Concrete as a Technology Enabler (CREATE)

WES Structural Materials and Manufacturing Processes Stage 1 Public Report

Arup

This project has been supported by Wave Energy Scotland

Project Introduction

The objective of Stage 1 of the Concrete as a Technology Enabler (CREATE) project was to identify where concrete has most potential for Wave Energy Converter (WEC) prime mover structures and to demonstrate that the material could enable a step change in the Levelised Cost of Energy (LCoE). The project was commissioned by Wave Energy Scotland (WES) and led by Ove Arup and Partners Scotland Ltd (Arup). The study focused on the use of concrete for WEC prime mover structures, rather than other areas where concrete is already known to be beneficial, e.g. foundations.

The primary advantages of reinforced concrete over steel include a low unit cost (cost per tonne), access to an extensive supply chain and increased durability. Where feasible, equivalent concrete structures have a significantly lower CAPEX. In addition offshore concrete structures typically have a minimum design life of 50 years and therefore further cost saving can be realised when this design life is utilised. Concrete structures are heavier than steel equivalents for a given strength. However minimising weight is not a primary concern for many WEC devices, particularly those requiring additional ballast. In these cases structural concrete can present a more efficient solution by using the weight of the structure directly, rather than requiring additional ballast.

The project team brought together leading expertise in WEC loads analysis, concrete design and concrete construction methods as described in Table 1. The project is WEC technology agnostic, but WEC developers provided realistic geometries and design requirements against which the material was tested.

Stage 1 of the CREATE project aimed to confirm that concrete is a suitable construction material for WECs and then develop the most promising configurations (WEC type + concrete technology) to a sufficient level to quantify advantages relative to steel. The success of the technology developed by the project can be measured through LCoE, compared to the WES target of £150/MWh, based on a detailed design and manufacturing plan minimising technical risks.

Table 1. CREATE project team

Project Partner	Role
ARUP	Structural design, manufacturing assessment, cost assessment and project management.
cruz atcheson CONSULTING ENGINEERS	Detailed loads and performance analysis.
mpa The Concrete Centre	Independent manufacturing review, engagement with contractors and the material supply chain.
Carnegie clean energy; Sea Power Ltd; Wello	Leading WEC developers providing example geometries and realistic design requirements.

Description of Project Technology

The project is technology agnostic, both in terms of the concrete material technology and WEC type. Initially, a high level review was undertaken which considered all main WEC types and all forms of concrete technology to identify promising configurations (WEC type + concrete technology). The review highlighted that traditional reinforced concrete materials and construction methods were suitable for a range of WEC types, particularly those with significant ballast requirements. Traditional concrete technology therefore formed the focus of the remainder of the project.

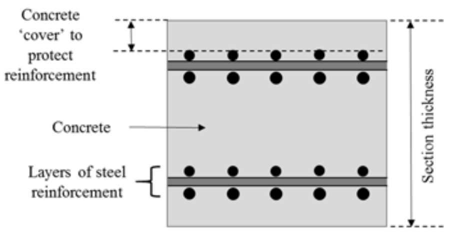
The primary advantages of reinforced concrete over steel include a low unit cost, access to an extensive supply chain and increased durability. A range of more exotic concrete technologies exist, e.g. corrosion resistant reinforcement, fibre reinforcement (steel or glass) and ultra-high strength concrete. By focusing on traditional concrete however, its key advantages, particularly a low unit cost, could be realised.

The specific technologies considered following the high level review are described in Table 2 and include:

- Traditional reinforced concrete with in-situ or precast (modular) construction;
- Post-tensioning technology;
- Modified Normal Density Concrete (lightweight);
- Sprayed concrete (or "shotcrete").

The above technologies are well-understood offshore materials, which helps control costs and reduce construction risks. In WEC construction, their use therefore represents an understood technology applied in a novel application.

Table 2. Concrete materials and construction methods considered

Material and Construction Method	Description
Traditional reinforced concrete with in-situ construction 	Concrete's primary constituents are aggregate, cement and water. The aggregate comprises crushed rock, which is bound by cement to form concrete. Concrete is combined with carbon steel bars which provide tensile strength to complement the materials intrinsic high compressive strength. The steel is contained a set distance from the surface of the concrete (the 'cover') which protects the encased steel from corrosion and hence improves durability. Concrete sections can be cast 'in-situ', whereby formwork is erected and the concrete poured onto a mesh of reinforcement where it sets. Due to the simplicity of this construction technique, concrete gives access to an extensive and mature supply chain.
Traditional reinforced concrete with precast construction 	Precast concrete is a construction method where components are produced using traditional concrete and reinforcement material, but using a reusable formwork (or mould) in a controlled environment. Precast components are then assembled on site and additional concrete is used to form connections. In the context of WECs, precast construction has the advantage of allowing production of a large number of similar components without having to repeatedly erect or dismantle formwork, which saves cost for serial production. It has the additional advantage of enabling better weight control due to higher precision moulds, particularly important in this context.
Post-tensioning 	Post-tensioning involves stressing additional steel cables within the concrete to generate a permanent state of compression. For durability purposes, post-tensioning strands are typically grouted once stressed when used offshore. Post-tensioning is predominantly used to control concrete cracks, an important consideration for WECs to ensure durability and water-tightness.
Modified Normal Density Concrete (MNDC)	Where weight is an important consideration, lightweight aggregates can be used to generate less dense concrete with the same strength. MNDC contains a mixture which generates concrete with 10% lower density. Although lighter weight mixtures are available, MNDC has been more widely used and so has a minimum impact on costs and supply chain availability.
Sprayed concrete ('shotcrete') 	Shotcrete involves spraying concrete onto reinforcement where complex geometries mean that traditional casting between formwork would not be practical. Similar strengths and durability are achievable with shotcrete. However, shotcrete requires more rigorous control of the fabrication process to ensure the quality, finish and thickness of the concrete. Shotcrete is specialist, and its specification would limit the number of available suppliers. There is also no precedent for combining shotcrete with post-tensioning. In the context of WECs, shotcrete may be useful for producing complex geometries from concrete.

Scope of Work

The CREATE project took a sector wide approach to identify where concrete has most potential for WEC prime mover structures, before developing the most promising options to quantify the advantages.

The project initially considered all main WEC types and forms of concrete technology. Following this broad assessment, promising configurations (WEC structural system + applicable concrete technology) and the associated manufacturing processes were developed. The output of the study was a pre-FEED level design of the most promising configuration, with an accompanying manufacturing plan, cost assessment and technical risk register.

In line with this approach, the project was conducted in three main stages. Stage I comprised a high-level review to identify opportunities. Stage II comprised design, manufacture and cost assessment of three WEC types where the use of concrete is likely to be advantageous. Stage III comprised the development of a pre-FEED level design and a refined manufacturing, cost and risk assessment of the most promising configuration. The process is illustrated in Figure 1.

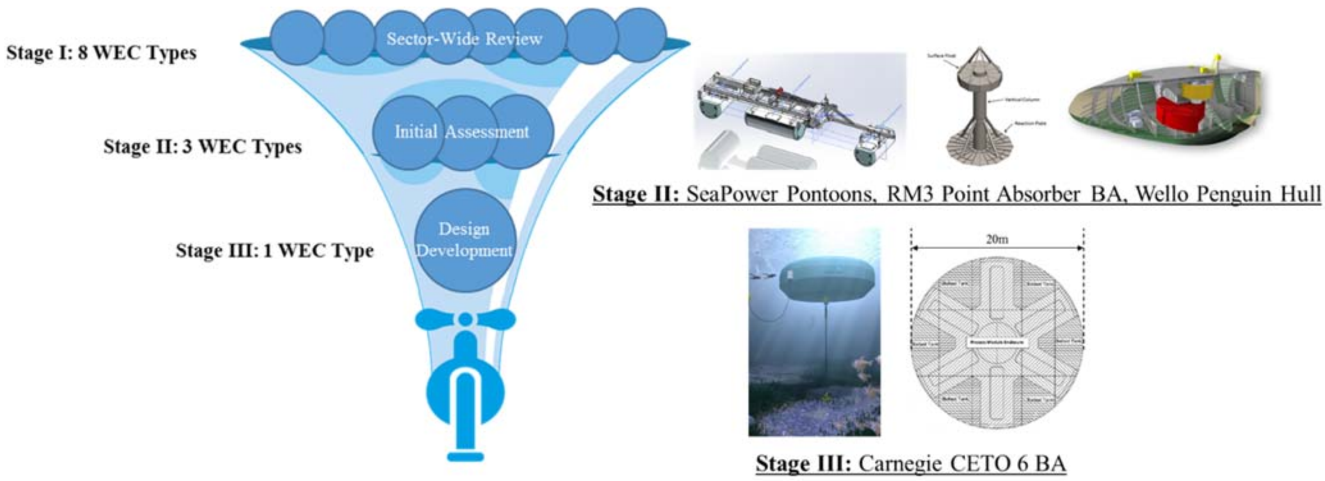


Figure 1. CREATE project overview

The Stage I review was conducted by an expert panel comprising all project participants and offshore concrete experts within Arup. The review highlighted the potential for using concrete for attenuator pontoons (based on the SeaPower Platform), the hull of rotating mass devices (based on the Wello Penguin) and point absorber floats (based on the RM3 generic geometry). These therefore formed the focus of the Stage II design, manufacturing and cost assessment.

Feasible concrete designs where produced for the 3 configurations considered but the one assesed to have the most potential was the point absorber float. Based on this conclusion, Stage III comprised pre-FEED level design, external manufacturing assessment and cost and risk assessment for a concrete submerged pressure differential BA. The Carnegie Clean Energy (CCE) CETO 6 pressure differential device was used as an example geometry, as it had similar dimensions and mass properties to the RM3 device float but represents a high TRL device rather than a generic geometry. This detailed assessment quantified opportunities and identified key risks, enabling progression towards a commercial concrete WEC product.

Project Achievements

Sector wide investigation into the feasibility of concrete

The Stage I sector wide review identified that concrete is a feasible structural material for many WEC device types, as many have significant ballast requirements. The outcomes of the review have been summarised into four categories in terms of the potential feasibility of concrete, shown in Table 3.

Table 3. Summary of the suitability of WEC types for concrete fabrication

	Description	WEC Types
Category I	Unsuitable	• Bulge wave
Category II	Possibly suitable, but may require expensive/novel concrete technologies	• Submerged pressure differential • Point absorber • OWSC
Category III	Possibly suitable using standard concrete technology	• Rotating mass • Attenuator
Category IV	Large static structures that are likely suitable, or already fabricated from concrete	• Oscillating water column • Overtopping device

Note: These conclusions were relevant following the Stage I sector wide review. Subsequent project stages confirmed that concrete is a feasible structural material for many WEC devices, including Category II devices.

Confirmation of cost reduction

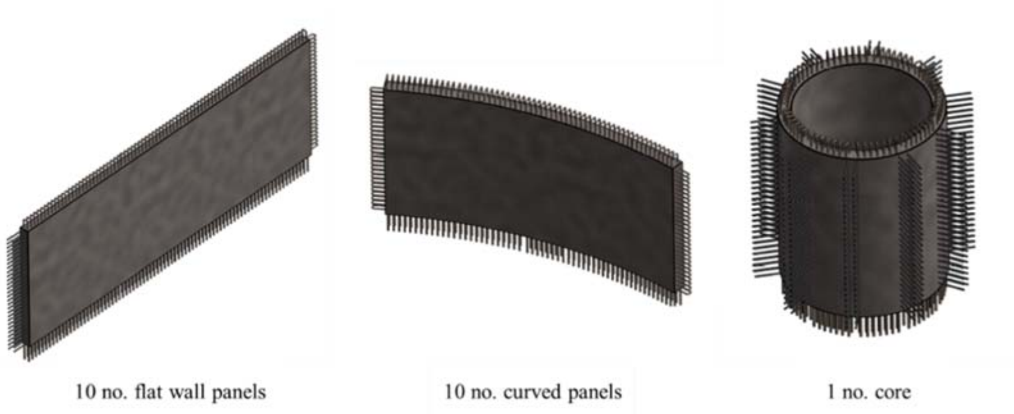
In Stage II cost assessment was conducted for four concrete WEC designs and universally showed a reduction in CAPEX relative to a steel device, see Table 4. The superior durability of concrete over steel structures offers further potential for cost reduction, demonstrated by sensitivity analysis to understand the effect of design life on LCoE.

Table 4. Relative CAPEX impact from concrete construction

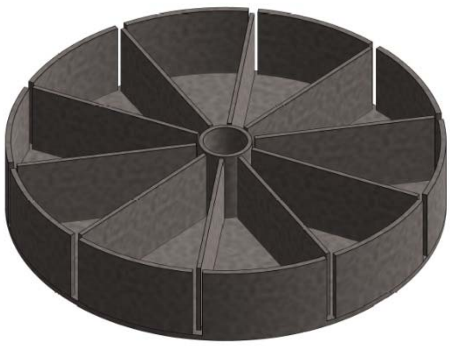
	SeaPower Pontoon	Wello Rotating Mass (original geometry)	Wello Rotating Mass (simplified geometry)	RM3 Point Absorber	Carnegie Submerged Pressure Differential
CAPEX benefit rel. to steel	**-8%**	**-30%**	**-40%**	**-40%**	**-22%**
LCoE benefit rel. to steel	**-3%**	**-15%**	**-20%**	**-10%**	**-3%**

Confirmation of the feasibility of precast construction

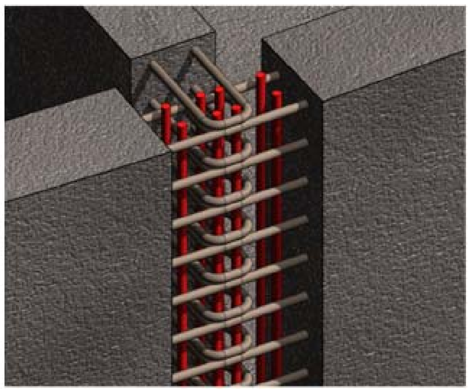
In Stage III the feasibility of using precast construction for both prototype and serial production of the concrete Carnegie BA was confirmed through input from experienced contractors and members of the supply chain. Precast construction has the advantage of allowing production of a large number of similar components without having to repeatedly erect or dismantle formwork, which saves cost for serial production, see Figure 2.



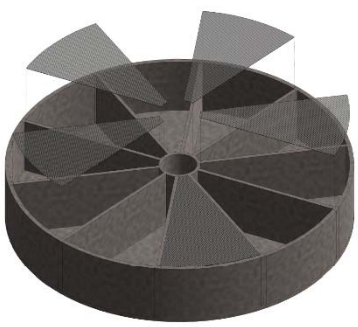
Stage 1: Manufacture precast units



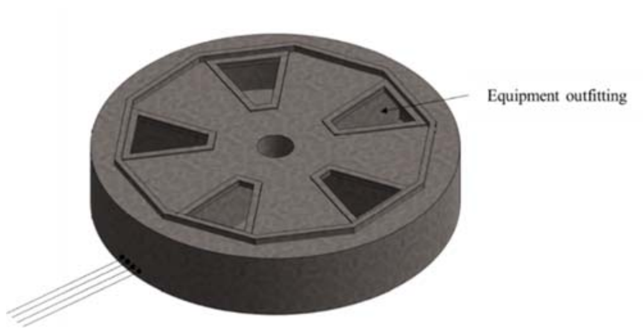
Stage 2: Lift precast wall units into place and cast base slab



Stage 3: Stitch together wall units



Stage 4: Fix permanent formwork



Stage 5: Cast roof slab.
Thread, stress and grout post-tensioning

Figure 2. Precast manufacturing method for the Carnegie BA

Confirmation of potential sites for construction and launch

Independent feedback from the concrete supply chain confirmed material availability and highlighted several sites in Scotland suitable for the construction and launch of the concrete devices, see Figure 3. The project also identified general logistical limits associated with manufacture of large scale WEC devices, such as limits on road transport, craneage and fabrication yard sizes.

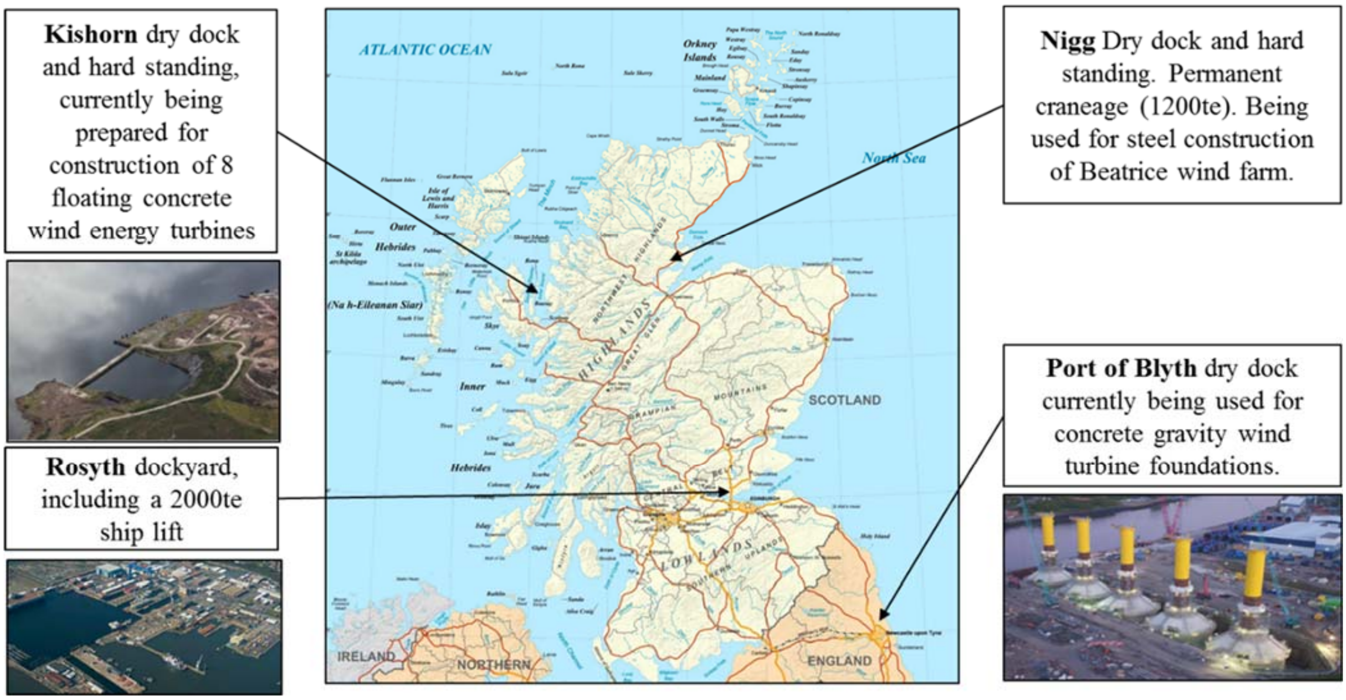


Figure 3. Potential construction sites (map courtesy of Eric Gaba)

The commercial opportunity of a concrete submerged pressure differential BA

The CREATE project quantified the commercial opportunity of a concrete submerged pressure differential BA, based on the Carnegie CETO 6 device. As well as demonstrating feasibility through the development of a pre-FEED level design, a significant CAPEX reduction was predicted relative to steel. The steel CETO BA was designed to withstand significantly lower loads than the concrete version, as the steel variant had been designed for a more benign site than EMEC. A greater cost benefit would therefore be expected if the designs were of equal strength, and hence the estimated cost reductions are conservative. A predominant advantage of offshore concrete structures compared to steel is increased durability and the concrete BA was designed for a 50 year life. In order to investigate the sensitivity to durability, the LCoE was also calculated considering a 50-year design life. This highlighted a potential absolute LCoE of **£105/MWh**, significantly below the original target.

Table 5. Commercial opportunity associated with a concrete submerged pressure differential BA (100 devices)

	CETO BA	Upper Bound	Lower Bound
CAPEX benefit rel. to steel	**-22%**	+2%	-37%
Rel. LCoE benefit with 50 year design life	**-13%**	-9%	-16%
Absolute LCoE with 50 year design life	**£105/MWh**	**£109/MWh**	**£102/MWh**

Further Opportunities

The project highlighted additional opportunities that could not be fully investigated given the focus of the SMMP programme.

There is opportunity for a rotating mass device with a concrete hull, if the hull geometry could be simplified. Development of such a design would involve iteration between device performance and design for manufacture, which was not feasible in the timescale of the project. The project highlighted other devices where concrete could play a role, in particular large static structures such as oscillating water column and overtopping devices. Further investigation into the use of precast concrete in these structures would be beneficial.

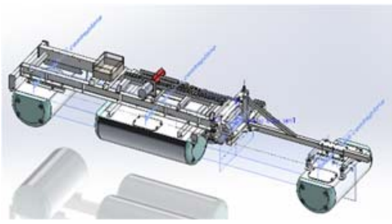
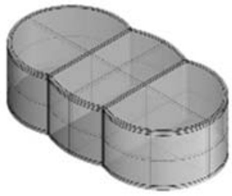
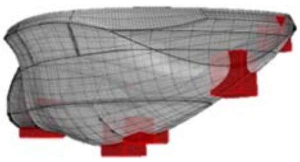
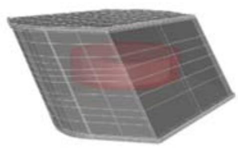
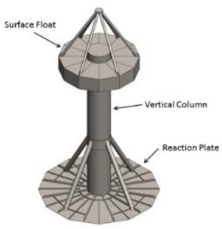
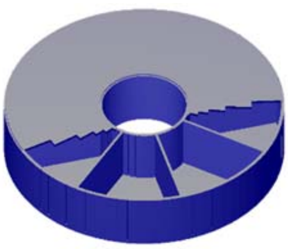
The loads assessment highlighted the sensitivity of the load magnitude to the methodology for load calculation and the statistical post-processing method. A robust and conservative method was adopted, but there is opportunity to further investigate this for the benefit of the wider wave energy sector.

Applicability to WEC Device Types

A key output of the CREATE project was identification of WEC device types where concrete technology could be beneficial. The project confirmed that a range of WEC devices are suitable, predominantly as minimising weight is not a primary concern for energy absorption for many device types. The increase in mass associated with concrete can therefore be tolerated enabling the cost and durability advantages to be realised.

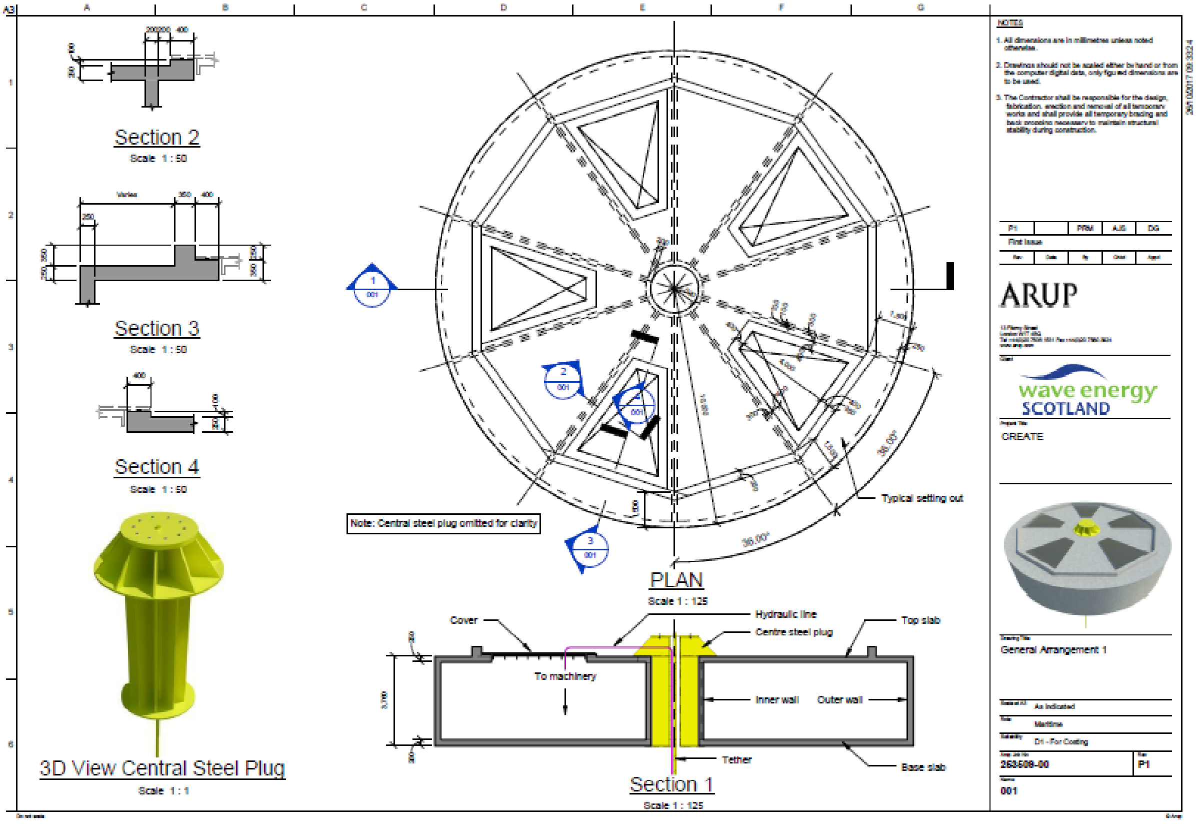
The project included a systematic down-selection process to focus subsequent stages where concrete had the most opportunity. This highlighted the feasibility of attenuator pontoons (based on the SeaPower Platform), the hull of a rotating mass device (based on the Wello Penguin) and a point absorber float (based on the RM3 generic geometry) as shown in Table 6.

Table 6. Feasible concrete WEC design developed throughout the CREATE project

Device	Feasible Concrete Design	
 SeaPower Platform (Attenuator)	 Concrete pontoon I	 Concrete pontoon II (reduced cost)
 Wello Penguin (Rotating Mass)	 Concrete hull I (original geometry)	 Concrete hull II (design for manufacture)
 RM3 Point Absorber Device	 Concrete BA Structure	

Based on a range of metrics, the most promising WEC structure for concrete construction was found to be the BA for point absorbers or submerged pressure differential devices. A concrete BA was therefore developed to a pre-FEED level of design using the Carnegie CETO 6 device as an example, see Figure 4.

The concrete solution represents a reasonably generic BA for these device types, and it is anticipated that the lessons learned from this design are applicable to a range of point absorber or submerged pressure differential device developers and standalone PTO suppliers.



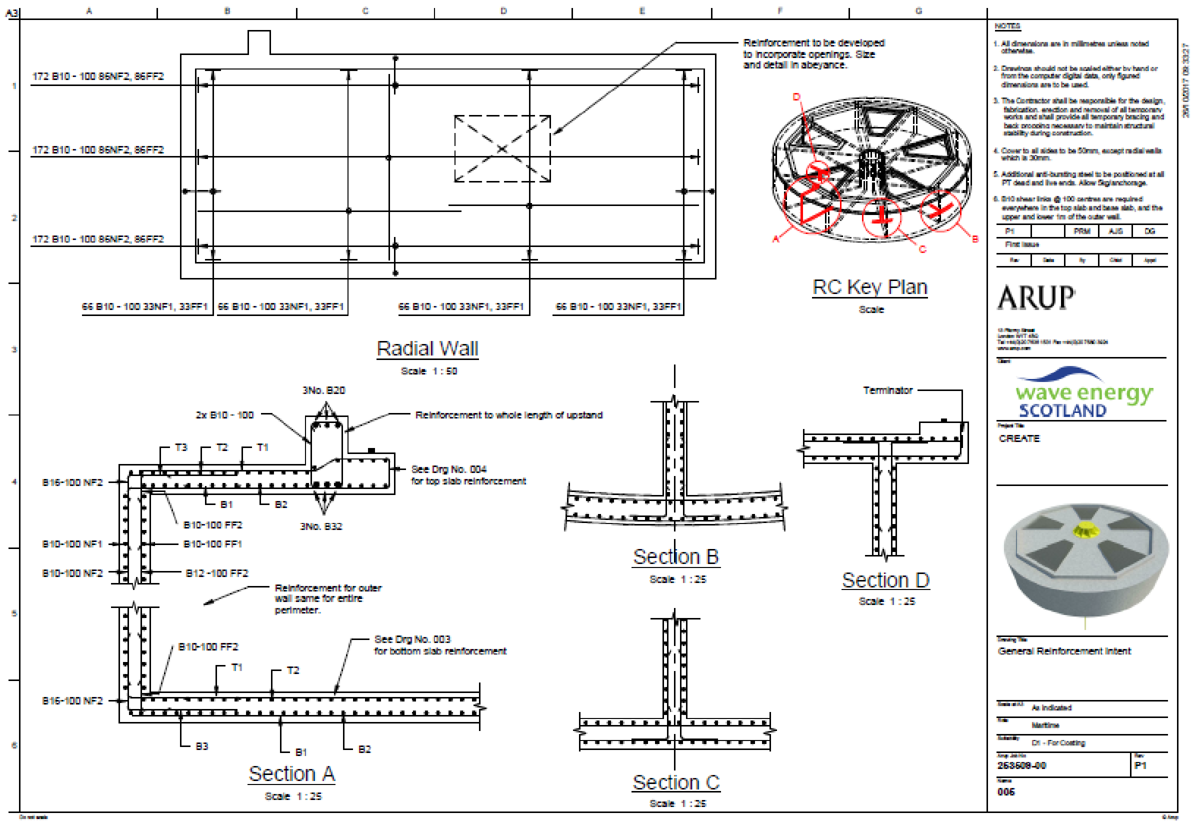


Figure 4. Example pre-FEED level drawings of the concrete Carnegie BA

Communications and Publicity Activity

The CREATE project has been included in several press releases and externally by Arup, including the links below.

http://renews.biz/106553/arup-signs-for-scots-wave-study/

http://www.waterpowermagazine.com/news/newsarup-to-study-alternative-materials-for-wave-power-devices-5778759

https://www.waterbriefing.org/home/technology-focus/item/13792-arup-to-investigate-alternative-materials-to-advance-wave-power-technology

http://www.scottishenergynews.com/arup-wins-new-scot-govt-wave-power-energy-convertor-contract/

http://www.arup.com/news/2017_04_april/04_april_arup_to_investigate_alternative_materials_to_advance_wave_power

A technical poster describing the project was also developed for the 2017 WES annual conference, which has been attached to this report.

Recommendations for Further Work

Loads assessment and structural design

To reduce risk at the detailed design stage the loads analysis methodology should be expanded to include significant nonlinear events and accidental loading. In addition agreement on the statistical post-processing method for loads should be sought, this is currently taken directly from oil and gas standards. The Stage 1 assessment provided a conservative first pass approach, but it is likely that a more efficient structure could be developed with more detailed analysis. This could involve more advanced methods, such as computational fluid dynamics (CFD), or data from existing tank tests, e.g. those conducted by Carnegie.

The structural design should be progressed to FEED level. A manufacturing partner with precast experience should be brought on board at an early stage, to ensure design for manufacture.

Development of a FEED would significantly de-risk the concrete product and enable manufacture of a full scale device as part of Stage 3 of the WES SMMP. Design of the precast connections would also provide the basis for any qualification testing required, as described below.

Installation, operations and maintenance strategy

The increased mass of a concrete structure may impact the operations and maintenance strategy. For example, the concrete BA cannot be lifted from the water without a specialist crane, and so the maintenance strategy should involve easy removal of critical equipment from a permanently floating structure. This maintenance strategy needs to be developed. As well as de-risking the design, this would form the basis of a more rigorous bottom up OPEX assessment. As concrete is significantly more durable than steel, this represents another potential cost saving relative to steel.

Construction and material qualification

Typically within civil engineering, prototyping is neither cost-effective nor practicable. For that reason, the design codes and material specifications are designed to remove much of the need for testing the main structural elements. The typical testing requirements of reinforced concrete structures, e.g. to verify the strength of the concrete, will be carried out at the time of construction. The water-tightness of the concrete superstructure itself would be tested after completion of the BA unit during initial flotation tests. Testing of the roof seals could be carried out by assessing whether a small over-pressure within the BA unit can be maintained.

The use of precast concrete for the design of a submerged pressure differential BA represents a novel application of an understood technology. Given the unique loading and environmental conditions for WECs, specific testing ahead of detailed design would be beneficial to de-risk long-term deployment. Many of these tests would result in broad benefit by enabling the use of concrete across the wave energy sector. Priority tests based on the project's technical risk register are listed in Table 7. The testing could be undertaken in one of the Scottish Energy Laboratory Facilities, for example the University of Strathclyde (SEL14) or the University of Dundee (SEL46).

Some of the testing could be augmented with detailed numerical modelling. These models can be calibrated against initial testing and enable assessment of a range of geometries or sensitivities without the need for testing each individually.

Wider applicability

Many of the risks identified are generic regarding the use of concrete for WECs and mitigation strategies would have general applicability for the long term deployment of concrete WECs. Given the generic nature of the BA structure, it is also likely that conclusions from the design itself will be applicable to a range of point absorber or submerged pressure differential device developers and certain standalone PTO suppliers.

Table 7. Priority material and construction testing

Structural Component	Purpose	Description
Precast connections	The strength and water-tightness of the precast connections should be verified using testing where necessary. This is particularly important to confirm a 50 year structural design life under cyclic loading. The precast connections may require the additional complication of pre-stressed bars or post-tensioning to guarantee performance.	A demonstrator unit would be built by a precast manufacturer, including additional water-proofing measures such as hydrophilic strips. This would then be tested under both cyclic operational loading (with a high static head to ensure water-tightness) and ultimate loading.
Post-tensioning fatigue	Fatigue testing of the post-tensioning, reinforcement and anchor bolt arrangements will not be required as testing of components is already carried out as part of Eurocode requirements. However, fatigue testing of post-tensioning strands would be beneficial to the long-term deployment of the WEC devices given the divergence in performance seen in the various design codes. This is particularly important to confirm a 50 year structural design life.	Stressed post tensioning strands in a representative configuration would be subject to representative cyclic loading to ensure long term performance.
PTO and moorings interface	This represents a unique and critical component involving the interface between concrete and steel. This will exert significant localised loads.	Detailed numerical modelling (nonlinear finite element analysis) would be undertaken to justify the design.

Useful References and Additional Data

Project Documents (available on request)

Ref.	Author	Title	Issue
[1]	Arup	WES CREATE: D03 Design Basis: 253509-REP-002	Rev 0
[2]	Arup Cruz Atcheson The Concrete Centre	WES CREATE: D05 Interim Report: 253509-REP-002	Rev 0
[3]	Cruz Atcheson	WES CREATE: D06 Loads Analysis Report: 1043-R-01	Rev A
[4]	Arup	WES CREATE: D06 Structural Design Report: 253509-REP-003	Rev 0
[5]	Arup	WES CREATE: D06 Concrete Carnegie BA Structural Design Drawings	Rev 0
[6]	Arup The Concrete Centre	WES CREATE: D07 Manufacturing Assessment: 253509-REP-004	Rev 0
[7]	Arup	WES CREATE: D08 Cost of Energy Assessment: 253509-REP-005	Rev 0
[8]	Arup	WES CREATE: D09 Technical Risk Register: 253509-CAL-004	Rev 0
[9]	Arup	WES CREATE: D09 Summary Report: 253509-REP-006	Rev 0

Design Codes and Standards (publicly available)

Ref.	Code	Title	Issue
[10]	DNV-OS-C502	Offshore standard: Offshore Concrete Structures	Sep 2012
[11]	BS EN 1992-1-1:2010	Eurocode 2 Design of concrete structures, Part 1-1, General rules and rules for buildings	2010
[12]	BS 4449:2005	Steel for the reinforcement of concrete – Weldable reinforcing steel, bar, coil and decoiled product	2005
[13]	BS 5896:2012	High tensile steel wire and strand for the prestressing of concrete – Specification	2012
[14]	BS 8500-2:2015	Concrete - Complementary British Standard to BS EN 206. Specification for constituent materials and concrete	2015