Experimental Overtopping Investigation for the Wave Dragon

effects of reflectors and their attachments

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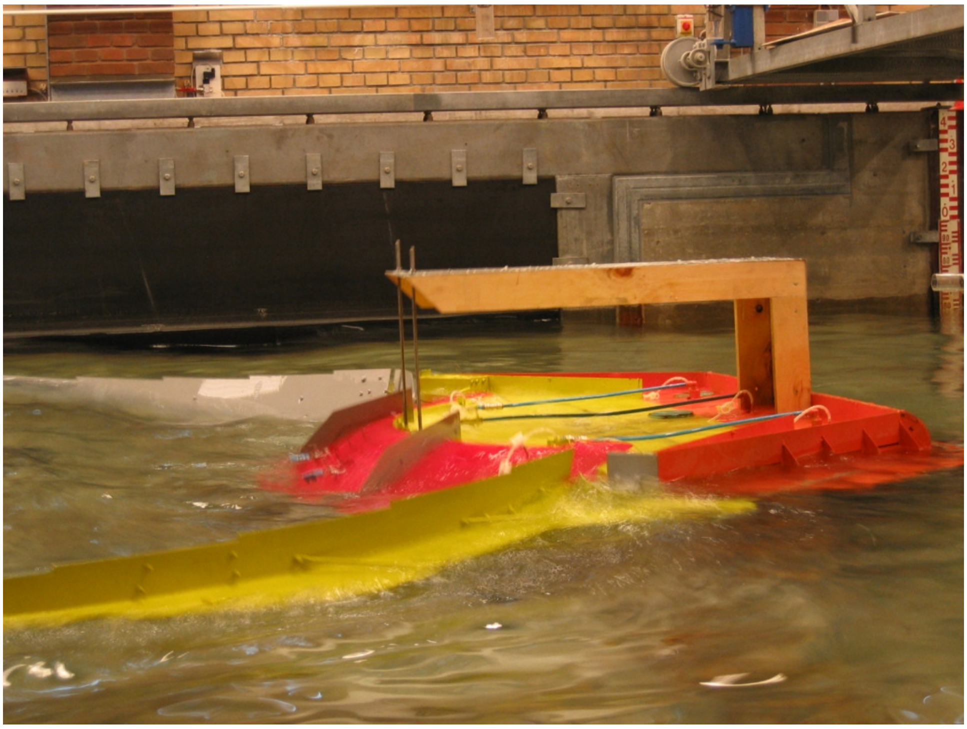

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AALBORG UNIVERSITY
Department of Civil Engineering

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Laboratory of Hydraulics and Coastal Engineering

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by

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Contents

Introduction

The present report displays the results from overtopping tests carried on the 1:51.8 Wave Dragon model in September 2007. This tests have been carried on by Bruno Borgarino, James Tedd and Jens Peter Kofoed in the wave tank facilities of Aalborg University.

The objective was to provide an updated predictive model of the average overtopping flow depending on the sea state and the floating/crest level. The need of a new model come from real sea testing, which showed that the way of attaching the arms to the main body has an influence on the overtopping flow.

1 Previous overtopping tests on the Wave Dragon

A floating model of the Wave Dragon was built in autumn 1998 by the Danish Maritime Institute in scale 1:50. This model was subjected to a series of model tests and subsequent modifications at Aalborg University. Overtopping, forces and sustainability have been investigated. The Wave Dragon have been re-designed in 2000, to the scale 1:51.8, with a double curved overtopping ramp.

For each generation model (see [3] and [5]) the overtopping flow has been measured, in order to establish a predictive model. The most recent overtopping equation of the Wave Dragon comes from Hald & Lynggaard, 2001 [5]:

$$Q = 0.017e^{-48R} \quad (1)$$

$$Q = \frac{q\sqrt{\frac{S_{op}}{2\pi}}}{\sqrt{g.Hs^3.L}} \quad (2)$$

$$R = \frac{Rc}{Hs}\sqrt{\frac{S_{op}}{2\pi}} \quad (3)$$

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, an accurate predictive overtopping model is still to be established, for several reasons:

- The previous model only applies to a restricted number of sea states. It has been found inaccurate outside this limited range.
- The way of expressing Q and R in tne previous model directly comes from models describing dikes and breakwaters nexposed to breaking waves. Consequently it is inappropriate:
  - the model refers to the steepness, despite the fact that the double-curved ramp has been specifically designed to avoid wave breaking
  - the slope does not extend to the seabed

The influence of the way the arms are fixed to the main body have to be investigated. Indeed, real sea tests have shown technical difficulties for this point [4]:

- The first fixation devices were rubber fenders. This system suffered from the hard environment and failure occured. Significantly roll occured.

- The second tested device was a ball joint. Hydraulic cylinders have been added to reduce the roll movement and extract power, used to smooth the power production.

Given that the role of the arms is to focus the waves and to increase the significant height in front of the ramp, the influence of the roll movement on the overtopping flow must be investigated. Indeed results from real sea testing have shown a very low efficiency of the arms, probably due to this movement [1].

2 Testing conditions

2.1 Tested sea states

Most of the previous tests have been carried only on the principal sea states of the North Sea (see Table 2.1 on page 2). One of the goals of this study is to have a relation applying to a more complete sea description. Table 2.1 on page 2 shows the tested sea states. The waves which have been applied are irregular 2D waves from the Jonswap spectrum, with a peak enhancement factor of $\gamma = 3.3$, corresponding to North-Sea conditions.

Hs (m)	Tp (s)
1	4
2	6
3	8
4	10
5	12

Hs (m)	Tp (s)
1	6
2	4
3	6
3	10
4	12
5	10

Table 1: Tested sea states (left: sea states already investigated; right: new sea states)

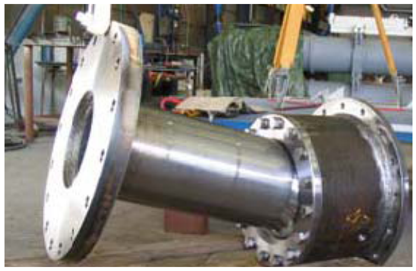
2.2 Wave Dragon configurations

Three different configuration have been experienced:

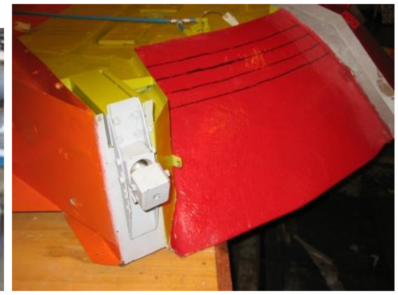
- The Wave Dragon without arms (only the main body).
- The Wave Dragon with moving arms: the way the arms are connected to the main body allows yaw, pitch and roll motion.
- The Wave Dragon with rigid arms: only pitch and yaw are allowed. The roll movement is blocked.

2.3 Ways of fixing the reflectors

The ball joint from previous tests (Tedd, 2005), has been kept in the current test to simulate the last joint layout. Later, this joint has been kept, but the roll motion has been blocked by adding two metal plates on each side of the joint. The plates can slide, so that the pitch motion is still free.



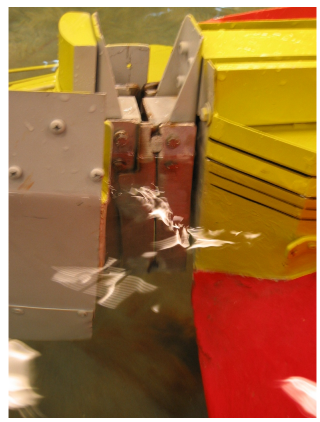
(a) Nissum Bredning prototype



(b) Wave tank model

Figure 1: Ball-joint

(a) Nissum Bredning prototype



(b) Wave tank model

Figure 2: Rubber fender and equivalent setup (metal plates)

2.4 Measurement setup

The installed measurement setup allows measurement of the following quantities:

- volume of water which overtopping to the reservoir
- force at the main mooring point
- heave, pitch and surge of the device
- surface elevation in several points of the wave basin.

Moreover, for each test a picture of the position of the device is taken. Movements of the device with and without arms have been recorded on video for a few sea states.

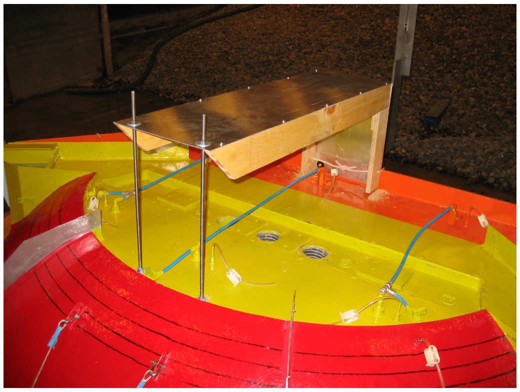
During all the tests the depth has been 0.6 m (31 m in prototype scale), which is a depth corresponding to the planned operating condition of the Wave Dragon.

2.4.1 Overtopping volume measurement

The overtopping flow is expelled from the reservoir of the Wave Dragon with three pipes. These pipes lead the water to a storage tank, where the water level is measured with a surface elevation gauge. This tank contains a pump controlled by the data acquisition system.

When the water level is above a certain value, the pump automatically runs for 3 seconds and brings the water back to the wave tank. The volume taken by the pump during this time has previously been calibrated. Consequently, the total overtopping volume of the test can be deducted by the number of cycles of the pump and the difference between initial and fnal water level.

(a) Interimary tank, with pump and wave gauge



(b) View of the Wave Dragon tank, with exhausting holes and reflecting plates

(c) View of the model from underneath: exhausting pipes and air chambers

Figure 3: Overtopping measurement

2.4.2 Force measurement

The forces are measured by two force gauges linked to the mooring point. These gauges have been calibrated with weights. The measurement is not relevant for the overtopping study.

2.4.3 Motion measurement

The motions are measured by three ultra-sound displacement sensors. Two aluminum reflecting plates (see Figure 3 on page 4) have been added to the Wave Dragon in order to show vertical and horizontal movements by measuring the distance from the plates. Two sensors record the vertical movements of the front and the rear of the Wave Dragon. They have been calibrated in order to have directly the front and rear crest level. Consequently pitch and heave around the center of gravity can be deducted (see Figure 4 on page 5). The crest level is calculated from these values.

$$\text{(heave)} = \frac{y_1 + y_2}{2}$$

$$\text{(pitch)} = \frac{y_1 - y_2}{d}$$

$$\text{(surge)} = x$$

where

x = horisontal ultrasound signal

y_1, y_2 = two vertical ultrasound signals

d = distance between the two vertical ultrasound signals

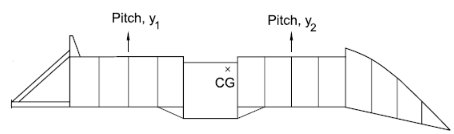


Figure 4: Definition of movements

2.4.4 Waves measurement

The waves are measured with a linear set of 4 wave gauges, placed in front of the Wave Dragon. One other wave gauge, placed in a zone away from wave reflection, is used to check the accuracy of the measure. It is assumed that no reflected waves are sent back to the Wave Dragon:

- the Wave Dragon will send oblique reflected waves (because of the shape of the ramp and arms)
- after being reflected by the paddles, these waves are dissipated by the absorbers (installed each side of the paddles)

2.4.5 Recording set

All the signal are sampled at 10 Hz. Wave gauges are connected to a wave recorder. The other signals and signals from the wave recorder transit to a computer through a 8 Hz low pass filter and a data acquisition box. Acquisition and post-processing use the software WaveLab. This software is also in charge of the pump regulation: an output of the data acquisition boxes connected to a relay, running or stopping the pump. Rules for pump regulation and force and displacement gauges calibrations are entered in WaveLab.

2.4.6 Scaling

All quantities in the following paragraph will be referred to the prototype scale device. Froude scaling law was used for scaling data from model to prototype scaled Wave Dragon. The factors displayed in

Table 2 on page 6 have been used.

Quantity	Scale factor
Length	1:51.8
Time	$1{:}51.8^{0.5}$
Discharge	$1{:}51.8^{2.5}$

Table 2: Scale factors

3 Results

3.1 Visual obserations

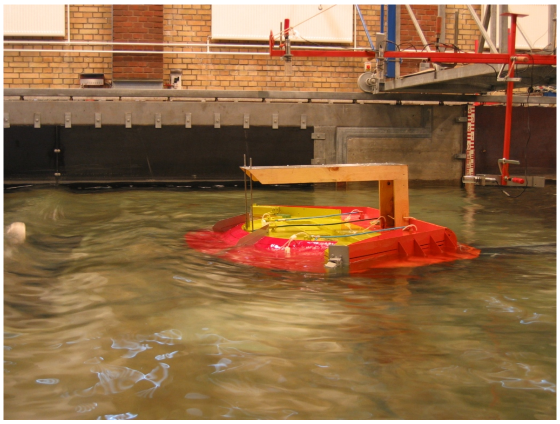
For $0.6 < R < 0.9$, the crest level fits well the sea state, as the behaviour of the Wave Dragon seems reasonnable (no important motion, no sinking, no spillage losses). Water is correctly drained by the three pipes. The heave and pitch movements remain small. For a small value of R, the overtopping flow is very large and the pipes capacity can become insufficient, so that the water which has overtopped returns to the sea instead of being drained. Water jets can overtop the back of the reservoir. The overtopping volume can consequently be underestimated in these situations.

In very big waves, the Wave Dragon can have a tendencie to be immerged on the back. Consequently the water is directly pumped in the basin and the overtopping flow is overevaluated.

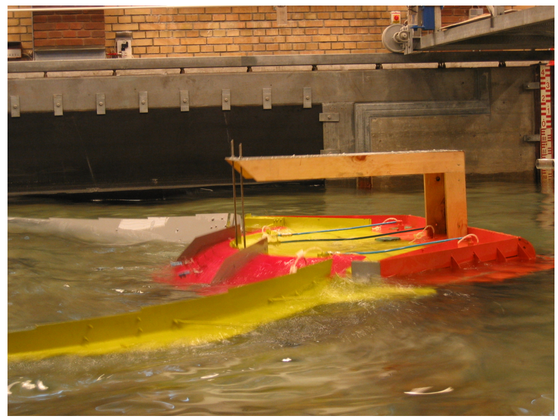
The presence of the arms triggers complex reflections between the arms.

The use of the arms fixed with the ball joint only increases the stability, by adding inertia and damping. With small waves, the arms have no roll movement and seem to increase the wave height. With big waves, the roll movement transmits waves on the back of the Wave Dragon. The arms can be overtopped by the waves.

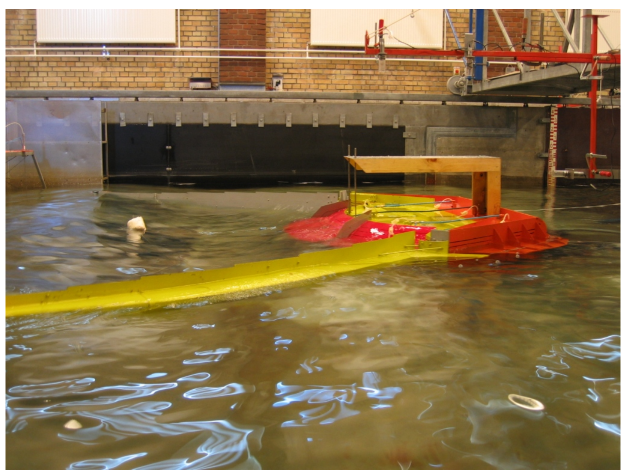
The arms fixed with the plates have a small yaw movement and no roll motion. Even if it is not blocked, the pitch movement between arms and body seems limited by the friction of the plates. The global structure itself is more rigid (arms and body moving together). No waves are sent by the arms. Some wave breaking can happen between the arms for the waves having a large steepness.



(a) Without arms



(b) With moving arms



(c) With rigid arms

Figure 5: Model on operating conditions

3.2 Numerical results

3.2.1 Non-dimensional quantities

Non-dimensional parameters are:

$$Q = \frac{q}{\lambda_{dr}\sqrt{g.Hs^3}} \tag{4}$$

$$R = \frac{Rc}{Hs} \tag{5}$$

$$\lambda_{dr} = 1 - \frac{sinh(2k_p d(1-\frac{d_r}{d})) + 2k_p d(1-\frac{d_r}{d})}{sinh(2k_p d) + 2k_p d} \tag{6}$$

Where:

d the depth

d_r the draft

k_p the peak wave number

q the average overtopping flow

Rc the crest level

The type of expression searched is:

$$Q = a.e^{bR} \tag{7}$$

The application range of such a formulation is $0.5 < R < 1.5$.

3.2.2 General results about overtopping

This results back on a Hs deducted by time series analysis from a wave gauge away from reflection effects. These data gave the smallest scatter. Figure 6 on page 9 shows the results. Despite the efforts made to remove unreliable points, the scatter remains large. However, an uncertaincy factor of 5 is not rare in the overtopping literature. The lines are the exponential tendency curves for each series. Curve fitting gives the following results:

$$Q_{No\,Arms} = 0.12e^{-3.27R} \tag{8}$$

$$Q_{Moving\,Arms} = 0.05e^{-1.46R} \tag{9}$$

$$Q_{Rigid\,Arms} = 0.07e^{-1.40R} \tag{10}$$

The results cleary show that the movement of the arms significantly reduces the overtopping flow. For high sea states, the overtopping discharge without arms and with moving arms is the same, because most of the extra energy get by the arms is dissipated by the roll movement (damping and waves sent on the back). Refering to the trendlines, rigid and moving arms keep having a positive influence on

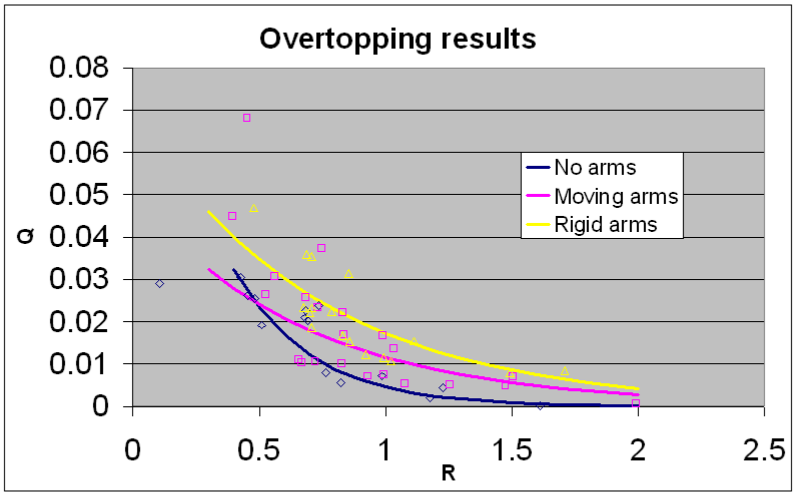


Figure 6: Overtopping results

the overtopping. Refering to the scatter only, this tendency is less obvious. This fits with results from Nissum Bredning, which have shown almost no effect of the arms.

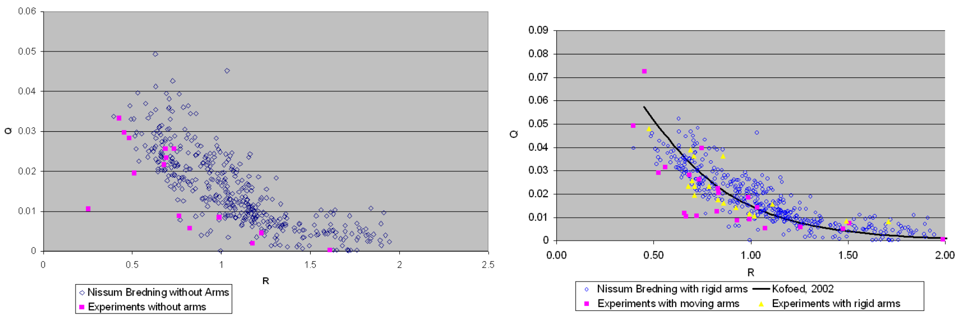
It would have seemed logical that the curve with moving arms crosses the curve with rigid arms for a high value of R: for small waves the roll movement is very small and the arms behave as is they were rigidly fixed. The results do not show this tendency in the reasonnable range of use of the model ($0.5 < R < 1.5$).

In Figure 7 on page 10, the results have been compared to previous data:

- overtopping results from the Nissum Bredning prototype without arms and with moving arms
- reference model for an optimal single level device (see [2]).

It can be seen that the results generally agree with data from Nissum Bredning. The data from the test are included in the scatter of the data from Nissum Bredning, but they fit with the smallest values of the scatter. Several reasons can explain this:

- In the case of moving arms, the stiffness of the shoulder connection has not been measured. No conclusion can be made from the comparison between the two sets of data.
- The important motions of the model can maybe be incriminated (see later).
- The used formulation tends to show a lower efficiency for smaller waves, at a fixed $R = \frac{Rc}{Hs}$ [1]. But during the tests, depending the values of Rc, the higher values of Hs have not been experienced, in order to avoid an underestimated overtopping flow due to spillage losses (as the exhausting pipes capacity is limited). Consequently mainly the lower part of the scatter is shown here.



(a) No arms

(b) Moving arms

Figure 7: Comparison of the results with previous data

3.2.3 Modelling of the moving arms

The fact that logically $Q_{No\,Arms} \leq Q_{Moving\,Arms} \leq Q_{Rigid\,Arms}$ lead to express $Q_{Moving\,Arms}$ as a function of the two overtopping flow taken as references:

$$Q_{Moving\,Arms} = \mu(R).Q_{Rigid\,Arms} + (1 - \mu(R)).Q_{No\,Arms} \tag{11}$$

Where μ is a weight function depending on R (as the sea states influence the efficiency of the arms by causing a roll movement) and characterisctic of the stiffness of the attachment. No measurement of this stiffness has been performed, so this point needs further investigations. This function has to be defined on a reasonnable range in order to have $0 \leq \mu(R) \leq 1$. This function is equal to zero when the arms have no effect ($Q_{Moving\,Arms}$ crosses $Q_{No\,Arms}$).

The calculation of μ from the results, on the range $0.2 \leq R \leq 1.5$ shows that it can be approached quite well with a an exponential expression (see Figure 8 on page 11):

$$\frac{\mu(R)}{\mu_{max}} = 1 - e^{k(R-R_0)} \tag{12}$$

Where:

μ_{max} is the maximal value of μ (here $\mu_{max} = 0.69$)

R_0 is the value of R for which $Q_{Moving\,Arms}$ crosses $Q_{No\,Arms}$ (here $R_0 = 0.47$)

k is a negative fitting coefficient (here $k = -5.5$)

This formulation can be convenient. However, investigations are still necessary to have an idea of the stiffness dependency of the three parameters, and see if the mesure of the stifness only can lead to a reliable expression of the overtopping discharge (without the need of a compete setup of overtopping measurement). Increasing the stifness should normally reduce R_0 and increase μ_{max}.

3.2.4 Movements of the device

The influence of parameters such as heave, pitch and surge on overtopping have been investigated. As the selected points of measure present no spillage losses, no significant tendencies have been detected.

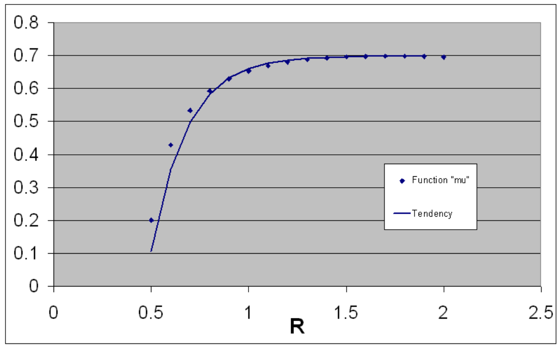


Figure 8: Estimation of the function μ

However, the motions are probably bigger than on the full scale Wave Dragon. Indeed, the Wave Dragon floats on open-air chambers. The behaviour of the air for the model is relatively much more stiff than for the full scale or Nissum Bredning scaledevice. Consequently there can be some differences in the motions, influencing maybe the overtopping results.

Conclusion

This report presents overtopping results for three configurations of the Wave Dragon: without arms and with arms fixed rigidly or floppy. Results show a relatively good agreement with real sea data. The overtopping flow is slightly smaller for the model than for the Nissum Bredning prototype, but this tendency can be explained. Results clearly show that the roll motion of the arms significantly decreases the overtopping flow. This can explain results from Nissum Bredning tests.

In this report it is proposed to express the overtopping discharge in case of floppy arms as a weighted function of the discharge without arms and with rigid arms. The weigth function dependency on the stiffness need further investigations.

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