



Aalborg Universitet

AALBORG UNIVERSITY
DENMARK

Development of a Generic Power Simulation Tool for Overtopping Based WEC

Bogarino, Bruno; Kofoed, Jens Peter; Meinert, Palle

Publication date:
2007

Document Version
Publisher's PDF, also known as Version of record

[Link to publication from Aalborg University](#)

Citation for published version (APA):
Bogarino, B., Kofoed, J. P., & Meinert, P. (2007). Development of a Generic Power Simulation Tool for Overtopping Based WEC. Aalborg: Department of Civil Engineering, Aalborg University. (DCE Technical Reports; No. 35).

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

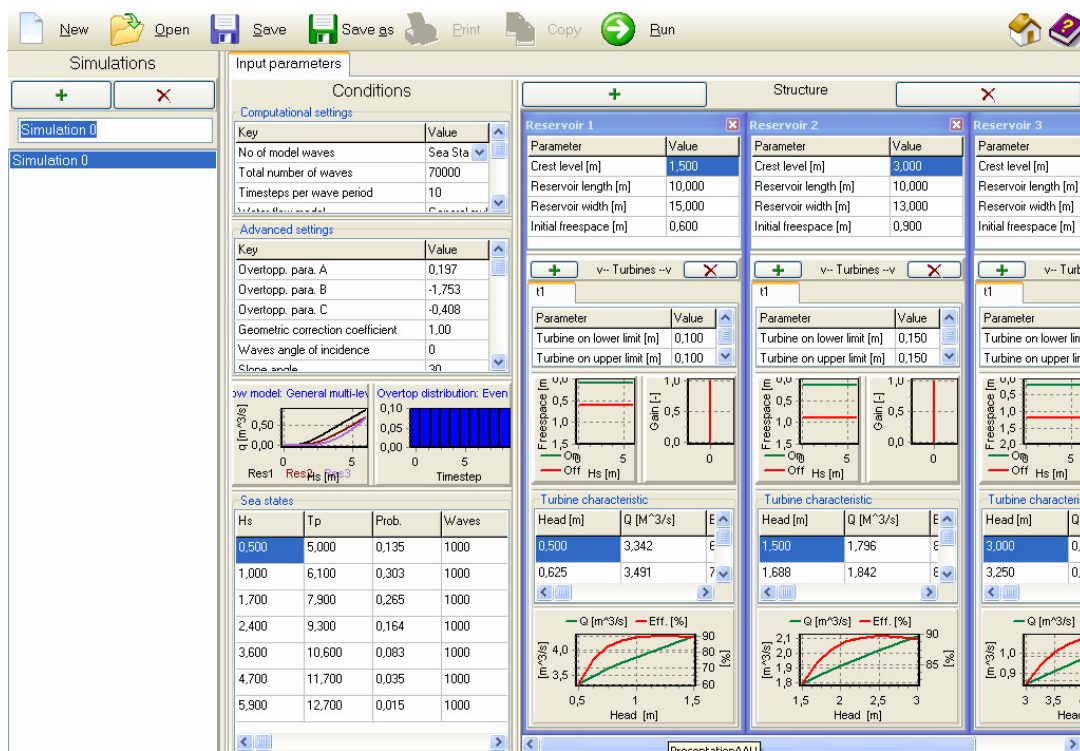
- ? Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- ? You may not further distribute the material or use it for any profit-making activity or commercial gain
- ? You may freely distribute the URL identifying the publication in the public portal ?

Take down policy

If you believe that this document breaches copyright please contact us at vbn@aub.aau.dk providing details, and we will remove access to the work immediately and investigate your claim.

Development of a generic power simulation tool for overtopping based WEC

B. Borgarino
J. P. Kofoed
P. Meinert



Aalborg University
Department of Civil Engineering
Laboratory of Hydraulics and Coastal Engineering

DCE Technical Report No. 35

Development of a generic power simulation tool for overtopping based WEC

by

Bruno Borgarino
Jens Peter Kofoed
Palle Meinert

September 2007

© Aalborg University

Scientific Publications at the Department of Civil Engineering

Technical Reports are published for timely dissemination of research results and scientific work carried out at the Department of Civil Engineering (DCE) at Aalborg University. This medium allows publication of more detailed explanations and results than typically allowed in scientific journals.

Technical Memoranda are produced to enable the preliminary dissemination of scientific work by the personnel of the DCE where such release is deemed to be appropriate. Documents of this kind may be incomplete or temporary versions of papers—or part of continuing work. This should be kept in mind when references are given to publications of this kind.

Contract Reports are produced to report scientific work carried out under contract. Publications of this kind contain confidential matter and are reserved for the sponsors and the DCE. Therefore, Contract Reports are generally not available for public circulation.

Lecture Notes contain material produced by the lecturers at the DCE for educational purposes. This may be scientific notes, lecture books, example problems or manuals for laboratory work, or computer programs developed at the DCE.

Theses are monographs or collections of papers published to report the scientific work carried out at the DCE to obtain a degree as either PhD or Doctor of Technology. The thesis is publicly available after the defence of the degree.

Latest News is published to enable rapid communication of information about scientific work carried out at the DCE. This includes the status of research projects, developments in the laboratories, information about collaborative work and recent research results.

Published 2007 by
Aalborg University
Department of Civil Engineering
Sohngaardsholmsvej 57,
DK-9000 Aalborg, Denmark

Printed in Aalborg at Aalborg University

ISSN 1901-726X
DCE Technical Report No. 35

Recent publications in the DCE Technical Report Series

Borgarino, B. and Brorsen, M.: *Estimation of wave conditions at Liseleje location*. DCE Technical Report No. 23, ISSN 1901-726X. Dep. of Civil Eng., Aalborg University, July 2007.

Borgarino, B. and Kofoed, J. P.: *Development of a generic power simulation tool for overtopping based wave energy devices*. DCE Technical Report No. 35, ISSN 1901-726X. Dep. of Civil Eng., Aalborg University, September 2007.

Borgarino, B., Kofoed, J. P. and Meinert, P.: *Power production from integration of overtopping based WEC in a breakwater at Liseleje*. DCE Technical Report No. 36, ISSN 1901-726X. Dep. of Civil Eng., Aalborg University, September 2007.

Borgarino, B., Kofoed, J. P. and Tedd, J.: *Experimental overtopping investigation for the Wave Dragon – effects of reflectors and their attachments*. DCE Technical Report No. 37, ISSN 1901-726X. Dep. of Civil Eng., Aalborg University, September 2007.

List of symbols and abbreviations

MWL	Mean Water Level
SSG	Seawave Slot-Cone Generator
WD	Wave Dragon
WEC	Wave Energy Converter
A_b [m ²]	buoyancy area (floating devices)
A_{res} [m ²]	reservoir area
A, C [-]	coefficients of overtopping formula
B [-]	coefficient of overtopping vertical distribution
d [m]	water depth
d_r [m]	draft
$EffOv$ [%]	overtopping efficiency of the reservoir
$EffRes$ [%]	reservoir efficiency, considering the spillage
$EffTurb$ [%]	average turbine efficiency
f [m]	freespace
g [m/s ²]	gravity
h [m]	head applied to the turbines
Hs [m]	significant wave height
L [m]	length of the reservoir (in the direction of wave propagation)
L_{op} [m]	deep water wave length
$N_{reservoirs}$ [-]	number of reservoirs (simulation software)
$N_{substeps}$ [-]	number of time steps per wave
N_{waves} [-]	number of waves per sea states
P_{ov} [-]	probability of overtopping occurrence
$prob$ [-]	probability of wave occurrence
P_{wave} [W/m]	available power per meter of wave crest
q [m ³ /s/m]	dimensional average overtopping flow per meter of wave crest
Q [-]	dimensionless average overtopping flow per meter of wave crest
q_{in} [m ³ /s]	instant overtopping water flow in the reservoir
q_{over} [m ³ /s]	spill back to sea water flow
q_{res} [m ³ /s]	flow change in the reservoir
q_{turb} [m ³ /s]	water flow expelled by the turbines
R [m]	dimensionless crest level
Rc [m]	crest level
S_{op} [-]	wave steepness

T_{on} [m]	turbine turn on level
T_{off} [m]	turbine turn off level
T_p [s]	peak period of the wave spectrum
W [m]	width of the overtopping ramp and of the reservoir
z [m]	altitude
α [°]	slope of the overtopping ramp. α_m is the optimal slope angle
β [°]	wave attack angle
γ [-]	JONSWAP enhancement peak
γ_β [-]	overtopping correction coefficient for non perpendicular waves
η_{turb} [%]	characteristic turbine efficiency
κ [-]	coefficient equal to 0.41
λ_α [-]	overtopping correction coefficient for slope angle different from α_m
λ_{dr} [-]	overtopping correction coefficient for overtopping slope not extending to the seabed
λ_s [-]	overtopping correction coefficient extend results from Van de Meer and Jansen
ρ [kg/m ³]	mass of water per cubic meter

Contents

1	Overtopping models	1
1.1	Geometry of overtopping wave energy converters	1
1.2	Overtopping discharge models	2
1.2.1	Introduction to overtopping	2
1.2.2	Reference single level	3
1.2.3	SSG : a three reservoir device	3
1.2.4	Wave Dragon	4
1.2.5	Time dependency of overtopping	5
2	Presentation of the original simulation software	5
2.1	Input and output of the software	5
2.1.1	Input data	5
2.1.2	Output results	6
2.2	Fundamental equations and algorithms	6
3	Modifications of the software	7
3.1	Insertion of new overtopping models	7
3.2	Computation of the buoyancy	8
3.3	Option of several turbines per reservoirs	12
4	Validation of the new software	13
4.1	Test 1: comparison on the main results, one reservoir, one turbine	13
4.2	Test 2: comparison on the main results, models general multi levels, reference single level, 3resOpti	14
4.3	Test 3: influence of the correction parameters	14
4.4	Test 4: buoyancy level	14
4.4.1	Evolution range	15
4.4.2	Validation of the corrections	18
4.5	Test 5: several turbines per reservoir	18
4.5.1	General results	19
4.5.2	Repartition of the power between the turbines	19
A	Insertion of new overtopping models	23
B	Computation of the buoyancy	24
C	Possibility of several turbines per reservoir	24

Introduction

The overtopping based wave energy converters work by collecting the water from waves in one or more reservoirs above the mean sea water level. The water is then evacuated through one or several turbines and thereby produces electrical energy.

As the waves in real sea have a stochastic variation in wave height and period, it is very difficult to predict how much water the next wave will bring. Thus, for a given wave state, an optimum turbine operating strategy must be found, minimising the sum of head and spilling losses over a certain period of time. This can only be done by modelling the behaviour of the whole system in the time domain, thus permitting an integration of losses and production over a suitable time span. A specific software has been developed by Aalborg University, in order to test different setups for the overtopping device SSG (Seawave Slot-Cone Generator) and improve the energy production [8].

This report presents the way this software has been enhanced to describe generic overtopping based devices. The first part presents the overtopping formulations used later in the software. The second part gives an overview of how the software works. The last part presents the changes applied to the initial program and the tests which have been carried to validate these changes. The appendixes displays the coding modifications file by file.

1 Overtopping models

1.1 Geometry of overtopping wave energy converters

Overtopping depends not only on wave climate parameters, but also on the geometry of the structure. The parameters used to describe the geometry of an overtopping WEC are similar for onshore and floating devices (see Figure 1 on page 1).

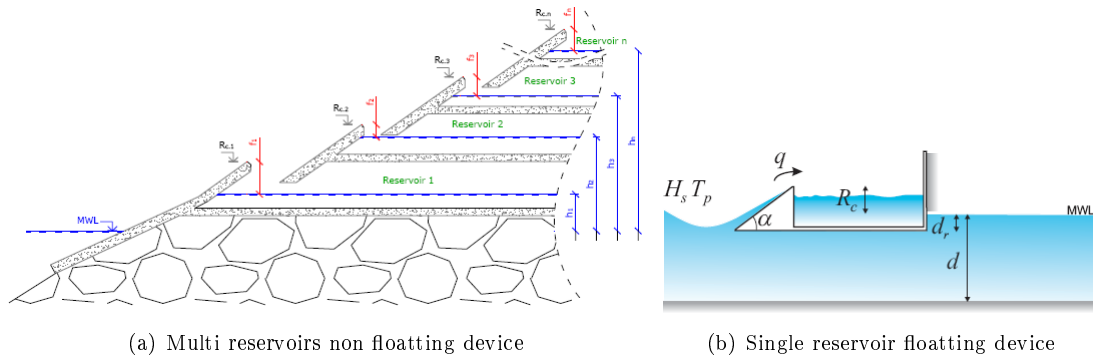


Figure 1: Parameters used to describe an overtopping WEC (cross section views)

These parameters are:

Crest level (Rc_i) Also named crest freeboard. This is the elevation of the crest of the reservoir i above the MWL.

Freespace (f_i) The freespace is the distance between the crest level and the water level in the reservoir i . It is equal to zero when the reservoir is full. Some specific water levels in the reservoir (for example for turbine regulation) refer to this freespace. They are consequently defined in the opposite sense of the vertical axis.

Head (h_i) The head is the difference of altitude between the water level in the reservoir and the MWL. It describes the pressure difference applied to the turbines. It can be deducted by:

$$h_i = Rc_i - f_i \quad (1)$$

Draft (d_r) The draft shows the distance between the MWL and the end of the overtopping slope (see Figure 1 on page 1).

Length (L_i) It is the length of the storage reservoir in the direction parallel to wave propagation. Increasing this length will increase the total storage capacity without any influence on the overtopping flow.

Width (W_i) The width is the size of the overtopping ramp (in the direction perpendicular to wave propagation). It has a direct influence on the overtopping flow q , defined as a flow per meter of ramp.

1.2 Overtopping discharge models

This section provides a brief introduction to overtopping formulation. It displays the overtopping formulas used later in the software. These formulas are necessary to deduct the overtopping flow from the wave climate and the geometry of the structure. They are fundamental for the design of devices which maximize the extracted energy and to predict the power production.

1.2.1 Introduction to overtopping

The literature about overtopping mainly deals with the design of dikes and breakwaters. It focused on structural designs that minimize the amount of overtopping. Moreover, a number of the proposed wave energy devices utilizing overtopping are floating structures which means that the structures are not extending all the way to the seabed but have a limited draft. Only very limited information is available in the literature on how to estimate overtopping of such structures. Furthermore, some of the proposed wave energy devices utilizing overtopping are using reservoirs at more than one level, which also raises the question of the vertical distribution of the overtopping discharge.

Overtopping is a very non-linear phenomenon, which explains that most of the available information lies on experimental tests.

Overtopping formulations aim to link together the flow which passes the ramp per meter of wave crest and the crest freeboard, taking into account various wave climate parameters as significant wave height (H_s), peak period (T_p), etc. The flow and the crest level are expressed as non-dimension values (Q and R). These equations give the average overtopping flow on a large time span; they can not be used for a single wave.

Next sections describe the formulas used in the current project. These formulas mainly come from Kofoed 2002 and later; they are based on Van de Meer and Jansen formulation (1995), where $R = \frac{Rc}{H_s}$. In Kofoed 2002 and later, many different geometrical configurations have been tested, and these formulations have been enhanced with various correction coefficients. Vertical distribution of the overtopping discharge has also been studied for the projects SSG and Power Pyramid.

1.2.2 Reference single level

Kofoed 2002 [4] gives the overtopping formula for a device which ramp has a straight slope, in case of non breaking waves (with $A = 0.2$ and $C = -2.1$).

$$Q = \frac{q}{\lambda_\alpha \cdot \lambda_{dr} \cdot \lambda_s \cdot \sqrt{g \cdot H s^3}} = A e^{C \frac{Rc}{Hs} \frac{1}{\gamma_r \cdot \gamma_b \cdot \gamma_h \cdot \gamma_\beta}} \quad (2)$$

$\gamma_b, \gamma_r, \gamma_h$ These coefficients are introduced to take into account the influence of a berm, shallow foreshore, roughness. They have been taken equal to 1 in this report (no influence of these parameters).

γ_β This coefficient represents the influence of the wave angle of attack β .

$$\gamma_\beta = 1 - 0.0033\beta \quad (3)$$

λ_α The average overtopping discharge is slightly dependent on the slope angle α . A correction factor is introduced to consider this dependency. $\alpha_m = 30\text{deg}$ is the optimal slope.

$$\lambda_\alpha = \cos^3(\alpha - \alpha_m) \quad (4)$$

λ_{dr} This parameter represents the fact that when the slope does not extend to the seabed, some energy passes under the device. The expression taking this dependency into account is based on the ratio between the time averaged amount of energy flux integrated from the draft up to the surface, and the time averaged amount of energy flux integrated from the seabed up to the surface (k_p is the peak wave number, κ is a parameter equal to 0.41):

$$\lambda_{dr} = 1 - \kappa \frac{\sinh(2k_p d(1 - \frac{d_r}{d})) + 2k_p d(1 - \frac{d_r}{d})}{\sinh(2k_p d) + 2k_p d} \quad (5)$$

λ_s This coefficient comes from a comparison between the results of Kofoed (2002) and Van de Meer & Jansen (1995). It permit to extend their formulation to a larger range of experimental data.

$$\lambda_s = \begin{cases} 0.4 \sin(\frac{2\pi}{3} R) + 0.6 & \text{if } R < 0.75 \\ 1 & \text{if } R \geq 0.75 \end{cases} \quad (6)$$

This model is considered as a reference for single level devices. From now it is called ‘‘reference single level’’. The coefficients described above, excepted λ_s , can be applied for other devices if necessary, even if they are not always explicitly included in the non-dimension expression of the overtopping discharge, because taken as default equal to 1.

1.2.3 SSG : a three reservoir device

Kofoed 2002 [4] showed that the continuous vertical distribution of the overtopping can be expressed this way:

$$\frac{\frac{dq}{dz}}{\lambda_{dr} \sqrt{g \cdot H s^3}} = A e^{B \frac{z}{Hs}} e^{C \frac{Rc_1}{Hs}} \quad (7)$$

The total overtopping flow depends only on the lower crest level Rc_1 . The altitude z of the reservoir influences the repartition of the flow between the different reservoirs. Later, experiments on the SSG model gave the values

of the coefficients A, B, C, for a device with fronts (see Kofoed, April 2005 [6]). The integration of (7) gives the overtopping flow for each reservoir i (z_1 and z_2 are the lower and higher altitudes of the reservoir):

$$\frac{q_i(z_1, z_2)}{\lambda_{dr} \sqrt{g} \cdot H s^3} = \frac{A}{B} e^{C \frac{Rc,1}{Hs}} (e^{B \frac{z_2}{Hs}} - e^{B \frac{z_1}{Hs}}) \quad (8)$$

The SSG is defined by the coefficients $A = 0.197$, $B = -1.753$ and $C = -0.408$. This model description is quite general and will be named from now “general multi level”.

Later (see Kofoed, June 2005 [5]), a more accurate expression of the overtopping discharge have been found for a specific device, with three reservoirs at 1.5 m, 3 m and 5 m above the MWL. This expression cannot be synthesized as a formula, so it has been directly included in the simulation software (model named “3resOpti”, see [8]). Figure 2 on page 4 compares these models.

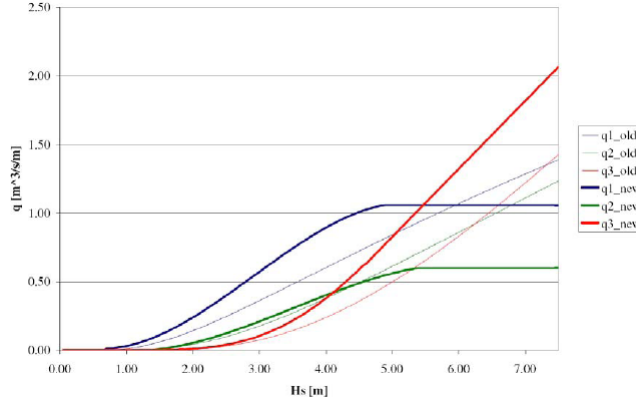


Figure 2: SSG: comparison of experimental data from Kofoed (April 2005) and Kofoed (June 2005).

1.2.4 Wave Dragon

The most recent overtopping equation of the Wave Dragon comes from Hald & Lynggaard, 2001 [9]:

$$Q = 0.017e^{-48R} \quad (9)$$

$$Q = \frac{q \sqrt{\frac{S_{op}}{2\pi}}}{\sqrt{g} \cdot H s^3 \cdot L} \quad (10)$$

$$R = \frac{Rc}{Hs} \sqrt{\frac{S_{op}}{2\pi}} \quad (11)$$

Where $S_{op} = \frac{Hs}{L_{op}}$ is the wave steepness, with L_{op} the deep water wave length (corresponding to the peak period Tp). However, this relation should be updated in order to consider experience from real sea states. As experiments have been carries on recently [1], the effective integration of a new Wave Dragon model is not described in this report.

1.2.5 Time dependency of overtopping

It is important to know how the irregular nature of sea waves influences the variation of the overtopping discharge. This information is needed in order to optimize the reservoir size and the control strategy for the turbines. According to Jacobsen & Frigaard (1999), and Franco & Al. (1994), the overtopping flow for each wave can empirically be calculated by two steps. The probability that the wave overtop is given by:

$$P_{ov} = e^{-\left(\frac{1}{1.21} \frac{H_s}{R_c}\right)^{-2}} \quad (12)$$

Then, the overtopping flow is bigger if the probability is low:

$$q_{in} = 0.84 \frac{q}{P_{ov}} (-\ln(1 - p_w))^{0.75} \quad (13)$$

where q is the average flow calculated by the previous formulas and p_w is a random number.

2 Presentation of the original simulation software

The software simulation tool “SSG Power Simulation 2” has been originally developed in June 2006 by Aalborg University (see [8] for detailed information). It computes the power output of a SSG depending on a complete set of parameters, including wave climate, geometry of the device, turbine strategy, characteristic curves and losses.

The computation is based on overtopping formulas deducted from wave tank experiments (see 1.2). The program generates a random series of waves from the sea states description, and simulates the production answer of the device in the time domain.

2.1 Input and output of the software

2.1.1 Input data

Wave climate The wave climate is defined by a list of sea states. Sea states are characterized by the following values:

- Significant wave height H_s (m)
- Peak period T_p (s)
- Probability of occurrence
- Number of waves generated in the simulation

Turbine strategy and characteristic The turbine is mainly defined by two characteristic curves depending on the head: the flow in the turbine (m^3/s) and the efficiency (%). This curves are interpolated in the simulation.

The turbine strategy depends on the water level in the reservoir. Turbines have to turn off when the water level is low, and to turn on when the reservoir is almost full, to make room for the next wave. A turn-on level and a turn-off level, expressed as a distance from the crest level, have to be defined. A gain and an offset can be fixed in order to have these levels as linear functions of the significant wave height.

The start-up and shut-down phases of the turbines are not instantaneous: time is necessary to accelerate the water and the turbines, depending for instance on the inertia of the generator. Turn on and turn off durations can be settled.

Geometry of the device The device can be made of one or more reservoirs, whose crest level, width of ramp and length can be fixed. These parameters mainly influence the overtopping flow and the storage capacity of the device.

2.1.2 Output results

The output results are displayed in a summary printed at the end of each simulation. The time series of key production values as power, overtopping flow, etc. can also be plotted. The results are displayed first generally (for instance, production for one reservoir), and then in more detailed ways (production depending on the sea states).

Production results Different average flows are computed for each reservoir. They show how much energy has been extracted from the waves and finally converted in mechanical energy by the turbines:

q_{in} flow which crosses the overtopping ramp

q_{over} flow which goes back to the sea because the reservoir is full (spillage losses)

q_{turb} flow which goes through the turbines

q_{res} is the total mean flow change in the reservoir

From these flow the corresponding efficiencies can be calculated. The final production results displayed are the estimate of the annual mechanical energy production and the average power.

Efficiencies The efficiency of the SSG is determined at three steps in the energy conversion process. Different energies are compared to the incoming wave energy:

$EffOv$ potential energy overtopping the ramp. Only the geometry of the ramp has an influence. The calculation do not consider the spill back to sea if it occurs.

$EffRes$ potential energy stored in the reservoirs. Here the spill back is taken into account. Energy will be lost if the reservoir is full and some water returns to the sea.

$EffTurb$ energy transformed into mechanic energy by the turbines. This will be less than above, due to start/stop penalties and turbine efficiency below 100%.

These efficiencies are computed for each sea state and reservoir or turbine.

2.2 Fundamental equations and algorithms

The central equation of the software is the continuity equation, ensuring that the input and output water flows are the same:

$$q_{in} = q_{over} + q_{turb} + q_{res}$$

For each wave, the overtopping flow is calculated using Algorithm 1.

The main simulation algorithm treats each sea state separately. The principle is to calculate the overtopping flow for each wave of the sea state using the random number p_w , as shown in Algorithm 1. Then each wave period is

Algorithm 1 Calculation of overtopping flow from a single wave

Input : Hs , Tp and Rc

Output : q_{in}
 $P_{ov} = e^{-(c\frac{Hs}{Rc})^{-2}}$

$q = q(Hs, Rc)$ is determined from experimental data in section 3.3

$p = \text{new random number}$

if $p > P_{ov}$ then

$pw = \text{new random number}$

$q_{in} = 0.84 \frac{q}{P_{ov}} (-\ln(1 - pw))^{0.75}$

else

$q_{in} = 0$

end

split on a defined number of time steps and the time simulation runs. In each time step values for each reservoir are computed.

The power of the turbine is give by (14):

$$P = \rho g \cdot q_{turb}(h) \cdot \eta_{turb}(h) \cdot h \quad (14)$$

Then energies and efficiencies can be deducted from the time serie of the power for each turbine. The computation steps are given by Algorithm 2.

3 Modifications of the software

This chapter describes the modifications applied to the software “SSG Power Simulation 2”. The goal of these modifications is to have a more complete software, in order to simulate easily the power production of a wide range of devices from the family of the overtopping based wave energy converters. These modifications are here described precisely to facilitate further development of this software. They include the integration of more overtopping discharge models, the modelling of the buoyancy for the floating devices, and the possibility of having several turbines in the same reservoir.

3.1 Insertion of new overtopping models

The insertion of new overtopping models is in two parts:

- effective integration of four new models
- possibility to define a set of new parameters for these models.

Three of the added models are floating devices:

- two aiming to represent the Wave Dragon (one reservoir). There are two models of the Wave Dragon, depending on if the reflectors are installed or not.

- one aiming to describe a multi-reservoirs floating overtopping device. The overtopping formula for the multi-reservoir device is for the moment the same than for the onshore general multi level device (see (8)).
- the fourth added model is a reference model: the single level onshore device. It is the best founded model, for which plenty of data are available (see (2)).

In order to describe precisely the different devices, a component “Advanced settings”, adapted to the overtopping model, has been added. This component let the user settle the value of the constants in the overtopping formula, and some correction parameters. Most of these parameters are describes in 1.2.

Overtopping parameters A, C : used to compute the total overtopping flow, given the crest level of the ramp.

Overtopping parameter B : for multi-levels devices, used to compute the vertical distribution of the overtopping, depending on the altitude of the reservoirs.

Geometric correction coefficient λ_m : this coefficient is used to describe the effect on overtopping of the environment of the device: converging walls, bathymetry.

Wave angle of incidence β : this parameter let to compute the correction coefficient γ_β , describing the negative effect on overtopping of non perpendicular waves.

Slope angle α : the optimal slope angle of the ramp to maximize overtopping is 30 deg. This parameter let to compute the correction coefficient λ_α , describing the negative effect on overtopping of a slope angle different from 30 deg.

Buoyancy area A_b : this parameter is used to compute the vertical movement of floating devices.

The ratio between depth and draft has an influence on the overtopping flow, via the parameter λ_{dr} . Depth and draft are added in the component “Computational settings”. The correction coefficient λ_s directly included in the code and cannot be changed by the user; it is automatically computed for the “reference single level” device.

Table 1 on page 9 summarizes the characteristics of these parameter.

3.2 Computation of the buoyancy

This part concerns only floating devices. The total weight of these devices is affected by the quantity of water contained in the reservoir. The overtopping is consequently modifying the balance of the vertical forces applied to the device and consequently changes the floatting level. Consequently, the head applied to the turbine will be influenced. The overtopping itself is not influenced, because the overtopping formulation are expressed in average: tests in wave tank consider the variation of the crest level and draft by the use of floatting models.

As a major production parameter [7], the time evolution of the floating level requires a to be modelled. It is assumed that the floating devices adapt their buoyancy level to best fit the sea state and maximize the potential energy got by overtopping [2]. A first modification has been to add the possibility of chosing $Rc_{,1}$ for each sea state.

The chosen buoyancy model has the following characteristic and simplifications:

- only vertical forces (weigth and Archimede force) and movements
- quasi-static model, which solves the static buoyancy equation at each time step.
- the buoyancy area is supposed to be constant (in reality, because of the complex structure of the devices, the area can be changing with the floatting level)
- the representative variable used is the crest level of the first reservoir, $Rc_{,1}$.

	Depth	Draft	A	B	C	λm	Wave attack angle β	Slope angle α	Buoyancy area	Data fit λs
Unit	m	m					degrees	degrees	m ²	
Optimized SSG	X	X								
Reference single level	X	X				X	X	X		X
General multi levels	X	X	X	X	X	X	X	X		
Wave Dragon with reflectors	X	X	X		X	X			X	
Wave Dragon without reflectors	X	X	X		X				X	
Floating multi levels	X	X	X	X	X			?	X	
Range	Depth>0	0<Drafts<Depth	A>0	B<0	C<0	$\lambda m \geq 1$	$0 \leq \beta \leq 90$	$0 \leq \alpha \leq 90$		$0 < \lambda s \leq 1$
Special conditions	Let the computation of $\lambda d r \leq 1$ at each wave is the main algorithm						Computation of $\gamma \beta \leq 1$	Computation of $\lambda \alpha \leq 1$	Must be superior than the area of the larger tank	Computed for each sea state

Table 1: Advanced parameters available for each device

Algorithm 2 Main algorithm to compute produced mechanical energy

Input : $Hs, Tp, Nwaves, Nsubsteps$, geometry and turbine characteristics
Output : $q_{in}, q_{turb}, q_{res}$ and $PTurb$
// Calculate constant parameters in the time series:
for $j = 1..Nreservoirs$ do
 $P_{ov} = e^{-(c\frac{Hs}{Kc})^{-2}}$
end
//Determine mean water flow q_j into each reservoir
// Loops to generate time series:
for $k = 1..Nwaves$ do
 $p = \text{new random number}$
 $pw = \text{new random number}$
 // Loop over number of reservoirs:
 for $i = 1..Nreservoirs$ do
 Algorithm 1
 for $m = 1..Nsubsteps$ do
 // Determine current head depending of crest height and current freespace
 $h_i = Rc_i - f_i$
 // Determine if turbines should be turned on in the current time step
 if $f_i < Ton(Hs)$ then
 Start turbine j
 end
 if $f_i > Toff(Hs)$ then
 Stop turbine i
 end
 if Turbines turned on then
 $(q_{turb}, \eta_{turb}) = \text{TurbineCharacteristic}(h)$
 else
 $(q_{turb}, \eta_{turb}) = (0, 0)$
 end
 $f_i = f_i + \frac{(q_{in,i} - q_{turb,i})\Delta t}{A_{res,i}}$
 if $f_i < 0$ then
 $q_{over} = \frac{f_i \cdot A_{res,i}}{\Delta t}$
 $f_i = 0$
 end
 Increment the flow and production results
 end
 end
end
for $i = 1..Nreservoirs$ do
 Calculate the average of the flow and production results depending on time scales
end

Algorithm 3 Simulation of the buoyancy for a floatting device

Calculate the height of the ramp = initial $Rc_{,1}$ + initial d_r
for each sea state
 Initialize $Rc_{,1}$ to the required value
 Calculate d_r , λ_{dr} and q
 For each reservoir i
 Calculate the overtopping vertical distribution $q_{in,i}$ based on q
 End reservoir
 For each wave
 For each time step in the wave period
 For each reservoir i
 Calculate the overtppong flow of the time step, based on $q_{in,i}$ and the
 overtopping time distribution
 Calculate the flow through the turbines and the spill back to sea
 Compute the head h_i depending on the crest level, and deduct the
 power ((14))
 End reservoir
 Calculate the total added weight for the step time (perturbation)
 The height of the ramp is constant: calculation of a new $Rc_{,1}$
 End time step
 End Wave
End Sea State

The computation follows Algorithm 3. This algorithm is included in the main simulation algorithm. Here we can see a strong interaction between the overtopping, the buoyancy level and the turbine regulation. The average overtopping discharge is only calculated once for each sea state.

The displayed results have to show the global evolution range of the buoyancy level and its time evolution:

- $Rc_{,1}$ is plotted depending on the time
- The summary displays the following information for each sea state:
 - Asked crest level
 - Mean crest level calculated during the simulation
 - Evolution range during the simulation, deducted by the recorded maximum and minimum values of $Rc_{,1}$.
 - Theory evolution range, calculated from the turbine regulation strategy, the initial crest level, the geometrical characteristic of the device.

With these results it is possible to check if the asked $Rc_{,1}$ is reached or not, or if the computed evolution range is reasonable. An important difference between the target crest level and the average value of $Rc_{,1}$ cannot be accepted: the overtopping flow calculated at the beginning of the computation would not fit the actual value of $Rc_{,1}$. The plot permits to check the dependencies between turbine activation, overtopping and buoyancy level.

3.3 Option of several turbines per reservoirs

The turbine regulation strategy is a key of the energy production. To improve that regulation several turbines can be useful. The modification of the main computation algorithm is simple: a loop has been added in the reservoir loop in order to calculate the flow trough each turbine. No specific modelling has been required here. The main effort has been to choose what new available results are valuable and to compute them. Compared to the previous version of the software, two types of results have been added: the produced power for each turbine, and the number of cycles per hour.

Table 2 on page 12 shows how are expressed the different results related to the turbines. It is possible to have a global view of the turbines behaviour, or to focus one more specific problem for a precise design of the turbines strategy. For the plots, the previous key values have been extended: for each turbine are plotted the efficiencies, the power, the water flow through the turbines depending on the time. The only new plot is the total number of turbines running for each reservoir.

	Results expressed per...		
Efficiency through the turbine	Turbine and sea state and reservoir	Turbine and reservoir	Reservoir
Turbine work efficiency			
Turbine on time			
Turbine on time (%)			
Turbine characteristic efficiency			
Number of cycles per hour			
Produced energy			

Table 2: Results displayed for multi turbines devices

4 Validation of the new software

After these modifications, the program seemed to run properly, and gave coherent results. It has been necessary to carry on systematic tests to validate its accuracy, taking into account the following points:

- The overtopping models included in this software are deducted from laboratory experiments. The comparison between the results of the software and the experimental data would be senseless. Only other data available are from the Nissum Bredning Wave Dragon prototype, but the overtopping model is still to be updated and integrated into the software.
- However, to check programming errors, it is possible to refer to the previous version of this software. Its results are reliable: indeed the presented method in Section 2 have been independently programmed at Aalborg University and at the Technical University of Munich. Results have been found to be the same [3].
 - Some mistakes have been found in the first version of the software and corrected. It will be necessary to deactivate some of these corrections in order to compare.
 - The question of the accuracy in the comparison had to be discussed. A relative deviation of 0.1% between the results of the two softwares has been chosen.
- Given the few data available, the best way to check the accuracy of the added components will back on logical considerations.

Tests will be carried from now on a set of seven sea states (see Table 3 on page 13). These sea states come from the wave climate on the island of Kvistov (SSG pilot site).

Hs (m)	Tp (s)	Prob
0.5	5.0	0.135
1.0	6.1	0.303
1.7	7.9	0.265
2.4	9.3	0.164
3.6	10.6	0.083
4.7	11.7	0.035
5.9	12.7	0.015

Table 3: Sea states used for tests on the software

4.1 Test 1: comparison on the main results, one reservoir, one turbine

A simple device has been chosen. The tested model is the general multi level, with one reservoir and one turbine. All the correction coefficients have been turned to zero, by fixing the value of the parameters so as to nullify them ($d = d_r$, $\alpha = 30$, $\beta=0$). A correction adapted to the turn-off of the turbines (see 4.4.2) has been deactivated.

A comparison has been made for the results on each sea state, for two different numbers of time steps per wave (10 and 25). The final energy production has been tested. The relative deviation between the results of the two versions has been found equal to zero. Consequently, the changes applied (loop on the turbine, buoyancy level) have not triggered any error on the simplest case.

4.2 Test 2: comparison on the main results, models general multi levels, reference single level, 3resOpti

The values of the final energy production displayed on the summary are identical whatever the version is for the model “general multi level” (different numbers of reservoir have been tested) and for the model “3resOpti” (where the number of reservoirs is fixed). In these tests, the turn-off correction (see 4.4.2) has been deactivated.

It has been checked that the overtopping flow of the “reference single level” device is approximately the same than the sum on all the reservoirs for the two multi reservoir models, with the same Rc and W .

4.3 Test 3: influence of the correction parameters

The good calculation of the correction parameters has been tested. These parameters influence only the overtopping discharge. The ratio between the optimal and the corrected discharge (for which the λ and γ parameters are different from zero) is compared to the value of the correction coefficient, calculated manually. This ratio and this value are equal for all the coefficients, so the coefficients are correctly computed in the software. They are all responsible of a decrease of the overtopping flow. The tests on λ_{dr} and γ_{β} have been performed for only one sea state, because of their dependencies on Tp .

These coefficients have been tested only for the general multi levels device, but their computation is independent from the chosen model. For the reference single level λ_s has been tested separately.

At the same time, the constants A , B , C of the overtopping model have been briefly tested. The overtopping discharge changes in a logical way when one of these constant is modified.

4.4 Test 4: buoyancy level

The calculation of λ_{dr} is deactivated.

Algorithm accuracy The following conditions are applied to compare the results of the last version, depending on if the device is floating or not:

- The comparisons are made using the models “general multi levels” and “floating multi levels”, based on the same overtopping discharge equation. The comparison will be made between the values of q_{in} depending on the model. This value is relevant, because since the movements are nullified, q_{in} is the only input value from which all the other production results can be deducted.
- At first, devices with only one reservoir are considered.
- The range of the vertical movements for the floating device is determined by the ratio $\frac{A_b}{A_{res}}$ (A_b : buoyancy area, A_{res} : reservoir area). So as to nullify this movement and compare floatting and non floating devices, the influence of this parameter will be tested.
- Each sea state has to be computed in a different simulation: in order to compare, it is necessary for the non floating device to fix a new Rc for each simulation.

Figure 3 on page 15 shows the relative deviation between the results on q_{in} for the floating and non floating device, depending on the ratio $\frac{A_b}{A_{res}}$. It is clear that the range of these movements decreases with this ratio, so that the results between the two devices converges. The range of the ratio $\frac{A_b}{A_{res}}$ here has no physical meaning; huge value are tested to check that the model converges. With a ratio close to zero, the movements are nullified, and the results

are the same. Consequently there is no mistake introduced in the computation algorithm by the buoyancy. The results of the software are physically coherent.

The relative deviation is higher for low sea states: this can be explained as follows. The simulations have been made with an important initial freespace f . When the reservoir is full, R_c has been decreased of an important value; the lower H_s is, the larger is the decrease of R . This overtopping discharge (see (8)) is consequently more modified by the buoyancy for the lower sea states.

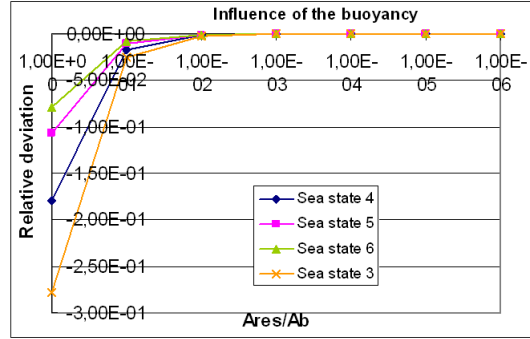


Figure 3: Influence of the ratio $\frac{A_{res}}{A_b}$ on the overtopping discharge

With an important ratio $\frac{A_b}{A_{res}} \approx 10^8$, the same tests have been carried for a device with 3 reservoirs, and the results between floating and non floating devices have been the same. It confirms that the buoyancy does not trigger any mistake in the main computation algorithm.

4.4.1 Evolution range

The range of the vertical movements has been tested, with one reservoir. In order to simplify the check, A_b has been chosen equal to A_{res} . If the program works correctly, the range of the movements will be the same than the range of the water level in the reservoir.

This ideal range is deduced from:

- The turn on limit of the turbine: it tells how much water can be added in the tank from the beginning of the simulation, before the flow through the turbine is activated.
- The turn off limit of the turbine: it tells how much water can be expelled from the reservoir since the beginning of the simulation

This calculation of the ideal range assumes that the turbine instantly starts or stops, and has the capacity of empty all the water flow immediately. R_c is adapted to each sea state, so the range has to be recalculated each time. The initial situation is considered in the model as an equilibrated state.

Table 4 on page 16 shows the comparison between the actual range and the ideal range, depending of the number of time steps per wave.

The ideal range is systematically exceeded. It shows that the water level in the reservoir exceeds the turn-on and the turn-off limits of the turbine. The minimal values of R_c only depends on the turn on limit of the turbine, here 10 cm from the crest level. The minimal value fits with a totally filled reservoir; the extra water overtopping immediately returns to the sea, and has no influence. The maximal value of R_c fits with a water level going under

Minimal values of R_c						
Number of time step						
Sea state	5	10	15	20	25	Ideal range
1	0,15	0,15	0,15	0,15	0,15	0,25
2	0,90	0,90	0,90	0,90	0,90	1
3	1,95	1,95	1,95	1,95	1,95	2,05
4	3,00	3,00	3,00	3,00	3,00	3,1
5	4,80	4,80	4,80	4,80	4,80	4,9
6	6,45	6,45	6,45	6,45	6,45	6,55
7	8,25	8,25	8,25	8,25	8,25	8,35

Maximal values of R_c						
Number of time step						
Sea state	5	10	15	20	25	Ideal range
1	0,77	0,76	0,76	0,75	0,75	0,75
2	1,52	1,51	1,51	1,51	1,51	1,5
3	2,59	2,57	2,56	2,56	2,56	2,55
4	3,64	3,62	3,61	3,61	3,61	3,6
5	5,45	5,43	5,42	5,41	5,41	5,4
6	7,11	7,08	7,07	7,06	7,06	7,05
7	8,91	8,88	8,87	8,87	8,86	8,85

Table 4: Vertical movements range (m)

the turn off limit of the turbine: the device become lighter than planned and goes up. In order to approach the ideal condition, a simulation with infinite capacity turbine ($1000 \text{ m}^3/\text{s}$) is made. This turbine, as in the previous simulation, starts and stops immediately. Table 5 on page 16 displays the results.

Sea state	Min R_c value		Max R_c value	
	Actual min	Ideal min	Actual max	Ideal max
1	0,245	0,250	1,359	0,750
2	0,990	1,000	2,355	1,500
3	2,028	2,050	3,803	2,550
4	3,065	3,100	5,165	3,600
5	4,825	4,900	7,255	5,400
6	6,450	6,550	9,148	7,050
7	8,250	8,350	11,171	8,850

Table 5: Movement range with infinite capacity turbine (m), 25 time step/wave period

The results are slightly better for the minimum value of R_c with low sea states, but really worst for the maximal value of R_c . These results underline two computation problems in the main algorithm.

- First, when the turbine turns on: in case of a large flow in the reservoir, the water level overpasses the turn on limit. The buoyancy calculation was made at the end of the time step, before the turbine turns on. That is the reason why an infinite capacity turbine had no significant influence on the previous results.

Figure 4 on page 17 shows the compared evolution of the water in the tank and of the main crest level. It is clear that the device immediately sinks when a wave overtops. It has been chosen to postpone the buoyancy calculation of one time step to avoid this problem.



Figure 4: Compared evolution of the main crest level and the flow in the reservoir

- Secondly, when the turbine turns off: the water level can cross the turn-off limit of the turbine between two calculation points, which trigger a bad evaluation of the water level in the tank. Figure 4.4.1 on page 17 gives an explanation of this problem. Figure 4.4.1 on page 17 shows that the relative deviation between ideal and actual range depends on the number of time steps and confirms this hypothesis.

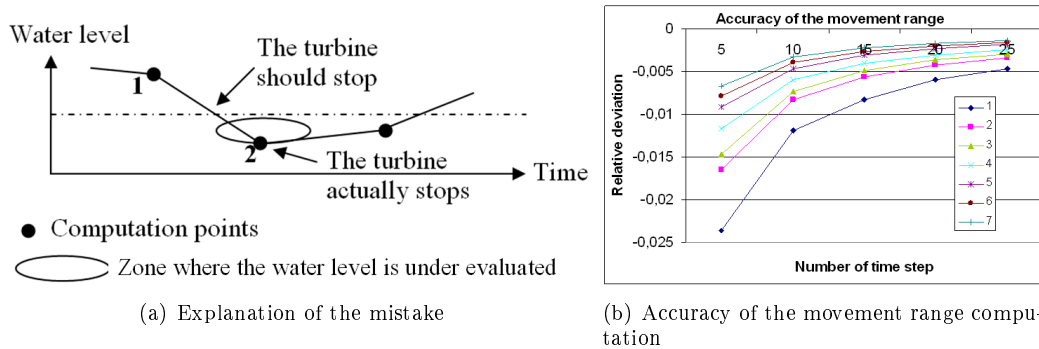


Figure 5: Turn off computation mistake

This mistake in the evaluation of the water level applies on the floating and non floating devices. It has an influence on the flow through the turbines and the power production, and on the buoyancy level. This influence increases with:

- The total capacity of the turbine(s): that is why with an infinite capacity turbine (see Table 5 on page 16), the results are senseless.
- The duration of the time step (see Figure 4.4.1 on page 17).

This mistake has been corrected using the following steps:

- Record the two points 1 and 2 (see Figure 4.4.1 on page 17)
- By linear interpolation, find at what time t the turbine should have turned-off
- At point 2, adjust the water level to the turn-off level
- Using the continuity equation, find an equivalent flow through the turbine between 1 and 2
- Using this equivalent flow and t , correct the power, the energy, the running time for this time step.

4.4.2 Validation of the corrections

The turn-on correction has no influence on the main computation algorithm. For the turn off correction, it has been checked that the minimum ideal buoyancy level was not exceeded. Because this correction changes production results, further tests have been carried:

- It has been checked that the continuity equation is respected.
- Numerical convergence of the produced energy has been studied, has a reference for the accuracy of the computation. The influence of the turbine capacity has been tested.

Figure 6 on page 19 displays the relative deviation for the produced energy using as reference the energy computed with 30 time steps per wave, for 3 different sea states, before any correction has been applied. Figure 7 on page 19 displays the same results with the two corrections. It shows that the accuracy decreases with the turbine capacity and an important sea state. These corrections generally reduce the relative deviation, what is more visible for small sea states. The maximal deviation is still concentrated on the important sea states. A comparison has been made between the results of the corrected and non corrected version. The final results on the produced energy are slightly different, but the maximum standard deviation is around 10^{-2} . The same test made with a three reservoir devices gives the same range of relative deviation on the production results. The produced energy is more important with the corrections, probably because it maintains a higher water level in the tank.

These corrections do not have a large influence on the power production. However, they ensure that the buoyancy results will be correct, and secure the program in case of high turbines capacity. The fundamentals equations are respected by these corrections.

4.5 Test 5: several turbines per reservoir

This test series is dedicated to the multi-turbines devices. So as to have the same water level applied to each turbine of the same reservoir, the corrections before had to be integrated into the turbine loop, which triggered important coding changes.

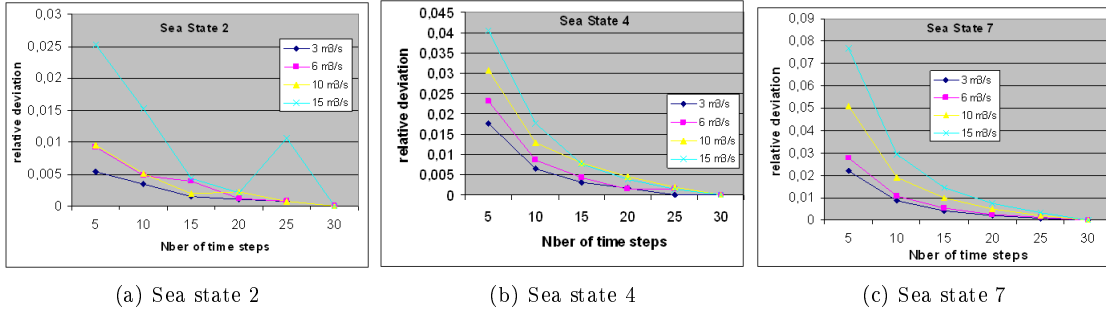


Figure 6: Numerical convergence on energy production depending on the turbine capacity (without correction)

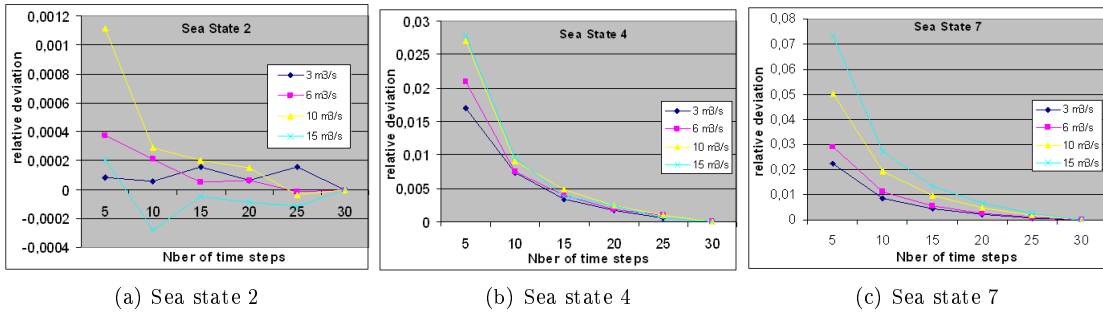


Figure 7: Numerical convergence on energy production depending on the turbine capacity (with correction)

4.5.1 General results

The results have been compared to the previous version with three reservoirs and one turbine per reservoir, and have been found equal. The continuity equation is still respected. For a three levels floating device, the buoyancy is computed correctly.

From now focus is on the results with more than one turbine, and one reservoir. In order to check if the algorithm works with more than one turbine, a test as been made with two turbines, which one has no capacity. The results have been compared with the results with one turbine and have been found almost equal.

4.5.2 Repartition of the power between the turbines

A first simulation has been made with two identical turbines. Figure 4.5.2 on page 20 shows that the power production was not equally shared. This mistake come from the fact the turbine flows are always computed in the same order: the turbine 1 (black) benefit from a higher head than the turbine 2 (red). At the beginning of the turbine loop, a “shift number” is computed, to change the order of the turbine at each time step. Graphically it can be seen that with this solution the production of the two turbines get closer (see Figure 4.5.2 on page 20).

A study has been made on the influence of:

- the number of time steps per wave
- the number of turbines.

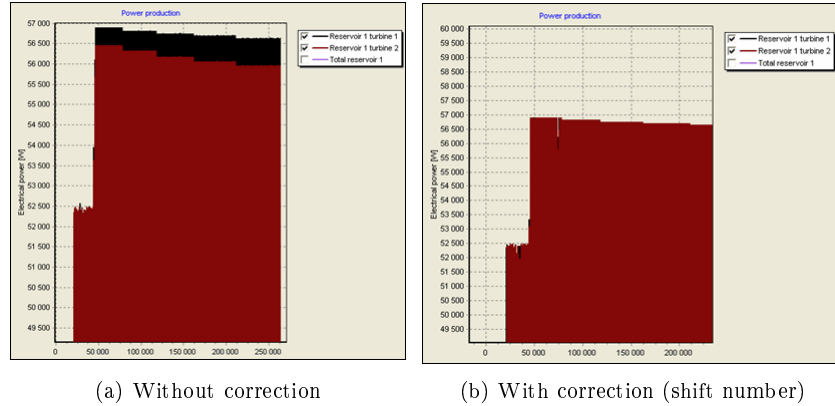


Figure 8: Repartition of the production between two identical turbines

As a reference, the deviation coefficient on the series of the produced energy for each turbine has been tested. All the turbines have the same strategy. Figure 4.5.2 on page 20 displays the results for the sea states 3 and 6.

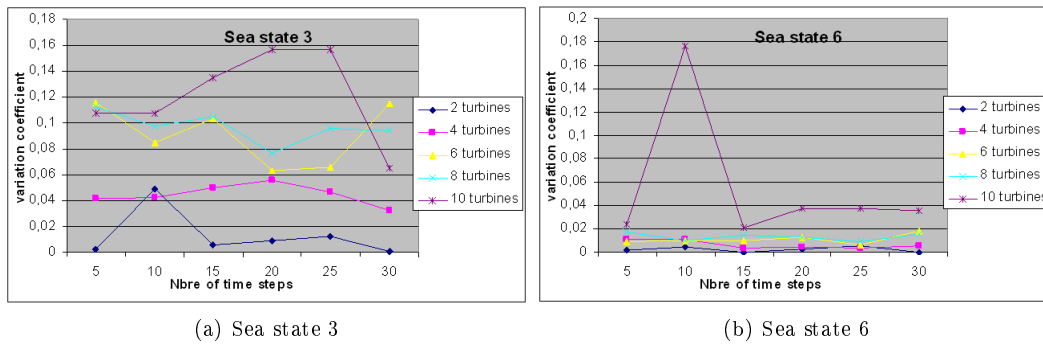


Figure 9: Variation coefficient on the series of produced energy per turbine

It can be seen that the variation coefficient on production energy can reach 18%: the flow through the turbines is not balanced, despite the fact they are identical. There is no regular evolution depending on the number of time steps per wave. This point and the fact there is a maximum for the sea state 6 when the number of turbines is equal to the number of time steps suggests a resonance effect.

Simulations have been carried with 4 turbines with the sea state 4 only. The influence of the number of time steps on the energy production per turbine has been tested. Figure 4.5.2 on page 21 displays the results. It is obvious that the standard deviation on the production for each turbine is the higher when the ratio $n = \frac{\text{number of time steps}}{\text{number of turbines}}$ or its inverse are integers, what is the typical signature of a resonance. In these cases, the “shift number” has no effect, because at each time step the same turbine is computed first.

The pink plot on Figure 4.5.2 on page 21 is the average of the scatter on each “period” (4 points). It shows that in spite of the resonance peaks, the global precision is still improving with a higher number of time steps per wave.

Despite the fact this problem can trigger important mistakes, it only happens in two conditions:

- Several turbine must be running at the same time (it does not mean they have necessarily the same strategy)

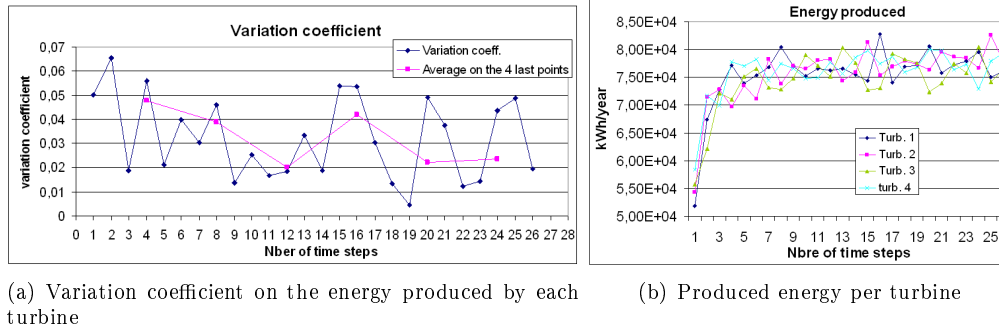


Figure 10: Numerical resonance effect on turbines production

- The number of time steps is not chosen the good way (n or $\frac{1}{n}$ are integers)

This means that increasing the number of time steps does not necessary improve the accuracy, depending on the turbine strategy. With turbines with different strategies, this error can occurs

This resonance problem could be solved by generating a random “shift number”; it is also simply avoidable by choosing the right number of time steps.

Conclusion

In the current report the enhancements of the power simulation tool for overtopping based wave energy converters has been described. The software is now a powerful tool capable of predicting the yearly power production of most types of overtopping based wave energy converters, as well as optimization of the structure, turbine configuration and control strategy.

The enhancements includes added overtopping models, modelling of buoyancy for floating devices, several turbines per reservoirs, etc. The performance of the added components, as well as the overall performance of the simulation tool, has been validated thorough testing, which is also documented in the report. The final version of the software is called WOPSim: Wave Overtopping Power Simulation.

References

- [1] Bruno Borgarino, Jens Peter Kofoed, and James Tedd. Experimental overtopping investigations for the wave dragon - effect of reflectors and their attachments. Technical report, Hydraulic and Coastal Engineering Laboratory, Department of Civil Engineering, Aalborg University, 2007.
- [2] Jens Jakobsen and Jens Peter Kofoed. Wave dragon buoyancy regulation study. Technical report, Hydraulic and Coastal Engineering Laboratory, Department of Civil Engineering, Aalborg University, 2005.
- [3] Wilfried Knapp. Comparison of results obtained with the aau and the tum ssg power simulation program. Technical report, Technical University of Munich, 2006.
- [4] Jens Peter Kofoed. *Wave overtopping of marine structures utilization of wave energy*. PhD thesis, Hydraulic and Coastal Engineering Laboratory, Department of Civil Engineering, Aalborg University, 2002.
- [5] Jens Peter Kofoed. Experimental hydraulic optimization of the wave energy converter seawave slot-cone generator. Technical report, Hydraulic and Coastal Engineering Laboratory, Department of Civil Engineering, Aalborg University, 2005.
- [6] Jens Peter Kofoed. Model testing of the wave energy converter seawave slot-cone generator. Technical report, Hydraulic and Coastal Engineering Laboratory, Department of Civil Engineering, Aalborg University, 2005.
- [7] Jens Peter Kofoed, James Tedd, and Erik Friis-Madsen. Influence of buoyancy control performance on power production by the wave dragon nissum breeding prototype. In *ISOPE*, 2007.
- [8] Palle Meinert, Lasse Gilling, and Jens Peter Kofoed. User manual for ssg power 2. Technical report, Hydraulic and Coastal Engineering Laboratory, Department of Civil Engineering, Aalborg University, 2006.
- [9] Hald Tue and Jakob Lynggaard. Hydraulic model tests on modified wave dragon. Technical report, Hydraulic and Coastal Engineering Laboratory, Department of Civil Engineering, Aalborg University, 2001.

A Insertion of new overtopping models

Class TSimCondition: this Delphi class describes the general conditions chosen for the simulation

- Addition of the Depth and the Draft as properties of this class
- Addition of the record TAdvancedSettings as a property of this class. This contains the parameters described before, and their default values, which are applied if the user does not modify them.

Form frmSimCond: part of the user interface to settle the simulation conditions

- Addition of the object vleAdvancedSettings (type TValueListEditor). In this list, the user can fix the value of the displayed parameters.
- Addition of the procedure MoveSimToScreenAdvancedSettings: this procedure displays the parameters of the list vleAdvancedSettings depending on the model chosen. The non displayed parameters keep their default values. It triggers the plot of the chart of the overtopping flow.
- Addition of the function ValidScreenInputAdvancedSettings: check if the entered values have a correct format and range, regarding the condition of Table 1 on page 9.
- Addition of the function MoveScreenToSimAdvancedSettings: if the screen input is correct, the simulation conditions are recorder before the computation.
- Function PlotFlowModel : calculation of λdr for the highest sea state, used for in the overtopping plot on the user interface

Class tsReservoir, function Qmean: this function calculates the overtopping flow for each wave.

- Addition of new formulas to calculate Qmean, depending on the model.
- Integration of the calculation of the correction coefficients $\lambda\alpha$, $\lambda\beta$, λs , depending on the model
- The mean flow for each wave is corrected.
- Class tsTurbineSimulation: this class contains the core functions for the computation of the simulation.
- Addition of the function CalculateDraftCoefficient to calculate λdr . It is a function of the draft, the depth, and of Hs and Tp for each sea state. It has to be computed for each sea state, during the simulation.
- Integration of this calculation in the procedure flowSimulate, to correct the overtopping flow calculated for each wave. Because the draft can change in a sea state (in case of floating device), cpDraft is calculated for each wave instead of for each sea state.

Unit ReportUnit:

- Function InputAdvOptions: the advanced parameters are printed at the end of the results summary, depending on the model chosen.

Consequently, after this series of changes, it is possible to:

- Choose between the six models
- Change the value of the coefficients, see directly their influences on the overtopping plot displayed on the user interface.
- Launch a normal computation: the results displayed have not been changed.

B Computation of the buoyancy

Form frmSimCond: so as to facilitate the display of the sea states depending on the chosen model, the grid SgSeaState (object TStringGrid) has been made an independent component:

- Addition of the procedure MoveSimToScreenSeaStates. If a floating device is chosen, the user can change $R_{c,1}$ for each sea state.
- Addition of the function ValidScreenInputSeaState: check if the entered values have a correct format
- Addition of the function MoveSimToScreenSeaStates.

Class TsTurbineSimulation: modification of the main procedure “flowSimulate”

- The buoyancy algorithm as been included
- The calculation of the theory evolution range, of the actual range and of the mean crest level have been included

Class tsResults: this class define the type of results which have to be displayed after the simulation

- Addition of a vector in the “plot” record for the main crest level depending on the time
- Addition of the properties link to the range evolution and the mean crest level

form frmResults: this form displays the plots

- In the constructor: creation of the new series “Main Crest Level”
- In the procedure “checkSeries”: drawing of the main crest level depending on the time

Unit ReportUnit: this class contains the necessary procedures to edit the final summary

- In the procedure SimulatedSeaStates, the values of the asked crest level, the actual mean crest level, and the evolution ranges are edited in case of a floating device.

C Possibility of several turbines per reservoir

Class TReservoir: this class describes the characteristic of the reservoir (geometry, turbines)

- The Turbine property has been replace by a TurbineList, compund by several objects TTurbine.

Unit tsTurbine:

- The class TTurbineList has been defines as an array of turbines, so as to have one list of turbines of several turbines for each reservoir. The turbines themselves keep the same properties.

Form frmReservoir: this form let the user fix the parameters linked to the turbine and the reservoir.

- The object pgcTurbine (type TPageControl) has been added: it permits to add, delete or count the turbines.

- The objects included in `pgcTurbine` are from the type `frmTurbine`: this object, which describes each turbine independently, has not been change.

Unit `tsResults`: some results have now to be stored depending on three variables: the sea state, the reservoir and the turbine.

- Creation of the class `TTurbineResults`. It contains the following items:
 - Matrixes: time evolution for each turbine of:
 - * The flow through
 - * The power output
 - * The efficiency
 - Vectors: for each turbine, value of:
 - * The mean efficiency
 - * The number of steps while the turbine produces
 - * The percentage of time the turbine is running
 - * The energy through the turbine and its related efficiency
 - * The energy produced by the turbine and its related efficiency
- In the class `TSimResults`:
 - Addition of an array of `TTurbineResults` in the record “Plot”: the properties of `TTurbineResults` used will be he three matrixes
 - In the records `Mean` and `Plot`, the previous properties redundant are deleted
 - Addition of an array of array of `TTurbineResults` in the record “Mean”: the properties of `TTurbineResults` used will be the three vectors

Class `TTurbineSimulation`: all the changes are made in the procedure `flowSimulate`.

- At each step time, a loop is added on all the turbines of each reservoir, so as to compute the different results.
- Given the new way of expressing the results, this computation is slightly changed.

Form `frmResults`:

- Constructor and function `CheckSeries`: for each reservoir, a loop is added on the number of turbines to plot the power production, the flow through the turbines and the efficiencies.
- Constructor and function `CheckSeries`: the series “Number of running turbines” has been added.

Unit `ReportUnit`:

- Procedure `TotalResults`: the results for each turbine of each reservoir as in Table 2 on page 12 are computed and printed
- Procedure `ReservoirResults`: the results for each turbine and each sea state as in Table 2 on page 12 are computed and printed.