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Research paper

The rebirth and eco-friendly energy production of an artificial lake: A case study on the tidal power in South Korea

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ABSTRACT

In light of climate change and greenhouse gas reduction, countries around the world are doing their part to develop various types of eco-friendly energy. In this context, the Shihwa Tidal Power Plant is an advanced energy generation infrastructure which uses the resources of the sea, a project that pioneers and practices low-carbon, green growth engineering. Not only as an advanced energy generation infrastructure but also it is an eco-friendly infrastructure that resurrected 'the dead lake', which had suffered extreme water pollution due to cutoff in seawater circulation after the completion of the tide embankment in 1994. By circulating the water of the lake, new mud flats have appeared in the upstream area, an area once submerged due to the embankment. These new mud flats are providing new shelters for various organisms, thus transforming the lake into an eco-friendly, life-giving one. Most tidal power plants are difficult to construction due to geological features. The Sihwa tidal power plant was developed harmoniously by utilizing the unique geological features and tidal power plant principles on the West coast of the Korean peninsula. Shihwa Tidal Power Plant is a special and differentiated development example of renewable energy production and environmental improvement along with the significant water quality improvement effect of Shihwa Lake due to increased seawater exchange rates. This article therefore presents the review of Shihwa Lake's environmental issues and eco-friendly energy production process with the aim to identify the good practices, the challenges as well as the lessons learnt from their experience. This development will be another case of a country seeking to develop new marine energy. This is also a good practice of improving the environment of freshwater lakes in coastal areas.

1. Introduction

In light of climate change and greenhouse gas reduction, countries around the world are doing their part to develop various types of eco-friendly energy. In this context, the Shihwa Tidal Power Plant is an advanced energy generation infrastructure which uses the resources of the sea, a project that pioneers and practices low-carbon, green growth engineering.

The Shihwa Tidal Power Plant was completed in 2011, and is the first tidal power plant in Korea, and the largest one yet in the world. The former largest tidal plant was in Rance, France, which has a generation capacity of 240 MW. The plant at Shihwa Lake has a generation capacity of 254 MW, which is equivalent to powering approximately 500,000 households in the vicinity. The plant's annual power production amount is 552 million kWh (Frau, 1993).

The Shihwa Tidal Power Plant operate the Cultural Center. The cultural center is located in the T-Light Park. The name, 'T-Light' was coined to symbolize the 'light' made by the 'Tide', and 'T' implies the tides, two-way, and tomorrow (Cha et al., 2012). The park became a local landmark providing light and delight to the local community. Also, the cultural center provide various information and contents including the operation and principles of the plant, the history of the lake, etc. The Shihwa Tidal Power Plant Information Center also include a 75-m high observatory, an international conference center, and seminar halls. With the new cultural center, the T-Light Park became a local landmark and a tourist attraction in the near future (see Fig. 1).

The Shihwa Tidal Power Plant project not only has contributed in lowering CO_2 through eco-friendly energy production, but also in improving the Lake's water quality through regular circulation. Before the plant construction, the COD level presented over 4 ppm, making the lake a level-3 body of water, the worst water quality condition. The mud flat of the lake was rotten and its ecosystem was destroyed, hence the nickname: the dead lake (Anon, 2021a) (see Figs. 2 and 3).

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Fig. 1. The Shihwa tidal power plant.

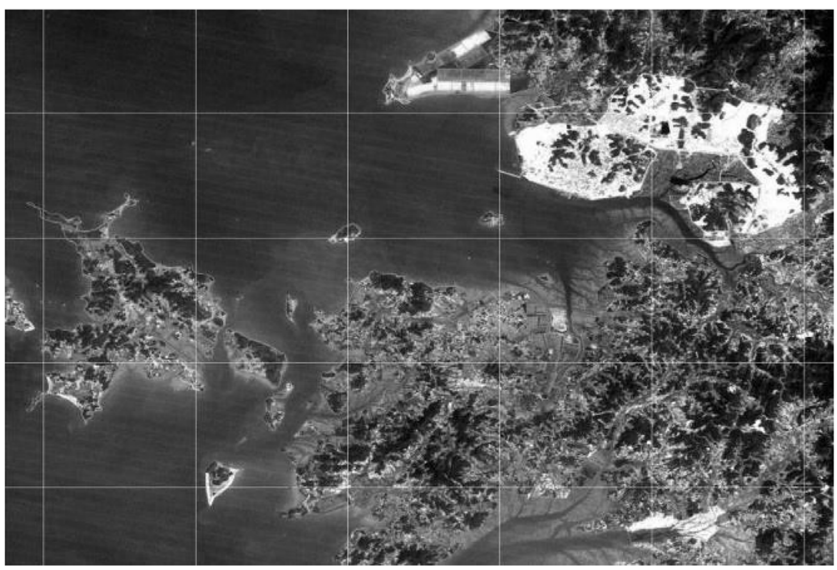


Fig. 2. Satellite photograph before the Shihwa Tide Embankment construction, 1987.

But now, it is transforming into an eco-lake, and the water is currently being circulated through the 8 sluices of the tidal plant, twice a day, during ebb tides. Approximately 147 million cubic m of seawater is exchanged during these times, which makes up about the half of the entire lake. The COD level at Shihwa lake is currently at 2 ppm – from 3.7 ppm before – which is similar to that of the West Sea (Yellow Sea), indicating that its water quality is improving. Moreover, by circulating the water of the lake, new mud flats have appeared in the upstream area, an area once submerged due to the embankment. These new mud flats are providing new shelters for various organisms, thus transforming the lake into an eco-friendly, life-giving one.

Most tidal power plants are difficult to construction due to geological features. The Shihwa tidal power plant was developed harmoniously by utilizing the unique geological features and tidal power plant principles on the West coast of the Korean peninsula. Tidal power cannot only be developed on a large scale, but also uses gravity energy caused by celestial motion such as the moon, sun, and earth, which have accurate periodicity. As a result, tidal power has the advantage of renewable energy such as wind power and solar power in that it can make accurate long-term predictions (Kim, 2011). In other words, tidal power can also have significant synergies because it can accurately predict marine information years from now. And it is possible to predict problems in advance and respond quickly (Anon, 2008). In addition, tidal power generation usually has less fall than 10 m compared to hydroelectric power, so the efficiency of turbine generators is key to power generation technology (Lee, 2012). The development of large-scale tidal power plant has yet to be realized due to insufficient economic feasibility. However, the need for renewable clean energy has been growing recently due to the burden of greenhouse gas reduction obligations due to climate change and the depletion of fossil fuels (Kolk and Pinkse, 2005). In particular, as Shihwa Tidal Power Plant was converted to Sea Lake as part of water quality improvement, tidal power plants were installed as an efficient method of utilizing Shihwa Lake. Shihwa Tidal Power Plant is a special and differentiated development example of renewable energy production and environmental improvement

Fig. 3. Satellite photograph after the Shihwa Tide Embankment construction, 1994.

along with the significant water quality improvement effect of Shihwa Lake due to increased seawater exchange rates (Moon, 2013).

This development will be another case of a country seeking to develop new marine energy. This is also a good practice of improving the environment of freshwater lakes in coastal areas.

This article therefore presents the review of Shihwa Lake's environmental issues and eco-friendly energy production process with the aim to identify the good practices, the challenges as well as the lessons learnt from their experience. In particular, the review focuses on the following perspectives.

1. The challenges for environmental pollution and energy problems in freshwater lakes
2. The geological features and design principles of tidal power generation
3. The eco-friendly construction method of tidal power plant
4. The operation and maintenance of sustainable tidal power system

This article is organized into the following sections. Section 2 describes causes and issues of marine energy and Section 3 describes environment planning, design, and technical principles of the tidal power plant. Sections 4 and 5 elaborate on the Shihwa tidal plant' development process journeys respectively about construction method, development process, maintenance, etc. Analysis, lessons learnt and technical implications are presented in Section 6. Section 7 concludes the article and points to potential future work and outlook.

2. Solution for the lack of energy and environmental pollution

2.1. Dealing with energy supply & demand

In the past, Korea has experienced large-scale blackouts due to power shortages. As a country that depends on imported energy sources for 97% of its total power generated, we are extremely sensitive to the changes in foreign and global energy market. Energy consumption in Korea is at 5.3TOE (Ton of Oil Equivalent) per capita, which is higher than the OECD average of 4.4TOE, and is marking an annual increase of 2.7% (Anon, 2020).

However, it has become a global trend to decrease dependence on fossil fuels, and with the nuclear disaster in Fukushima, Japan, it has become evident that the nuclear energy is no longer the safest way to produce power. Researches on new and renewable energy are on the rise, but the development of such alternative energy is not an easy one: solar power cannot be sufficiently generated if the weather is not favorable; wind power is unproductive if winds slow down. Therefore, development of new alternative energy sources other than solar or wind power is needed to be accomplished, with more stability and security.

2.2. Issues regarding the environment

Korea, with its geological advantage – a peninsula – has the best conditions for developing marine energy. Not only will marine energy never run out, but it can also be used without generating contaminants that would harm the environment. With such an infinite amount of marine resources, tidal power generation is gaining attention as an efficient way to procure electrical power.

Tidal power plants in other countries are usually constructed for large unit power generation, however, the Shihwa plant was originally constructed with aims to enhance water quality of the lake. This is the main difference in the background of its birth.

The Shihwa lake is an artificial lake, created by linking the three cities – Si-heung, Ansan, and Hwasung – with the Shihwa tide embankment. The embankment spans 12.7 km, enclosing the lake to an area of 56.6 km^2, equivalent to seven-times the area of Yeoui-do in Seoul, and a drainage area of 476.5 km^2. The lake stores approximately 3.22 million tons of water on average (Anon, 2021b) (see Fig. 4).

The embankment of the lake was motivated by a decision to make new cities within the vicinity of the capital, Seoul. In 1976, the government began projects to build large industrial complexes covering 3.3 million square meters of land. At the time, immense number of people flocked to the capital as well as to places in the vicinity of Seoul in search of jobs, and the migration lead to a dramatic and uncontrollable increase in population. Moreover, many industrial foundations were being concentrated near Seoul around the same time, and therefore dispersing the population of Seoul and those in migration to the capital was an important project at the national level.

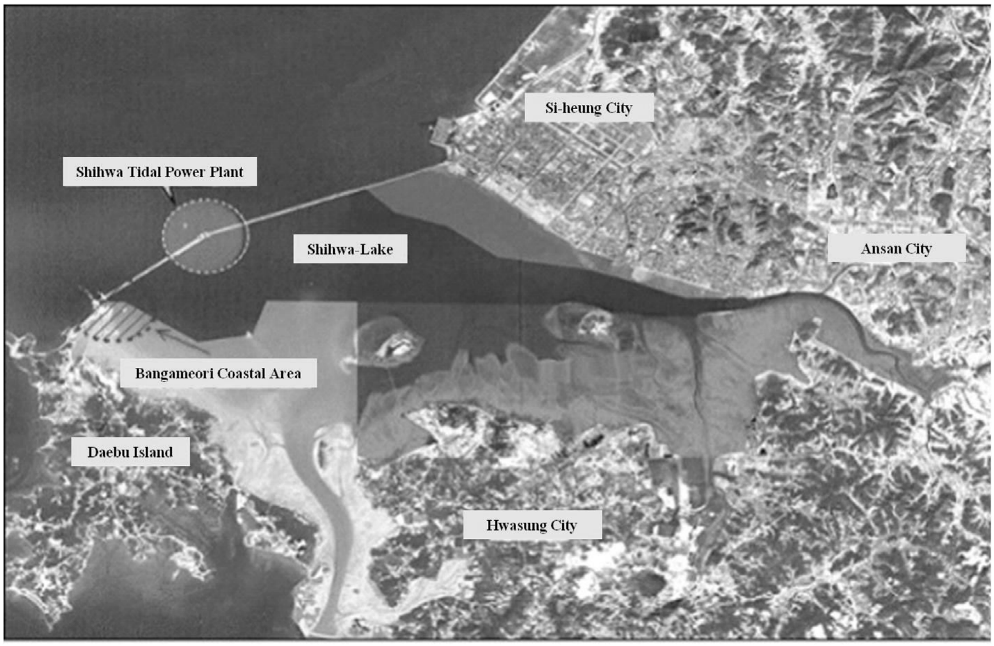


Fig. 4. Local situation around the Shihwa tide embankment and the Shihwa lake.

The embankment construction began in 1987 and was completed in 1994, allowing the construction and the development of the three new cities with enormous sizes of industrial complex on the large reclaimed land.

After the embankment of the Shihwa lake, the inflow of freshwater into the lake was cut off, and thus began the deterioration and contamination of 'the dead lake'. Moreover, after the completion of the embankment, population increased 4.7 times, and livestock increased 3.3 times in the nearby area (Anon, 2010a). Moreover, large amounts of industrial wastewater, as well as domestic sewage that flowed into the lake rapidly contaminated the isolated body of water. These events brought the death of hundreds of thousands marine life, and the lake had become a representative example of water pollution (see Fig. 5).

Thus for the past 20 years, after the government designated the lake as a special control area for special treatment; however, not much improvement. The measurement of the lake's COD concentration, in 2010, presented over 4 ppm, making it a level-3 body of water with the worst water quality (Anon, 2010b).

In 2000, the government officially began a project to improve water quality of the lake, by surrendering its freshwater status and reinstating it as a seawater lake. In 2002, K-Water, the official water management authority, had established plans to construct and operate a tidal power plant embedded in the embankment of the lake, with the primary aim to improve the water quality.

3. Special feature and design idea of Shiwha tidal power plant

3.1. Geological features of Shihwa-lake

The Shihwa Tidal Power Plant was ordered by the K-Water (Korea Water Resources Corporation). Saman Engineering, a leading engineering company with renowned expertise in plants and dams, was selected as the designer, and the construction was carried out by Daewoo Consortium. The total cost of the construction was approximately 389 billion KRW (Korean Won) (USD 370 million).

For turbine supply, Australia's Hydro Tasmania participated in the project. Also, Austria's VerbundPlan and Canada's Annapolis Royal Generating Station participated as consultants of the project.

The construction began in December 2004, and after seven years of construction, and in December 2011, a plant with eight dike sluices and ten turbine generators with a total generation capacity of 254 MW, was completed (see Fig. 6).

Above the roof and side of the plant, super and substructures mainly consisting of vehicle roads were also built-in. The road has opened in September 2010, and now it is responsible for large amounts of traffic that passes through every day. The roads were designed and built as the same height of the original embankment, although 80% of the plant structure is actually submerged. The super and substructure roads, including some relevant apparatus are what we are able to see above the surface. The rest of the plant is underwater, so that if seen from above, the plant may appear as an elaborate bridge.

The Shihwa Tidal Power Plant is located at an ideal place for tidal generation. The difference between the rise and fall of the tide on the West coast of the Korean peninsula is 9.16 m at maximum, which is one of the largest in the world, making it the ideal coastlines for building tidal power plants with efficient power generation (see Fig. 7).

Tidal power generation is a technology that utilizes the tidal range that happens at rising and ebb tides. Tides occur twice a day, making the sea level rise or drop. Tidal power generation utilizes this difference in water levels to operate the turbines and generate electrical power.

3.2. Design idea of the Shihwa tidal power plant

There are two types of tidal barrage: the double-basin system utilizes the difference in water levels in both rising and ebb tides; the single-basin system seizes the incoming tide into a lake, and utilizes the difference in water levels at ebb tide, by letting the water out back into the sea.

The Shihwa Power Plant is constructed with a single-basin system. This is due to the fact that double-basin generation system requires the Shihwa lake to rise up to 4.5 m, which would flood the nearby cities and towns. Moreover, during generation periods, the maintained drop is within two meters, therefore the single-basin generation system was considered more economical (see Fig. 8).

Fig. 5. Death of fish and shellfish of 'the dead lake'.

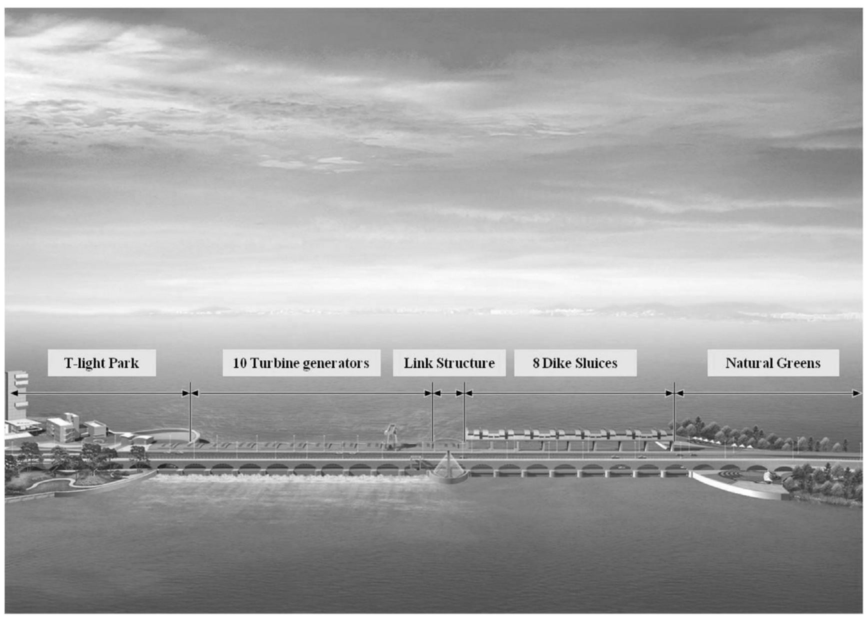


Fig. 6. Overview of the Shihwa tidal power plant.

Fig. 7. Difference of the Shihwa lake water levels between rising tides and ebb tides.

In a single-basin system, there are two ways to generate energy: the flood tide generation and ebb tide generation. The Shihwa plant uses the ebb tide generation, and it is capable of operating twice per day, approximately 4 h and 25 min each time for generation. The sluices are closed before the flood tide, and when the sea level raises approximately two meters above the lake water level, the flow control gate opens, and the sluices let the seawater pour into the lake, turning the propellers of the

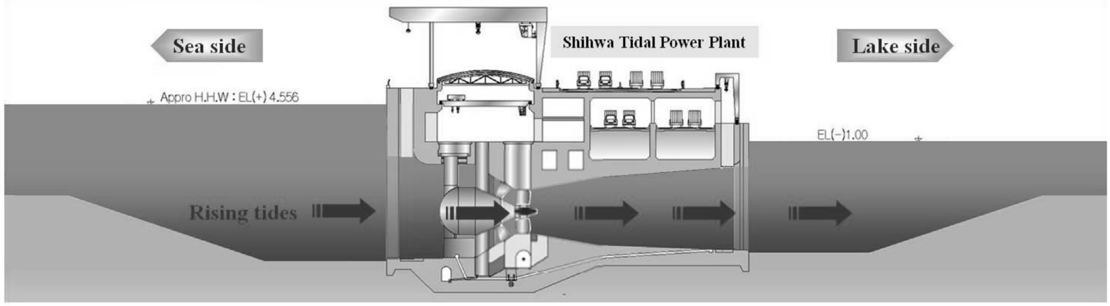


Fig. 8. Principle of the Shihwa tidal power plant generation.

Fig. 9. Propeller turbine of the Shihwa tidal power plant (Seo, 2010).

generator turbines. The estimated amount of seawater pouring into one generator turbine is approximately 500 metric tons per second—equivalent to three times the amount of water of the Han River that passes by the Yeoui-do in Seoul.

Inside the Shihwa plant, propeller turbines attached to a submarine-shaped generators fixed to concrete structures turn the spindles attached to electrical generators to produce electricity. There are ten separately installed generators side by side at the Shihwa plant. Each generator is capable of producing 25,000 KW of electricity, thus making the Shihwa Tidal Power Plant the largest capacity tidal power plant in the world. Also, because the propeller turbines that spin underwater take the form of a light bulb, they are often called 'bulb type' generators (Anon, 2009).

A single propeller turbine chamber receives 482,000 L of seawater per second, and electricity is generated from the water dropped from a point of 5.8 m. In this chamber, a gigantic turbine generator with a diameter of 7.5 m is placed. A total of ten propeller turbines are the main components of the Shihwa Tidal Power Plant (see Fig. 9).

The propeller turbines used at the plant are synchronous generators, each turning at an average speed of 64 RPM (rounds per minute). Speed governors are installed to deliberately turn the generators slow, and have full control over the RPM. Also, eco-friendly elements such as fish paths were taken into account.

Generally, there are four runners attached to a single propeller turbine; however, having taken the fish path into account, the propellers at the Sihwa Tidal Power Plant only have three runners each.

Each runner weighs approximately 53 metric tons; the turbine spindle, 54 metric tons; the impeller (rotor), 12 metric tons; thus the weight of the entire revolving element is at approximately 209 metric tons. Moreover, one propeller turbine at the Shihwa plant weighs approximately 800 metric tons, making the plant the largest in weight and scale in the world (Kim, 2010) (see Fig. 10 and Table 1).

4. Eco-friendly construction method of tidal power

4.1. Development of construction technology which minimize environmental damage

The construction of a temporary cofferdam was carried out in order to make available the foundations of the tidal plant on the solid bedrock, 35-meters below sea level. It was the first and foremost, and the most important construction stage of the Shihwa Tidal Power Plant project.

The objective of the construction was to secure a stable and safe construction site for the following stages. It was an extremely difficult process as it had to withstand the strong waves of the West Sea, and surmount the large difference between tides.

The temporary structure was divided into three sections: seaside, connector, and lakeside. The seaside section was built using Circular cells made of I-type steel sheet piles which were filled with sand, in order to block the penetration of seawater (see Fig. 11).

Specifically, the circular cell method has solved the problem of station keeping on the sea surface and the initial installation, which usually was a problem from the traditional method (series of land assembly, transportation, on-site installation). Moreover, the traditional method used sand pump dredger vessels to fill the sand that produce wastewater; the applied method utilizes conveyor belts to minimize the flow of wastewater.

Along with the circular cells, rubble mound breakwater method which does not affect much from the sea conditions, were also used to block the seawater. On the lakeside, steel sheet piles were applied to block water, and to provide earth retaining function as the lake floor consists mainly of soil and sand. In addition, steel sheet piles are readymade goods which are easy to quality control (Cha et al., 2009a).

The circular-cell cofferdam method, compared to other methods such as double sheet pile or rubble mound, provides structural stability similar to that of a permanent structure, meanwhile minimizing soil and sand spills at dismantling stage, and also minimizes the possible environmental damage (see Table 2).

For the construction of the harbor, circular-cell cofferdam method was applied instead of rubble mound, to secure structural stability and minimize environmental damage.

Table 1
Information on the resources of Shihwa tidal power system.

Power generation method	Single-basin and flood generation system, Power generation twice a day
Total generation capacity	25.4 MW × 10 turbine generators
Turbine type	10 Kaplan Bulb Turbine type
Turbine runner type	Horizontal type, 3-blade synchronous generator
Runner diameter	7.5 m (3 blades)
Operating-flow of turbines	481.23 m^3/s
Revolution Per Min	64.29 rpm
Head	Net Head 5.82 m, Max 7.50 m, Min 1.00 m

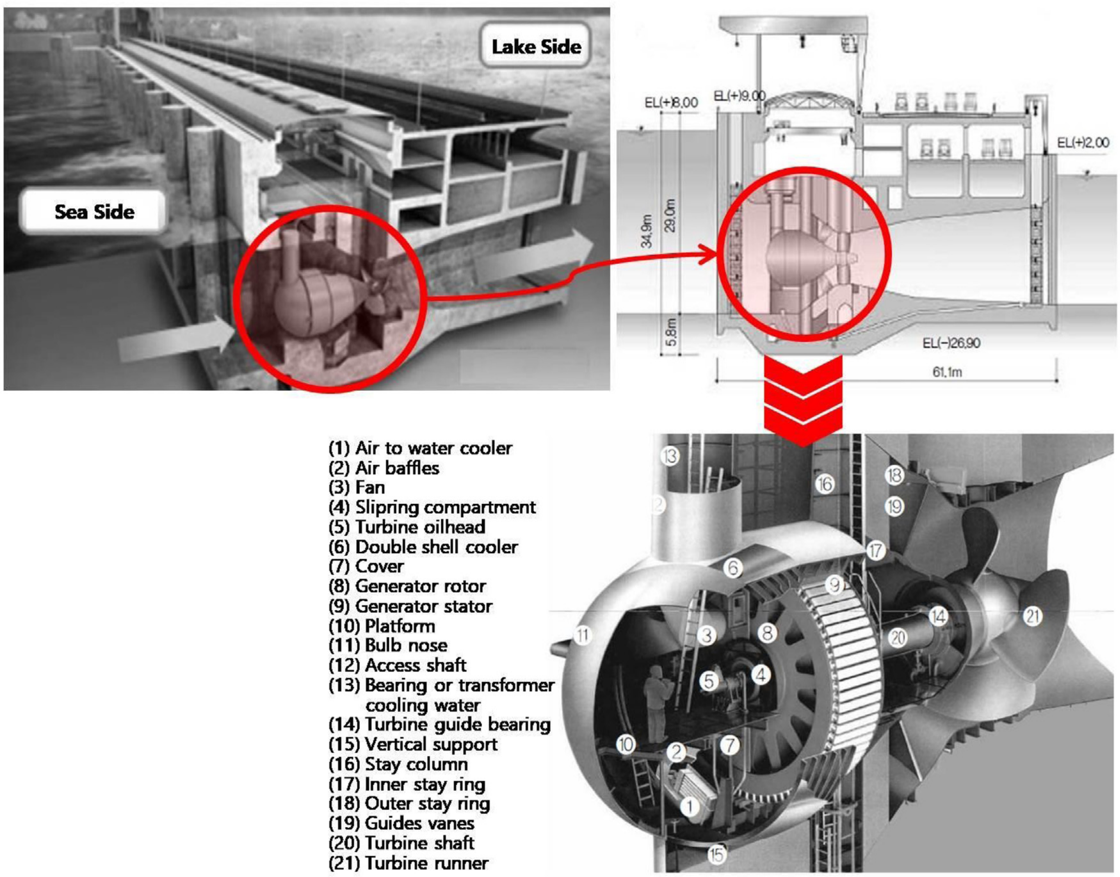


Fig. 10. Structure of a single generator.

4.2. Temporary cofferdam construction technology

The circular-cell cofferdam consists of two types of templates made from flat sheet piles: the circular cell and the arc cell. They are tentatively assembled and moved to their installation sites, where they are installed with precision.

The template piles are hammered deep into the seafloor using a vibro-hammer, each connected by another pile after pile in a circular shape approximately 20 m in diameter. Then, the circular cell is filled with sand and is reinforced with the arc cells on the outer part of the structure, and altogether they work to block the inflow of seawater (see Fig. 12).

The sand used to fill the circular and the arc cells were 228,654 m^3, which was later recycled to build the T-Light Park and the Cultural Center (see Fig. 13).

The circular cell cofferdam method was first used in Korea for the foundation work of the Seo-hae Bridge pylon construction. At the time, the construction crew used this method to assemble the circular cells on land and move them to the construction site.

However, moving the completed cells on water was quite difficult and challenging. Therefore, the new method applied to the Shihwa Tidal Plant assembled the cells which were set with concrete on-site. The applied method was first of its kind in Korea, but it required precision to overcome the strong winds of the West Sea (see Fig. 14).

Installing the 29 circular cells (each 20.382 m in diameter) and 28 arc cells (each 4.12 m in diameter) was a complex project that required 10 months of construction. The cofferdam construction required extreme accuracy to minimize errors due to waves (Ordonez et al., 2019). The crew utilized a specialized equipment called Self Elevated Plate (SEP) Barge that can fix and install objects from the sea surface to the sea-bed. This equipment prevents final closure error of the Flat Sheet Piles (see Fig. 15).

The construction site of the tidal power plant surrounded by cofferdams was approximately 138,000 square m , equivalent to

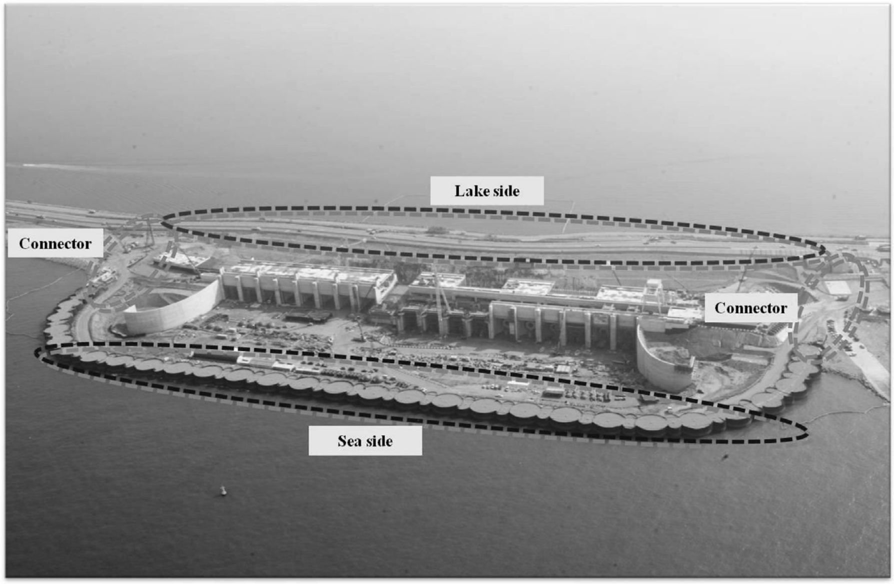


Fig. 11. Temporary cofferdam of the Shihwa tidal power plant.

Fig. 12. Circular cell on site positioning and installation.

Fig. 13. Circular cell sand filling.

Table 2
Structure of temporary cofferdam.

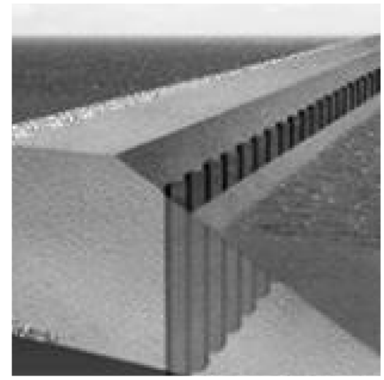
Seaside	Connector	Lakeside
Circular cell (750 m)	Rubble mound breakwater (200 m)	Steel sheet pile (790 m)
		

Fig. 14. Circular cell on land construction and marine transportation (left), on-site installation (right).

Fig. 15. Circular cell temporary cofferdam construction by SEP barge.

12 football fields. The depth of the site was 34.5 m, equivalent to a 12 storey apartment. For the temporary cofferdam construction, 29 circular cells, each with a diameter of 20 m, and 128 sheet piles, were installed (see Fig. 16).

5. Sustainable operation and maintenance management

5.1. Securing safety of the cofferdams through monitoring

For the construction of the tidal plant, a cofferdam spanning 600 m in length and 200 m in width was built to block the seawater, and to secure a bas-sea-level construction space.

To accurately monitor the site ground and the dynamic behaviors of the cofferdams in real-time, instrumentation control system was applied (Cha et al., 2009b). The instrumentation control system transmits monitored data to the server every hour, making it accessible over the internet. If a monitored result exceeds the set standard, the system sends text messages to the site manager (Choi et al., 2008).

Monitoring the temporary structure of the site was a constant countenance against challenges as there were no precedents or similar cases. About a year after the temporary structure had been in place, the collected data was analyzed to observe the dynamic behavior of the structures. Based on this knowledge, additional instruments were installed and operated before the actual initiation of the main construction. With them, safety analyses of the temporary cofferdam, and the dynamic behavior interpretations of the circular cells, as well as pore water pressure analyzes were

Fig. 16. Overview of the circular cell and arc cell temporary coffer dam construction site.

carried out. The construction management has been performed more efficiently due to the results (Kim et al., 2009).

5.2. Efficient construction management through 4-dimensional simulation development and operation

The Shihwa Tidal Power Plant construction project was a difficult and challenging engineering process with ten enormous turbines and gigantic structures. For a continuous and smooth control over the building process, the entire construction plan was divided into 46 stages. Following the 2-dimensional blueprints, every stage was recreated to 3-dimensional models, and then developed into 4-dimensional simulations on a web site (Heesom and Mahdjoubi, 2004).

As shown in Fig. 17, the process progress screen shows a comparison of the planned process image versus the actual process image according to the current process progress date at the top. In practice, the system works on an Excel schedule with 3D modeling data according to the process sequence to retrieve each image when input is made. Fig. 17 shows one generator. It represents the planned process image at the top and the actual process image at the bottom. It is supposed to invoke a section of 46 stages, and it adjusts transparency to indicate that the previous process is transparent and that the current process is opaque. In addition, each stage is stored in Data-Base through an ID, indicating a consistent linkage. Later, as shown in Fig. 18, the system shows the visual effects of parts through color, with Gray showing the completed process, Yellow showing the progress, RED showing the delayed process, and Green showing the progress as planned.

The 4-dimensional simulation enables a preliminary review of the project through 3-dimensional visualization of the construction process, allowing the detection and correction of work errors at each stage in advance, and enabling prediction of the process (Mallasi, 2006).

Not only can 4-dimensional simulation system identify the differences between existing 2D and 3D systems by linking them to process processes, but it also links them with data such as materials, cost, and manpower to automatically check, modify, and predict the current status of each process (Choi and Shin, 2014).

The screen configuration for 4-dimensional simulation consists largely of a text date, an image data, and a 3-dimensional model screen. Fig. 19. visualizes the assembly and installation process in accordance with the construction sequence through the screen configuration of the 4D system. Visualization design information such as (1) Design simulation, (2) Design details, and (3) Target location areas are delivered.

(1) In the Simulation area, structures can be rotated, specific parts can be expanded and reduced, and the scheduled process status can be reviewed at a specific point in time. (2) In the Information area, information is linked through ID as part that shows detailed information about the process shown on the Simulation screen. (3) The Location area is a screen with CAD drawings in color, and information is linked through ID attributes.

Each 3D model is capable of connecting sequential frameworks through a Lego style 3-dimensional model, as shown in Fig. 20-(a). Not only can manager see problems in advance through the interference checklist about the assembly of these components, but manager can also conveniently assemble the structures in the order in which the work process is carried out (Choi and Han, 2012). In addition, the system has the advantage of being able to visually review the structure through various viewing functions in the program.

The 4-dimensional simulation system allowed both the engineers and stakeholders to easily understand the construction project, as well as review and analyze the progress of each stage process in advance. Moreover, the system was effective as it aided a smooth construction management by discovering and responding to constraints in each process (Kim et al., 2008) (see Fig. 21).

5.3. Development of K-TOP program for optimal operation of tidal power

Sihwa Tidal Power Plant operates in a single-current creative development method if there is a management level below a certain level to prevent damage such as urban construction and flooding inside the seawall (Cornett et al., 2013a). However, if the level of management is similar to that of the outer sea at high tide, the method of power generation may be selected in

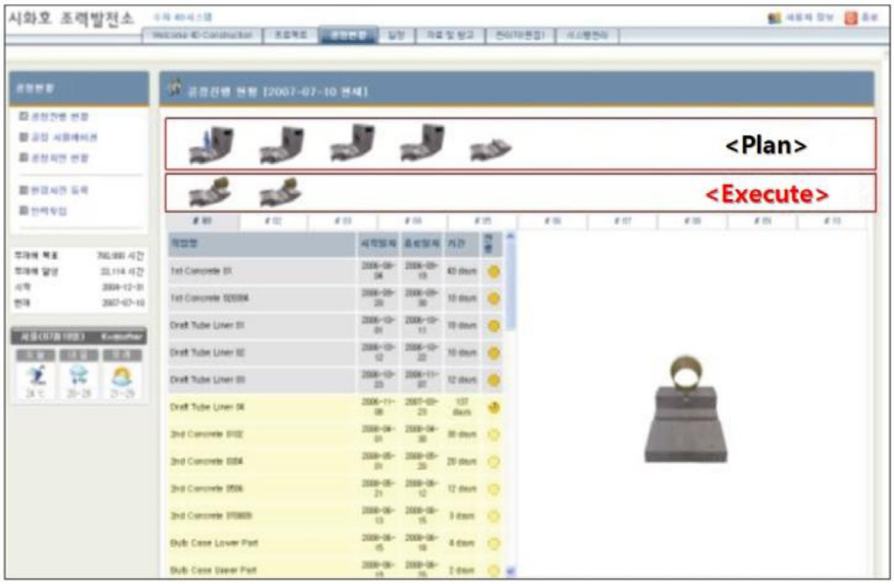


Fig. 17. The process progress screen of 3D modeling.

Fig. 18. Visualize the progress of 3-dimensional process.

consideration of efficiency (Kiho et al., 1996). Unlike hydroelectric power generation, tidal power will be operated in real time in line with tidal changes. That energy is permanently lost, if the generator misses the available time (Batten et al., 2007). Therefore, power generation facilities must utilize fixed time and energy due to tidal changes. It can only produce maximum power generation if it finds the optimal time of development (De Vries and Harink, 2007). Shihwa Tidal Power Plant developed the K-TOP (K-water Tidal Power Operation Program), an optimal tidal power operation program. K-TOP is an optimal tidal power operation program developed based on the operating data and experience of Shihwa tidal power plant operated by K-water. At the time of design, Shihwa Tidal Power Plant lacked technology for tidal power generation, making it difficult to calculate the optimal timing of operation at the operational stage. Therefore, the plant developed K-TOPs with improved functionality through power generation operation data and self-study to improve the inaccuracy of the underlying program provided at the time of design (Cho and Park, 2014).

K-TOP improved the accuracy by improving the volume of Shihwa arc, predictive tides, and calculation time interval according to the time flow of design and operation. In addition, K-TOP applied improvements that were not initially reflected, such as considering drainage characteristics and time spent joining the system. K-TOP used its own VBA-based programming from 2011 to 2015, and in 2016 it took Windows-based Oracle or MS Access DB data to simulate it for general availability. The development environment was centered on MS Visual Studio and designed Architecture using open-source S/W. Customization was configured to be possible for future applications to other domestic and foreign environments and developed in consideration of the transition to the cloud.

The main screen of the program is shown in Fig. 22, and additional functions such as calculating the power generation volume, analyzing the amount of power generation, and monitoring are developed. Tidal analysis can compare the predicted tides with the error rate of the actual tides and the magnitude of the tides. In addition, the analysis system allows research analysis by changing the preference according to various power generation operation conditions through power generation analysis. The tidal wave monitoring function can help calculate power generation by linking with DB depending on the user's environment to know the amount of changes that reflect real-time tidal waves.

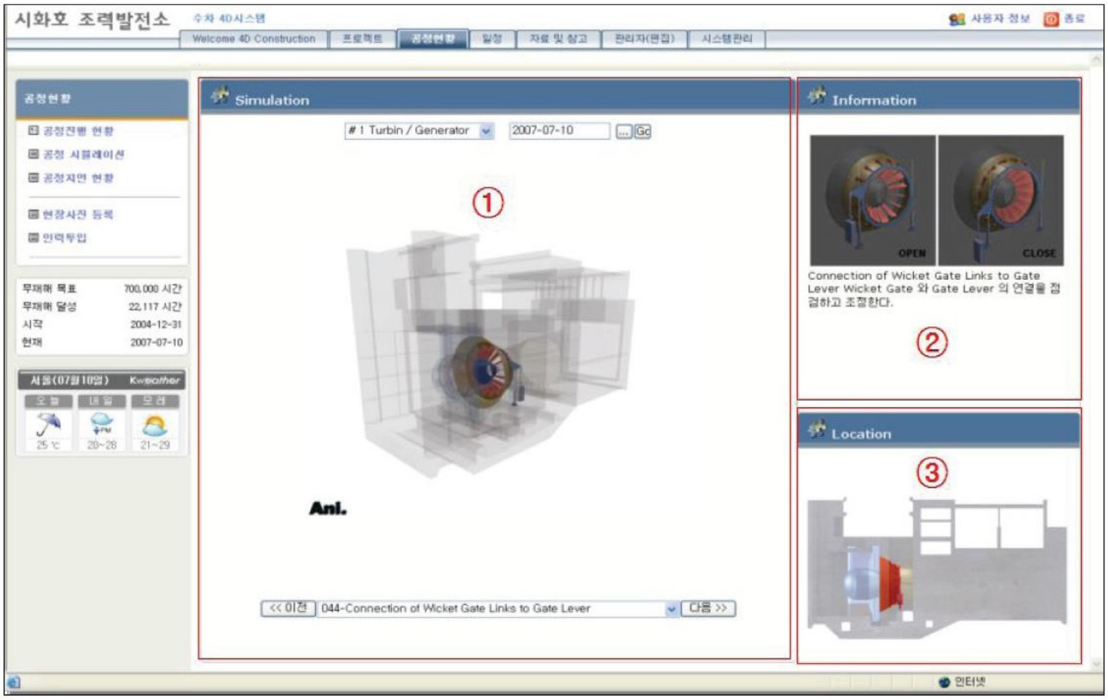


Fig. 19. 4-dimensional simulation system screen configuration.

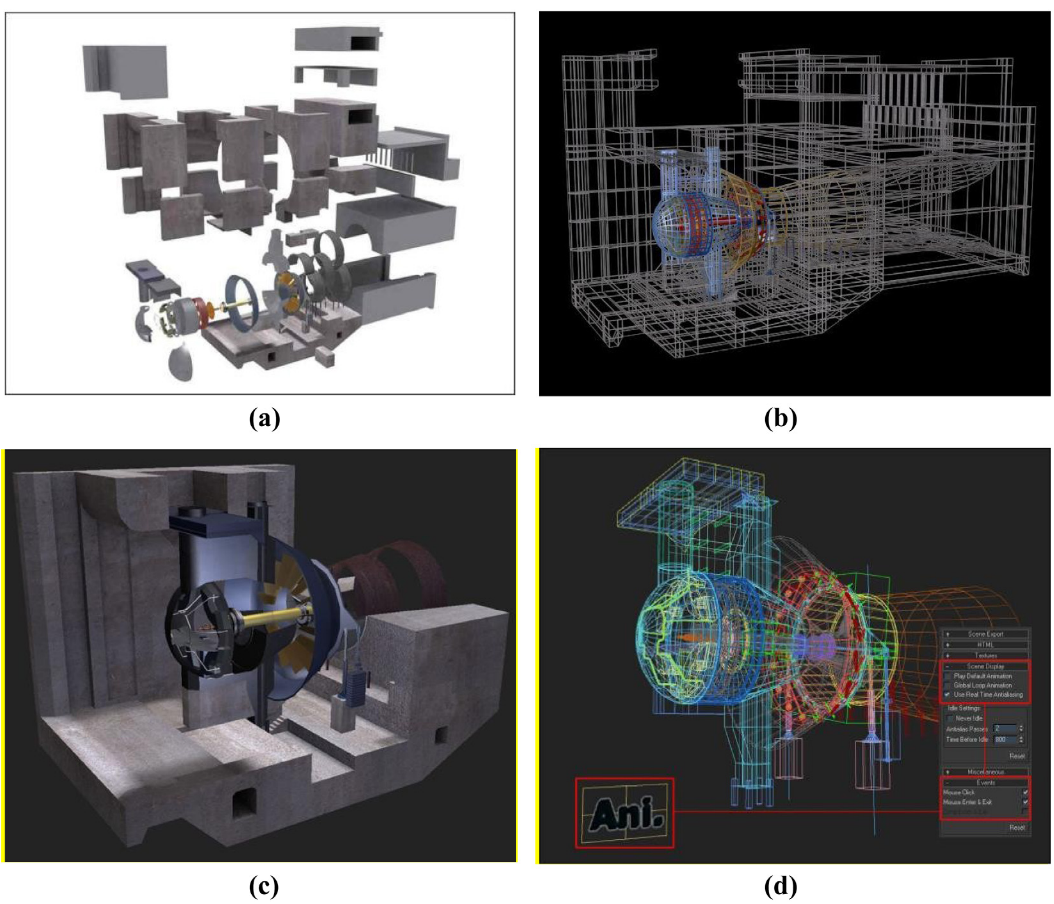


Fig. 20. 3D Model in Shihwa Lake Power Plant. (a) Sequential 3D Model of Lego-style in Shihwa Lake Power Plant; (b) Full-scale modeling of generation systems; (c) Partial modeling of individual generator; (d) Virtual event simulation of specific power generator.

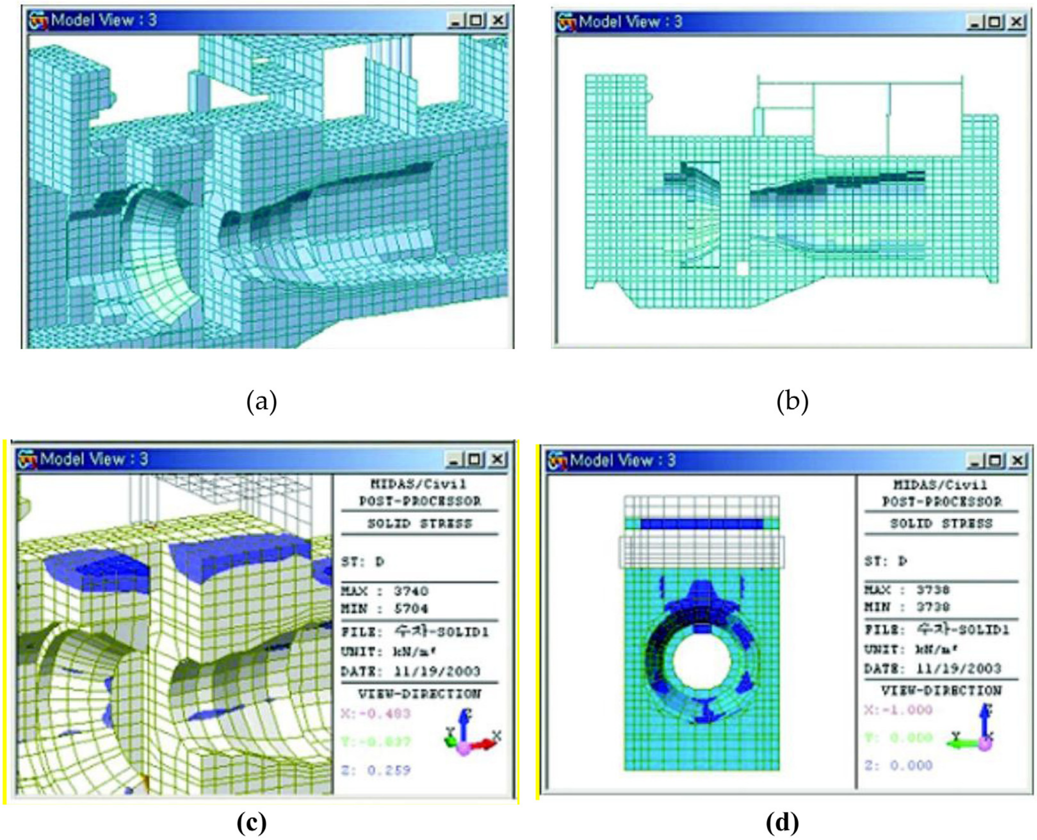


Fig. 21. The 4-dimensional simulation system. (a) Feature of Shihwa tidal power system based on 3D modeling; (b) Cross-sectional Feature of power generation; (c) Detailed simulation of specific power system; (d) Cross-sectional simulation of power generation facilities.

Fig. 22. K-TOP Program Screen for Calculating Power Generation of Shihwa Tidal Power Plant.

5.4. Application of water quality improvement technology

The turbines at the Shihwa Power Plant are gigantic spinning structures that use biodegradable oils as its lubricant and hydraulic fluid. Such types of oil were selected in case of leaks, which would flow into the ocean, but would not affect the environment.

The biodegradable hydraulic fluid would be broken down to CO_2 or H_2O by marine microorganisms, thus reducing the risk of soil or water pollution (Cornett et al., 2013b).

During a tidal generation period at Shihwa plant, approximately 110,000 L of hydraulic pressure oil and 30,000 L of lubricant oil is used. Biodegradable oils far surpass the prices of common mineral oils. However, they are used to accomplish the goal of improving the water quality of the lake, which makes it essential.

5.5. Operation of an advanced maintenance system

The plant is equipped with a state-of-the-art maintenance system, in case any problems arise while the tidal generators are in operation, or during regular maintenance overhauls carried out every five years. The system consists of routine, daily, weekly, monthly, quarterly, yearly, and full checkups, each with its respective equipments and checklists, and is carried out elaborately.

The front and the back of the generator chambers are cut off by stop-logs, and the suspended water is drained out. The maintenance crew enters the chamber through a manhole to carry out their duties (see Fig. 23).

The stop-logs are usually stored separately during regular operation, and they are installed by large gantry cranes when needed, which piles them up from the chamber floor to block the in and out flows of the water. There are leaks, however, the drainage pump is strong enough not to let water interfere with maintenance duties.

The full checkup is also known as an overhaul. It consists of fully dismantling and reassembling the generators, during when worn-out parts or mechanisms are replaced.

For an overhaul, stop-logs are installed to block the water, and the chamber is completely drained, and the maintenance crew enters for an elaborate check on the conditions of the generators. Possible damages due to salts are very closely looked at, because the plant make frequent contact with seawater.

There are ten turbine generators at Shihwa Tidal Power Plant, and the plant stores enough stop-logs for two turbines.

In case of emergency, two stop-logs are stored to cope with problems in the other unit with the floodgates inserted for inspection. Shihwa Tidal Power Plant is a large-scale structure located at sea. There are many parts submerged in the sea, and even if it is exposed, there are many difficulties in maintenance because repair work is not easy. If immediate action is not taken in the event of cracks, exposure to seawater, including salts, can seriously affect rebar. Shihwa Tidal Power Plant contains many of these difficulties, so more careful maintenance and continuous management of repair areas are systematically carried out.

6. Discussion

Operational tidal power plants around the world are located in Rance, France; Annapolis, Nova Scotia, Canada; and Jiangxia, China, etc. The plant at Shihwa Lake generates approximately 552 million kWh per annum, far surpassing the one in Rance, making it the largest capacity tidal power plant.

There are many places around the world exhibiting large tidal ranges, including the English Channel, the North and the South America, China, Russia, and Korea's West coast (Incheon Bay, Asan Bay, Garorim Bay, Cheonsu Bay, etc.). Korea inclusive, countries with tidal power capabilities, especially the US, Australia, and India, etc., are currently undertaking their respective tidal power projects.

Building tidal power infrastructures in these locations will allow a potential generation of 1 billion kW per annum, which is four times the conventional hydro power generation, making it the possible future alternative energy in case fossil fuel runs out.

Moreover, compared to other types of new renewable energy, tidal power generation allows accurate predictions and effective production. Solar or wind power generation, as a rule, are impossible to generate when their sources are absent; however, electrical generation through tidal power is possible two times per day, at predictable times, it allows a stable, and a semi-permanent production of energy.

As such, the Shihwa plant will be able to provide approximately 254,000 KW of electricity to 500,000 households annually, using eco-friendly and clean resources. This much electricity, if produced with fossil fuels, would require 862,000 barrels of oil equivalent to 80 billion KRW spent in importing them. Thus, making the tidal plant an ideal substitute. Also, by not using fossil fuels in the power production process, the plant has the potential to reduce 315,000 metric tons of CO_2 per annum. This is equivalent to the amount of air 60 million pine trees purify.

Such green potential of the plant was recognized in 2006, by the UN's CDM (Clean Development Mechanism) project, approving the plant to join them. Moreover, the reduction of 315,000 metric tons of CO_2 would bring about 8 billion KRW in revenues, with respect to CERs (Certified Emissions Reductions). This indicates that the Shihwa Tidal Power Plant was built based on the CDM project, and is recognized by the global community that it is a facility which would dramatically decrease CO_2, the main culprit behind global warming. The significance of the Shihwa project, which was founded on the UN's CDM project, is that it has gained CER and actively satisfies not only the Korean government's policies on expanding alternative energy resources, but also the Kyoto Agreement.

7. Conclusion

The Shihwa Tidal Power Plant is an eco-friendly infrastructure that rebirthed 'the dead lake', which had suffered extreme water pollution due to cutoff in seawater circulation after the completion of the tide embankment in 1994. Moreover, through the construction of the power plant, which is a development foreseeing a future short of conventional energy, we are able to bring about the substitution effect for oil import and improvement in energy self-sufficiency. It has opened the way to enter the eco-friendly energy market for local electricity stability.

In 230 countries worldwide, there are only about ten countries that have the natural conditions allowing tidal power generation. The first and foremost condition of tidal power generation is to have locations with large tidal ranges, and only a few countries have them. The largest range in the world is currently exhibited at 15 m; on the West coast of the Korean peninsula, the largest is 10 m. Thus, it can be said that Korea possesses one of the most efficient tidal power generation, and therefore making tidal power the most favorable clean energy source.

Korea's current tidal resource potential ranges from 4.05 million to 5.09 million KW, and it takes up about 7.4% of the entire energy production pie. This sheds light on tidal power generation as the new source of energy.

Also, geographically speaking, the Korean peninsula is estimated to have been endowed with 14 million kW of marine energy, making it one of the rarest and ideal place on Earth for tidal power generation. Moreover, the shores of the West Sea and the South Sea not only store immense amount of marine energy, but are also the new marketable future energy foundations, where various added value resources such as new ecosystem developments, tourist attraction establishments, or scientific researches.

Globally, international demand for renewable energy development, which can replace fossil fuels, is becoming a reality to minimize climate change due to greenhouse gas reduction. Therefore, it is time to diversify energy sources and research efforts of various methods for exporting power generation facilities are needed more than ever. The world's tidal power installation capacity is 3000 G, but it is estimated that 1000 GW is economically viable. The tidal power service market in France, Canada, China, Russia, and South Korea, which is in operation, amounts to about KRW 113.5 billion annually, and has formed a market worth about KRW 750 billion since 2020.

South Korea will pursue R&D projects to secure its own foundation for industrialization of marine energy, but there are still

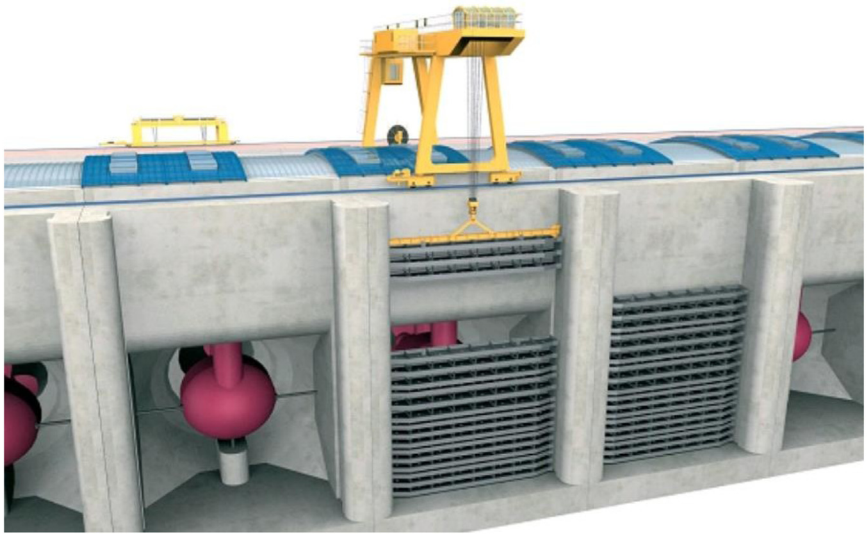


Fig. 23. Stop-log installation for the check-ups.

technical challenges to be solved in commercial use of marine energy. Developed countries, including Britain, are actively developing technologies to dominate the market. Korea has also been pushing for a national maritime energy R&D roadmap since 2009 and various policies to transform the industry into a low-carbon economic society capable of energy independence and climate change. By 2030, the Korean government has come up with a plan to supply 11 percent of its total energy consumption with renewable energy and an investment plan. Korea has long-term goals of developing and disseminating 255 MW by 2010 and 1948 MW by 2020 and 3228 MW by 2030 to expand the supply of marine energy. It is strengthening R&D by marine energy sources such as tidal power, algae, wave power, and sea temperature differences, and is pushing for the practicalization of key element technologies. In this sense, this research information could be a motivation for tidal power technology in countries with similar topographical conditions based on future energy. Already, operation of the world's largest Shihwa Tidal Power is being monitored for future expansion of markets.

In terms of technology, Shihwa Tidal Power Plant has operated a 4D simulation system to effectively operate construction work. The 4D simulation system was able to efficiently manage the entire construction of power generation facilities, identify planning process information, or smoothly adjust the schedule of subsequent construction processes. The 4D simulation have been utilized very effectively, among other things, for large-scale facility construction, facilitating the identification of process errors or interference checks.

In addition, tidal power has a highly sensitive structure to seawater penetration in terms of sustainable operation and maintenance. In the case of turbine structures, continuous monitoring and management are required because power generation facilities are feared to be flooded in the event of seawater infiltration through new joints and cracks. As a technology for this purpose, Sihhwa Tidal Power Plant deploys two stop logs to accurately check the condition of the generator through an itemized checklist. This is an effective manual for sustainable maintenance considering the nature of tidal power.

The Shihwa plant boasts an infinite amount of value as a tourist attraction. It is projected to make a tourism belt that includes the nearby Daebu-do (Daebu island), already renowned for its beautiful land and seascapes.

To make such things possible, the tidal plant and its partners had also built an eco-friendly marine park called T-light Park, using the soil and sand from the dismantled cofferdams. The name, 'T-Light' was coined to symbolize the 'light' made by the 'Tide', raising awareness of the importance of the circulation of new renewable energy and the tides of the West Sea.

For the development of the surrounding area, the Korean government plans to invest 3.8 trillion won by utilizing abundant renewable energy sources and marine ecological leisure facilities in tidal power plants. It is a green complex in the west sea that is linked to Songsan Green City, Shihwa Multi-Techno Valley, e-Science Park, Marine Complex, Marina Facilities, and Gyeonggi International Boat Show, where Universal Studios will be located.

In the future, tidal power projects need to develop and accumulate coastal structure design and construction technology, corrosion prevention technology by seawater, sea-water flow numerical models suitable for the local environment, water quality changes in lakes, eco-system changes, and environmental impact assessments.

The methodology of this paper focused on the environment and sustainability of energy installations through case analysis. Overall, technology was presented to design the methodology in accordance with Korea's limited environment. Few countries in the world have geographical conditions optimized for tidal power such as Korea's west coast. This could be a limitation as a global technology. However, I hope this paper will contribute to the development of new opportunities and technologies for the development of eco-friendly energy and sustainable environment. However, this paper will contribute to the creation of new opportunities and technological development for the development of eco-friendly energy and sustainable environment.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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