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LARGE SCALE TESTS ON A GENERALISED OSCILLATING WATER COLUMN WAVE ENERGY CONVERTER

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This short paper outlines tests in the GWK during March / April 2014 on a generalised Oscillating Water Column (OWC) wave energy converter. The tests (at approximately 1:5 to 1:9 of full scale) measured wave loads, water column movements, air pressures and air flows through a number of orifices simulating turbine losses, including full closure. The tests will provide unique calibration data for CFD models using compressible air in the chamber. Additionally, by direct comparison with small-scale physical model tests, scale effects in wave loading and device performance will be explored in detail.

1. INTRODUCTION

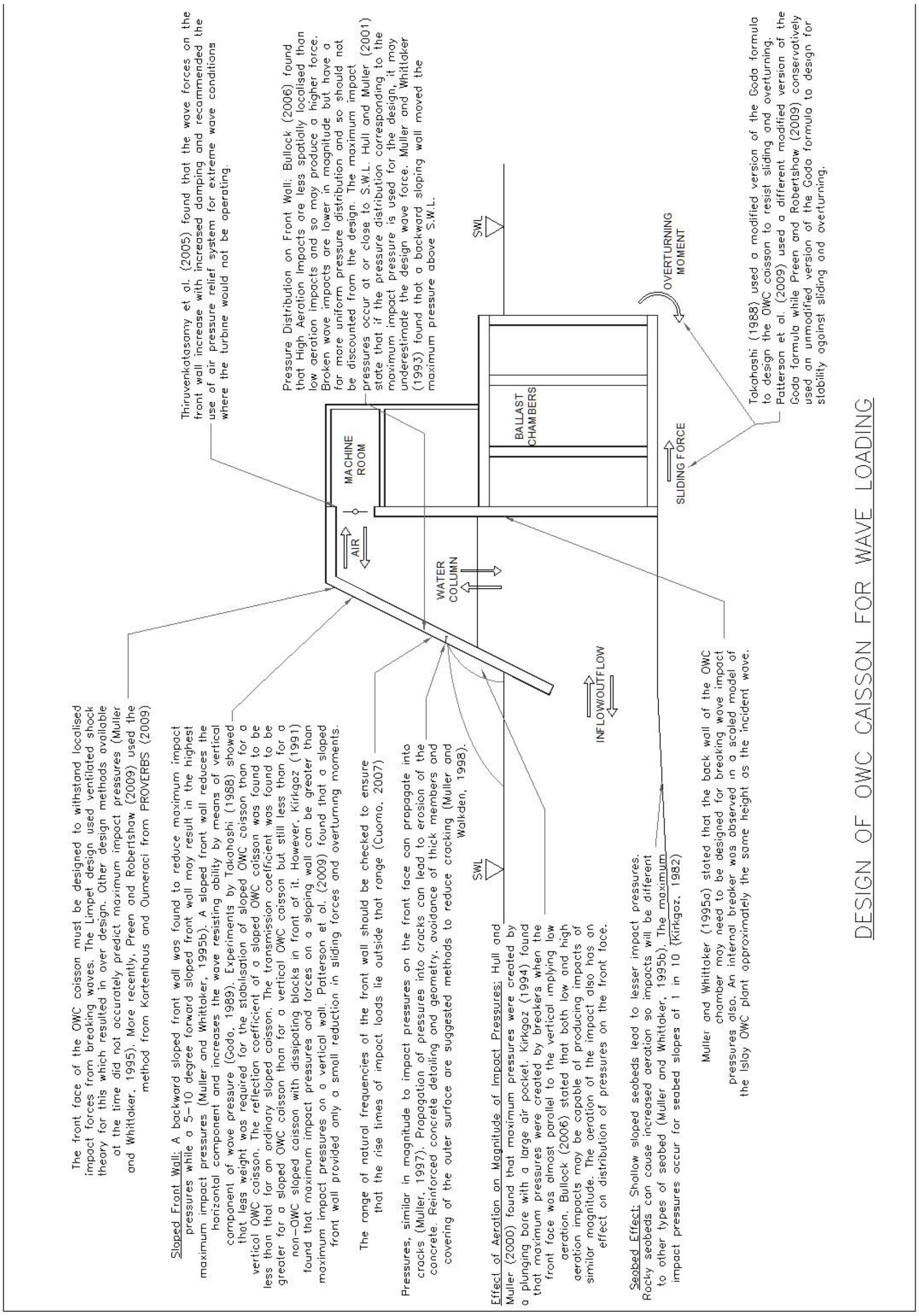
Many national governments have prioritised wave and tidal marine energy for investment in 'green energy' generation. In September 2010, the Scottish Government raised its renewable energy electricity target from 50% by 2020, to 80% by 2020. While much of this expansion will be in established technologies, UK's marine energy resources have immense potential. Generation costs for wave technologies remain higher than for offshore wind, but many enabling measures have seen improvements to efficiency and in manufacture and deployment.

Coastal Wave Energy Converters (WECs) based upon the Oscillating Water Column (OWC) principle have been operating since the mid-90s on the scale of pilot plants. While the air turbines are generally subject to patents / licensing, the configuration of the OWC housings remains relatively unrestricted. Despite early successes, e.g. the grid-connection of the LIMPET plant in 2001 (Wavegen, 2002), progress with OWC WECs has not been uniformly positive, with successor plants experiencing damage in construction and/or during early operation, Torre-Enciso *et al* (2009, 2010), perhaps implying that the coastal OWC WEC has little future. Proposed developments in UK and eleswhere suggest otherwise, especially when viewed alongside recent work (Folley *et al*., 2009) suggesting that the coastal and nearshore settings may not be as disadvantageous in energy terms as was often assumed.

In 2009, the 4MW Siadar Wave Energy Project was consented by the Scottish Government. If built, it would be the largest wave power installation in the world. The further development of the technology is however impeded by construction costs, influenced in part by uncertainties in design wave loads. One major source of uncertainty derives from the universal use of small-scale testing to derive performance and loading characteristics, despite the inherent scale errors in air flows / pressures implicit in the small-scale hydraulic model testing used. This project therefore addresses these uncertainties, especially those influencing how knowledge based on numerical and small-scale physical model studies can be scaled up to prototype scale.

Prediction of wave loads on OWC caissons currently uses a Goda-type approach developed for simple caissons, *e.g.* Preen & Robertshaw (2009), or using a modified version for OWCs suggested by

Takahashi (1988), *e.g*. Patterson & Dunsire (2009). OWC caissons represent a distinctive new class of structure and, with guidance not verified under controlled large-scale laboratory conditions, uncertainties remain which, if they could be reduced, would move the ultimate price of electricity (POE, *i.e* p/kWh) downwards.



The front face of the OWC caisson must be designed to withstand localised impact forces from breaking waves. The Limpet design used ventilated shock theory for this which resulted in over design. Other design methods available at the time did not accurately predict maximum impact pressures (Muller and Whittaker, 1995). More recently, Preen and Robertshaw (2009) used the method from Kortenhaus and Oumeraci from PROVERBS (2009)

Sloped Front Wall: A backward sloped front wall was found to reduce maximum impact pressures while a 5–10 degree forward sloped front wall may result in the highest maximum impact pressures (Muller and Whittaker, 1995b). A sloped front wall reduces the horizontal component and increases the wave resisting ability by means of vertical component of wave pressure (Goda, 1989). Experiments by Takahashi (1988) showed that less weight was required for the stabilisation of sloped OWC caisson than for a vertical OWC caisson. The reflection coefficient of a sloped OWC caisson was found to be less than that for an ordinary sloped caisson. The transmission coefficient was found to be greater for a sloped OWC caisson than for a vertical OWC caisson but still less than for a non–OWC sloped caisson with dissipating blocks in front of it. However, Kirkgoz (1991) found that maximum impact pressures and forces on a sloping wall can be greater than maximum impact pressures on a vertical wall. Patterson et al. (2009) found that a sloped front wall provided only a small reduction in sliding forces and overturning moments.

The range of natural frequencies of the front wall should be checked to ensure that the rise times of impact loads lie outside that range (Cuomo, 2007)

Pressures, similar in magnitude to impact pressures on the front face can propagate into cracks (Muller, 1997). Propagation of pressures into cracks can lead to erosion of the concrete. Reinforced concrete detailing and geometry, avoidance of thick members and covering of the outer surface are suggested methods to reduce cracking (Muller and Walkden, 1998).

Effect of Aeration on Magnitude of Impact Pressures: Hull and Muller (2000) found that maximum pressures were created by a plunging bore with a large air pocket. Kirkgoz (1994) found that maximum pressures were created by breakers when the front face was almost parallel to the vertical implying low aeration. Bullock (2006) stated that both low and high aeration impacts may be capable of producing impacts of similar magnitude. The aeration of the impact also has an effect on distribution of pressures on the front face.

Seabed Effect: Shallow sloped seabeds lead to lesser impact pressures. Rocky seabeds can cause increased aeration so impacts will be different to other types of seabed (Muller and Whittaker, 1995b). The maximum impact pressures occur for seabed slopes of 1 in 10 (Kirkgoz, 1982)

Muller and Whittaker (1995a) stated that the back wall of the OWC chamber may need to be designed for breaking wave impact pressures also. An internal breaker was observed in a scaled model of the Islay OWC plant approximately the same height as the incident wave.

Thiruvenkatasamy et al. (2005) found that the wave forces on the front wall increase with increased damping and recommended the use of air pressure relief system for extreme wave conditions where the turbine would not be operating.

Pressure Distribution on Front Wall: Bullock (2006) found that High Aeration Impacts are less spatially localised than low aeration impacts and so may produce a higher force. Broken wave impacts are lower in magnitude but have a far more uniform pressure distribution and so should not be discounted from the design. The maximum impact pressures occur at or close to S.W.L. Hull and Muller (2001) state that if the pressure distribution corresponding to the maximum impact pressure is used for the design, it may underestimate the design wave force. Muller and Whittaker (1993) found that a backward sloping wall moved the maximum pressure above S.W.L.

Takahashi (1988) used a modified version of the Goda formula to design the OWC caisson to resist sliding and overturning. Patterson et al. (2009) used a different modified version of the Goda formula while Preen and Robertshaw (2009) conservatively used an unmodified version of the Goda formula to design for stability against sliding and overturning.

Figure 1: Design guidance on wave loadings on OWC WECs (O'Callaghan, 2010)

2. OUTLINE OF THE OWC TESTING PROJECT IN THE GWK

The overall aim of this GWK testing is to reduce design uncertainty for OWC WECs. We highlighted above the paucity of large-scale physical model data for verification of design guidance combining small-scale physical models, CFD, and consideration of scale effects. These large-scale tests were therefore proposed to HYDRALAB in December 2012. The suggested OWC project team, led by Dr

Tom Bruce of the Institute of Energy Systems at University of Edinburgh, included: HR Wallingford represented by Professor William Allsop, Dr Giovanni Cuomo and Mr John Alderson; Queen's University of Belfast, represented initially by Mr Cuan Boake, but later by Dr Viviana Russo supported by Professor Trevor Whittaker; 2nd University of Naples represented by Professor Diego Vicinanza, assisted by Dr Vincenzo Ferrante; and Dr Mark Cooker at University of East Anglia. The team were unified by interests in physical model testing and in the physics of air / water / structure interactions, having worked together in large EU or UK research projects including PROVERBS and VOWS / Big-VOWS.

The large scale tests in the Grosse Wellenkanal (GWK), operated by Forshungszentrum Küste (FZK) in Hannover, were planned for early 2014. The project team had six weeks of access time to GWK under the EC FP7 “Hydralab IV” project (EC FP7 contract no. 261520). The testing schedule was (approximately):

- January and February 2014: preparation of model elements at GWK
- OWCs project team on site from Monday 3rd March, for six weeks (30 days).
- week 1 (w/c 03/03/14) Set-up and calibrate instrumentation
- week 2 (w/c 10/03/14) Commission full test set-up (waves + instrumentation + data acquisition + storage)
- week 3 (w/c 17/03/14) Testing
- week 4 (w/c 24/03/14) Testing
- week 5 (w/c 31/03/14) Testing
- week 6 (w/c 07/04/14) Testing (contingency); data archive; demount and clear

The guiding principle was that these tests were to explore scale effects and were therefore not aimed *per se* at device optimisation. Following usual practice, the pneumatic performance was simulated by a set of alternative orifice plates in the air ducts. The main responses measured were:

- air pressure difference across the orifice, from which device energy conversion efficiency may (later) be deduced; and air velocities in the air duct above the structure;
- wave loading on the front face, on the rear wall and roof of the OWC chamber;
- water levels within the OWC chamber.

The influences of the following will be explored:

- wave period; wave height, and therefore wave steepness;
- regular versus irregular waves;
- water depth; curtain (front) wall submergence depth;
- orifice diameter, including full closure;
- impact loading (wave breaking) on front face of structure.

After the access period, GWK results will be compared with small-scale and CFD data, with differences due to scale evaluated against analytical predictions.

3. MODEL DESIGN AND INSTRUMENTATION

The experiments in the GWK were designed at a nominal Froude scale of approximately 1:9 relative to a prototype, and 9:1 relative to small scale tests in Edinburgh. The flume is 307 m long, 7.0 m deep and 5.0 m wide. Regular and random (irregular) waves can be generated by the piston paddle, up to 2m, controlled by an online absorption system to reduce re-reflections.

Three OWC caissons were installed across the flume with the central one instrumented. The caissons have been placed with the front face 97.5m from the wave generator. In front of the caissons, a 1 in 6 slope rises from the flume floor level over a distance of approximately 11m A set of stop-logs were also placed in groves in the flume walls, installed up to a level above the caisson roof, thus (partially) sheltering the air ducts and pressure instruments / cabling. The lower point of the front wall was later adjusted to change the opening height in the OWC entry.

Four wave gauges (WG05-WG08) were installed to measure the water surface at 1m intervals from the caisson front face, Figure 2. Further out towards the wave generator, an array of 4 wave gauges (WG01-WG04) measured incident and reflected waves.

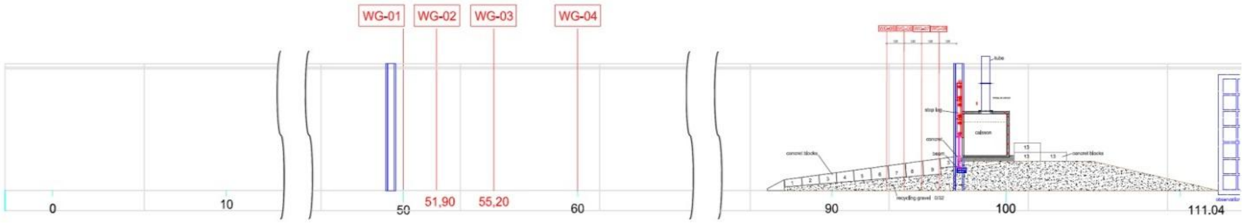


Figure 2: Overall GWK test layout

The central of the three caissons was fitted with pressure transducers to measure air and water induced pressures on the front face, internal back wall and roof of the caisson. To control the air flows in and out of the caissons, a 0.5m diameter hole was cut in the centre of each caisson roof and 3m long, 0.5m diameter duct fitted with an orifice mounting bracket half-way up, see Figure 3.

Figure 3: Installation of three OWC caissons in the GWK with 1:6 approach slope, front curtain wall, and three air ducts with orifice plates

During testing, the main responses measured were:

- air pressure difference across the central orifice;
- air velocities in the central air duct above the structure;
- wave loading on the front face of the structure;
- wave / fluid loading on the rear wall and roof of the OWC chamber;
- water levels within the OWC chamber.

The intended locations of the main instruments are shown in Figure 4. In addition, two video cameras recorded water movements. An external camera viewed the front face from above the side of the flume; and an internal (infra-red) camera viewed the water surface inside the central chamber, angled across from a top corner to the opposing side / rear corner. Recordings from this camera give a clear picture of water motion within the chambers, both in magnitude, and in the type of wave motion, whether primarily vertical, or substantially sloshing.

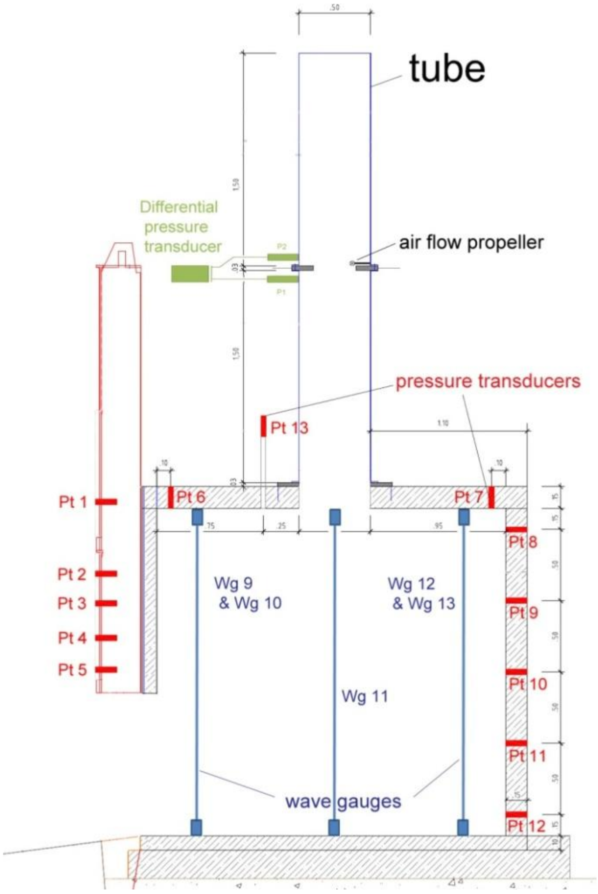


Figure 4: Caisson instrumentation layout

The main intended test conditions are outlined in Table 1. Most tests were run at a water level of +3.5m (above flume floor), but selected tests towards the end of the test programme were run at water levels of +3.0m or +3.2m.

Table 1 Summary of main wave conditions, H (m) and T (s)

Name	H_s	T_p	L_p	H_s /L_p		Name	H	T
Irr1	0.2	2.5	9.8	0.02		Reg1	0.26	3
Irr2	0.4	2.5	9.8	0.04		Reg3	0.52	3
Irr3	0.5	2.5	9.8	0.05		Reg5	0.78	3
Irr4	0.4	3	14.1	0.03		Reg6	0.4	4
Irr5	0.5	3	14.1	0.04		Reg8	0.8	4
Irr6	0.7	3	14.1	0.05		Reg10	1.2	4
Irr7	0.8	3	14.1	0.06		Reg11	0.54	5
Irr8	0.7	4	25.0	0.03		Reg12	0.81	5
Irr10	0.4	6	56.2	0.01		Reg13	1.07	5
Irr11	0.7	6	56.2	0.01		Reg16	0.67	6
Irr13	0.26	4.5				Reg18	1.33	6
Irr14	0.4	6.5				Reg21-29	0.1-0.2	3-6

4. TEST PROGRAMME

The test programme was configured to run through a series of regular and random wave conditions, with the main structural change being the orifice sizes from 0.3m diameter down to 0.05m diameter, or full closure. Initial sets of tests checked the measurement equipment, particularly the differential pressure transducer across the orifice, and the impeller velocity meter.

The first main tests started with the 0.3m diameter orifice plate covering the range of regular and random wave conditions, all at +3.5m water level. For these tests the generated regular wave height exceeded 1.0m, and the random waves H_s=0.67m. Notable shoaling was seen over the 1:6 caisson toe slope increasing wave heights at the caisson above generated incident wave height.

The second test series used the 0.05m orifice plate, proceeding with caution to check that the air ducts were sufficiently robust. These tests did not exceed H=0.81m, or H_s=0.54m. The third test series used the 0.1m orifice plate, and still held to the limits of H=0.81m, or H_s=0.54m, and the fourth series with 0.2m orifice was very similar.

The fifth test series, with the closed chamber, took rather longer as the air ducts initially leaked some air at the higher pressure differences reached. A number of ad hoc solutions were explored, the emphasis being on speed and simplicity! Following success with the later 'closed' tests, selected tests in the sixth series repeated the 0.05m orifice. The seventh series used rather larger random waves than previously with the 0.2m orifice, reaching H_s=1.0m.

For the eighth series, the water level was dropped to +3.0m, and regular and random waves were used up to H=1.07m or H_s=0.67m. Then for the ninth series, the water level was returned to +3.5m, but the front curtain wall was dropped by 0.3m, narrowing the OWC aperture. A tenth series then reduced the water level by the same amount, down to +3.2m, retaining the narrowed aperture. A single final test, at H_s=1.0m, T_p=6s, was then run at the higher water level (+3.5m), so strictly this tests belongs to the ninth series.

Over the some 4 weeks of testing, a total of some 187 (apparently) successful tests were recorded, 143 using regular waves, 43 using random waves (each 1000 * T_p in duration), and a single 'shake-down' test using a solitary wave of 0.6m height.

5. COMPRESSIBLE AIR MODELLING

Linked to the Edinburgh-led GWK testing project, HR Wallingford are supporting an in-house funded research project (CAY0490) to advance their technical abilities in wave interactions with 'solid' coastal structures, particularly in this instance with OWC wave energy converters (WEC). As well as supporting the physical modelling in the GWK, the Wallingford research project particularly focuses on development and validation of CFD tools to simulate water and (compressible) air movements / pressures. The three major tasks are therefore to:

- Provide technical support, review and analysis for the multi-institute testing in the GWK, with particular attention on measurements, data handling, and analysis;
- Develop CFD tools to simulate water and (compressible) air movements at and within a range of OWC devices, particularly supporting the design of the experiments;
- Test and calibrate those CFD tools using data from both small and large scale to check the correct simulation of relative air compression effects, and thus to map out ways to correct for model / scale effects.

6. DISCUSSION

Observations during the large scale tests in the GWK with individual waves in excess of 2m have already provided useful insights into the effects of differing levels of pneumatic damping, particularly informing on water movements within the OWC chambers. Once the measurements are analysed, it is expected that the results of the project will provide a unique database of wave / air / structure effects in conditions where small-scale tests may be strongly affected by air-compression scale effects. When that analysis is complete, these new understandings and techniques will be disseminated in a series of journal and/or conference papers.

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