Vertical Distribution of Wave Overtopping for Design of Multi Level Overtopping Based Wave Energy Converters

Kofoed, Jens Peter

Published in:
Proceedings of the 30th International Conference on Coastal Engineering : ICCE '06

Publication date:
2007

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

VERTICAL DISTRIBUTION OF WAVE OVERTOPPING FOR DESIGN OF MULTI LEVEL OVERTOPPING BASED WAVE ENERGY CONVERTERS

Jens Peter KOFOED[1]

This paper presents an expression describing the vertical distribution of overtopping, the experimental work leading to this, as well as the use of the expression for numerical optimization of the geometrical layout of the multi level overtopping based wave energy converter Seawave Slot-cone Generator. The numerical optimization is also assisted by further experimental investigations focused on optimization of the finer details of the concept with respect to amount of potential energy in the overtopping water.

INTRODUCTION

Motivation

Over the recent years an increasing number of developers of wave energy converters (WEC's) have been focusing on utilizing wave overtopping for production of electrical power. The primary focus has so far been on investigation of overtopping with respect to optimization of the amount of potential energy obtained in the overtopping water for a single reservoir layout, Kofoed & Burcharth (2002). This approach is used in the design of e.g. the Wave Dragon (WD) WEC, Sørensen et al. (2003) and Friis-Madsen et al. (2005).

However, overtopping based WEC's using multi level reservoirs, such as the Seawave Slot-cone Generator (SSG), have also been suggested, since these will have a higher overall efficiency, compared to a similar single reservoir structure.

In the design of such structures the overtopping prediction formulae available in the literature are not sufficient, as these are typically only valid for single reservoir layouts and hold no information of the vertical distribution of the overtopping above the lowest reservoir crest. Furthermore, the geometry of the fronts on the individual reservoirs above the lowest one also influences the overtopping rates into the individual reservoirs.

---

[1] Department of Civil Engineering, Aalborg University
Sohngaardsholmsvej 57, DK-9000 Aaalborg, Denmark

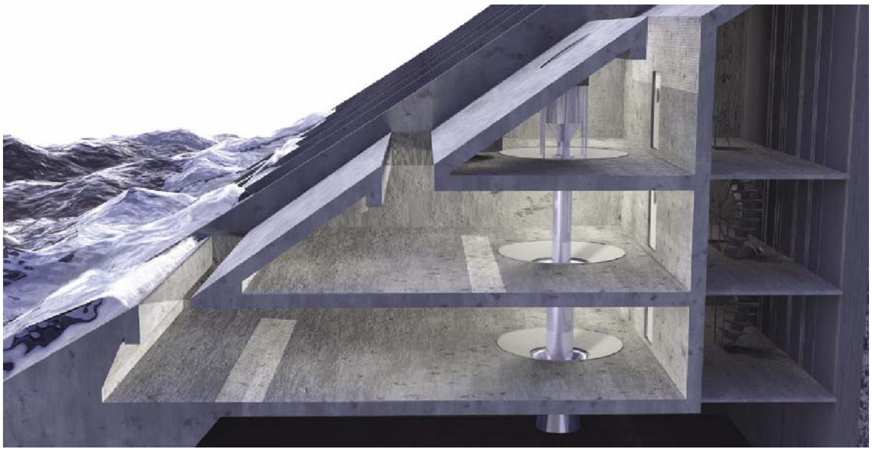

Figure 1. Sketch of the SSG principle, courtesy of WaveEnergy AS.

Figure 2. Photo montage and location of pilot plant to be installed on the west coast at the island of Kvitsøy, near Stavanger, Norway, courtesy of WaveEnergy AS.

The SSG structure

The Seawave Slot-cone Generator (SSG) under development by the Norwegian company WaveEnergy AS is a WEC utilizing a total of three reservoirs placed on top of each other. The SSG is designed as a near-shore concrete structure with the turbine shaft and the gates controlling the water flow as virtually the only moving part of the mechanical system, see figure 1. The idea is that the WEC can be integrated into a breakwater structure, which will lead to sharing of cost (and thereby cost effectiveness) and potentially better breakwater performance (due to efficient absorption of energy, which minimizes reflection).

A full scale technical prototype pilot plant, with a width of approx. 10 m and an installed capacity of 150-200 kW, is planned for deployment at the west coast of Kvitsøy, Norway (near Stavanger) during 2007, see figure 2. At this site the average available wave energy resource is approx. 18 kW/m.

Outline

On this background physical model studies have been performed in which it is investigated how a range of different geometrical parameters influence the overtopping rates for the individual reservoirs when the structure is subjected to heavily varying wave conditions. It is also investigated how these new results fits with overtopping prediction formulae reported in the literature.

As a first step model tests have been carried out to study the vertical distribution of wave overtopping over a single crest. This has lead to the formulation of an empirical formula relating the dimensionless derivative of the overtopping discharge with respect to the vertical distance to the relative vertical distance and the relative crest freeboard, as described by Kofoed (2002).

Based on this expression a numerical optimization has been carried to establish the optimal crest levels for a multi level structure exposed to a given combination of sea states, with respect to maximizing the amount of potential energy in the overtopping water. However, this approach does neither take into account the presence of fronts on the individual crest on the levels above the lowest one, nor the geometries of these fronts. Thus, it was found that an interactive use of model tests and numerical optimizations based on the empirical formulae established from the model tests where necessary.

Therefore, for the specific design of the SSG, two rounds of model tests have been carried out, assisted by numerical optimization.

EXPERIMENTAL SETUP

Vertical distribution

In model tests performed to establish the vertical distribution of the overtopping a model was setup in a 25 x 1.5 m wave flume at the Hydraulics & Coastal Engineering Laboratory, Aalborg University. A water depth of approx. 0.75 m was used.

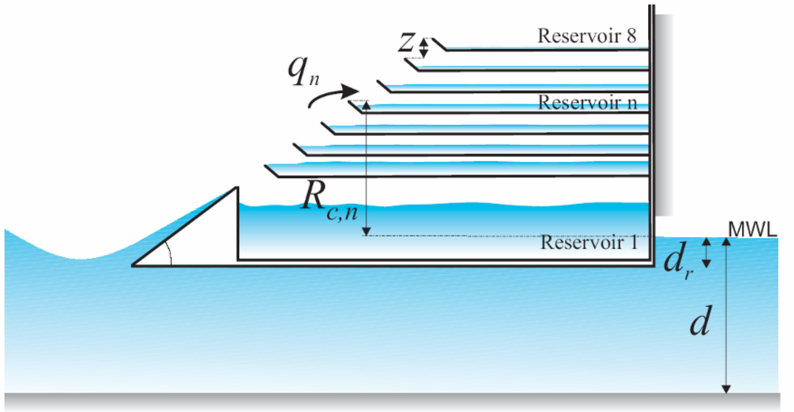

Figure 3. Definition sketch for model tests on vertical distribution of overtopping.

Figure 4. Model test setup for vertical distribution of overtopping.

The setup primarily consists of 3 components, see fig. 4:

- Leading walls (with a distance equal to the width of the test section, 0.5 m, model scale) installed in front of the test section, in order to have well defined 2-D incoming waves. The incoming waves are measured by three wave gauges placed be between the leadings walls (in the hereby established flume) in front of the test section.
- The test section it self. A total of 8 trays were mounted above the crest of the overtopped ramp and each tray was connected to a tank behind the test section where the collected overtopping water was measured using water elevation gauges and calibrated pumps. As indicated on the definition sketch in fig. 3 some of the tests were performed using a limited draught.
- Reservoir tanks. Each of the eight trays in the test section has a reservoir tank which is used to measure the amount of overtopping in the individual reservoir. In each reservoir tank a level gauge and a pump was placed. The level gauge and the pump were connected to a PC programmed to emptying the reservoir tanks and thereby recording the amount of overtopping water in the individual reservoirs.

During the tests average overtopping discharges into the individual trays as well as the waves have been measured. Prior to the testing the wave gauge, level gauges, volume of reservoir tanks and pump capacities have been calibrated.

In these model tests wave conditions typical for the Danish part of the North Sea was used (significant wave height from 1 to 5 m).

SSG optimization

In two rounds model tests, aiming at optimizing the geometrical layout of the SSG with a total of three crest levels, have been performed in a 3-D wave tank at the Hydraulics & Coastal Engineering Laboratory, Aalborg University. Although the wave making facility in the used wave tank is capable of producing 3-D wave conditions, only 2-D irregular wave conditions have been applied.

The setup used in these tests resembles the previously described one, except that no tests were performed with limited draught and a total of three trays (or reservoirs) were used, see fig. 6. In these tests the reservoirs above the lowest one were also equipped with fronts. The initial geometry was provided by WaveEnergy AS, but the test section was constructed so modification here of could relatively easy could be made.

A total of 17 different geometrical layouts characterized by the parameters illustrated in fig. 5, have been tested (10 during first round, Kofoed, 2005a, and 7 in the second, Kofoed, 2005b). Each of the geometries has been subjected to 3 to 6 irregular 2-D wave conditions (consisting of 1000-2000 waves, 30 min. tests, model scale).

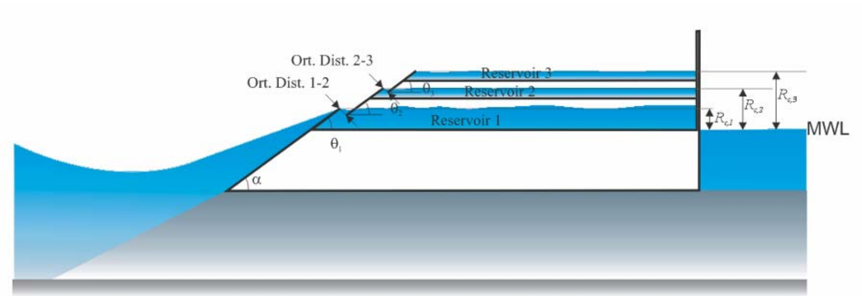

Figure 5. Definition sketch for model tests on SSG optimization.

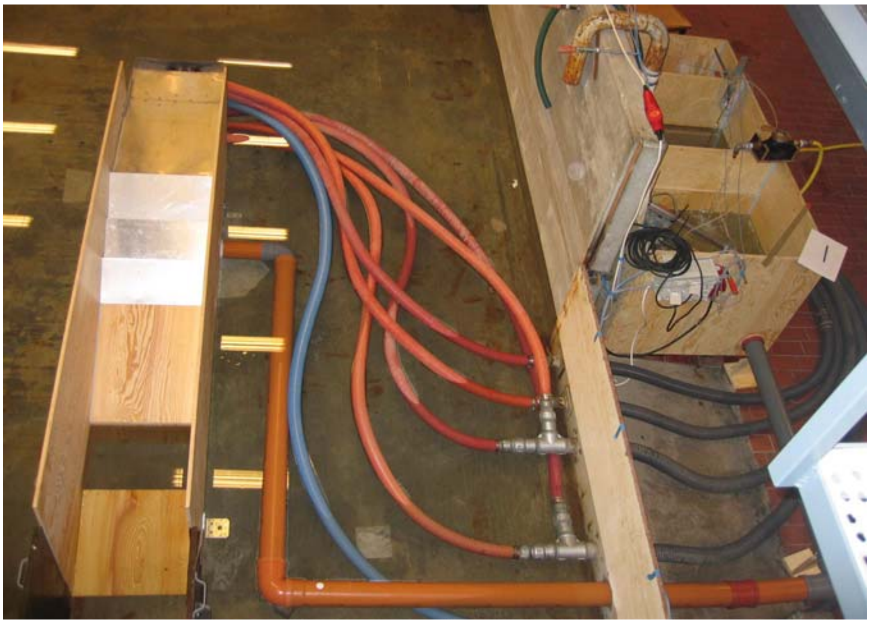

Figure 6. Model test setup for SSG optimization.

In the first round of tests a water depth of 6 m was used. However, after investigation of charts of the bathymetry in front of the prototype location, made available after these tests (as referred in Kofoed and Guinot, 2005), it was found that this water depth did not represent the area at the prototype location well. Therefore, in second round it was decided to model the foreshore using a general water depth of 15 m and a 1:2 (26.6°) slope leading up to the position of the tested structure (at the water depth of 6 m). Furthermore, it was decided to change the length scale from 1:15 to 1:25 in order to allow for the increased water depth and increase the overtopping measuring capacity of the setup.

In the tests wave conditions corresponding to offshore conditions at the pilot plant location were generated (significant wave height from 1 to 7 m). However, due to wave breaking occurring in the more energetic sea states, the target wave parameters were not achieved in all conditions. Since the waves arriving at the structure were measured and all results are normalized using these parameters, this is not considered to influence the drawn conclusions.

RESULTS

Vertical distribution

An expression for prediction of the vertical distribution of overtopping on the form

$$Q' = \frac{dq/dz}{\lambda_{d_r}\sqrt{gH_s}} = Ae^{B\frac{z}{H_s}+C\frac{R_{c,1}}{H_s}} \tag{1}$$

where Q' is the dimensionless derivative of the overtopping discharge with respect to the vertical distance z, $R_{c,1}$ is the crest freeboard of the lowest reservoir and H_s is the significant wave height, has been suggested by Kofoed (2002). λ_{d_r} is a coefficient describing the dependency of the draught, see definition after eq. 5 later in the text (λ_{d_r} = 1 for structures extending to the sea bed). The coefficients A, B and C were fitted to experimental data for the case with no fronts on the reservoirs above the lowest one and the found values are 0.37, -4.5 and 3.5, respectively.

SSG optimization

In the work focusing on optimizing the geometrical layout of the SSG structure tests have been performed with fronts mounted on the individual reservoirs. Analyses of selected data sets from the first round of tests, where only the crest freeboards have been varied, have lead to a new set of coefficients A, B and C by fitting to eq. 1. These are 0.197, -1.753 and -0.408, respectively. The correlation coefficient for the fit is R^2 = 0.96. The fit is shown in figure 7 where the calculated overtopping rates for the individual reservoirs q_n are found by integration of eq. 1, resulting in eq. 2, using the crest freeboard of the current reservoir as the lower limit z_1 and the crest freeboard of the reservoir above as the upper limit z_2

$$q_n(z_1, z_2) = \sqrt{gH_s^3}\,\frac{A}{B}e^{C\frac{R_{c,1}}{H_s}}\left(e^{B\frac{z_2}{H_s}} - e^{B\frac{z_1}{H_s}}\right) \tag{2}$$

Based on this expression a numerical optimization of the reservoir crest levels were carried out by calculating the potential energy contained in the overtopping water for each reservoir as it passes over the crests, called P_n, as

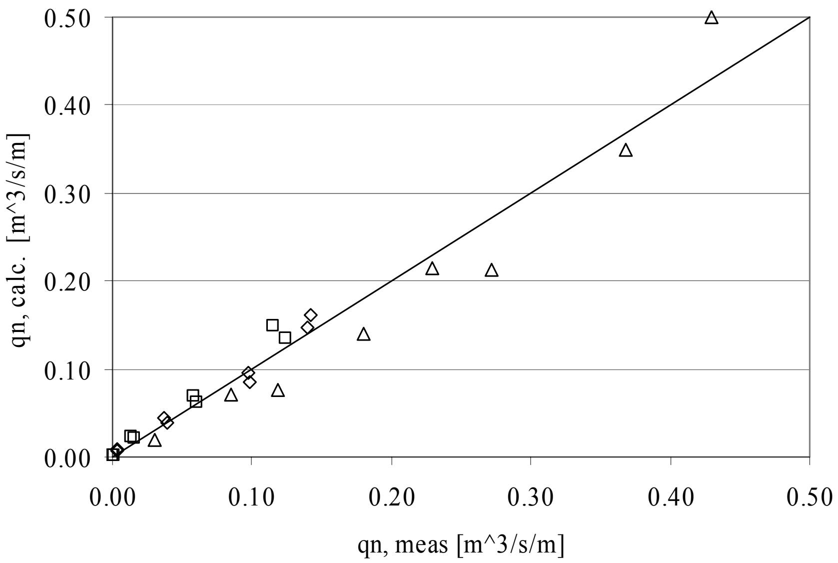

Figure 7. Comparison of measured vs. predicted overtopping rates for individual reservoirs with fronts (line representing eq. 2). Values scaled to prototype.

$$P_n(z_1, z_2) = q_n(z_1, z_2) z_1 \rho_w g \tag{3}$$

where ρ_w is the density of the water and g is the gravitational acceleration. P_{total} for each wave condition can then be found as the sum of P_n of the three reservoirs. The overall efficiency in terms of energy in the overtopping water related to the energy in the waves are then calculated as

$$\eta_{overall} = \frac{\sum_{m=1}^{k} P_{Total}^{m} P_{occur}^{m}}{\sum_{m=1}^{k} P_{wave}^{m} P_{occur}^{m}} \tag{4}$$

where P_{occur} is the probability of occurrence of the individual considered wave condition and k is the number of considered wave conditions.

By systematically running through a large number of combinations of crest levels it was found that the optimal crest configuration was obtaining using crest levels for reservoir 1, 2, and 3 of 1.5, 2.5 and 4.0 m, respectively. For the considered combination of wave conditions this corresponded to an overall efficiency of 37 %.

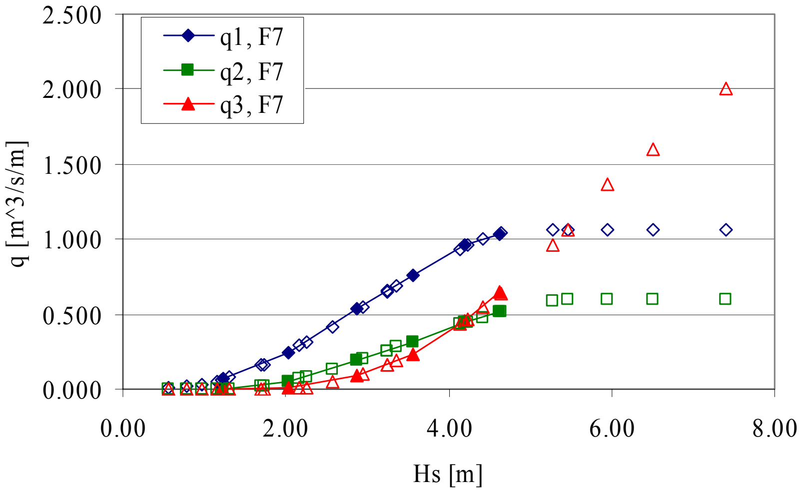

Figure 8. Model test results optimal geometry (full markers), together with inter- and extrapolated data used in interpretation of results.

The second round of tests was then carried out using the results of the numerical optimization as a starting point. The aim was now to look at the influence of the geometry of the reservoir fronts (in terms of the parameters shown in fig. 5) on the overall efficiency and to maximize this by testing different layouts. During the testing it was found that because of the improved performance due to the optimization the optimal crest freeboards were changing as well. Therefore, the last part of the second round of testing was performed with crest levels of 1.5, 3.0 and 5.0 m.

Obtained optimal geometrical layout and its hydraulic performance

The conclusion of the second round of testing was that a geometry described by the following was found to be optimal (parameters referring to fig. 5):

- α, β, θ_1, $\theta_{2,3}$: 26.6°, 26.6°, 35.0°, 35.0°, respectively.
- $R_{c,1}$, $R_{c,2}$, $R_{c,3}$: 1.5 m , 3.0 m, 5.0 m, respectively.
- Ort. dist. 1-2, 2-3: 1.5 m, 1.0 m, respectively.

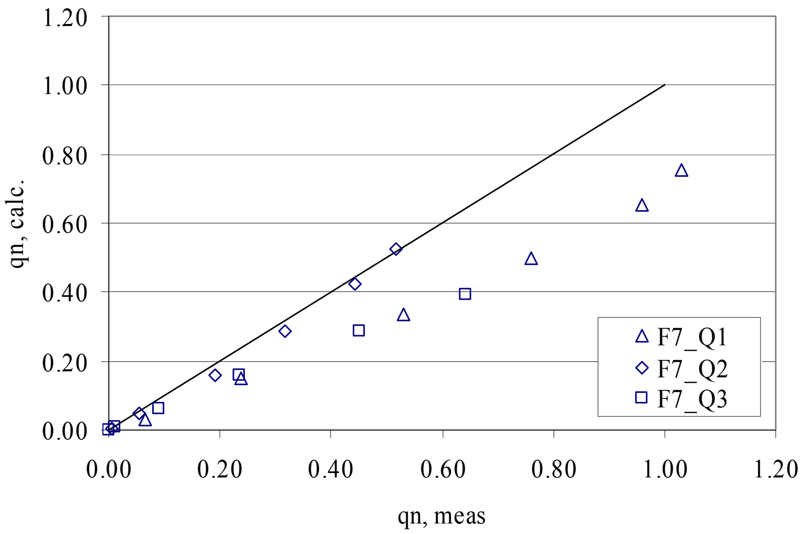

Figure 9. Comparison of calculated (straight line representing eq. 2) and measured data for optimized geometry.

Using this geometry the overtopping rates for the three levels indicated in fig. 8 was obtained. In order to estimate the overall performance of the optimized geometry the measured data was inter- and extrapolated. The overall average efficiency using the offshore wave conditions was found to be 51 %. Thus, a significant increase has been obtained during the optimization (compared to the value of 37 % found after the first round of tests). This is also illustrated in fig. 9 where the straight line represents the eq. 2 with the coefficients found from the first round of tests in the SSG optimization. From here it is also seen that the improvements in performance are primarily due to increased overtopping rates in the upper and lower reservoirs.

As all tests with the optimized geometry was performed using the same crest freeboards, sufficient data for updating the coefficients in eq. 1 and 2 is not available.

Check of results against expression for single level reservoir

As a check of the measured overtopping rates the total overtopping rates in all three reservoirs have been summed for the individual tests and made non-dimensional as in the overtopping expression by Kofoed and Burcharth (2002):

$$Q = \frac{q}{\lambda_\alpha \lambda_{d_r} \lambda_s \sqrt{gH_s}} = 0.2 e^{-2.6 \frac{R}{H_s} \frac{1}{\gamma_r \gamma_b \gamma_h \gamma_\beta}} \qquad (5)$$

where

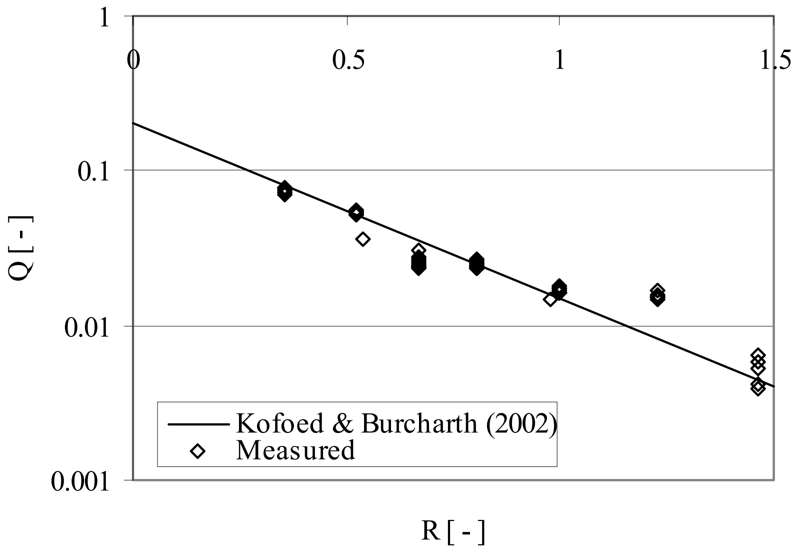

Figure 10. Measured total overtopping rates compared to expression by Kofoed and Burcharth (2002).

$$\gamma_r = \gamma_b = \gamma_h = \gamma_\beta = 1$$

corresponding to no berm, non-shallow foreshore, no roughness and head-on wave attack.

$$\lambda_\alpha = \cos^3(\alpha - 30°)$$

accounting for the effect of using a slope angle α different from 30°

$$\lambda_{d_r} = 1 - 0.4\frac{\sinh\left(2k_p d\left(1-\frac{d_r}{d}\right)\right) + 2k_p d\left(1-\frac{d_r}{d}\right)}{\sinh(2k_p d) + 2k_p d}$$

accounting for the reduction in overtopping rates due to ramp not extending all the way to the seabed. Intended for use where the waves are allowed to pass under the structure, but has here been applied where the ramp has been cut off, leaving a vertical from the lowest point of the ramp to the seabed.

$$\lambda_s = \begin{cases} 0.4\sin\left(\frac{2\pi}{3}R\right) + 0.6 & \mathit{for} \quad R < 0.75 \\ 1 & \mathit{for} \quad R \geq 0.75 \end{cases}$$

accounting for low relative crest freeboards.

k_p peak wave number $2\pi/L_p$.

L_p peak wave length.

d_r draught of ramp.

R relative crest freeboard, R_c/H_s. Here set at $R_{c,1}$.

From fig. 10 it is seen that the measured total overtopping rates in general agrees well with the overtopping expression.

CONCLUSIONS

By use of model tests the expression describing the vertical distribution wave overtopping by Kofoed (2002) has been applied and adjusted to allow prediction of overtopping rates for individual multiple reservoirs with fronts.

By using the proposed expression a numerical optimization of the crest levels the SSG WEC (in terms of maximizing the obtained potential energy in the overtopping water, for a given set of wave conditions with corresponding probability of occurrence) has been performed. Using the hereby found crest levels as a starting point, the finer details of geometry of the fronts of the reservoirs has been optimized during physical wave tank testing. This optimization has lead to a 35 % increase of overall hydraulic efficiency, which for the final geometry is found to be 51 % when the offshore wave conditions are applied.

The overtopping measurements performed on multi level structures have also been validated by comparison to established overtopping expression from literature valid from single crest level designs.

FURTHER WORK

A number of items influencing the overtopping of the SSG pilot plant, such as wave transformation from offshore to near shore, local bathometry effect on overtopping, effect of oblique wave attack, 3-D layout of structure, 3-D wave effects, have not been taken into account during the study described in this paper. 3–D model tests with modeling of the local bathometry and the 3-D structure are currently being carried out, and through these the above mentioned items will be considered. Furthermore, a power simulation software tool have been developed, which can simulate the conversion of the energy in the overtopping water into electrical energy by calculating the variation in time of the overtopping rate, water level and spillage in each reservoir, flow through the turbines etc. This is being used in the design of reservoir and turbine capacity and control strategy in the design of the Kvitsøy SSG pilot plant.

ACKNOWLEDGEMENTS

The study has been carried out at Hydraulics & Coastal Eng. Lab. Aalborg University, and has been funded by the Danish Energy Agency, through the Danish Wave Energy Program, and WaveEnergy AS, Norway.

REFERENCES

Friis-Madsen, E., Kofoed, J. P. and Knapp, W.: *Prototype Testing of the Wave Energy Converter Wave Dragon*. European Regional Meeting, WREC 2005, Aberdeen, Scotland, May, 2005.

Kofoed J. P.: *Wave Overtopping of Marine Structures – Utilization of Wave Energy*. Ph. D. Thesis, Hydraulics & Coastal Engineering Laboratory, Department of Civil Engineering, Aalborg University, December, 2002.

Kofoed, J. P. and Burcharth, H. F.: *Estimation of Overtopping Rates on Slopes in Wave Power Devices and Other Low Crested Structures. Kofoed.* The 28th International Conference on Coastal Engineering (ICCE 2002), Cardiff, Wales, July 2002.

Kofoed, J. P. (2005a): *Model testing of the wave energy converter Seawave Slot-Cone Generator.* Hydraulics and Coastal Engineering No. 18, ISSN: 1603-9874, Dep. of Civil Eng., Aalborg University, April 2005.

Kofoed, J. P. and Guinot, F.: S*tudy of Wave Conditions at Kvitsøy Prototype Location of Seawave Slot-Cone Generator*. Hydraulics and Coastal Engineering No. 25, ISSN: 1603-9874, Dep. of Civil Eng., Aalborg University, June 2005.

Kofoed, J. P. (2005b): *Experimental Hydraulic Optimization of the Wave Energy Converter Seawave Slot-Cone Generator.* Hydraulics and Coastal Engineering No. 26, ISSN: 1603-9874, Dep. of Civil Eng., Aalborg University, June 2005.

Sørensen, H.C., Friis-Madsen, E., Panhauser, W., Dunce, D., Nedkvitne, J., Frigaard, P., Kofoed, J. P., Knapp, W., Riemann, S., Holmén, E., Raulund, A., Præst, J., Hansen, L.K., Christensen, L., Nöhrlind, T., Bree, T. and McCullen, P.: *Development of Wave Dragon from Scale 1:50 to prototype*. The Fifth European Wave Energy Conference, Cork, Ireland, Sept. 2003.

Van der Meer, J. W. and J. P. F. M. Janssen (1994). *Wave run-up and wave overtopping of dikes*. Wave forces on inclined and vertical wall structures, ed. N. Kobayashi.

14

KEYWORDS – ICCE 2006

VERTICAL DISTRIBUTION OF WAVE OVERTOPPING FOR DESIGN OF MULTI LEVEL OVERTOPPING BASED WAVE ENERGY CONVERTERS
Jens Peter Kofoed
430

Wave overtopping
Vertical distribution
Wave energy converters
Physical model tests
Multi level