

Exploring Gravity-Based Structures for Oscillating Water Column Wave Energy Conversion: An Ongoing Hydrodynamic Study

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HIGHLIGHTS

This work presents an ongoing hydrodynamic assessment of a patented wave energy converter design that repurposes decommissioned gravity-based structures using oscillating water column principles, and represents a continuation of the study by Le Floch et al. [1].

1 INTRODUCTION

Wave energy converters (WECs) provide sustainable means of generating electricity without greenhouse gas emissions and are gaining increasing attention as a complementary technology within the global renewable-energy portfolio due to their relatively high energy density and reduced intermittency compared to solar and wind alone. Recent reviews emphasize ongoing research and development to enhance WEC performance and integration with other renewable systems [2]. Performance enhancement and cost reduction remain critical challenges, with design optimization, reliability, and levelized cost of energy reduction representing key areas for future research. This underlines the relevance of advancing hydrodynamic understanding and practical design strategies for new concepts.

In this context, a patented WEC design has been proposed by Mr. Sjetnan to convert gravity-based structures (GBSs) into oscillating water column (OWC) devices. The concept involves creating openings in the concrete cylindrical structure, allowing water levels inside the chamber to oscillate under wave excitation and drive a bidirectional turbine for energy generation. The implementation of this solution requires systematic assessment of hydrodynamic performance, energy conversion, and structural integrity. The initial assessment of this concept, reported in [1], employed a stepwise strategy: (i) semi-analytical solutions examined the influence of opening size and submergence on wave transmission and energy-conversion efficiency within a linear, potential-flow, frequency-domain framework, building on approaches established in the literature, particularly the one by Evans and Porter [3]; and (ii) two-dimensional OpenFOAM simulations investigated real-flow effects, providing additional insight into resonance phenomena and local air-water flow features.

These tools were applied at one potential site simplifying the platform as a single circular cylinder with a single opening aligned with the mean wave direction. The results demonstrated that the WEC concept could achieve peak efficiency under resonance conditions and for longer wave periods, aligning with the dominant wave climate at the selected site. Parametric studies indicated that increasing the opening size enhances transmission and efficiency, although structural limitations impose constraints. Overall, the concept showed competitive power-conversion potential relative to existing WEC technologies.

Despite these promising findings, several questions remain open. The prior analysis considered a single opening and neglected three-dimensional effects, primarily relevant for diffraction features but also potentially affecting flow-separation mechanisms at the opening and the response of the internal wave. Additionally, the influence of multiple openings, non-linear wave effects, and realistic turbine-induced damping were not examined. Preliminary estimates suggest that multiple holes are required in three dimensions to reproduce the internal momentum flux and achieve power levels comparable to the 2D predictions. These aspects motivate the ongoing study, which aims to extend the hydrodynamic assessment including both 3D effects and multi-opening scenarios. In the following, we outline the case study and the methodological strategy, presenting selected preliminary results.

2 CASE STUDY AND METHODOLOGY

The case study builds upon the referred investigation of the proposed WEC concept, with focus on the Statfjord site. This location is selected due to its significant wave-energy potential, the availability of long-term metocean data, and the expected decommissioning of the Statfjord A platform in the near future. Wave statistics indicate that the dominant wave energy at this site is associated with peak wave periods in the range $7\text{ s} \leq T_p \leq 15\text{ s}$, with primary direction from the West, hereafter referred to as head-sea conditions, and with increased energy levels during winter conditions. These characteristics make the site well suited for oscillating water column applications. The OWC concept is simplified to a single column of a gravity-based structure, modeled as a fixed vertical cylindrical chamber with external diameter $D_e = 12\text{ m}$, internal diameter $D_i = 10.8\text{ m}$, and uniform water depth $h = 145\text{ m}$. At least one opening is placed below the mean water level to induce oscillations of the internal water column under wave excitation. Based on previous parametric analysis examining single-hole scenarios, the opening is assumed to be circular with diameter $D_o = 1.2\text{ m}$, with the top of the opening located at a depth $a = 9\text{ m}$ below the mean free surface. This configuration ensures submergence for the vast majority of sea states while maintaining favorable hydrodynamic performance. In two-dimensional analysis, D_o corresponds to the opening height and was selected as a compromise between maximizing the momentum flux through the opening and ensuring structural robustness.

The present study combines two complementary approaches. First (A), three-dimensional effects are examined using a linear potential-flow frequency-domain analysis based on the 1st-order Boundary Element Method (BEM) solver *Hydrostar* (Bureau Veritas). The cylinder is modeled with a single opening and subsequently with multiple openings, and is subjected to incident regular waves with periods T ranging from 2.5 s to 18 s under head-sea conditions, as well as under other wave headings relevant for the Statfjord site. The simulations assume the standard linearized free-surface boundary condition inside the cylinder; consequently, neither turbine-induced damping nor air compressibility effects are included in the model. Second (B), a laminar real-flow analysis is conducted using the open-source CFD solver *interFoam* within the OpenFOAM platform. The governing equations are discretized in space using a second-order finite-volume method and integrated in time using a first-order explicit Euler scheme. Regular head-sea waves with period $T = 8\text{ s}$ and wave height $H = 2\zeta_{0a} = 1\text{ m}$ are examined first, consistently with the conditions with maximum efficiency predicted by CFD studies in [1]. An adaptive time-stepping strategy is adopted enforcing a

maximum Courant number of unity and three iterations are performed within the pressure-correction loop at each time step. The ongoing CFD analysis focuses on two-dimensional configurations with two or three identical openings. Three-dimensional studies are also planned and will investigate the most promising incident-wave conditions as identified by the 3D BEM simulations.

In the A and B studies, simulations with a single opening (denoted O_1) will use an opening depth of 9 m. For configurations with multiple openings, a second opening (O_2) is placed at 12 m depth and, where applicable, a third opening (O_3) at 6 m depth. All openings are assumed to lie in a plane aligned with the dominant wave propagation direction at the site. Based on the semi-analytical studies in [1], for a single opening, the incident-wave period that maximizes the WEC efficiency is largely insensitive to the vertical position of the opening, provided the opening depth satisfies $a \geq 1.5$ m (see Table 1). Consequently, the depths of the O_1 - O_3 openings are expected to be sufficiently submerged to enhance the captured flux moment, while maintaining structural robustness and minimizing adverse hydrodynamic interactions.

Table 1: Incident-wave period T corresponding to the largest WEC efficiency based on the 2D semi-analytical results in [1], assuming optimal conditions and $D_o = 1.2$ m.

Opening depth a (m)	1	1.5	3	5	7	9
T (s)	≈ 13.5	≈ 6.0	≈ 6.0	≈ 6.1	≈ 6.2	≈ 6.3

This combined two- and three-dimensional study framework will allow a rigorous evaluation of the limitations inherent in two-dimensional and potential-flow modeling assumptions and facilitate a systematic assessment of the examined WEC concept.

3 PRELIMINARY RESULTS

The left panel of Fig. 1 presents the response amplitude operator (RAO) of the internal free-surface elevation for the single-opening cylinder subjected to waves with three different headings (with 180° corresponding to head seas). The RAO is evaluated at the center of the cylinder and at two additional probes, p25 and p29, located at $(0, 0.375D_i)$ and $(0.375D_i, 0)$ in the horizontal plane, respectively, with the origin defined at the cylinder center. The simulations were performed using a mesh refined in the vicinity of the opening and near the mean free surface (see the right panel of Fig. 1), and progressively coarsened with depth to improve computational efficiency while preserving accuracy, consistent with the predominantly deep-water wave conditions. The RAO results at the center of the cylinder are highly consistent across the different wave headings and exhibit a clear peak for a wave period $T \approx 7$ s, identifying, within the adopted period discretization, the range associated with piston-mode resonance for this configuration, between 6.6 s and 7 s. This range lies between the natural periods predicted by 2D potential-flow simulations (about 6 s) and 2D real-flow (about 8 s) simulations reported in [1]. It remains important to verify whether the WEC efficiency remains relatively high over a broad range of longer wave periods when turbine-induced damping is properly modeled, as suggested by the 2D CFD results in [1]. For $T > 6$ s, the RAOs at probes p25 and p29 are also consistent with the response at the cylinder center for all wave headings; this range of T is not shown in the figure for these two

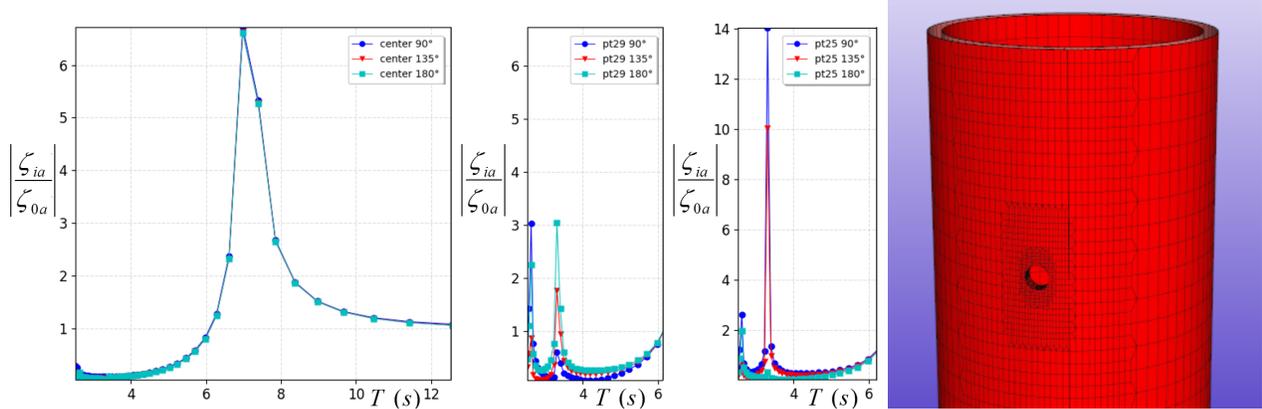


Figure 1: 3D BEM simulations for the cylinder with a single opening (O_1) in regular waves with three different headings. Left: Response amplitude operator of the internal water level at the center, at probe p29, and at probe p25 (from left to right). Right: Cylinder mesh used for the BEM simulations, with a close-up view near the opening.

probes. In addition, they exhibit a distinct peak around $T \approx 3.4$ s, which can be associated with the first sloshing mode. This interpretation is supported by the close agreement with the corresponding natural period predicted for a partially filled circular cylinder of the same dimensions [4]. This mode is characterized by a node at the cylinder center, consistent with the absence of a corresponding peak in the RAO evaluated at this location. Finally, all three probes display an additional peak at a smaller wave period, which is reasonably attributed to a higher-order sloshing mode.

The planned parametric investigation is ongoing, including additional CFD simulations, with the corresponding findings to be reported at the conference.

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