Hydraulic Model Tests on Modified Wave Dragon

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HYDRAULIC MODEL TESTS ON MODIFIED WAVE DRAGON

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“Wave Dragon. Reconstruction of an existing model in scale 1:50 and sequential tests of changes to the model geometry and mass distribution parameters”

Project no: ENS-51191/00-0067

Tue Hald & Jakob Lynggaard

November 2001

Hydraulic & Coastal Engineering Laboratory
Aalborg University
1. INTRODUCTION

A floating model of the Wave Dragon (WD) was built in autumn 1998 by the Danish Maritime Institute in scale 1:50, see Sørensen and Friis-Madsen (1999) for reference. This model was subjected to a series of model tests and subsequent modifications at Aalborg University and in the following this model is denoted the 1. generation model. Details concerning model tests and modifications are found in Koføed and Frigaard (1999), Frigaard et al. (1999), Martinelli and Frigaard (1999a) and Martinelli and Frigaard (1999b). Based on the previous findings the WD has been redesigned by Friis-Madsen and Armstrong Technology (2000).

The purpose of this report is to describe the model tests conducted with a new designed 2. generation WD model as well as obtained model test results. Tests are conducted as sequential reconstruction followed by physical model tests. All details concerning the reconstruction are found in Hald and Lynggaard (2001). Model tests and reconstruction are carried out during the phase 3 project: "Wave Dragon. Reconstruction of an existing model in scale 1:50 and sequential tests of changes to the model geometry and mass distribution parameters" sponsored by the Danish Energy Agency (DEA) wave energy programme. The tests will establish a well documented basis for the development of a 1:4.5 scale prototype planned for testing Nissum Bredning, a sea inlet on the Danish West Coast.

2. MODEL DESIGN AND SETUP

The structural configuration of the 2. generation WD is the Wave Dragon prototype designed for Nissum Bredning. Thus, reconstruction of the model for use in the laboratory is based on the structural drawings "Wave Dragon Prototype 1:4" by Friis-Madsen dated 8. March 2001. Details concerning the reconstruction are described in Hald and Lynggaard (2001) and in Table I an overview of the different modifications is given.

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Test description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A)</td>
<td>Stern wise expansion of reservoir, volume increased by 82% to 4764 m$^3$. Construction of additional open air chambers behind centre of gravity and separation of existing air chambers from bow to stern. Extension of reflectors by 25 m. Tests conducted by +1.5 m crest freeboard.</td>
</tr>
<tr>
<td>B)</td>
<td>Expansion of the reflector draught by 2 m.</td>
</tr>
<tr>
<td>C)</td>
<td>Expansion of the reflector draught by 2 m. Tests conducted by +1.5 m crest freeboard.</td>
</tr>
<tr>
<td>D)</td>
<td>Trimming the bow 1 m below the stern at different wave situations:</td>
</tr>
<tr>
<td></td>
<td>• Wave situation 2: 2 m bow freeboard, 3 m stern freeboard (1-2)+(2-3).</td>
</tr>
<tr>
<td></td>
<td>• Wave situation 3: 3 m bow freeboard, 4 m stern freeboard (2-3)+(3-4).</td>
</tr>
<tr>
<td></td>
<td>• Wave situation 4: 3 m bow freeboard, 4 m stern freeboard (3-4)+(4-5).</td>
</tr>
<tr>
<td></td>
<td>• Wave situation 5: 4 m bow freeboard, 5 m stern freeboard (4-5).</td>
</tr>
<tr>
<td>E)</td>
<td>Construction of doubly-curved overtopping ramp.</td>
</tr>
<tr>
<td>F)</td>
<td>Construction of perforated double-walled wave damper in turbine pit.</td>
</tr>
<tr>
<td>G)</td>
<td>Like D with wave situation 4 changed:</td>
</tr>
<tr>
<td></td>
<td>• Wave situation 4: 4 m bow freeboard, 5 m stern freeboard (4-5).</td>
</tr>
<tr>
<td>H)</td>
<td>Construction of two guiding walls on overtopping ramp and modifying the wave damper to a perforated single-walled wave damper at the back of the turbine pit.</td>
</tr>
<tr>
<td>I)</td>
<td>Adding ballast (973 t). Increasing height of guiding walls by 1.5 m</td>
</tr>
<tr>
<td>J)</td>
<td>Fixing reflectors to the shoulders with WD located with a crest freeboard of 4 m.</td>
</tr>
<tr>
<td>K)</td>
<td>Combine bow and stern air chambers by tube system.*</td>
</tr>
<tr>
<td>L)</td>
<td>Construction pitch stabilizing air chamber above MWL at stern.*</td>
</tr>
<tr>
<td>M)</td>
<td>Open reflectors above pontoon near shoulders to allow for entrapped ice to escape.*</td>
</tr>
</tbody>
</table>

Table I. Test and modification programme for 2. generation WD. * planned test.
Also in Table I the different aspects of the test programme is outlined. In Table II the different measured
mass distribution parameters of the 2. generation model are shown and compared to the 1. generation model.
The location of the centre of gravity and the mass moment of inertia is measured by weighing the model on
three load cells and by measuring the eigenperiod in air in yaw and pitch motion. This method of identifying
the mass distribution parameters is similar to the method applied to the 1. generation model described in
Frigaard et al. (1999).

<table>
<thead>
<tr>
<th>Model:</th>
<th>1. generation</th>
<th>2. generation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scale:</td>
<td>1:50</td>
<td>1:51.8</td>
</tr>
<tr>
<td>Mass:</td>
<td>[t]</td>
<td></td>
</tr>
<tr>
<td>Surge</td>
<td>[m]</td>
<td></td>
</tr>
<tr>
<td>Sway</td>
<td>[m]</td>
<td></td>
</tr>
<tr>
<td>Heave</td>
<td>[m]</td>
<td></td>
</tr>
</tbody>
</table>

Table II. Mass distribution parameters.

<table>
<thead>
<tr>
<th>Centre of gravity: (see Fig. 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surge [m]</td>
</tr>
<tr>
<td>Sway [m]</td>
</tr>
<tr>
<td>Heave [m]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mass moment of Inertia:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yaw [kg m²]</td>
</tr>
<tr>
<td>Pitch [kg m²]</td>
</tr>
<tr>
<td>Roll [kg m²]</td>
</tr>
</tbody>
</table>

The hydraulic behaviour of the WD is not only dependent of the structural geometry and mass distribution
but depends also on the stiffness of tension cables linking the two reflector arms and the stiffness of the
moorings. The Nissum Bredning WD is intended moored to a single pile in front by a single cable, see Figure
1. This cable is split in two in proximity of the WD body and in the 1. generation model the mooring elasticity
of the central cable was 1.4 MN/ m and finally, from the stern two mooring lines are fixed to the sea bed. The
two tension cables fix the reflector arms to the central mooring cable, both cables having an elasticity of 0.5
MN/ m. For the 2. generation model these stiffness have been kept. Both the tension cables and the mooring
cable has been pretensioned to approximately 1.0 MN and 1.5 MN respectively.

3. SCALING

All modifications were made on the 1:50 scaled 1. generation WD model described in Martinelli and Frigaard
(1999) and to be able to reuse major parts of this old model a scale of 1:51.8 was necessary for the 2. genera-
tion WD model to match the existing model.

Quantities describing the geometrical and hydraulic conditions will be scaled to prototype conditions. The
Froude scaling law applies for scaling the data from model to prototype and accordingly all quantities will
scaled as follows:

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Scaling law</th>
<th>Scaling factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>λₐₐ</td>
<td>51.8</td>
</tr>
<tr>
<td>Time</td>
<td>λₐₐ⁰⁵</td>
<td>51.8⁰⁵</td>
</tr>
<tr>
<td>Discharge</td>
<td>λₐₐ²⁵</td>
<td>51.8²⁵</td>
</tr>
<tr>
<td>Volume, mass, forces</td>
<td>λₐₐ¹⁰</td>
<td>51.8¹⁰</td>
</tr>
<tr>
<td>Stiffness</td>
<td>λₐₐ¹¹</td>
<td>51.8¹¹</td>
</tr>
</tbody>
</table>
4. TEST CONDITIONS AND TEST PROGRAMME

Tests were run for a different number of wave conditions according to the parameters in Table III. Wave situations 1 through 5 correspond to normal operating conditions while situation 6 and 7 are extreme wave conditions corresponding to a 50 years and 100 years return period respectively. The duration of each run was 30 minutes corresponding to approximately 4 hours in prototype and each 30 minute wave run was generated to match a JONSWAP spectrum with $\gamma = 3.3$. Accordingly the number of waves ranged from 1400 to 2500 depending on the wave period. Water depth was kept constant at 25 m which is fairly shallow for a North Sea location but fits the Nissum Bredning conditions when scaled 1:4.

<table>
<thead>
<tr>
<th>Wave ID</th>
<th>$R_c$ [m]</th>
<th>$H_s$ [m]</th>
<th>$T_p$ [s]</th>
<th>Probability [% time]</th>
<th>Percentage of total energy [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>NS 1</td>
<td>1.25</td>
<td>1.0</td>
<td>6.0</td>
<td>38</td>
<td>6.29</td>
</tr>
<tr>
<td>NS 2</td>
<td>2.0</td>
<td>2.0</td>
<td>7.7</td>
<td>27</td>
<td>22.90</td>
</tr>
<tr>
<td>NS 3</td>
<td>3.0</td>
<td>3.0</td>
<td>8.8</td>
<td>14</td>
<td>30.47</td>
</tr>
<tr>
<td>NS 4</td>
<td>4.0</td>
<td>4.0</td>
<td>9.7</td>
<td>6</td>
<td>25.76</td>
</tr>
<tr>
<td>NS 5</td>
<td>4.0</td>
<td>5.0</td>
<td>10.6</td>
<td>2</td>
<td>14.48</td>
</tr>
<tr>
<td>NS 6</td>
<td>-</td>
<td>9.0</td>
<td>13.4</td>
<td>0.00091</td>
<td>-</td>
</tr>
<tr>
<td>NS 7</td>
<td>-</td>
<td>10.0</td>
<td>14.1</td>
<td>0.00046</td>
<td>-</td>
</tr>
<tr>
<td>NS 8</td>
<td>-</td>
<td>12.0</td>
<td>15.0</td>
<td>0</td>
<td>-</td>
</tr>
</tbody>
</table>

$R_c = \text{crest freeboard relative to MWL}$
$H_s = \text{significant wave height}$
$T_p = \text{peak period}$
$\text{NS} = \text{North Sea}$

In Figure 1 the WD in the normal configuration is depicted and each of the force registration points can be seen. In the cables used to tension the two reflector arms forces are registered in the across cable A, the total mooring force was measured in one single line where the structure was anchored, and finally, three force components were measured in the junction between the right reflector and the shoulder. Movements were registered for three degrees of freedom (heave, pitch and surge). Finally, also the amount of overtopping water in the reservoir was registered.
5. TEST RESULTS

Waves were registered by two resistance type wave gauges placed on either side of the WD outside the reflector arms. The measured waves were not always coincident to the target values, thus registered forces, movements and overtopping were referred to measured waves. Wave situation 6-8 resulted in breaking waves in front and on the WD, thus measured significant wave heights were smaller than in Table III.

Mooring forces were registered by a load cell designed and manufactured by Aalborg University whereas cable forces and forces in the junction were registered by a 3D load cell and a z-gauge designed and manufactured by Danish Maritime Institute. Two characteristic values were retrieved from the signals: the root mean square (rms) value $F_{\text{rms}}$ for fatigue design and the average of the highest 1/250 of the peak forces $F_{1/250}$ being a representative for the maximum peak force.

Movements were registered by three ultrasound gauges: two places above the WD to register heave being the average of the two and pitch being the difference of the two, and one placed behind the WD to register surge motions. Heave, pitch and surge were obtained accordingly:

\[
\begin{align*}
\text{(heave)} &= \frac{y_1 + y_2}{2} \\
\text{(pitch)} &= \frac{y_1 - y_2}{d} \\
\text{(surge)} &= x
\end{align*}
\]

where

- $x =$ horizontal ultrasound signal
- $y_1, y_2 =$ two vertical ultrasound signals
- $d =$ distance between the two vertical ultrasound signals, $d = 25 \text{ m}$

The characteristics of interest are the root mean square value and the maximum value being defined as the average of the highest 1/250 of the positive and negative oscillations. Heave and surge movements were non-dimensionalized by the significant wave height and the pitch was non-dimensionalized by multiplying with half the distance between the two vertical ultrasound signals and dividing by the significant wave height, thus describing the vertical oscillations of such two points induced by the pitch. With a distance $d = 25 \text{ m}$ this corresponds to a position half the distance to the front and half the distance to the rear of the reservoir from the midpoint of the reservoir.

All signals were sampled at 10.0 Hz and the force signals were additionally low pass filtered at 8 Hz.
Overtopping was measured by collecting the water present in the reservoir into three exhaust tubes leading the water into a reservoir outside the wave basin. The water was lead into the outside reservoir by gravity from where the water was pumped back into the wave basin through an automatically controlled pump. To control switching the pump on and off, the water level in the reservoir was registered, and when exceeding a fixed level the pump was switched on for 3 sec. To estimate the amount of overtopping water the pump was calibrated according to the water level to give certain average discharge during the 3 sec and by counting the number of switching on the total amount of water was calculated by multiplying the discharge. In consequence of this measuring technique, the model reservoir of the WD is drained during each wave. This is not the situation in the prototype where the amount of drainage depends on the turbine management strategy.

According to the previous tests measured values of overtopping were non-dimensionalized and presented in the following form:

\[ Q^* = 0.017 \exp(-48R^*) \]  

(eq. 1)

where, 

\[ Q^* = \frac{q\sqrt{s_{op}/2\pi}}{gH^2_sL} \]

\[ R^* = \frac{R_c}{H_s}\sqrt{\frac{s_{op}}{2\pi}} \]

\[ q = \text{discharge due overtopping} \]

\[ H_s = \text{significant wave height} \]

\[ L = \text{ramp width} = 86.6 \text{ m} \]

\[ s_{op} = \text{wave steepness defined as } s_{op} = H_s/L_{op} \]

\[ L_{op} = \text{deep water wave length defined as } L_{op} = \frac{g}{2\pi}T_p^2 \]

\[ T_p = \text{peak period} \]

\[ R_c = \text{Mean value of crest freeboard relative to MWL} \]

Obtained results can be found in appendices A through H. Mooring forces, cable forces and X, Y and Z forces on the shoulders are presented as function of significant wave height. Movements are presented as function of peak period and overtopping is presented in discharge as function of wave height and in dimensionless form showing \( Q^* \) as function of \( R^* \).

Results of all overtopping tests are summarized in Figure H.10, H.11 and I.8 and a reevaluation of the existing overtopping equation is fitted based on measurements obtainied with the new doubly-curved overtopping ramp. The new overtopping equation is modified to:

\[ Q^* = 0.025 \exp(-40R^*) \]  

(eq. 2)
### 6. SUMMARY AND CONCLUSIONS

Within the programme the effects of the modifications on the WD on forces, movements and overtopping were analyzed. Details concerning results are found in appendices A through H and Table IV gives a short summary.

#### Test Results

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Results</th>
</tr>
</thead>
</table>
| A)      | • Force in cable A, $H_s = 5$ m: peak force: 0-3.5 MN, rms force 0.5-1.5 MN.  
• Mooring force, $H_s = 5$ m: peak force $\approx 4.5$ MN, rms force $\approx 2.3$ MN.  
• Shoulder force, $H_s = 5$: $X_{1/250} = 2.8$ MN, $X_{rms} = 0.5$ MN,  
  $Y_{1/250} = 5.0$ MN, $Y_{rms} = 1.0$ MN  
  $Z_{1/250} = 10.0$ MN, $Z_{rms} = 1.9$ MN  
• rms-motions: Surge: $\approx 0.2 \times H_s$, heave: $\approx 0.15 \times H_s$, pitch: $\approx \pm 0.15 \times H_s$.  
• Overtopping up to 21 m$^3$/s. 40% overall increase compared to 1. generation model. |
| B)      | No effect on cable force. 10% increase in mooring forces. Increase in $X_{1/250}$, $Y_{1/250}$ and $Z_{1/250}$.  
Overtopping increases compared to 1. generation model. |
| C)      | 10% increased in cable and mooring forces. 50% increase in $X_{1/250}$ and $Z_{1/250}$.  
Some (5%) increase in overtopping. |
| D)      | All forces and movements are comparable to test C.  
No increase in the amount of overtopping. However, the average freeboard along the ramp is higher than the freeboard without trimming. The trimming is adjusted to position the WD horizontal when the reservoir is full. |
| E)      | All forces are comparable to test B and C.  
Increased rms movements: Surge: 0.15-0.3×$H_s$, heave: 0.15-0.3×$H_s$, pitch: ±0.15-0.3×$H_s$.  
Overtopping increases by a factor 2. |
| F)      | Large increase force in cable A perhaps due to failure on load cell.  
Remaining forces and movements comparable to E.  
Further increases in overtopping. |
| G)      | Like D.  
Load cell in cable A failed. |
| H)      | All forces and movements comparable to test F.  
Load cell in cable A failed.  
Overtopping comparable to test E. |
| I)      | • Mooring force, $H_s = 5$ m: peak force $\approx 5$ MN, rms force $\approx 2.5$ MN.  
• Shoulder force, $H_s = 5$: $X_{1/250} = 4$ MN, $X_{rms} = 0.7$ MN,  
  $Y_{1/250} = 7.0$ MN, $Y_{rms} = 1.6$ MN  
  $Z_{1/250} = 18.0$ MN, $Z_{rms} = 3.8$ MN  
• rms-motions: Surge: $\approx 0.2 \times H_s$, heave: $\approx 0.15 \times H_s$, pitch: $\approx \pm 0.1 \times H_s$.  
100% overall increase in overtopping compared to 1. generation model. |
| J)      | No effect on overtopping, mooring forces similar.  
Shoulder force: $X_{1/250}$ comparable, $Y_{1/250}$ small increase (15%), $Z_{1/250}$ large decrease (100%). |
7. REFERENCES


Testseries A

Effect of enlarged reservoir and enlarged open air chambers

Crest freeboard: +1.5 m compared to table III
Figure A.1. Mooring force.

Figure A.2. Force along across cable A
Figure A.3. Shear force X on shoulder.

Figure A.4. Axial force Y on shoulder
Figure A.5. Vertical force Z on shoulder.
Figure A.6. Non-dimensional positive and negative rms amplitudes of heave, surge and pitch motions.

Figure A.7. Non-dimensional positive and negative peak amplitudes of heave, surge and pitch motions.
Figure A.8. Non-dimensional overtopping.

Figure A.9. Overtopping.
Testseries B

Effect of enlarged draught of reflectors
Figure B.1. Mooring force.

Figure B.2. Force along across cable A
Figure B.3. Shear force X on shoulder.

Figure B.4. Axial force Y on shoulder.
Figure B.5. Vertical force Z on shoulder.
Figure B.6. Non-dimensional positive and negative rms amplitudes of heave, surge and pitch motions.

Figure B.7. Non-dimensional positive and negative peak amplitudes of heave, surge and pitch motions.
Figure B.8. Non-dimensional overtopping.

Non-dimensional overtopping

\[ R^* = \frac{R C}{H S^* \sqrt{g \sigma p / (2 \pi)}} \]

\[ Q^* = \frac{q* \sqrt{S op / (2\pi)}}{\sqrt{g H S^3 L^2}} \]

Wave situation 1
Wave situation 2
Wave situation 3
Wave situation 4
Wave situation 5
Testserie B
3D case
Testseries C

Effect of enlarged draught of reflectors
Crest freeboard: +1.5 m compared to table III
Figure C.1. Mooring force.

Figure C.2. Force along across cable A
Figure C.3. Shear force X on shoulder.

Figure C.4. Axial force Y on shoulder.
Figure C.5. Vertical force Z on shoulder.
Figure C.6. Non-dimensional positive and negative rms amplitudes of heave, surge and pitch motions.

Figure C.7. Non-dimensional positive and negative peak amplitudes of heave, surge and pitch motions.
Figure C.8. Non-dimensional overtopping.

Non-dimensional overtopping

\[ Q^* = \frac{q^* \sqrt{S_{op}/(2\pi)}}{\sqrt{g H^3 L^2}} \]

Wave situation 1
Wave situation 2
Wave situation 3
Wave situation 4
Wave situation 5
Testserie C
3D case
Testseries D

Effect of trimming

<table>
<thead>
<tr>
<th>Trim</th>
<th>Waves</th>
<th>Bow:</th>
<th>Stern:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trim 1</td>
<td>NS 3</td>
<td>3m</td>
<td>4m</td>
</tr>
<tr>
<td>Trim 2</td>
<td>NS 2</td>
<td>2m</td>
<td>3m</td>
</tr>
<tr>
<td>Trim 3</td>
<td>NS 3</td>
<td>2m</td>
<td>3m</td>
</tr>
<tr>
<td>Trim 4</td>
<td>NS 2</td>
<td>1m</td>
<td>2m</td>
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<tr>
<td>Trim 5</td>
<td>NS 4</td>
<td>3m</td>
<td>4m</td>
</tr>
<tr>
<td>Trim 6</td>
<td>NS 4</td>
<td>4m</td>
<td>5m</td>
</tr>
<tr>
<td>Trim 7</td>
<td>NS 5</td>
<td>4m</td>
<td>5m</td>
</tr>
</tbody>
</table>
Figure D.1. Mooring force.

![Mooring force plot]

- Mooring force - prestress at rest, at approx. 1.5 MN

Figure D.2. Force along across cable A

![Force along across cable A plot]

- Force on across cable – prestress at rest, at approx. 1.3 MN

- $F_{1/250}$ extra tension
- $F_{rms}$ extra tension
- $F_{1/250}$ less tension
- $F_{rms}$ less tension
Figure D.3. Shear force X on shoulder.

Figure D.4. Axial force Y on shoulder.
Figure D.5. Vertical force Z on shoulder.
Figure D.6. Non-dimensional positive and negative rms amplitudes of heave, surge and pitch motions.

Figure D.7. Non-dimensional positive and negative peak amplitudes of heave, surge and pitch motions.
Figure D.8. Non-dimensional overtopping.

Non-dimensional overtopping

$R^* = \frac{R_C}{H_S} \sqrt{\frac{s_{op}}{2\pi}}$

$Q^* = \frac{q^* \sqrt{s_{op}}}{(\sqrt{g H_S^3 L^2})}$

Wave situation 1
Wave situation 2
Wave situation 3
Wave situation 4
Wave situation 5
Testserie D
3D case
Testseries E

Effect of double-curved overtopping ramp
Figure E.1. Mooring force.

Figure E.2. Force along across cable A
Figure E.3. Shear force X on shoulder.

Figure E.4. Axial force Y on shoulder.
Figure E.5. Vertical force $Z$ on shoulder.
Figure E.6. Non-dimensional positive and negative rms amplitudes of heave, surge and pitch motions.

Figure E.7. Non-dimensional positive and negative peak amplitudes of heave, surge and pitch motions.
Figure E.8. Non-dimensional overtopping.
Figure E.9. Sample time series of mooring force in wave situation 5. Measures in scale 1:51.8.

Figure E.10. Sample time series of cable force in wave situation 5. Measures in scale 1:51.8.
Figure E.11. Sample time series of shear force X in wave situation 5. Measures in scale 1:51.8.

Figure E.12. Sample time series of axial force Y in wave situation 5. Measures in scale 1:51.8.
Figure E.13. Sample time series of vertical force Z in wave situation 5. Measures in scale 1:51.8.
Testseries F

Effect of double-walled wave damper in reservoir
Figure F.1. Mooring force.

Figure F.2. Force along across cable A
Figure F.3. Shear force X on shoulder.

Figure F.4. Axial force Y on shoulder
Figure F.5. Vertical force $Z$ on shoulder.
Figure F.6. Non-dimensional positive and negative rms amplitudes of heave, surge and pitch motions.

Figure F.7. Non-dimensional positive and negative peak amplitudes of heave, surge and pitch motions.
Figure F.8. Non-dimensional overtopping.

Non-dimensional overtopping

\[ R^* = \frac{R}{C / H S^* \sqrt{g'}} \]

\[ Q^* = \frac{q^* \sqrt{S'}}{(\pi g H S^* L^2)} \]

Wave situation 1
Wave situation 2
Wave situation 3
Wave situation 4
Wave situation 5
Testserie F
3D case
Testseries G

Effect of triming

<table>
<thead>
<tr>
<th>Trim</th>
<th>Waves</th>
<th>Bow Freeboard</th>
<th>Stern Freeboard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trim 1</td>
<td>NS 2</td>
<td>2m</td>
<td>3m</td>
</tr>
<tr>
<td>Trim 2</td>
<td>NS 3</td>
<td>3m</td>
<td>4m</td>
</tr>
<tr>
<td>Trim 3</td>
<td>NS 4</td>
<td>4m</td>
<td>5m</td>
</tr>
<tr>
<td>Trim 4</td>
<td>NS 5</td>
<td>4m</td>
<td>5m</td>
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</tbody>
</table>
Figure G.1. Mooring force.
Figure G.3. Shear force X on shoulder.

Figure G.4. Axial force Y on shoulder.
Figure G.5. Vertical force $Z$ on shoulder.
Figure G.6. Non-dimensional positive and negative rms amplitudes of heave, surge and pitch motions.

Figure G.7. Non-dimensional positive and negative peak amplitudes of heave, surge and pitch motions.
Figure G.8. Non-dimensional overtopping.

Figure G.9. Overtopping.
Testseries H

Effect of guiding walls on ramp and single-walled wave damper in reservoir
Figure H.1. Mooring force.

Mooring force – prestress at rest, at approx. 1.5 MN
Figure H.3. Shear force X on shoulder.

Figure H.4. Axial force Y on shoulder.
Figure H.5. Vertical force Z on shoulder.
Figure H.6. Non-dimensional positive and negative rms amplitudes of heave, surge and pitch motions.

Figure H.7. Non-dimensional positive and negative peak amplitudes of heave, surge and pitch motions.
Figure H.8. Non-dimensional overtopping.

Figure H.9. Overtopping.
Figure H.10. Non-dimensional overtopping. All tests.

Figure H.11. Non-dimensional overtopping. All tests and reevaluated overtopping eq.
Testseries I

Effect of increasing height of guiding walls on ramp by +2 m and adding ballast
Figure I.1. Mooring force.
Figure I.3. Shear force X on shoulder.

Figure I.4. Axial force Y on shoulder.
Figure I.5. Vertical force $Z$ on shoulder.
Figure I.6. Non-dimensional positive and negative rms amplitudes of heave, surge and pitch motions.

Figure I.7. Non-dimensional positive and negative peak amplitudes of heave, surge and pitch motions.
Figure I.8. Non-dimensional overtopping.

Figure I.9. Overtopping.
Testseries J

Effect of fixing reflector arms to shoulders
Figure J.1. Mooring force.
Figure J.3. Shear force X on shoulder.

Figure J.4. Axial force Y on shoulder.
Figure J.5. Vertical force Z on shoulder.