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Development of Floating Tidal Current Energy Systems to Support Energy Independence in Island Areas

Sungwon Kim[†], Jun Seok Park[†], Sung Youn Boo[‡], and Jin-Soon Park[†*]

[†]Ocean Space Development & Energy Research Department
Korea Institute of Ocean Science and Technology
Busan, Republic of Korea

[‡]VL Offshore
Houston, TX, USA

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ABSTRACT

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Some of the optimum sites for the tidal current energy system in Korea are suggested to be in island regions with a deep-water depth. It is known that floating systems are more advantageous than fixed systems for a water depth of 20 m or deeper. In this study, a floating tidal current energy system development, thus, considered for sites deeper than 20 m such as Incheon, Gyeonggi, or Chungnam province. Floating systems with a total power rating of 100 kW were developed combining two 50 kW vertical axis turbines. The systems have a hybrid mooring configuration with catenary and taut mooring. Two different types of steel hull systems were sized and configured considering the turbine operating loads and sea states. The first one, the "base platform" is consisted of a circular pontoon barge, four cylinders, a damping plate, and turbine supporting structures. The other one, the "pontoon platform" is consisted of a circular pontoon barge and turbine supporting structures. Both platform displacements and weights are similar, but platform dimensions differ greatly. Platform motions and mooring line strength analysis were carried out for the site operating and extreme conditions. Results demonstrate that the design requirements are met so that the platform and mooring systems are technically feasible. The pontoon platform has shown somewhat better than the base platform in the performances of the motions, tensions, and costs. A single unit, excluding turbine cost, is estimated to be around \$4.7 to \$5.0 million depending upon the platform configurations and anchor options. Due to the slight cost difference, further analysis is recommended in the next phase, to identify the most viable option. Results suggest that drilled and grouted anchors may be a more cost-effective solution. However, further seabed study will be required to confirm an optimum anchor type.

ADDITIONAL INDEX WORDS: *Floating, tidal current, energy independence, island area.*

INTRODUCTION

As the need to develop ocean energy to prepare for the transition to a carbon-neutral society and lead Green New Deal has emerged, the Korean government is working out a roadmap led by the Ministry of Environment to grow a carbon-neutral community by 2050. Ocean energy is considered a vital reduction method in the roadmap. The Ministry of Oceans and Fisheries is also establishing a 2050 carbon-neutral roadmap in marine and fisheries. A need to apply a small marine energy power generation system developed previously to island regions has been raised at a New Renewable Energy Support Promotion Team meeting. Tidal energy can predict the amount of power generation without being affected by weather and sea state. Also, it is abundant near the island and can be built more effectively than an eco-friendly energy self-sufficient island equipped with wind or solar power. As a result, various studies have been conducted to develop a tidal current system: Reviewing current policy and technology of tidal current energy in Korea (Ko *et al*., 2019); assessment of tidal current energy potential in the southwestern coast of Korea (Ko, Park, and Lee, 2018); studying technologies, design considerations and numerical models of tidal current turbines (Nachtane *et al*., 2020); development of integrating the system of tidal energy (Almoghayer *et al*., 2022); site characterization for tidal energy system installation (Tawil, Charpentier, and Benbouzid, 2017); hydrodynamic analysis of vertical axis cycloidal tidal turbine (Jiang, Ju, and Yang, 2019); and so on.

Among many island regions in Korea, in Incheon, Gyeonggi, and Chungnam, the water depth is over 20 m. It is known that applying a floating tidal power system is more advantageous than fixed tidal power generation for maintenance, construction, and installation when the water depth is 20 m or more (Jo *et al*., 2018; Ma *et al*., 2015). Therefore, this study aimed to develop a floating tidal power generation system applicable to a water depth of 20 m.

METHODS

In this study, it was completed a conceptual design of the floating platform, which complies with international industry standards and guides for floating offshore structures (ABS, 2013; API, 2005; IEC, 2019). Two different con figurations of the platform were considered, and the dynamic and mooring analysis results were compared with each other: Base platform: Consisting of a circular pontoon barge, four hull cylinders with damping plate and turbine supporting frames; pontoon platform: Consisting of circular

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*Corresponding author: jpark@kiost.ac.kr

pontoon barge and turbine supporting frames.

The site of the tidal energy platform was assumed to be installed off the coast of the islands in Korea. Also, the site presents a water depth of about 20 m, and it was assumed that typhoons occasionally pass through the site during the summer and fall seasons.

Metocean Conditions and Design Criteria

Metocean conditions for operating and 50-yr extreme conditions are summarized in Table 1. JONSWAP spectrum was used for the presentation of the waves. The water depth of the site considered was 20 m, and a rated current velocity of 2.6 m/s was used as an operating current. Current profiles in the vertical direction were derived using interpolation. The site seabed assumed a rock-bed condition, so options of gravity anchor and drilled and grouted pile anchor was considered.

Table 1. *Site metocean conditions.*

Platform Condition	Operating	Extreme
Turbine Condition	Production	Parked
Environment Condition	Rated	50-yr
Wave Hs (m)	2.0	5.57
Tp (s)	6.3	12.7
Gamma	2.2	2.2
Current @ Surface (m/s)	2.6	2.8
Wind @ 10 m above MWL (m/s)	6	35.7

The offset of the platform during a 50-yr extreme event shall also be met to limit the platform offset. The design criteria of the platform mooring strength and offset are summarized in Table 2, while the mooring anchor design criteria are shown in Table 3.

Table 2. *Platform and catenary mooring design criteria.*

Loading Conditions	Mooring Line FoS	Platform Offset %WD
Operating	-	-
Extreme	≥ 2.0	30

Table 3. *Mooring anchor design criteria.*

Loading Conditions		Block Anchor FoS	Drilled and Grouted Pile Anchor FoS
Operating		-	-
Extreme	Horizontal	≥ 1.6	≥ 1.6
	Vertical	≥ 2.0	≥ 2.0

Here Factors of Safety (FoS) of the mooring strength are based on the non-redundant mooring line condition. The FoS is defined as MBL divided by maximum tension. The percentage (%) of water depth (%WD) is “Maximum Offset/ Water Depth x 100”.

RESULTS

Tidal Platform Configurations

Two 50 kW turbines were used to generate 100 kW power at the rated current speed. The rated flow velocity is 2.6 m/s with 3.0 m of rotor diameter. The blade length is 6.0 m, and the rotor weight is 3,344 kg, including the shaft. The weight of the generator is 5,500 kg, and the maximum thrust is 116 kN at the rated current speed. The distance between rotors is 4.125 m from center to center.

The designed platforms to produce a total of 100 kW power at a rated current are summarized in Table 4. The base platform configuration sketches are shown in Figure 1, and mooring layouts are illustrated in Figure 2.

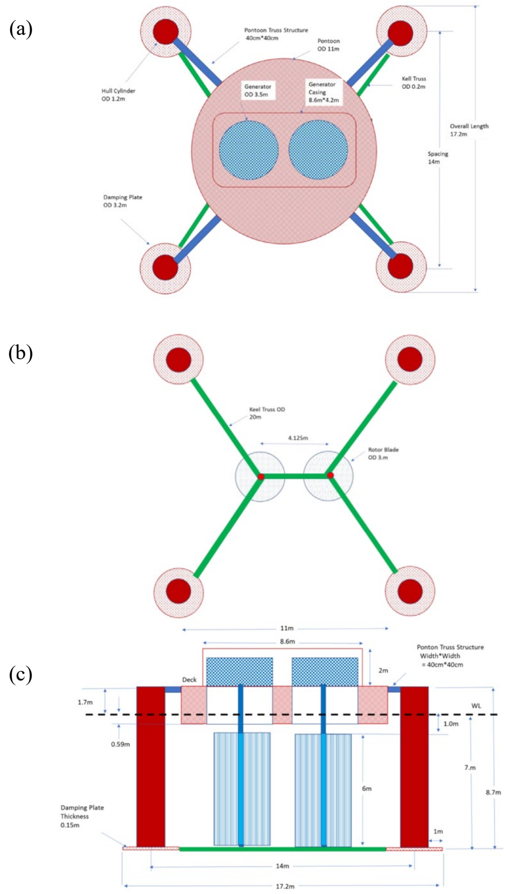


Figure 1. Base platform configuration (plan view at deck level (a), plan view at keel level (b), and elevation view (c)).

The mooring lines are configured to moor the platform with a combination of wire lines (seaward lines) and polyester lines (landward lines). One end of the wire lines is tied to the platform top edge, and the other end is connected to the seabed anchor. Whereas the polyester mooring lines are used between the platform top edge and the land. As such, one end of the polyester lines is tied to a shore structure. The seaward lines are in catenary shape while the polylines are taut configuration. Both base and pontoon platforms use the same size of wire and polylines. The pontoon platform configuration sketches are shown in Figure 3. Mooring layouts are illustrated in Figure 4.

Numerical Modeling

For the present analysis, the wind, wave, and current were assumed codirectional and flowing toward 90 deg, which is parallel to the shore bulkhead direction. As such, the turbine thrust will act toward 90 deg. The heading considered will produce a conservative platform motion and mooring tension. OrcaFlex was used for modeling and conducting the platform-mooring coupled time domain analysis.

Hydrodynamics coefficients of the platforms were computed with a 3-D diffraction panel method and imported to Orcaflex for the dynamic response analysis, as shown in Figure 5. Platform hull viscous damping was presented with Morrison elements of the pontoon, hull cylinders, and other submerged structures. Current loads were automatically included in the model due to the Morrison element.

A total turbine thrust of 232 kN was applied at the turbine dynamic pressure center at 4 m below the water line, during the turbine operating condition at a rated current speed of 2.6 m/s. However, the turbine was considered parked under the 50-yr extreme condition.

The turbines shown in cylindrical shape are for illustration purposes only and will not affect the platform dynamics. But all other submerged structures contributed to the viscous hull damping and current load due to the Morrison element.

Table 4. *Platform configurations for 100 kW production.*

Design Items		Unit	Base Platform	Pontoon Platform
Design Life		yr	20	20
Displacement		ton	83.44	84.95
Total Weight and Load		ton	83.52	84.23
CoG from MWL		m	-0.06	-0.06
Roll Radius Gyration: Rxx, w.r.t. MWL		m	4.33	4.33
Pitch Radius Gyration: Ryy		m	4.52	4.52
Yaw Radius Gyration: Rzz		m	5.16	5.16
GM_T		m	13.45	13.45
GM_L		m	13.45	13.45
Mooring Wire (Toward Seabed)	42mm Wire	kg/m	8.7	8.7
	Total Length	M	200	200
	# Lines	EA	2	2
Mooring Wire (Toward Shore)	100mm Polyester	kg/m	9.2	9.2
	Total Length	m	100	82
	# lines	EA	4	3

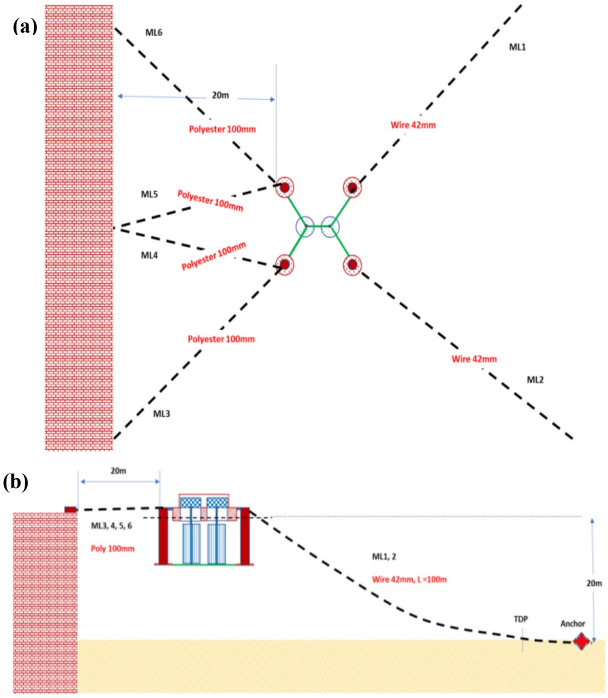


Figure 2. Base platform mooring layout (plan view (a) and elevation view (b)).

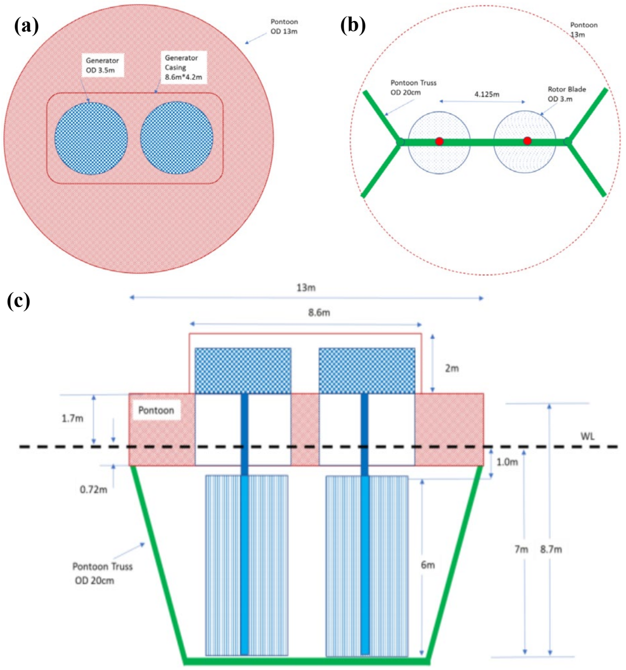


Figure 3. Pontoon platform configuration (plan view at deck level (a), plan view at keel level (b), and elevation view (c)).

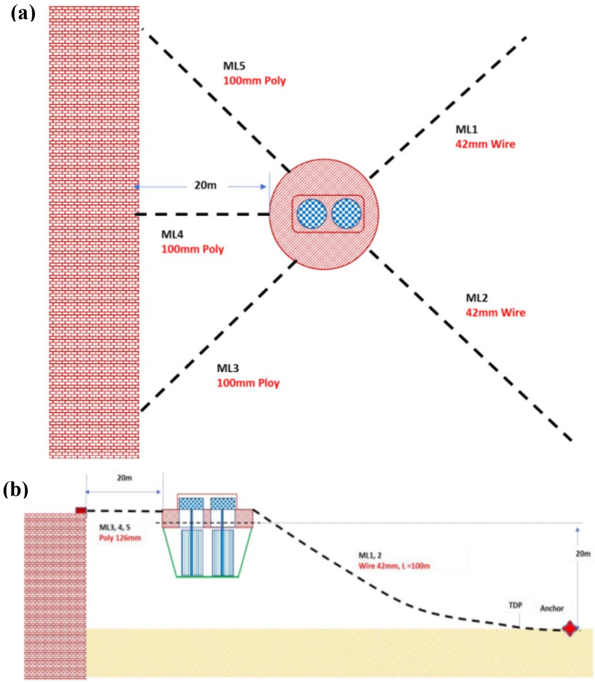


Figure 4. Pontoon platform mooring layout (plan view (a) and elevation view (b)).

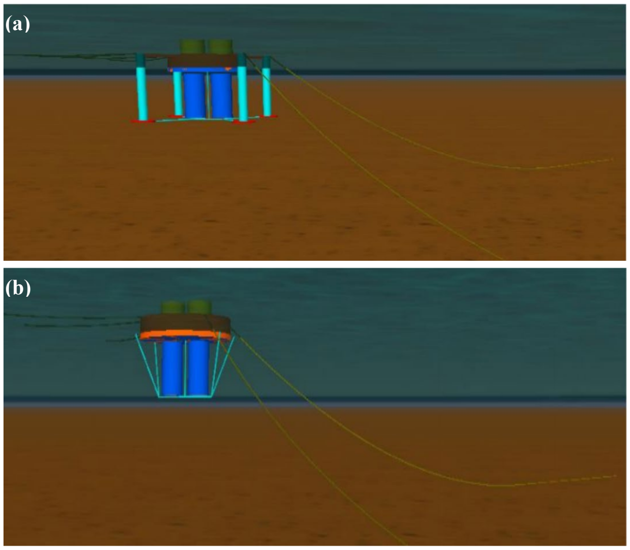


Figure 5. Platform and mooring system modeling (base platform (a) and pontoon platform (b)).

DISCUSSION

Platform Response Analysis

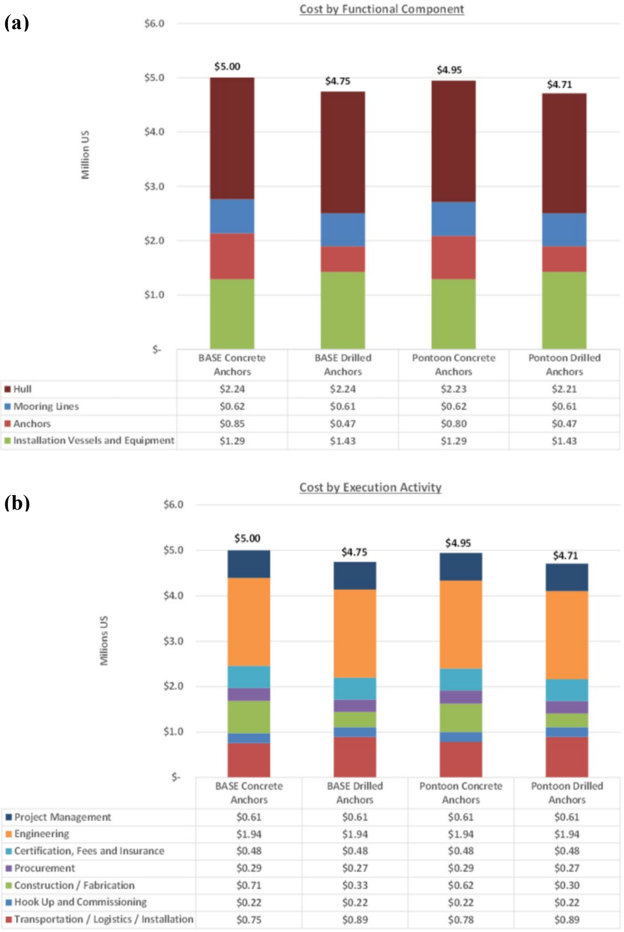
Due to the environment heading angle of 90 deg, the dominant motions of the will be sway, heave, and roll. Thus, the present analysis focused on these motions. Mean and dynamic motions for operating and 50-yr extreme conditions were compared. The mean roll of the operating condition was greater than the mean of the extreme roll, due to the operating turbine thrust, and dynamic heave and roll motions of extreme conditions were greater than the operating motions. Additional analysis for the offset was run for wind and wave heading 180 deg and current heading 90 deg to examine the minimum distance between the platform and shore. It is confirmed that the minimum distance estimated is about 17 m, meaning this will be no clashing issue between the platform and the shore.

The pontoon platform tends to present better performances in terms of roll angle during the operating and extreme seas. Platform offsets are well below the offset design criteria specified in Table 2.

Mooring Response Analysis

The most loaded line among the mooring lines was selected to evaluate the tensions and its factor of safety. Under the heading of 90 deg, ML #2 for the wire and ML #3 for the polylines shown in Figure 2 and Figure 4 would experience the greatest tension among others, so these two lines were picked for comparison. The max tensions are estimated using Rayleigh MPM as described earlier. Also, the mooring line strength was validated against the design criteria, and the results of FoSs were compared.

Operating mean tensions on the most loaded wire and polylines were much greater than the extreme mean tension, which is mainly due to the turbine thrust. The max tension of the pontoon platform presented a lower value than the base platform case, for both operating and extreme conditions. The mooring designs of the wire and polylines comply with the mooring strength design FoS criteria in Table 2.



	BASE Concrete Anchors	BASE Drilled Anchors	Pontoon Concrete Anchors	Pontoon Drilled Anchors
■ Hull	$2.24	$2.24	$2.23	$2.21
■ Mooring Lines	$0.62	$0.61	$0.62	$0.61
■ Anchors	$0.85	$0.47	$0.80	$0.47
■ Installation Vessels and Equipment	$1.29	$1.43	$1.29	$1.43

	BASE Concrete Anchors	BASE Drilled Anchors	Pontoon Concrete Anchors	Pontoon Drilled Anchors
■ Project Management	$0.61	$0.61	$0.61	$0.61
■ Engineering	$1.94	$1.94	$1.94	$1.94
■ Certification, Fees and Insurance	$0.48	$0.48	$0.48	$0.48
■ Procurement	$0.29	$0.27	$0.29	$0.27
■ Construction / Fabrication	$0.71	$0.33	$0.62	$0.30
■ Hook Up and Commissioning	$0.22	$0.22	$0.22	$0.22
■ Transportation / Logistics / Installation	$0.75	$0.89	$0.78	$0.89

Figure 6. Single unit cost by component (a) and execution activity (b).

Cost Estimates

The costs of the platform installed include the procurement, fabrication, and installation of the hull (platform), mooring lines, and anchors (gravity block or drilled and grouted pile). All fabrication and procurement, and all installation activities offshore were assumed to be undertaken by local and 2nd tier Korean firms and suppliers. Model basin tests, certification verification authority fees, and marine warranty surveyor costs were included.

The execution plan assumed power turbine integration quayside onto the hull at a fabrication yard and then dry transport of the complete system to the site where the platform would be offloaded and installed. The execution plan also assumed that the seabed anchors would be pre-installed at the site ahead of the power production unit. Execution costs include six months of detail engineering. Fabrication of the unit was assumed to be completed in 3 months.

Pre-sanction costs, such as project approvals, permitting, environmental impact studies, and site metocean and seabed surveys were not included. Power turbines, power cables, and shore anchor connections were not included. Insurance costs and contingencies for offshore operations were not included, however, the proximity of the site in very near shore and shallow water should require minimal offshore contingencies.

The total costs (CAPEX) for a single unit for the base and pontoon configurations with two seabed anchoring options, concrete block, or drilled and grouted pile were calculated. Total costs estimated were in the range of $4.71 to $5.00 million, excluding the turbine system. For the concept design level, the cost estimate has an uncertainty range of ±20%. Total CAPEX and breakdown costs for a single unit were compared in Figure 6.

In this study, the concept design of a 100-kW floating tidal platform with twin vertical axis turbines was conducted. The platform was designed to be installed at a location 20 m off the shore at a water depth of 20 m. A hybrid mooring configuration with catenary and taut mooring was implemented for the seabed anchor line and shore anchor line, respectively. A preliminary analysis was conducted to validate the present designs of the platforms and moorings, and a concept-level cost analysis of a single unit was also performed.

Analysis results suggest that the design requirements were met so that the platform and mooring systems are technically feasible. Further details analysis is recommended in the next phase to access the turbine, platform, and mooring performances for various current velocities and wave environments. The Pontoon platform showed somewhat better performances in motions, tensions, and costs than the base platform.

The cost of a single unit, excluding turbine cost, was around $4.7 to $5.0 million depending upon the platform configurations and anchor options. Due to a small difference in the cost, further analysis is required in the next phase, to identify the most viable option. Results suggested that drilled and grouted anchors may be the more cost-effective solution. However, further seabed study will be required to confirm. The cost estimate has an uncertainty range of ± 20%, but this cost range can be reduced by being realized from additional engineering development with considering additional execution options.

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