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The Application of Dynamic Tidal Power in Korea

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ABSTRACT

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Tidal power is attractive as a predictable renewable energy, but it requires a high tidal range. The west coast of Korea is a place where the extreme tidal range is observed, so various studies have been conducted. The largest tidal power, Sihwa Tidal Power Station was successfully built and operated there. However, subsequent projects have been postponed or cancelled due to environmental issues. Dynamic Tidal power (DTP) is an alternative way to a conventional tidal barrage system. Because DTP has to be a huge structure to produce diffraction of tides, it was tested by a numerical model. The 2D numerical model ADCIRC was used in the simulation. DTP was simulated in the largest tidal range of the Korean coast and it was examined in various ways. DTP generates power by the phase difference of tide and it is available even in a small tidal range. The tidal difference between the front and back of DTP becomes maximized on 180 degrees out of phase theoretically. Though the phase difference also increased with the length of DTP structure, it could not reach 180 degrees out of phase even at the DTP length of 50 km. Because the length of DTP structure should be longer than tens of kilometers considering the length of tide, it may cause economic and environmental issues. The phase difference was varied along DTP and it was increasing as the location of measurement moved closer to the coast. When the required length of DTP is optimized, it would be more practical. The study focused on the reduction of the DTP length and some shapes were suggested finally.

ADDITIONAL INDEX WORDS: *Dynamic Tidal Power, numerical simulation, ADCIRC, phase difference.*

INTRODUCTION

The interesting on renewable energy has been accelerating to reduce the use of fossil fuel, the main cause of climate change. Typical renewable energy sources are many types such as solar heating, photovoltaics, biofuel, biomass, wind power, hydropower, tidal power, wave power, and geothermal. The advantages of renewable energy are clean and unlimited supply. The disadvantages are less economical than fossil fuel and nuclear power, and energy density varies by region.

The tidal energy which was abundant in Korea was studied among renewable energy. The tidal energy can be predicted and harnessed regularly. However, it needs large scale investment at the beginning and the area where the economic power generation is available is limited.

The tidal energy was classified into four types such as tidal barrage, tidal stream, dynamic tidal power (DTP), and tidal lagoon. The tidal barrage is a representative tidal generation and it is used in Rance tidal power in France and Sihwa Tidal Power Plant in Korea. Because the large amount of water has to be trapped, it requires huge structures to cause environmental problems. The tidal stream is difficult to install due to high speed tidal current and it is mainly affected by a turbine performance. The first idea of DTP was released 20 years ago but it is still in the early stage of research. The first Tidal Lagoon is preparing for construction in Swansea bay, England (Baker and Leach, 2006).

Buchwald (1971) and Mei (2012) studied diffraction of tides used for the theoretical principle of DTP. Hulsbergen *et al*. (2005) started a fundamental study of DTP using analytical and numerical approach. Hulsbergen *et al*. (2008) estimated the amount of power generation by DTP in the Korean and Chinese coasts based on a numerical simulation. Shao (2017) simulated multiple DTPs and examined the interference effects of each other. When multiple DTP were installed, the amount of power generation would be slightly reduced comparing with single DTP. Dai (2017a,b) analyzed the effect of each tidal constituent on DTP production in Taiwan Strait, and M_2 tide is more influential than K_1 tide.

DTP is a kind of hydro dam in a sea and built from the coast as Figure. 1. Because DTP does not contain water, it is expected to reduce the environmental problems. Tidal diffraction was created by DTP and it caused a phase difference between both sides of the DTP structure. Due to the phase difference, the water level difference occurred on both sides of the structure. The phenomenon occurs four times a day in a semidiurnal tide area as the west coast of Korea. The high and low water level alternately occur with the tidal cycle. The water level difference by DTP generates an electric power like tidal barrage. The

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detailed principles of DTP evolution are described in Park (2017).

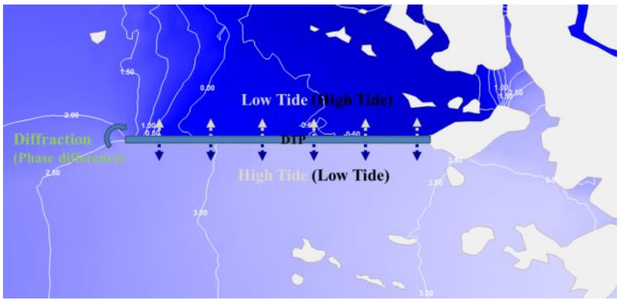

Figure 1. Mechanics of power generation by Dynamic Tidal Power.

Study Area

The study area is located in the west coast of Korea and it has the largest tidal range in the Yellow Sea. The Yellow Sea is located between the west coast of Korea and the east coast of China (Figure 2). Its average and maximum water depth are 44 m and 103 m. The distance between the study area and the coast of China is 320 km. The largest tidal range in the study area is more than 9.0 m and it is about 30 km m away from Sihwa Tidal Power Plant which is the largest tidal power plant over the world. The average tidal range at the spring and neap tide are 8.5 and 5 m respectively. It is a semidiurnal tide area and the power generation by DTP is available four times a day theoretically. The study area is adjacent to big cities such as Seoul and it is the most suitable area for tidal power generation.

Figure 2. Study area for a simulation of Dynamic Tidal Power in South Korea.

METHODS

In this study, a numerical simulation was used to analyze the characteristics of DTP. Because the detailed study has not been conducted yet, a preliminary study was carried to apply it to the west coast of Korea. For a numerical analysis, ADCIRC developed by US Army Corps of Engineers was used (Luettich *et al*. 1992). The applicability of DTP was examined by its shapes, Sea Leve Rise, and detached DTP. Each simulation was conducted for a month considering spring and neap tides. The governing equations of ADCIRC are as follows:

$$\frac{\partial \zeta}{\partial t} + \frac{\partial UH}{\partial x} + \frac{\partial VH}{\partial y} = 0 \quad (1)$$

$$\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial x} + V\frac{\partial U}{\partial y} - fV = -\frac{\partial}{\partial x}\left[\frac{p_s}{\rho_0} + g(\zeta - \alpha\eta)\right] + \frac{\tau_{sx}}{\rho_0 H} - \frac{\tau_{bx}}{\rho_0 H} + \frac{M_x}{H} - \frac{D_x}{H} - \frac{B_x}{H} \quad (2)$$

$$\frac{\partial V}{\partial t} + U\frac{\partial V}{\partial x} + V\frac{\partial V}{\partial y} + fU = -\frac{\partial}{\partial y}\left[\frac{p_s}{\rho_0} + g(\zeta - \alpha\eta)\right] + \frac{\tau_{sy}}{\rho_0 H} - \frac{\tau_{by}}{\rho_0 H} + \frac{M_y}{H} - \frac{D_y}{H} - \frac{B_y}{H} \quad (3)$$

where U and V are depth-averaged horizontal velocities, ζ is the free surface elevation, h is water depth, and $H = \zeta + h$ is total water height. Here, p_s is the atmospheric pressure at the free surface, ρ_0 is the density of water, g is gravitational acceleration, α is the effective Earth elasticity factor, η is the Newtonian equilibrium tide potential, τ_s is the applied free surface stress, τ_b is the bottom stress, Mx and My are vertically-integrated lateral stress gradients, Dx and Dy are momentum diffusion/dispersion terms, and Bx and By are baroclinic pressure gradient terms in the x and y directions.

The observational stations were located to measure the variation of tide at the beginning, middle and end of the DTP structure. Three are placed in the north, and the other three are in the south. The characteristics of the DTP were analyzed by the observed tidal difference. The tidal difference was calculated by difference between the observed north and south tidal levels centered on DTP. Park (2017) explained the fundamental characteristics of DTP. The tidal difference was varied along the location of DTP and the largest tidal difference was observed at the nearest coast. The tidal difference was also depended on the length of DTP. When the length of DTP is 10 km, 2.5 m of tidal difference was generated at spring tide. When the length of DTP is extended to 50 km, it becomes more than 4 m. The all tests were conducted with 50 km DTP in the study.

The applicability of DTP was examined in two ways. First, various tips of DTP were simulated to increase the tidal difference. Second, detached DTP was test to reduce the construction cost. Because DTP required a huge structure, methods to increase efficiency should be studied. Hulsbergen *et al*. (2008) showed that the increment of tidal difference by adding a bar at the end. Four different shapes of DTP were analyzed to increase the tidal difference (Figure 3). The lengths of added bars were 8.7, 15.8, and 5.3 km for T-shape, Large T-shape, and up-down bar DTP respectively. The ratios of each bar to the length of DTP were 17, 32, and 11 % respectively.

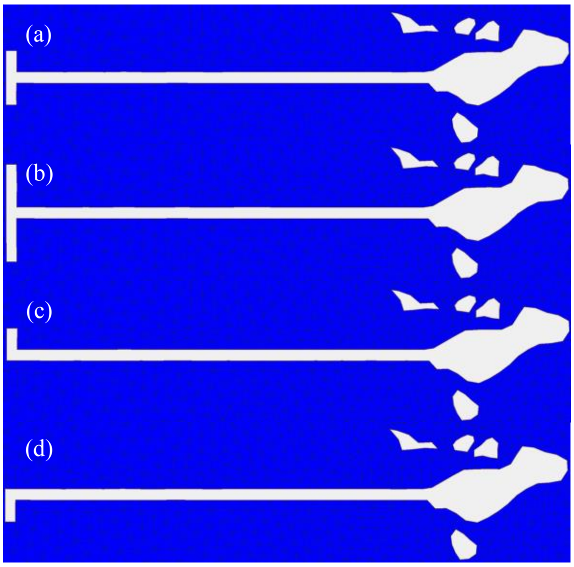

Figure 3. Various shapes of DTP. (a) T-shape, (b) large T-shape, (c) up bar, (d) down bar.

DTP generally is built from the coast and it caused environmental or navigational problem. If DTP does not block ocean current, the problem could be minimized. Therefore, DTPs were located 10 and 30 km away from the coast in Figure 4 and the tidal differences were analyzed. In this case, the lengths of DTP were 40 and 20 km by the detachment.

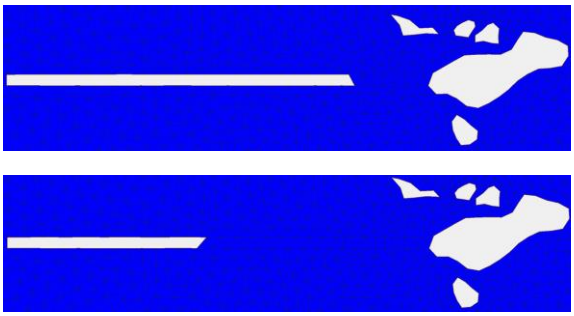

Figure 4. Detached DTP was simulated 10 and 30 km away from the coast.

RESULTS

The simulations were conducted in three ways such as the shape of DTP and influence by detached DTP. Each test case was simulated and the variations of tidal levels were observed and analyzed. The tidal elevations without DTP and the tidal differences by a simple shape of DTP were shown in Figure 5. In the figure, Ne represents the observational station in north end of DTP. In the same way, Sm and Nb mean South middle and North beginning respectively. If there was not any DTP, the maximum tidal elevations would be 3.96 m at the beginning station and 3.6 and 3.15 m at the middle and end station respectively (Figure 5).

Influence by shape of Dynamic Tidal Power

The maximum tidal differences of each shape of DTP were shown in Table 1. Because the characteristics of DTP were not understood completely, the maximum values of spring and neap tides were analyzed. The bar-shaped structures were added to increase the tidal difference at the end of DTP.

The maximum tidal differences by a simple DTP were 4.27, 3.62, and 2.79 m at the beginning, middle, and end station respectively (Figure 5). The tidal difference was caused by the phase difference and it was varied along the DTP structure. The phase difference also grew close to the coast. However, the period of tide and the phase difference were kept during 30 days simulation. Therefore, the variations of tidal differences were similar to those of the tidal elevation.

A bar-shaped structure was added to increase production as in the previous study but there was not a big difference in each test result (Table 1). The result was the same at spring and neap tide. The ratio of bar to stem was more than 70 % in Hulsbergen *et al.* (2008) but it was only 32 % in the large T-shaped DTP case. Because the ratio of bar to stem might be a key to determine production, additional T-shaped DTP was simulated. The length and ratio of the new T-shaped DTP were 10 km and 87 % respectively. Some improvement was shown in Table 2 but it was still small comparing to the previous studies.

Table 1. *Maximum tidal differences by different shapes of 50 km DTP.*

Shape of DTP	Tidal difference at spring tide (m)	Tidal difference at neap tide (m)
Simple	4.27	2.22
T-shaped	4.30	2.25
Large T-shaped	4.32	2.28
Up bar	4.29	2.25
Down bar	4.27	2.22

Table 2. *Maximum tidal difference by different shapes of 10 km DTP.*

Shape of DTP	Tidal difference at spring tide (m)	Tidal difference at neap tide (m)
Simple (10 km)	2.71	1.10
T-shaped (10 km)	2.95	1.20

Influenced by detached Dynamic Tidal Power

A structure of DTP needs to be reduced in size for practical applications due to its huge size. An offshore installation of DTP was studied to diminish interference. When DTP was not connected to the coast, the tidal difference by DTP was significantly decreased (Table 3). If it was located 30 km away, the tidal difference was smaller than those of 10 km simple DTP in Table 2.

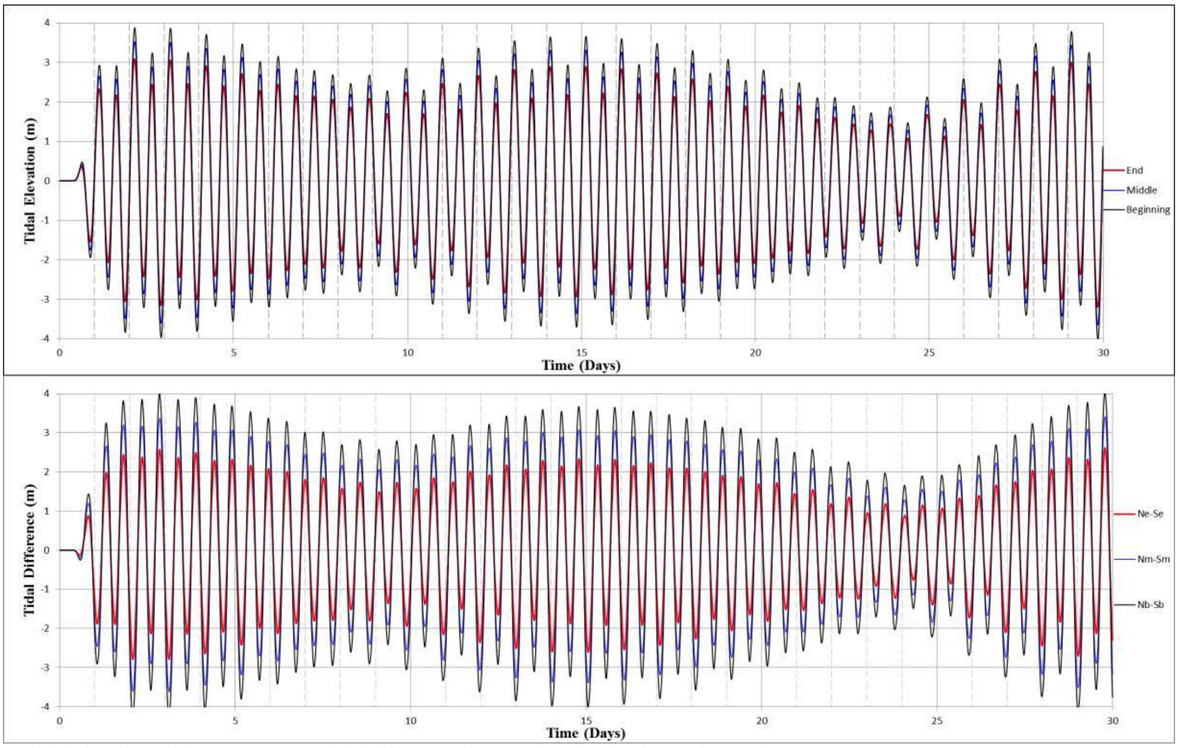

Figure 5. Tidal elevation without DTP (top), tidal differences by a 50 km simple shape of DTP (bottom).

Table 3. *Maximum tidal difference by detached DTP.*

Types of DTP	Tidal difference at spring tide (m)	Tidal difference at neap tide (m)
Simple	4.27	2.22
10 km away	3.10	1.40
30 km away	1.83	0.73

Table 4. *Current speeds of each DTP at A and B station.*

Shape of DTP	Average speed (m/s)		Maximum speed (m/s)	
	A	B	A	B
No DTP	0.7	0.7	1.0	1.3
Simple	1.6	0.8	2.9	1.4
T shape	1.3	0.8	2.3	1.4
Large T shape	1.1	0.8	2.0	1.4
Up bar	1.3	0.8	2.4	1.4
Down bar	1.5	0.8	2.7	1.4
Detached (10km)	1.5	0.7	2.8	1.3
Detached (30km)	1.3	0.7	2.4	1.3

The current speed was observed to analyze the change of environment at two observation stations (Figure 6). The variation of current speed affected on sediment transport, ecosystem, navigation of ship. The increment of current speed by all types of DTP was observed at the end of DTP (Table 4).

Figure 6. Two observational stations for measurement of current speed.

DISCUSSION

Many shapes of DTP were studied to increase its tidal difference in Table 1 but there was not a big difference comparing with a simple line shape of DTP. The results were the same at spring and neap tide. When a structure was added to the end of DTP, the tidal differences were increased in all cases. The T-shaped DTP was better than up and down bar DTP. It produced less tidal difference than the large T-shaped DTP. The up bar DTP was useful considering the direction of tidal diffraction. Because the phase difference was produced only in the north of DTP, the down bar might not work.

The next study was focused on the ratio of bar to stem considering of noticeable improvement in Hulsbergen *et al.* (2008). Though the ratio of the large T-shaped DPT was 32 %, the improvement was a little. When the ratio became 87 % in

Table 2, it showed a significant advancement. Because there was only a 10 % improvement, it would be more efficient to increase the length of a simple DTP instead of adding a bar at the end of DTP. However, the difference between an elongated and T-shaped DTP was not so much.

For a reduction of environmental issues, the detached DTP and ambient current speed were studied. The environmental issues by a general tidal power were studied by Frid *et al*. (2012). As DTP was installed away from the coast, the tidal difference was decreased significantly in Table 3. Considering that the tidal difference was 3.5 m by a simple 30 km DTP, the 10 km detached DTP would be an alternative. When DTP was not installed, the onshore current speed was similar to offshore in Table 4. Though the offshore current speed was nearly twice as fast as no DTP, the onshore current speed was not changed. Therefore, the impact of DTP could be ignored near to the shore. Comparing tidal difference with current speed, any strong relationship was not found.

CONCLUSIONS

Though DTP has an advantage to reduce environmental issues comparing with the conventional tidal power generation, a practical research has not been conducted yet. Because DTP has to be built as a huge structure, a study for the increment of production is required.

The various different shapes of DTP were simulated to increase the tidal difference using a numerical model but the attachment of a structure at the end of DTP did not show a dramatic improvement. The ratio of a bar to stem was important but the improvement was not so much. The larger T-shaped DTP did not show the better result and it has a limit to improvement. The simple DTP would be the best choice to satisfy the production and construction cost simultaneously. The size of T-shaped DTP should be optimized with local tides. Because it was completely different results from other studies, further study is needed in the future.

The better results would be expected by elongating of a simple DTP as long as the length of a bar. The maximum output would be expected at the case of 70 km long simple DTP and it would be almost 180 degree phase difference in the study area. Considering the result of detached DTP, the installation from an Island would be the better choice to minimize the environmental issue by tidal power generation in near-shore area. Thought the biggest tidal difference of DTP was generated in near-shore area, the both maximum and average current speeds were rarely changed at the location B. It means that the environmental impact may be much smaller than expected. Because the offshore current speed by DTP increased twice as fast as no DTP case, its impact has to be investigated in many different ways.

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