodic but the differences occur mainly in the area where air is entrapped. In this area the computations cannot become periodic because the numerical model accumulates air which does not lead to a periodic situation. However, the periodicity is satisfactory.

Figure 5 shows the computed surface elevation at a few points of time. The envelope of these surface elevations can be compared with Figure 3. The comparison shows that:

a) In the computation there is no increase in wave height in the first part above the 1:20 slope (x = 2-4 m) and there is no decrease in wave height (x = 4-6 m) before the breaking process starts (x = 8-10 m)
b) The breaking processes occur in the same area (x = 8-11 m)
c) The wave height before breaking is rather accurate (x = 6-7 m) although the increase in wave height just before breaking (x = 7-8 m) causes a somewhat larger wave height before a decrease in wave height occurs
d) The transmitted wave height is rather accurate
e) The breaking process in the numerical model occurs faster

ad a) The first disparity is partially due to inaccuracies of the measurements: at the concerning water depth the influence of the slope cannot cause such a significant increase in wave height which is due to shoaling. It is believed that the free higher order harmonics contribute to these changes in wave height, see also Section 3.3. Although the numerical model can deal with higher harmonics, the generation of these harmonics in the physical model tests is different due to slightly different incident waves and a longer fluid domain (the computations do not simulate the complete wave flume but only the section with the upward slope). The decrease in
wave height before breaking \((x = 4.6 \text{ m})\) is significantly larger than one would expect, due to shoaling.

ad b) In such a relatively long computational domain with a smooth 1:20 slope (in relation to the wave length) small systematic errors would easily cause the breaking process to occur in a different part of the computational domain; because the breaking process strongly depends on the wave height and the water depth, small errors in one of these cause the waves to break at a significant horizontal distance from the real area of breaking waves. Therefore, it is appropriate that the numerical model represents this phenomenon in the correct section.

ad e) In reality the decrease in wave height to the height of the transmitted wave develops slower. This is partially due to the fact that in the numerical model no increase in wave height occurs before breaking causing that the difference with the transmitted wave height is larger.

![Calculated Free Surface; 1:20 Slope](image)

Figure 5 Envelope of the calculated surface elevations

In the Figures B2-B11 comparisons between measured surface elevations and calculated surface elevations are shown for ten points in time \((T_0 \text{ is at } t = 7.92 \text{ in the computations})\). The comparisons show that:

f) The wave celerity in the computations is smaller (smaller wave length)

g) In the area where much air is entrapped (area between two dashed lines) the computations show a free surface which is positioned roughly in this area (taking the phase shift into account).

ad f) Although the discretisation of the time-dependent terms causes the wave celerity in the numerical model to be somewhat smaller than in reality, this is not the main cause of the differences in wave celerity. Small deviations of the wave height or in the velocities of the incident waves probably cause a slightly smaller wave celerity in the numerical model. However, in principle a deviation of wave celerity is not the main problem. If the phenomena are still represented correctly, these phenomena
only occur at a slightly different point in time which is no problem for most applications.

ad g) For this area the phenomena of air entrapment and floating of air-bubbles is important. In the model, these phenomena are not represented accurately and therefore the value of numerical results should not be overrated. However, comparison with the measurements in this part does not indicate that the model gives an incorrect impression of the flow field.

4.2 Verification of velocities

Figure 2 shows the positions at which velocities have been measured for comparison with the numerical model results. The measured time-signals at these 21 positions are compared with the numerical results of the computation as discussed in the previous section.

The signals in the first ray are in fact a comparison of the measured signals and the incident waves in SKYLLA obtained from the computer program RF-WAVE. In section 3.3, the differences between this incident wave signals and the measurement data in this ray are discussed. The main difference is that for the measurements the crest velocity minus trough velocities are larger (stroke is larger). Figures C2-C7 in Appendix C show signals from positions in the first ray. Figure 6 shows an example of these. The figure clearly shows that the vertical velocities are rather accurate. The trough velocity in the horizontal direction is underestimated, roughly 10-15% of the "crest minus trough" velocity.

Figure 6 Example of a comparison between measured and calculated velocities at the inflow boundary
Figures C8-C13 in Appendix C are comparisons of velocities before breaking takes place. Figure 7 shows an example of them. The comparisons show that a phase shift occurs just like as in the comparisons of the surface elevations. Except for this rather unimportant phase shift, the comparisons of the vertical velocities show relatively accurate results; the shape of the signals are similar although for the higher positions in the vertical the calculated maxima are higher. The calculated "crest minus trough" velocities are systematically lower. The differences of the "crest-trough velocity" are not much larger (roughly 15%-20%) than in the first ray although now the calculated crest velocities are higher than the measured ones and the calculated trough velocities are significantly lower than the measured ones.

Figures C14-C19 in Appendix C are comparisons of velocities in the area where breaking takes place: this is indicated by the irregularity in the measured signal. Both the measured crest velocities and the measured trough velocities are larger. These underestimations of the velocities are clearly related to the underestimation of the wave height at this location. The differences in the "crest-trough" velocities are roughly 15%-20%. The differences in the vertical velocities are smaller.

Figures C20-C22 in Appendix C show comparisons of velocities in a ray after breaking, just before the horizontal section of the bar. Obviously, a relatively turbulent flow field occurs in this area. Although the calculated signals do not show this irregularity in the signals due to the incapability of the model to simulate small-scale turbulence and small-scale convective transport, a comparison with the measured signals is not useful.

It can be concluded that

a) the differences between measured and calculated velocities are roughly 15%-20% of the "crest-trough" velocities
b) the measured "crest-trough" velocities are systematically higher
c) comparison of vertical velocities shows better results than for the horizontal velocities
d) the differences are for a large part caused by too low inflow velocities at the incident wave boundary. These low inflow velocities cause the wave propagation to deviate from that occurring in reality. The observed differences in wave height are related to the differences in velocities (underestimated wave height belongs to underestimated velocities).

4.3 Sensitivity analysis

A sensitivity analysis has been performed to study the influence of the choice of the viscosity and the choice of the grid size. Three computations with the same input parameters, except for the eddy-viscosity, have been performed to study the sensitivity of calculated surface elevations to variations in the eddy-viscosity. The computation for the verification has been performed with a viscosity of 0.001 m²/s except for the cells near the free surface (near empty cells) where 0.008 m²/s has been used for stability reasons. These comparisons for the verification of the model are shown in Appendix B and discussed in section 4.1. Two additional computations have been performed with eddy-viscosities of 0.005 m²/s and 0.008 m²/s in the whole computational area. In Appendix D the three computations have been mutually compared at several points in time. Appendix E shows comparisons of the surface elevations with the measured surface elevations.

Figures D1-D4 in Appendix D show that a larger viscosity leads to a faster wave propagation probably caused by the slightly higher average water level. Furthermore, a larger viscosity leads to larger maximum surface elevations. The comparisons in Appendix E show that the comparison for the computation with the smallest eddy-viscosity is better than the one with the largest eddy-viscosity. This was expected, because the eddy-viscosity is estimated still smaller than 0.001 m²/s in the area before breaking (x = 0-8 m). The differences between the computations with a viscosity of 0.001 m²/s and 0.005 m²/s are insignificant. As the main differences in the Figures D1-D4, of which Figure 8 is a characteristic example, are caused by phase differences and not by significant dissimilar phenomena, it is concluded that the influence of the eddy-viscosity is clearly present but that it not necessarily leads to an unusable representation of the flow field.

An additional computation has been performed to study the influence of the choice of the grid size. A computation with a grid size smaller than the one used for verification has been used (Appendix B). The grid size is decreased with a factor of 1.5 in both directions which leads to twice the number of grid cells in the computational domain. The computing time is significantly larger due to this larger number of cells which makes such computations relatively impractical for running on existent common work-stations. Figures E21-E28 show the comparisons of measured surface elevations with the computational results. Figures D5-D8 in Appendix D, of which Figure 9 is a representative example, show that the computation with the smaller grid size leads to insignificant differences in the area before breaking (x = 0-8 m). In the section where breaking occurs (x = 8-14 m) the computation with the smallest grid size shows little more detail. The differences are so small that it is not possible to indicate which computation gives the best results. It is concluded that the results are not very sensitive to the grid size considering the small grid sizes that have been applied.
Figure 8 Example of the influence of the viscosity on the calculated velocities

Figure 9 Example of the influence of the grid size on the calculated surface elevations
5 Conclusions and recommendations

The conclusions concerning the verification of RF-WAVE output and SKYLLA results have already been discussed. Here, the main conclusions will be repeated.

The computer program RF-WAVE has been used as incident wave supplier. The physical model test used to verify the model SKYLLA has also been used for comparison with RF-WAVE output. These comparisons concerned the surface elevations and the velocity profiles under the trough and crest of the incoming waves. Agreement between the measured and calculated surface elevations as functions of time is fairly good. Agreement between the measured and calculated profiles of the horizontal velocity under the crest and the trough of the wave is also fairly good. The differences between measured and calculated values may be attributed to the occurrence of free higher harmonics and to the occurrence of undertow. Based on the characteristics of RF-WAVE and the validation performed in this study, RF-WAVE is recommended as supplier of incident wave conditions to SKYLLA because the order of magnitude of the difference is satisfactorily small for the present purposes.

The surface elevations and the velocities as computed by SKYLLA were verified. Although the wave propagation is slightly different in the numerical model, the breaking process occurs in the same area. The breaking process itself develops faster in the numerical model; the decrease in wave height is faster. However, the transmitted wave is still rather accurate. The wave celerity in the computations is smaller (smaller wave length) but this is not a problem for most applications.

The differences between measured and calculated velocities are roughly 15%-20% of the "crest-trough" velocities. It appeared that the measured "crest-trough" velocities are systematically higher. The comparison of vertical velocities shows better results than for the horizontal velocities. The differences are for a large part caused by too low inflow velocities at the incident wave boundary. As a result the computed wave propagation and that in reality differ. The observed differences in wave heights are related to the differences in velocities (underestimated wave height belongs to underestimated velocities).

A sensitivity analysis has been performed with respect to the parameters eddy-viscosity and the grid size. It is concluded that the influence of the eddy-viscosity is clearly present but that it not necessarily leads to an unusable representation of the flow field. It is concluded that the results are not very sensitive to the grid size, considering the small grid sizes that have been applied.

It is recommended that the RF-WAVE model should be applied as an incident wave supplier although for cases with undertow the assumptions on which the program is based are not satisfied. This introduces deviations of which the magnitude must be considered for each application.

It is recommended that the model SKYLLA should not be applied for those scarce cases in which the wave celerity is of primary concern. However, for those cases where the space-step and time-step can be reduced significantly it is expected that also the wave celerity can be modelled rather accurate. For the smooth slope, as studied here, the model provides surface elevations and velocities of which the accuracy for many applications is satisfactory. The problem of the choice of the viscosity can be solved by implementing a simple model
for the eddy-viscosity. The eddy-viscosity can be made dependent on the property rotation which results in a eddy-viscosity which depends on time, space and the occurrence of vortices.

In addition, it is necessary to verify the model with other types of structures. The present verification gives insight in the accuracy of the model, but this is not sufficient for quantitative conclusions concerning waves on steep slopes, for instance. The simulation of the wave kinematics as studied here, however, gives sufficient confidence in the model to develop, extend and verify the model for a larger field of application.
References


Gent, M.R.A. van, H.A.H. Petit and P. van den Bosch (1994), SKULLA: Wave Motion in and on Coastal Structures; Implementation and verification of flow on and in permeable structures, draft report H1780, DELFT HYDRAULICS.


Petit, H.A.H. and P. van den Bosch (1992), SKULLA: Wave Motion in and on Coastal Structures; Numerical analysis of program modifications, MAST-G6S report, DELFT HYDRAULICS.

Petit, H.A.H., P. van den Bosch and M.R.A. van Gent (1994), SKULLA: Wave Motion in and on Coastal Structures; Implementation and verification of modified boundaries, Report H1780, DELFT HYDRAULICS.

Appendix A

Verification of incident wave signals
Figure A1  Comparison of measured surface elevation from different recordings at the same position after synchronization

Figure A2  Comparison of measured surface elevations at different positions in front of the 1:20 slope
Figure A3  Comparison of measured surface elevations and predicted surface elevations by RF-WAVE

Figure A4  Comparison of measured velocity profiles and calculated profiles by RF-WAVE
Appendix B

Verification of surface elevations
Verification of surface elevations

Input data for the computation for verification with measured surface elevations

Slope:

Impermeable
Submerged
Free slip boundary
Horizontal and 1:20 sections
Crest of structure : 0.60 m
Length of 1:20 slope : 12.0 m
Length of horizontal section : 1.50 m

Waves:

Regular
Wave height : 0.29 m
Wave period : 1.80 s
Wave length : 4.41 m
Still water level : 0.80 m

Boundaries:

Weakly reflecting
Waves generated with RF-Wave:
Number of Fourier components : 16
Net mass transport with c_{M} : 0.047 m/s
Mean Eulerian velocity c_{E} : 0.0 m/s
\rho_{w} : 1000 kg/m^3

Grid:

Non-equidistant
No. of cells in horizontal direction : 480
No. of cells in vertical direction : 50
Length of computational domain : 14.0 m
Height of computational domain : 1.20 m

Numerical computation:

Maximum time-step : 0.01 s
Length of computation : 13.0 s
Upwind fraction : 0.2
Eddy viscosity at the surface : 0.008 m^2/s
Eddy viscosity in inner part : 0.001 m^2/s
Figure B1  Comparison of calculated surface elevations to check the periodicity of the computations; two wave cycles between both recordings
Figure B2 Comparison of measured and calculated surface elevations.

Figure B3 Comparison of measured and calculated surface elevations.
Figure B4 Comparison of measured and calculated surface elevations.

Figure B5 Comparison of measured and calculated surface elevations.
Figure B6 Comparison of measured and calculated surface elevations.

Figure B7 Comparison of measured and calculated surface elevations.
Figure B8 Comparison of measured and calculated surface elevations.

Figure B9 Comparison of measured and calculated surface elevations.
Figure B10 Comparison of measured and calculated surface elevations.

Figure B11 Comparison of measured and calculated surface elevations.
Appendix C

Verification of velocities
Input data for the computation for verification with measured velocities

See Appendix B.

Figure C1 Positions for the comparison of measured and calculated velocities
Figure C2 Comparison of measured and calculated velocities; u denotes horizontal velocities, w denotes vertical velocities.

Figure C3 Comparison of measured and calculated velocities; u denotes horizontal velocities, w denotes vertical velocities.
Figure C4 Comparison of measured and calculated velocities; u denotes horizontal velocities, w denotes vertical velocities.

Figure C5 Comparison of measured and calculated velocities; u denotes horizontal velocities, w denotes vertical velocities.
Figure C6 Comparison of measured and calculated velocities; u denotes horizontal velocities, w denotes vertical velocities.

Figure C7 Comparison of measured and calculated velocities; u denotes horizontal velocities, w denotes vertical velocities (discontinuities in the signals are caused by dry periods within the wave cycle).
Figure C8 Comparison of measured and calculated velocities; u denotes horizontal velocities, w denotes vertical velocities.

Figure C9 Comparison of measured and calculated velocities; u denotes horizontal velocities, w denotes vertical velocities.
Figure C10  Comparison of measured and calculated velocities; u denotes horizontal velocities, w denotes vertical velocities.

Figure C11  Comparison of measured and calculated velocities; u denotes horizontal velocities, w denotes vertical velocities.
Figure C12  Comparison of measured and calculated velocities; u denotes horizontal velocities, w denotes vertical velocities.

Figure C13  Comparison of measured and calculated velocities; u denotes horizontal velocities, w denotes vertical velocities.
Figure C14 Comparison of measured and calculated velocities; u denotes horizontal velocities, w denotes vertical velocities.

Figure C15 Comparison of measured and calculated velocities; u denotes horizontal velocities, w denotes vertical velocities.
Figure C16  Comparison of measured and calculated velocities; u denotes horizontal velocities, w denotes vertical velocities.

Figure C17  Comparison of measured and calculated velocities; u denotes horizontal velocities, w denotes vertical velocities.
Figure C18 Comparison of measured and calculated velocities; u denotes horizontal velocities, w denotes vertical velocities.

Figure C19 Comparison of measured and calculated velocities; u denotes horizontal velocities, w denotes vertical velocities.
Figure C20 Comparison of measured and calculated velocities; u denotes horizontal velocities, w denotes vertical velocities.

Figure C21 Comparison of measured and calculated velocities; u denotes horizontal velocities, w denotes vertical velocities.
Figure C22 Comparison of measured and calculated velocities; u denotes horizontal velocities, w denotes vertical velocities.
Appendix D

Sensitivity analysis
Sensitivity analysis

Influence of variations in the eddy-viscosity

Three computations with the same input parameters except for the eddy-viscosity have been performed to study the sensitivity of calculated surface elevations to variations of the eddy-viscosity. See Appendix B for the input parameters. The first computation has been performed with a viscosity of 0.008 m$^2$/s at the free surface and a viscosity of 0.001 m$^2$/s in the inner part of the wet area. Two runs with a constant viscosity in the whole wet area including the free surface of 0.005 and 0.008 m$^2$/s respectively have been performed.
Figure D1  Sensitivity of calculated surface elevations to variations in the eddy-viscosity; $T=7.92$ s.

Figure D2  Sensitivity of calculated surface elevations to variations in the eddy-viscosity; $T=8.40$ s.
Figure D3  Sensitivity of calculated surface elevations to variations in the eddy-viscosity; T = 8.88 s.

Figure D4  Sensitivity of calculated surface elevations to variations in the eddy-viscosity; T = 9.36 s.
Influence of the density of the grid

Two computations with the same input parameters except for the grid size have been performed to study the sensitivity of calculated surface elevations to variations of the grid. See Appendix B for the input parameters for the first computation. The second computation has been performed with 2.25 times more cells which has been achieved by multiplying both the Δx and Δz with 1.5. This last computation uses a considerably longer computing time than the first one (approximately 4 times more).
Figure D5  Sensitivity of calculated surface elevations to variations in the grid size; T=7.92 s.

Figure D6  Sensitivity of calculated surface elevations to variations in the grid size; T=8.40 s.
Figure D7  Sensitivity of calculated surface elevations to variations in the grid size; $T=8.88$ s.

Figure D8  Sensitivity of calculated surface elevations to variations in the grid size; $T=9.36$ s.
Appendix E

Comparison of surface elevations with alternative computations
Comparison of surface elevations with alternative computations

Input data for the first alternative computation (with different viscosity)

Slope:

Impermeable
Submerged
Free slip boundary
Horizontal and 1:20 sections
Crest of structure : 0.60 m
Length of 1:20 slope : 12.0 m
Length of horizontal section : 1.50 m

Waves:

Regular
Wave height : 0.29 m
Wave period : 1.80 s
Wave length : 4.41 m
Still water level : 0.80 m

Boundaries:

Weakly reflecting
Waves generated with RF-Wave:
Number of Fourier components : 16
Net mass transport with \( c_M \) : 0.047 m/s
Mean Eulerian velocity \( c_E \) : 0.0 m/s
\( \rho_w \) : 1000 kg/m³

Grid:

Non-equidistant
No. of cells in horizontal direction : 480
No. of cells in vertical direction : 50
Length of computational domain : 14.0 m
Height of computational domain : 1.20 m

Numerical computation:

Maximum time-step : 0.01 s
Length of computation : 13.0 s
Upwind fraction : 0.2
Eddy viscosity at the surface : 0.005 m²/s
Eddy viscosity in inner part : 0.005 m²/s
Figure E1  Comparison of measured and calculated surface elevations; $\kappa = 0.005 \text{ m}^2/\text{s}$.

Figure E2  Comparison of measured and calculated surface elevations; $\kappa = 0.005 \text{ m}^2/\text{s}$.
Figure E3 Comparison of measured and calculated surface elevations; $\eta = 0.005 \text{ m}^2/\text{s}$.

Figure E4 Comparison of measured and calculated surface elevations; $\eta = 0.005 \text{ m}^2/\text{s}$.
Figure E5  Comparison of measured and calculated surface elevations; $\xi=0.005 \text{ m}^2/\text{s}$.

Figure E6  Comparison of measured and calculated surface elevations; $\xi=0.005 \text{ m}^2/\text{s}$.
Figure E7 Comparison of measured and calculated surface elevations; $\nu=0.005$ m$^2$/s.

Figure E8 Comparison of measured and calculated surface elevations; $\nu=0.005$ m$^2$/s.
Figure E9 Comparison of measured and calculated surface elevations; $\eta_0=0.005 \text{ m}^2/\text{s}$.

Figure E10 Comparison of measured and calculated surface elevations; $\eta_0=0.005 \text{ m}^2/\text{s}$.
Input data for the second alternative computation (with different viscosity)

Slope:

Impermeable
Submerged
Free slip boundary
Horizontal and 1:20 sections

Crest of structure : 0.60 m
Length of 1:20 slope : 12.0 m
Length of horizontal section : 1.50 m

Waves:

Regular
Wave height : 0.29 m
Wave period : 1.80 s
Wave length : 4.41 m
Still water level : 0.80 m

Boundaries:

Weakly reflecting
Waves generated with RF-Wave:

Number of Fourier components : 16
Net mass transport with $c_M$ : 0.047 m/s
Mean Eulerian velocity $c_E$ : 0.0 m/s
$\rho_w$ : 1000 kg/m$^3$

Grid:

Non-equidistant
No. of cells in horizontal direction : 480
No. of cells in vertical direction : 50
Length of computational domain : 14.0 m
Height of computational domain : 1.20 m

Numerical computation:

Maximum time-step : 0.01 s
Length of computation : 13.0 s
Upwind fraction : 0.2
Eddy viscosity at the surface : 0.008 m$^2$/s
Eddy viscosity in inner part : 0.008 m$^2$/s
Figure E11 Comparison of measured and calculated surface elevations; \( \nu = 0.008 \text{ m}^2/\text{s} \).

Figure E12 Comparison of measured and calculated surface elevations; \( \nu = 0.008 \text{ m}^2/\text{s} \).
Figure E13 Comparison of measured and calculated surface elevations; \( \gamma = 0.008 \text{ m}^3/\text{s} \).

Figure E14 Comparison of measured and calculated surface elevations; \( \gamma = 0.008 \text{ m}^3/\text{s} \).
**Figure E15** Comparison of measured and calculated surface elevations; $\xi=0.008$ m$^2$/s.

**Figure E16** Comparison of measured and calculated surface elevations; $\xi=0.008$ m$^2$/s.
Figure E17 Comparison of measured and calculated surface elevations; $\kappa=0.008$ m$^3$/s.

Figure E18 Comparison of measured and calculated surface elevations; $\kappa=0.008$ m$^3$/s.
Figure E19  Comparison of measured and calculated surface elevations; $\nu = 0.008 \text{ m}^2/\text{s}$.

Figure E20  Comparison of measured and calculated surface elevations; $\nu = 0.008 \text{ m}^2/\text{s}$.
Input data for the third alternative computation (with different grid size)

Slope:

- Impermeable
- Submerged
- Free slip boundary
- Horizontal and 1:20 sections
- Crest of structure: 0.60 m
- Length of 1:20 slope: 12.0 m
- Length of horizontal section: 1.50 m

Waves:

- Regular
  - Wave height: 0.29 m
  - Wave period: 1.80 s
  - Wave length: 4.41 m
  - Still water level: 0.80 m

Boundaries:

- Weakly reflecting
- Waves generated with RF-Wave:
  - Number of Fourier components: 16
  - Net mass transport with $c_M$: 0.047 m/s
  - Mean Eulerian velocity $c_E$: 0.0 m/s
  - $\rho_w$: 1000 kg/m$^3$

Grid:

- Non-equidistant
  - No. of cells in horizontal direction: 720
  - No. of cells in vertical direction: 75
  - Length of computational domain: 14.0 m
  - Height of computational domain: 1.20 m

Numerical computation:

- Maximum time-step: 0.01 s
- Length of computation: 13.0 s
- Upwind fraction: 0.2
- Eddy viscosity at the surface: 0.008 m$^2$/s
- Eddy viscosity in inner part: 0.001 m$^2$/s
Figure E21  Comparison of measured and calculated surface elevations; grid size 1.5 times smaller in both directions.

Figure E22  Comparison of measured and calculated surface elevations; grid size 1.5 times smaller in both directions.
Figure E23 Comparison of measured and calculated surface elevations; grid size 1.5 times smaller in both directions.

Figure E24 Comparison of measured and calculated surface elevations; grid size 1.5 times smaller in both directions.
Figure E25 Comparison of measured and calculated surface elevations; grid size 1.5 times smaller in both directions.

Figure E26 Comparison of measured and calculated surface elevations; grid size 1.5 times smaller in both directions.
Figure E27 Comparison of measured and calculated surface elevations; grid size 1.5 times smaller in both directions.

Figure E28 Comparison of measured and calculated surface elevations; grid size 1.5 times smaller in both directions.
Figure E29 Comparison of measured and calculated surface elevations; grid size 1.5 times smaller in both directions.

Figure E30 Comparison of measured and calculated surface elevations; grid size 1.5 times smaller in both directions.
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