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Application of tidal energy for purification in fresh water lake

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ABSTRACT: *In order to preserve the quality of fresh water in the artificial lake after the reclamation of an intertidal flat at the mouth of a river, we suggest two novel methods of water purification by using tidal potential energy and an enclosed permeable embankment called an utsuro (Akai et al., 1990) in the reclaimed region. One method uses an inflatable bag on the seabed within an utsuro, while the other uses a moored floating barge out of a dyke. Each case employs a subsea pipe to allow flow between the inside and outside of the utsuro. The change in water level in the utsuro, which is pushed through the pipe by the potential energy outside, caused circulation in the artificial lake. In this paper, we analyzed the inflatable bag and floating barge motion as well as the pipe flow characteristics and drafts as given by a harmonic sea level, and compared the theoretical value with an experimental value with a simple small model basin. The numerical calculation based on theory showed good agreement with experimental values.*

***KEY WORDS*:** Water purification; Reclamation; Inflatable bag; Floating barge; Utsuro.

INTRODUCTION

Reclamation of land from the sea at a river mouth is an important issue to secure farmland and to expand valuable economic zones. In order to sustain the area to be utilized, costal environmental issues such as water purification and circulation, sluice gate control and environmentally-friendly engineering solutions should be carefully addressed. However, these issues are not well addressed in many cases in the world.

After the construction of a dyke in Isahaya Bay in Japan, the water quality did not achieve the marine environmental target value (Yokoyama et al., 2003). Haringvliet dam with sluice gates in the Netherlands was intended to shut off incoming seawater, but the water quality inside was worse than before due to lack of water circulation (Stuyfzand et al., 2004). The Tuckombil waterway in Australia has deteriorated rapidly since a water gate was constructed for flood protection (Richmond River County Council, 2007). Further, Shihwa lake in Korea was planned for agricultural water use, however, an industrial zone was constructed in the vicinity of the estuary before the wastewater treatment plants, which control pollutants, was built, so that the fresh water process accelerates the salinity gradient in the water column and results in a low oxygen layer on the bottom of the water (Park et al., 1997). In the case of Semangeum, the sluice gate opening caused benthic organisms to develop around the gates and reduced coastal circulation as well (Suh et al., 2006).

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Nature-friendly reclamation should be accompanied by water quality management. The prevention and/or reduction of water pollution and eutrophication due to contamination by large pollutant effluent from the land should consider the surrounding marine environmental situation. As a self-purification system, a rockfill-type enclosed embankment in the dyke can be introduced. This rubble seawall, dubbed an "utsuro" (Akai et al., 1990), functions like a rubble mound breakwater introduced by Palmer et al. in 1998 to protect a coastal area from excessive waves. The Japanese word utsuro means a calm space enclosed by permeable embankment, and it is known that the water is purified after passing through the utsuro. An additional part is a system to generate water current across the dyke using tidal potential energy. Consideration of water level management is important because the water level pattern in the reclamation area is dramatically changed from running water before the dyke to stagnant water after dyke construction. Therefore, the water current in the lake is significantly reduced. This can result in degradation of water quality, since nutrient concentration in stagnant water is largely determined by external pollution such as supply via streams, rivers, and wastewater discharge. Heretofore, several researchers have studied the function of the "utsuro at sea" from physical (Akai et al., 1993), ecological (Otsuka et al., 1996), and experimental viewpoints since Akai's initial research in 1981.

In 2001, the first utsuro was constructed in the estuary of Kinokawa in Japan to improve the water quality in the region. The area of the utsuro is about 30,000 m^2, and the tidal height is about 1.5 *m*, so that the capability of purification will be approximately 90,000 *tons* per day. As for the bio-function of the utsuro, the surface of the rock in the rockfill embankments serves as a bio-film, in which many marine microbes live. Oxidation of organic matter and decomposition of the nitrogen and phosphorus containing compounds occur at the surface due to biological processes. Ocean benthos and seaweeds take part in the food chain so that the rock filter effect shows not only lower Chemical Oxygen Demand (COD) and higher Dissolved Oxygen (DO) but also more photosynthesis. For example, the quality of the water is improved with respect to several parameters, namely, 0.56 *mg/l* to 0.2 *mg/l* for turbidity, 4.64 *mg/l* to 3.7 *mg/l* for COD, and 6.06 *mg/l* to 4.61 *mg/l* for Suspended Solid (SS) as measured by Akai et al. (1990) in and out of the utsuro, respectively. Also, after installation of an utsuro downstream of the Yellow River in China, SS and turbidity values improved tremendously (Akai, 2008).

An option we suggest in this paper is to use the potential energy to circulate the water tidal differences outside the dyke. A connecting pipe is used for the connection between the inside of the utsuro and outside of the dyke in order to transfer the potential energy. There are two possibilities employing a pipe connection device at the both ends. First, an inflatable bag is placed inside the utsuro with an outside opening. A second option is an inside opening accompanied by a floating barge outside, which elevates due to the tide. Two kinds of tidal energy transfer systems to be used during the reclamation process are first introduced. Then, utilization of an utsuro in a fresh water lake is discussed, where an innovative idea is required to use tidal energy. We developed theories to analyze the systems and conducted numerical simulations. The results seem to accurately explain the performance of these systems.

REPRESENTATIVE RECLAMATIONS IN JAPAN AND KOREA

Isahaya reclamation

Seventeen years have passed since 1997 when Isahaya Bay in the Ariake Sea, Japan was separated from the sea with a dyke about 7 *km* length. The planed area of reclamation was about 9.42 km^2. During the reclamation period, environmental changes have occurred in this area causing a red tide that led to a decrease in fish and marine products and a decline in the seaweed harvest. In 2002, the government changed the Isahaya Bay Project to reduce the reclamation area by half and to conduct more marine environmental assessments. The scientific field data show that most water contamination parameters such as COD and TP (total phosphorous) grew worse after closing the dyke. Annual mean COD concentration in the Isahaya Bay changed from 2.2 *mg/l* in 1987 to 7.7 *mg/l* in 2000, while TP changed from 0.067 *mg/l* to 0.234 *mg/l* (Teiichi, 2001). Thus, the government decided in 2010 to open the sluice gates at the end of December 2013 to see whether it would affect the environment in the Ariake sea or not.

Fig. 1 Isahaya bay located in Nagasaki prefecture, southwest Japan (scale: 5 *km*, photo by Google).

Lesson from shihwa lake

Lake Shihwa is an artificial lake located on the west coast of the Republic of Korea. The construction of the breakwater, with a length of 12.6 *km*, was completed in 1994. The Korean government plan aimed at creating 133.7 km^2 of reclaimed land and 42.3 km^2 of a freshwater lake to be used for irrigation purposes. When the freshwater lake was closed off, they began to build two industrial complexes and a new city in the northern part of the lake. Due to insufficient water supply to the lake, a lack of wastewater treatment capacity, and the increasing pollution load, the brackish lake suffered from severe eutrophication, resulting in 17.4 *mg/l* of annual mean COD in 1997. Finally, late in 2000, Lake Shihwa was changed to a seawater lake rather than a fresh water resource for farmland by the government. Instead, a tidal power station has been discussed as one action plan in a Shihwa Integrated Management Plan (2001 to 2016) under the Ministry of Oceans and Fisheries. As the world's largest tidal power installation, it has been operated by the Korean Water Resource Corporation since 2011. Annual mean COD concentration of lake Shihwa decreased to 3.3 *mg/l* with a TP of 0.065 *mg/l* in 2012 (Korean Government Report by Ministry of Land, Transport and Maritime Affairs, Korea 2012). Sewage treatment facilities have been constructed and the water exchange in the lake improved via operation of a barrage sluice gate as well.

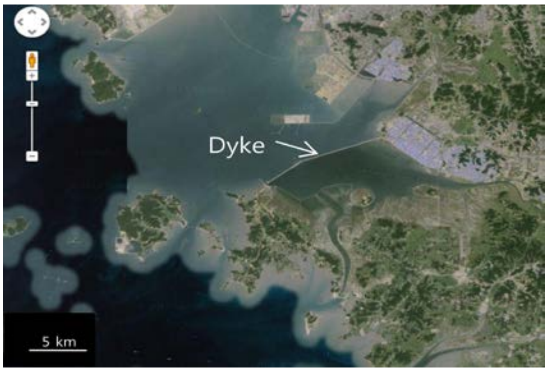


Fig. 2 Lake Shihwa located in western South Korea (scale: 5 *km*, photo by Google).

Saemangeum reclamation

Saemangeum reclamation is the world's largest coastal reclamation, which involves a 33 *km* long seawall, reclaimed land with an area of 283 km^2, and a freshwater lake with an area 118 km^2. It is located near the estuary of the Mankyong and Dongjin rivers. As completion in 2006, there are two sluice gates, which consist of 8 Garyeok flaps (287.5 *m*) and 10 Shinsi flaps (368.5 *m*). The flow rate is about 7,000 *tons* and 8,800 *tons* per second for each gate. One way-pipes were added under the gates in order to cope with an accumulation of saline water on the seabed inside of the estuary reservoir.

As part of an effort for increasing environmental quality and encouraging environmentally-friendly development, the Saemangeum project should be carried out with careful consideration of the water quality and water level management (Choi et al., 2013). During the construction in 2012, annual COD and TP variations were very large: COD varied from 0.6 *mg/l* to 15.4 *mg/l*, and TP varied from 0.030 *mg/l* to 0.409 *mg/l* at the center of the lake. The fresh water becomes increasing after construction of the inner dyke step by step and decreasing the salinity concentration (Korea Rural Community Corporation, 2012).

TWO NOVEL PURIFICATION SYSTEM USING TIDAL ENERGY

We propose two types of new engineering purification systems for water in the reclamation area. In both, tidal potential energy is utilized in order to force water circulation in the region. These two methods may reduce the stagnant places in the reclamation area.

Fig. 3 Saemangeum reclamation located in western South Korea (Scale: 5 *km*, photo by Google).

Purification method using inflatable bag in utsuro

The first suggested system consists of an impermeable submerged inflatable bag located at the bottom of the utsuro, as shown in Fig. 4(a). A pipe connects the sea to the bag. Tide flows into the pipe, and the bag is swelled by sea water at high tide. As the level of water in the utsuro increases, the water level inside the utsuro becomes higher than the water level outside. This causes the flow outward through the embankment of the utsuro (and vice versa) over the course of two tides per day. Sea water and fresh water remain separated because the inflatable bag swells up and down via the incoming and outgoing sea water in the pipe, that is, the sea water passes two ways in it. “F” and “S” refer to fresh water and salt water, respectively. Figs. 4(b), (c) and (d) show the managed water level W.L. is 0, positive, and negative, respectively according to the tide. Higher tidal difference results in larger flow exchange through the rubble so that we may expect good purification by an utsuro placed inside lake.

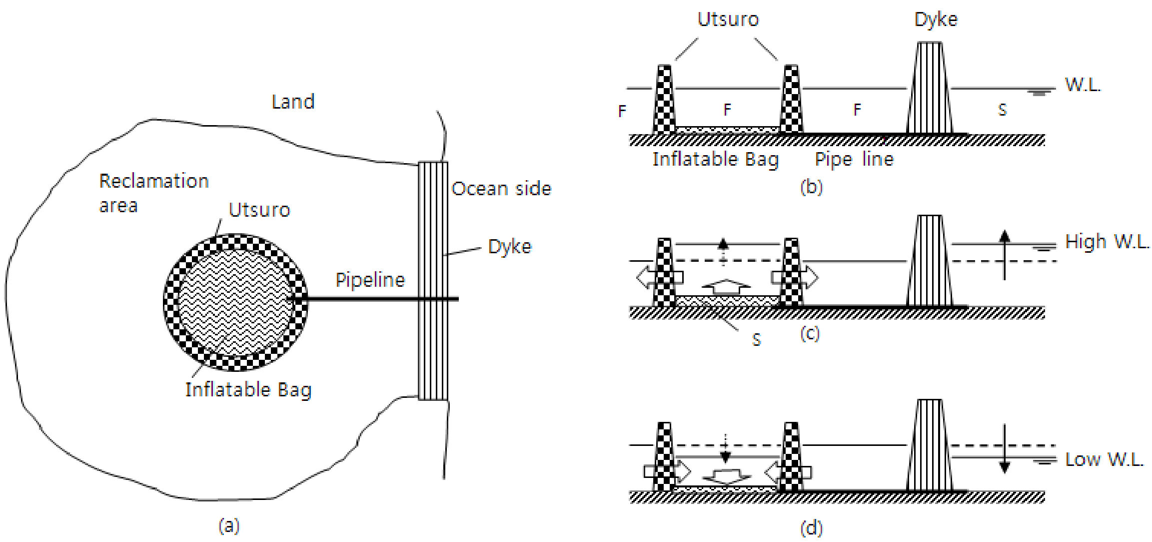


Fig. 4 A schematic view of a suggested system using inflatable bag in an utsuro (F: fresh water, S: sea water).

Purification method using floating body out of dyke

A second suggestion to use the tidal difference is shown in Fig. 5(a), which provides a plan view of the system. In this option, we place a float at sea connected to the utsuro in the lake with a pipe. There is no inflatable bag here, as was suggested in the previous section. So, we may be concerned that the level of the surface in the utsuro and that in the float would be equal, as in Fig. 5(b). Furthermore, the level of the surface inside and outside the utsuro would also be equal in Figs. 5(c) and 5(d). Once the float goes up due to the tide, the water flows from the float to the utsuro via the pipe because the water level inside the float tends to equal the level in the utsuro. The transferred water within the utsuro moves toward the outside of the utsuro through the embankment of the utsuro, as shown in Fig. 5(c). When the float goes down, the water flows from the utsuro to the float, and the water outside the utsuro moves inside the utsuro through the embankment, as shown in Fig. 5(d). The water having with potential energy in the pipe transfers two ways between the float and the utsuro.

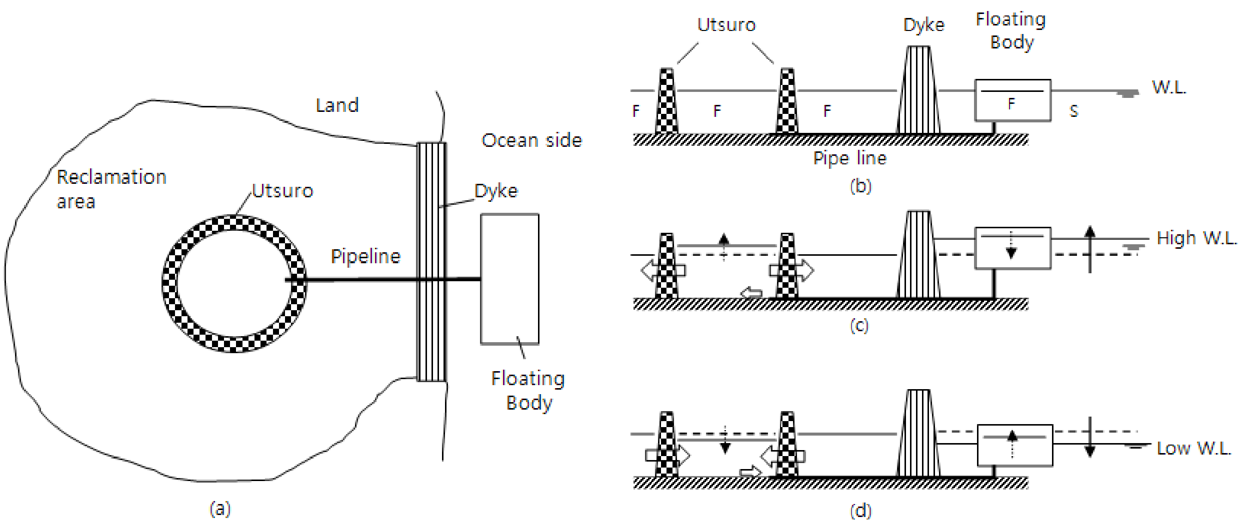


Fig. 5 A schematic view of a suggested system using a floating body out of the dyke (F: fresh water, S: sea water).

NUMERICAL SIMULATIONS

Purification method by inflatable bag in utsuro

In the following, an example of water flow between utsuro in a fresh water lake and the sea is discussed. A suggested system using an inflatable bag is shown in Fig. 6. Let D_0 and D_1 be the water depth in the lake and sea, respectively.

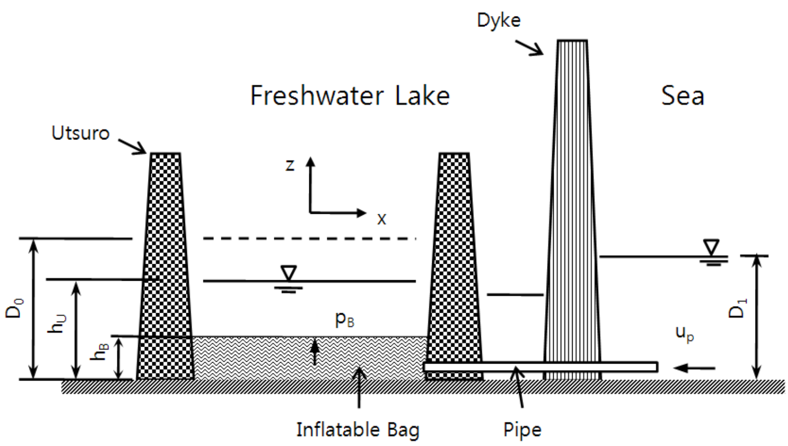


Fig. 6 A proposed system using an inflatable bag.

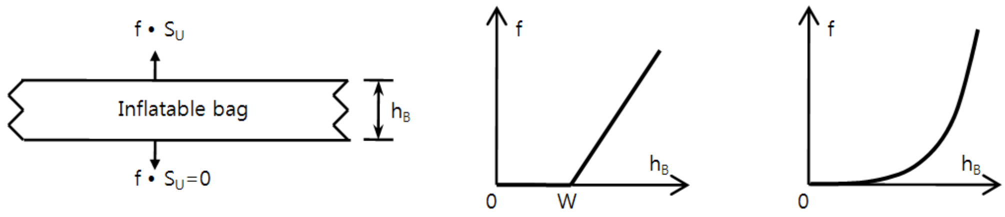
D_1 is given by the tide as:

$$D_1 = D_m + A\sin\left(\frac{2\pi}{T}t\right) \tag{1}$$

where D_m, A, T and t are the mean depth of the water at sea, amplitude of the tide, period of the tide, and time, respectively. The pressure p_B at the upper surface of the inflatable bag is given by:

$$p_B = \rho_F g(h_U - h_B) + f(h_B) \tag{2}$$

where g, ρ_F, h_U, h_B, and f are the gravitational acceleration, density of fresh water, height of the water surface in the utsuro, expansion height of the inflatable bag, and restoring force of inflatable bag, respectively. The restoring force f consists of k and a coefficient χ, which is a function of the expansion depth h_B of the inflatable bag, as illustrated in Fig. 7.

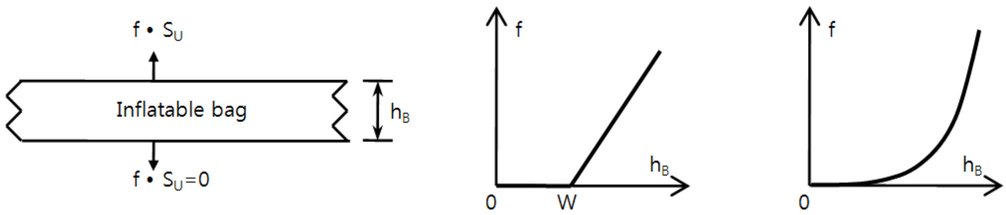


(a) (b) (c)

Fig. 7 (a) Model of inflatable bag, (b) and (c) mechanical properties of inflatable bag.

The restoring force f on the upper part (moving part) of the inflatable bag may be given, for example, by:

$$f(h_B) = \begin{cases} 0 & \text{when } h_B < W \\ k(h_B - W) & \text{otherwise} \end{cases} \quad \text{or} \quad f(h_B) = kh_B^{\chi} \tag{3a,b}$$



(a) (b) (c)

Fig. 7 (a) Model of inflatable bag, (b) and (c) mechanical properties of inflatable bag.

When $\rho_S g D_1 > \left[\rho_F g(h_U - h_B) + f\right] + \rho_F g h_B$, we obtain, by applying Bernoulli's equation,

$$\frac{1}{2}\rho_S u_p^2 + \left[\rho_F g(h_U - h_B) + f\right] + \rho_F g h_B + \frac{1}{2}\rho_S \mu u_p^2 = \rho_S g D_1 \tag{4}$$

where μ, ρ_S, and u_p are the frictional coefficient of pipe flow, density of fresh water, and flow velocity in the connecting pipe, respectively. From Eq. (4), u_p is obtained as:

$$u_p = \sqrt{\frac{2g}{1+\mu}\left(D_1 - \frac{\rho_F}{\rho_S}h_U - \frac{f}{\rho_S g}\right)} \tag{5}$$

when $\rho_S g D_1 < \left[\rho_F g(h_U - h_B) + f\right] + \rho_S g h_B$, we have

$$\left[\rho_F g(h_U - h_B) + f\right] + \rho_F g h_B = \frac{1}{2}\rho_S u_p^2 + \rho_S g D_1 + \frac{1}{2}\rho_S \mu u_p^2 \tag{6}$$

and

$$u_p = -\sqrt{\frac{2g}{1+\mu}\left(-D_1 + \frac{\rho_F}{\rho_S}h_U + \frac{f}{\rho_S g}\right)}. \tag{7}$$

Hence, the governing equations are given by:

$$u_p = \mathrm{sgn}\left(D_1 - \frac{\rho_F}{\rho_S}h_U - \frac{f(h_B)}{\rho_S g}\right)\sqrt{\frac{2g}{1+\mu}\left|D_1 - \frac{\rho_F}{\rho_S}h_U - \frac{f(h_B)}{\rho_S g}\right|} \tag{8}$$

$$S_U\frac{dh_U}{dt} = u_p S_P - \alpha\,\mathrm{sgn}(h_U - D_0)\sqrt{g\,|h_U - D_0|}\,l_U\begin{cases} h_U - h_B & \text{when } h_U \ge D_0 \\ D_0 - h_B & \text{when } h_U < D_0 \end{cases} \tag{9}$$

$$S_U\frac{dh_B}{dt} = u_p S_P \tag{10}$$

where ρ_S, S_U, S_P, l_U, and α are the density of sea water, water surface area of the utsuro, cross sectional area of the connecting pipe, circumferential length of S_U and permeability coefficient of the utsuro, respectively. Eqs. (9) and (10) are the mass balance of the utsuro and that of the inflatable bag, respectively.

Substituting $u_p = u_p(h_U, h_B, D_1(t))$ into Eqs. (9) and (10), we obtain ordinary differential equations for h_U and h_B. The unknowns h_U and h_B are obtained numerically by a Runge-Kutta method. Eq. (3b) is used for the restoring force f.

A numerical calculation was conducted. The parameters used in the calculation are shown in Table 1, and the results are shown in Fig. 8. A slightly smaller change in the water level than that of the sea surface took place in the utsuro and a small phase difference occurred because of the friction in the flow in the connecting pipe.

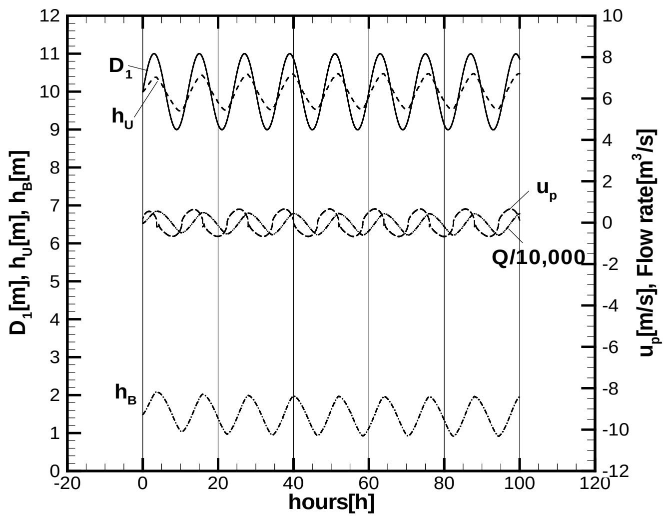


Fig. 8 Motion of water in utsuro including height of sea surface D_1, water height in utsuro, h_U, height of bag h_B, flow velocity in pipe u_p, and volume of outflow from float *Q/10,000*.

Table 1 Parameters used in a numerical example of an inflatable bag.

Item	Value	Item	Value	Item	Value
g	9.8 m/s^2	S_U	10,000 m^2	T	12 h
ρ_F	1000 kg/m^3	S_p	1 m^2	χ	3
ρ_S	1040 kg/m^3	D_m	10 m	k	1000 Nm^{-2}
μ	0.2	h_U	10 m	dt	1 s
α	0.000001	h_B	4 m		
D_0	10 m	A	1 m		

Purification method by floating body

In the following, an example of water flow between an utsuro in a fresh water lake and a floating body in the sea is discussed. A suggested system using a floating body is shown in Fig. 9. Let D_0 and D_1 be the water depth in the lake and sea, respectively.

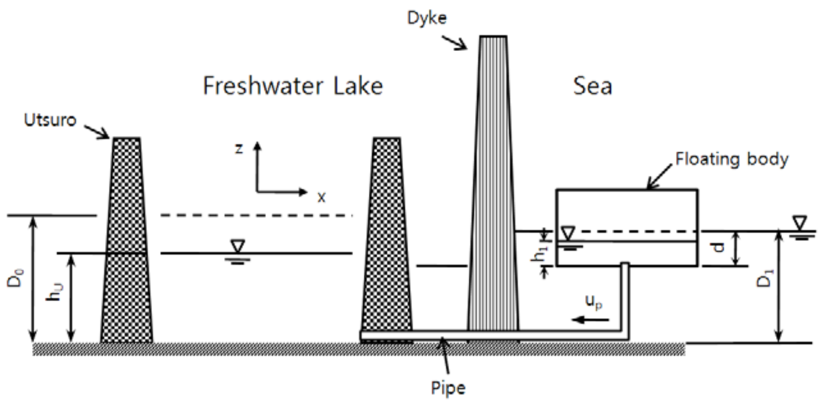


Fig. 9 A proposed system using a floating body.

D_1 is given by the tide:

$$D_1 = D_m + A\sin\left(\frac{2\pi}{T}t\right) \tag{11}$$

where D_m, A, T and t are the mean depth of water at sea, amplitude of the tide, period of the tide and time, respectively.

When $D_1 - d + h_1 > h_U$, we apply Bernoulli's equation to obtain:

$$\frac{1}{2}\rho_F u_p^2 + \rho_F g h_U + \frac{1}{2}\rho_F \mu u_p^2 = \rho_F g(D_1 - d + h_1) \tag{12}$$

where g, ρ_F, μ, u_p, h_U, h_1, and d are the gravitational acceleration, density of fresh water, frictional coefficient of pipe flow, flow velocity in the connecting pipe, water depth in the utsuro, water depth in the float, and draft of the float, respectively. From Eq. (12), u_p is obtained as:

$$u_p = \sqrt{\frac{2g}{1+\mu}\left((D_1 - d + h_1) - h_U\right)} \tag{13}$$

Further, if $D_1 - d + h_1 < h_U$, Eq. (12) is replaced by:

$$\rho_F g h_U = \frac{1}{2}\rho_F u_p^2 + \rho_F g(D_1 - d + h_1) + \frac{1}{2}\rho_F \mu u_p^2 \tag{14}$$

or

$$u_p = -\sqrt{\frac{2g}{1+\mu}\left((D_1 - d + h_1) + h_U\right)}\ . \tag{15}$$

Hence, the governing equations are given by:

$$u_p = \mathrm{sgn}((D_1 - d + h_1) - h_U)\sqrt{\frac{2g}{1+\mu}|(D_1 - d + h_1) - h_U|} \tag{16}$$

$$S_U \frac{dh_U}{dt} = u_p S_P - \alpha\,\mathrm{sgn}(h_U - D_0)\sqrt{g\,|h_U - D_0|}\,l_U \begin{cases} h_U & \text{when } h_U \ge D_0 \\ D_0 & \text{when } h_U < D_0 \end{cases} \tag{17}$$

$$S_1 \frac{dh_1}{dt} = -u_p S_P \tag{18}$$

$$\ddot{d} + \frac{\rho_S g d}{M_1 + \rho_F h_1 S_1}\left(S_1 + b(1 + 0.5\gamma d) l_1\right) = -\left(\frac{2\pi}{T}\right)^2 A \sin\left(\frac{2\pi}{T}t\right) + g \tag{19}$$

where M_1, S_1, $b(1+\gamma d)$, l_1, ρ_S, S_U, S_P, l_U and α are the mass of the float, the surface area of fresh water in the float, the thickness of the wall of the float at draft d, the circumferential length of S_1, the density of sea water, the water surface area of the utsuro, the cross sectional area of the connecting pipe, the circumferential length of S_U, and the permeability coefficient of the utsuro, respectively. Thickness of the bottom plate is assumed to be zero, and S_P is assumed small. The following relation is thus used to obtain Eq. (19):

$$\int_0^d b(1+\gamma z) l_1 dz = b(d + 0.5\gamma d^2) l_1 \tag{20}$$

The equation of motion of the float including cargo water, Eq. (19), is derived in Appendix A. Eqs. (17), (18) and (19) are the mass balance of the utsuro and that of the float, and vertical force equilibrium of the float, respectively. Since, the period T of the tide is very long, the added mass of the float and wave and viscous damping are neglected in Eq. (19).

Substituting $u_p = u_p(h_U, h_1, d)$ into Eqs. (17) and (18), we obtain ordinary differential equations for h_U, h_1, and d. The static draft d_{sta} is a recursive function of h_1 and d_{sta} from Eq. (19), where the dynamic effects are neglected:

$$d_{sta} = \left[\frac{M_1 + \rho_F h_1 S_1}{\rho_S b l_1} - 0.5\gamma d_{sta}^2\right] \Bigg/ \left(1 + \frac{S_1}{b l_1}\right) \tag{21}$$

The static draft d_{sta} is determined by iteration using Eq. (21). The water depth h_U, h_1, and draft d are obtained numerically by a Runge-Kutta method.

The parameters used in the calculation are shown in Table 2, and the results are in Fig. 10. The main parameters such as the water surface area of the utsuro S_U , its permeability α , frictional coefficient of pipe flow μ , and initial height parameters D_m and h_U were the same as the simulation case of the inflatable bag to compare the fluid velocity in the pipe. The calculated h_U values were greater than those of the bag case because the velocity in the pipe was almost two times larger. It was found that h_U shows a small phase difference from D_1, and a $\pi/2$ difference from h_1. The differences resulted in faster pipe flow. It is noted that, as the α value becomes larger, the h_U variation will be small because of the gap size in the rockfill.

Table 2 Parameters used in a numerical example of a floating body.

Item	Value	Item	Value	Item	Value
g	9.8 *m/s*^{2}	S_U	10,000 *m*^{2}	l_1	400 *m*
ρ_F	1000 *kg/m*^{3}	S_p	0.5 *m*^{2}	γ	0 *m*$^{-1}$
ρ_S	1040 *kg/m*^{3}	D_m	10 *m*	dt	1 *s*
μ	0.2	h_U	10 *m*	A	1 *m*
α	0.000001	h_1	5 *m*	T	12 *h*
D_0	10 *m*	M_1	4,000,000 *kg*		
S_1	10,000 *m*^{2}	b	4 *m*		

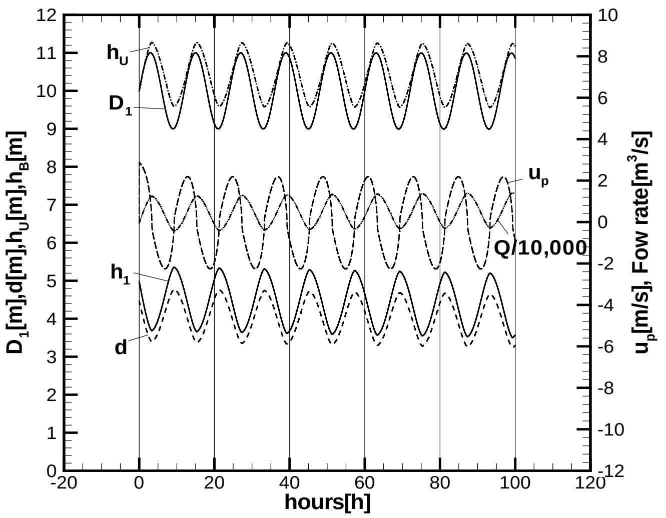


Fig. 10 Motion of water in the utsuro employing a float including height of sea surface D_1, draft of float d, water height in the utsuro h_U, water height in sea h_1, time rate of change of h_1, flow velocity in pipe u_p, and volume of outflow from float $Q/10,000$).

In order to evaluate the permeability α how it works on this simulation, we have been simulated with parameters which are used in the Table 2 with the five cases of α ; 1.0×10^{-6}, 1.0×10^{-5}, 1.0×10^{-4}, 1.0×10^{-3}, and 1.0×10^{-2}. It is noted that the α should be chosen carefully for the design of the usutro's permeability because it is affected in all systems. The simulation results are shown in Fig. 11 by means of a half-amplitude of h_U, u_p, h_1, and d , and it is noted that those values are subtracted by the each mean values(h_U is 10 *m* and h_1 is 5 *m* as input parameters in Table 2). The horizontal α are depicted as a log-scale. The amplitude of water depth of utsuro h_U becomes smaller when α becomes larger. In the bag or the barge system design, the higher h_U is more attractive because it takes place breaking the stationary water around the utsuro outside. According to the α variation, u_p has a range between 2.3 *m/s* to 4.0 *m/s*. The amplitude of the floating barge draft d and water draft in the barge h_1 have two times larger than those that are small α . The amplitude of h_1 is always larger than d , and those gaps are about 0.25 *m* in the simulation.

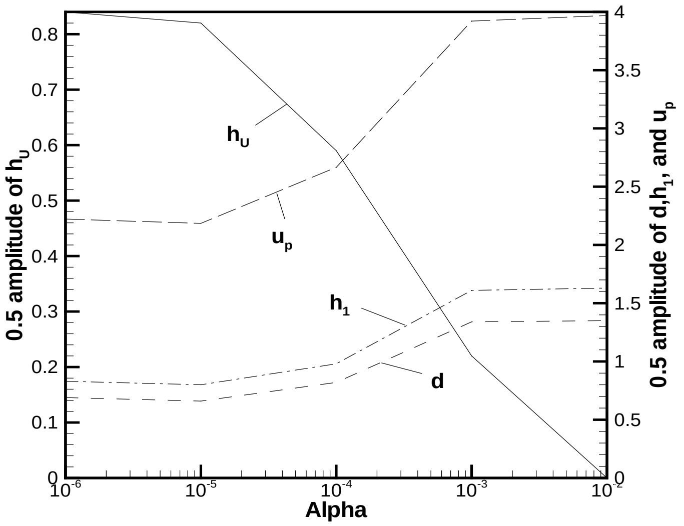


Fig. 11 Half-amplitude of useful design parameters vs. permeability parameter α .

Verification of theory with experiments

Since Eqs. (8) and (16) are the keys to the theory, we conducted experiments to verify the appropriateness of these equations. The main objectives for this experiment were to measure the level h_1 of the water coming through the hole at the bottom of a model with increasing time. Then, the velocity u_p given by Eqs. (8) and (16) can be estimated experimentally. This test is considered to understand the increase in water level when the barge is installed at a certain draft.

A simplified experimental setup is shown in Fig. 12 and consists of a 0.5 *m* × 0.5 *m* square fresh water tank and a 0.3 *m* × 0.3 *m* square acrylic model box in it with draft, d, and a box thickness of 0.3 *cm*. A small hole on the bottom of the box was closed until the start of the experiments (h_1 =0 at start). A thin distributor was set just above the hole to make the water level stable. A heavy plate placed on the top of the water tank kept the draft constant. In order to keep the draft constant during experiments, water was supplied from a nozzle located on the right side of the tank and the flow was controlled manually by a valve. The change of the level h_1 with time was measured using a CCD camera set in the front of the experimental apparatus.

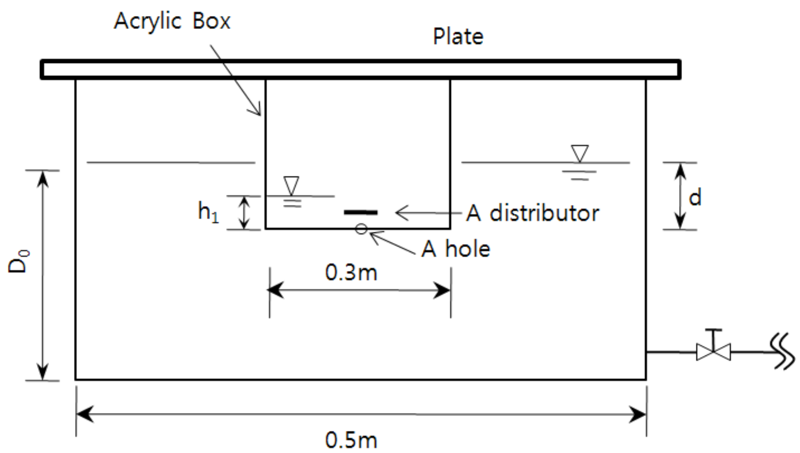


Fig. 12 Experimental apparatus to measure u_p of water flowing through a bottom hole.

The experiments were carried out for four draft cases: d=18 *cm*, 14 *cm*, 10 *cm*, and 6 *cm*. In order to compare the results from experiments with those by theory, we prepared parameters for the comparisons. Table 3 shows parameters for the numerical calculations. Descriptions of each of these items are the same as in Sections 4.1 and 4.2.

Table 3 Parameters used in a numerical calculation for the comparison with experiments.

Item	Value	Item	Value	Item	Value
g	9.8 m/s^2	S_p	0.000003 m^2	b	0.003 m
ρ_F	1000 kg/m^3	D_0	0.7 m	l_1	1.2 m
μ	0.2	h_1	0 m	γ	0 m^{-1}
S_1	0.09 m^2	dt	1.0 s		

h_1 can be simulated from its initial value of 0 using the relation of Eq. (25) by applying Bernoulli's equation as $h_1 < d$. D_0 and d are now constant.

$$u_p = \text{sgn}(h_1 - d)\sqrt{\frac{2g}{1+\mu}|h_1 - d|} \quad \text{and} \quad S_1 \frac{dh_1}{dt} = -u_p S_P \tag{25}$$

Fig. 13 shows comparisons of h_1 obtained by experiment and simulation for the four drafts. All four cases give good agreement on the h_1 trends and the final draft between the experiments and simulations. In addition, in order to confirm the relationship between the flow velocity u_p and square root of the water surface position difference $\sqrt{(d-h_1)}$ in Fig. 14, it shows that all four cases have gradients of $-\sqrt{2g/(1+\mu)}$ when μ is 0.2. However, the experimental values at the early stage of the experiments where $\sqrt{(d-h_1)}$, largely deviate from the abovementioned trend because the flow coming through the hole is rather violent.

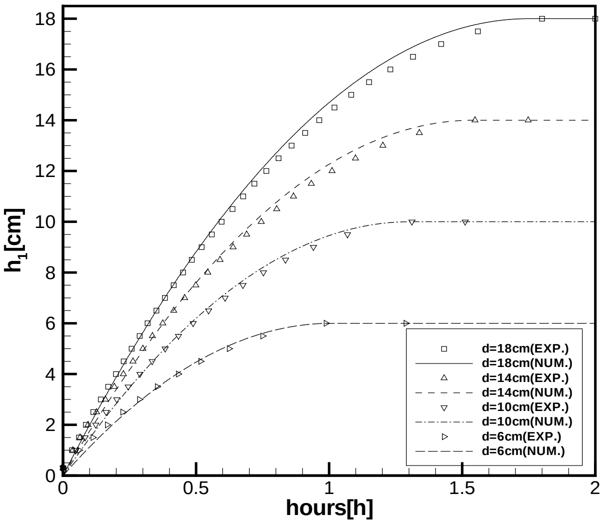


Fig. 13 Water level of four given drafts with advancing time.

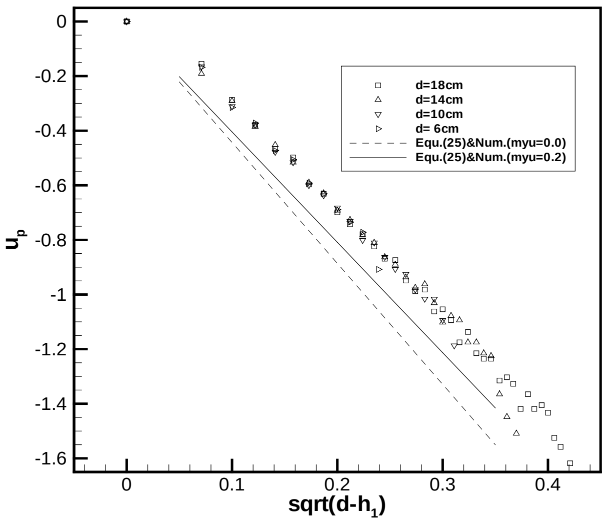


Fig. 14 Water level rising velocity u_p with respect to $\sqrt{(d-h_1)}$.

CONCLUDING REMARKS

To expand the utilization of coastal areas at river mouths, many nations have conducted reclamation projects to provide environmental protection. Water purification is the most important issue for the reclamation. We focused on reducing the pollution of a freshwater lake after closing the breakwater at the region of a large tidal current during the process of the reclamation. The potential energy of the tidal differences could be used to make an internal circulation of water in the region because the stationary water causes environmental problems. The energy transfers through a connecting pipe between the inside and outside of the breakwater.

We suggest two new types of purification systems. One uses an inflatable bag on the seabed within the utsuro. The seawater is charged into an impermeable bag and discharged from the bag through the connecting pipe using the reciprocal motion due to the tidal difference. The water level on the bag in the utsuro changes, and the water passes through the utsuro. Finally, the up-down water level at the utsuro boundary prevents the stagnation of water in the reclamation area. The other type uses a floating body in the sea out of breakwater. Due to the hydrodynamic effect, a flow is generated through the pipe connecting the inside of the utsuro and the floating body. The final object is the same as the impermeable bag case.

A theory using Bernoulli's equation was developed based on the two suggested ideas for estimating the performance of a system. For simulation of the inflatable bag case, we modeled the restoring effect for the bag in the equation to estimate the velocity in the pipe, and the mass balance for height of the water surface in the utsuro (h_U) and expansion height of the inflatable bag.

Another simulation on the floating body case shows there is an increased possibility of purification effects because the height of the water surface in the utsuro is 1.5-times larger than the bag case. According to the permeability parameter α , the h_U values have about $\pm 0.8\ m$ differences from the simulations. More enhancement of water exchange through the utsuro, more purification effects take part in. The two suggested ideas using the ocean tidal energy is in effect the purification around utsuro because it makes any circulation. Through the simulation, it shows the floating body type has more amplitude value which enhances the circulation than the inflatable bag. Moreover, it needs to study how far the effect is propagated from one utsuro because the fact will be helpful to design how much size of it and how many it is needed in one fresh water lake for the engineering applications.

Experiments were carried out to compare key variables such as velocity in the pipe and water level in the float with those obtained theoretically. The water level from experiments compared well with that obtained by theory, and the gradient of velocity u_p obtained by experiments is in good agreement with that obtained by theory when μ is 0.2.

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APPENDIX A

Equation of motion of float including cargo water.

If the period T is very long, we can neglect the added mass of the float and the viscous friction. Furthermore, if the cross sectional area S_p of the connecting pipe is small, the water in the float can be thought of as cargo. Then, we can approximate the equation of motion of the float including the cargo water as:

$$(M_1 + \rho_F h_1 S_1)(\ddot{D}_1 - \ddot{d}) = -g(M_1 + \rho_F h_1 S_1) + \rho_S g d \left(S_1 + b(1 + 0.5\gamma d) l_1 \right), \quad \text{(A1)}$$

where $(M_1 + \rho_F h_1 S_1)$ is the additional mass of the tank itself and the cargo water, and $(\ddot{D}_1 - \ddot{d})$ is the vertical acceleration of the tank. The first and second terms on the right hand side, that is, $-(M_1 + \rho_F h_1 S_1)\ddot{D}_1$ and $\rho_S g d \left(S_1 + b(1 + 0.5\gamma d) l_1 \right)$ are the gravitational force and the buoyant force acting on the float, respectively.

Rewriting, we have:

$$(M_1 + \rho_F h_1 S_1)\ddot{d} = (M_1 + \rho_F h_1 S_1)\ddot{D}_1 + g(M_1 + \rho_F h_1 S_1) - \rho_S g d \left(S_1 + b(1 + 0.5\gamma d) l_1 \right). \quad \text{(A2)}$$

Substituting Eq. (A1) into Eq. (A2), we obtain:

$$\ddot{d} + \frac{\rho_S g d}{M_1 + \rho_F h_1 S_1} \left(S_1 + b(1 + 0.5\gamma d) l_1 \right) = \ddot{D}_1 + g = -\left(\frac{2\pi}{T} \right)^2 A \sin\left(\frac{2\pi}{T} t \right) + g \ . \quad \text{(A3)}$$

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