Mathematical Statistician and Engineering Applications
ISSN: 2094-0343
2326-9865

Study on Quantitative Estimation of Seawater Quality in Harbor Using Wind-Powered Seawater Exchange System

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Article Info
Page Number: 483 – 493
Publication Issue:
Vol. 71 No. 3s (2022)

Article History
Article Received: 22 April 2022
Revised: 10 May 2022
Accepted: 15 June 2022
Publication: 19 July 2022

Abstract

The seawater exchange breakwater (SEB) constructed at Jumunjin Harbor on Korea's eastern coast is composed of a semicircular overtopping seawall on the north side of the offshore breakwater and single outlet through the breakwater (CASE 0). Additional counter-measures, CASE 1 and CASE 2, work to improve water quality in the harbor are examined here. A wind-powered seawater exchange system (WSES) including a transit pipeline with 781.9 meters in length and 1.5 meters in diameter is linked to 3 multi-outlets set along the berthing areas of the harbor. The WSES pumps up offshore seawater by a hydraulic pump operated from wind power. The outflow at each outlet for each case is calculated and compared with the existing case, CASE 0. When the actual discharge is 71,000m3/day, the coefficient of correlation is measured Cq=0.11. The seawater exchange rates in the harbor concerned three cases were computed using coupled flow and diffusion numerical modeling system. The numerical model results demonstrate that CASE 2 for the WSES with transit pipeline and multi-outlet are more effective than CASE 0 for the SEB with single outlet in spite of reduced influx rate due to long transit pipeline, and consequent increment of head loss.

Keywords: Wind-powered seawater exchange system, multi-outlets, Seawater exchange rate, head loss, numerical model.

1. Introduction

Harbors are enclosed by breakwater except the entrance waterway so that wave and current penetrate into the harbor. If the harbor entrance is narrow and the tidal range at the site is small, water quality problems may arise. The seawater exchange breakwater has widely been studied by ocean, civil, and environmental engineers in Korea and abroad, the purpose of which is to maintain the original function of structure and to allow not clean water come into the harbor through the seawater exchange breakwater. Japan started constructing the seawater exchange breakwater in 1960, and has installed many seawater exchange breakwaters to improve water quality and fish preserve in harbors. In Hokkaido, the seawater exchange breakwater installed harbors over the whole harbors is about 14~15% (Ministry of Land, Transport and Maritime Affairs of Korea, 1999), also several seawater exchange breakwaters have been installed in Korea as well. The shape of the rectangular channel sectioned inside the breakwater is "L" instead of straight line, see Lee et al. (1994, 2002).

Jumunjin Harbor on Korea’s eastern coast suffered water quality problem for long time until 2003. Existing semi-circular seawall is situated in front of single outlet through the north side of the offshore breakwater. According to field measurements, the seawater exchange breakwater (SEB) functioned to the extent that the water quality inside Jumunjin Harbor was much better than before. However, some zones in the harbor still had poor quality as dead zones. Mean spring tidal range at the site is about 0.2 m, which does not much help water circulation at the harbor, while waves are relatively high outside the east breakwater, i.e. annual average significant wave height is about 0.6 m. Sewage outlets are positioned inside the harbor (Kim, 2004).

2. Wind-powered Water-exchange System Experiment

2.1. System Data

A seawater exchange system with wind power was constructed at Jumunjin Habor, Gangreung-City, Gangwon-Do, Korea. To make up for the weak points of the existing SEB, this study was carried out the relative merits of the existing SEB and developed wind-powered seawater exchange system (WSES). The WSES was built up with a transit pipeline and multi-outlets connected to wind-power generation, see, Fig.1. The WSES was composed of a power transfer unit that utilizes a hydraulic motor (5.5cc/rev x 2, 1,800 rpm) powered by wind energy to activate a water pump (2.2 KW x 2, 1,800 rpm). The most important factor in the experiment was considered the wind speed, of which the limits were set from 4 m/s to 20 m/s. The blade length of one side of the windmill was 3.0 m and the total height 10.0 m. This device was developed to be able to pull up 0.005 m3/sec of outer sea water when the blade activates the hydraulic pump and creates 10 KW. The wind-power generation specs are shown in Table 1, Fig 2 is the blue prints of the experimental device and Fig 3 is the installed hydraulic pump for in situ.

Fig. 1; Satellite Images of Study Area (from Daum-Map) and Installed the WSES

Table 1. Specification of Seawater Exchange System with Wind Power

Rotor diameter (approx.)	7.5 m
Rated power 10 Kw	10 kW
Nominal tip speed	30 m/s
Max. tip speed	35 m/s
Cut-in Wind-speed	4 m/s
Cut-out wind-speed	20 m/s
Max. power coefficient	0.4
Design tip speed ratio	10
Blade length	3 m
Max. chord length	450 mm
Materials	FRP
Blade root construction	FRP
Blade weight	70 kg x 3
Hydraulic pump	11cc/rev x 2
Hydraulic motor	2.2 kW x 2
Sea water pump	5 L/sec x 2
Total weight	1480 kg/unit

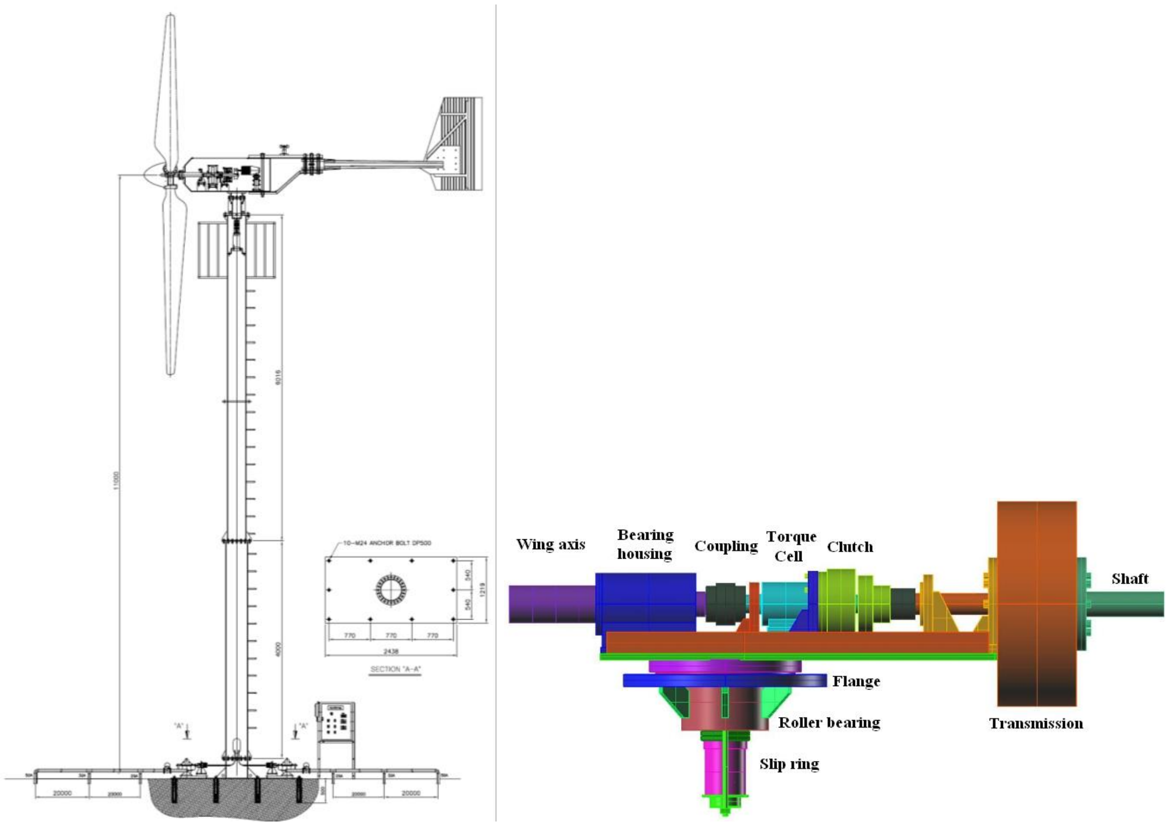

Fig. 2; A Sketch of Seawater Exchange System with Wind Power

Fig. 3; Hydraulic Pump

2.2. Live Sea Experiment

The experiment was successful in extracting sea water with hydraulic pump when wind speed was at or over 4 m/s. A transit pipeline was installed to show every 5-10 minutes the wind speed during the wind-power generation activation was 4.5-4.8 m/s, and the hydraulic pump pressure and revolutions were 150 bar and 700 rpm, respectively. And the hydraulic motor pressure and wing revolutions were 150 bar and 140 rpm. Fig 4 illustrates successful extraction of sea water when the WSES is activated the transit pipeline without the multi-outlets. Fig 5 shows the multi-outlets installed and water extracted with system performing at 50 m of length. The amount extracted of 0.003-0.004 m3/s was obtained by subtracting losses from the base pump extraction rate 0.005 m3/s.

The seawater supply to the harbor was calculated from Manning's empirical formula. Computed influx includes inaccuracy of the assumption of unsteadiness and uniformity involved in Manning formula, and the inaccuracy in head loss coefficients. The computed influx was scaled down by a coefficient, so that the annual influx through the SEB matched the field measurements.

Fig. 4; Outflow of Seawater

Fig. 5; Outflow of Seawater through One of Multi-outlets

3. Calculation of Extraction amount into Port

The numerical modeling system was applied to examine the performance of the new development plan of transit pipeline and multi-outlets. First, steady water circulation was obtained from the unsteady depth-average flow module solving the shallow water equation. A steady flow field was obtained after a long execution of the module. Then, the unsteady depth-average advection-diffusion module was solved to create concentration distribution of a material around the harbor. In this case, clean influx water has a ficticious concentration of 1.0, while dirty water inside the harbor has a concentration of 0.0. As shown in Fig. 6, three locations of the multi-outlets were selected for quantitative estimation the seawater circulation rate of each case. The WSES including a transit pipeline with 781.9 meters in length and 1.5 meters in diameter is linked to 3 multi-outlets set along the berthing areas of the harbor. According to recent data from Ministry of Land, Transport and Maritime Affairs of Korea, the seawater supply through the SEB for CASE 0 was 71,000 m3/day (0.137 m3/sec). therefore, the seawater supply through WSES for CASE 1 and CASE 2 assumed 0.137 m3/sec.

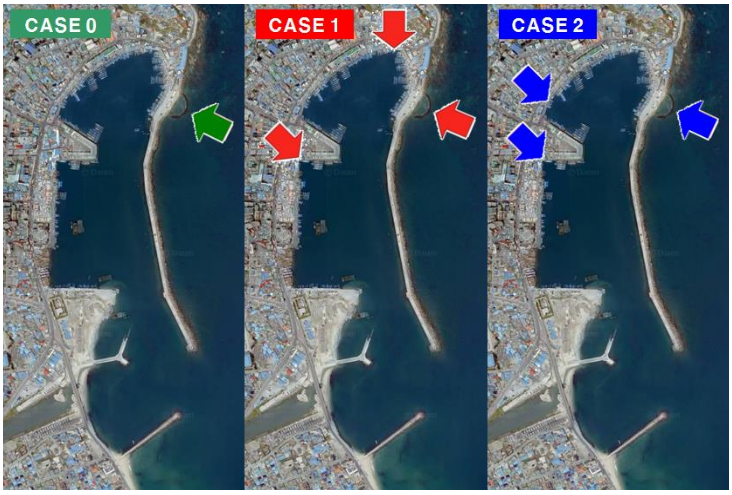

Fig. 6; The Locations of the Multi-outlets for Three Cases

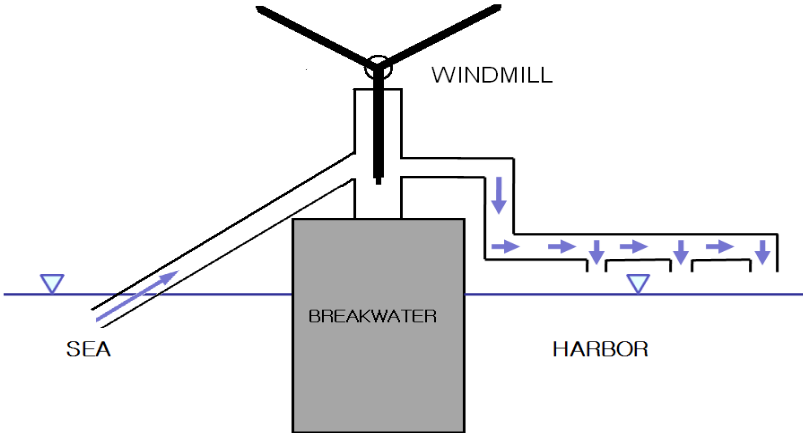

Fig. 7; Basic Concept in Hydraulics

When the transit pipeline and multi-outlets are installed, the flow is assumed to be steady as in Fig 7. At each instant the wave level in the reservoir is provided from the linear wave level as far as the level is higher than the crest level of the seawall. The water levels for the two outlets inside harbor are assumed to be identical, and Eq.1, Eq.2 and Eq.3 are applied to calculate the discharge, Q2, and Q3.

$$H = (f_e + f_1 \frac{L_1}{D_2}) \frac{Q_1^{\,2}}{2gA_1^{\,2}} + (f_o + f_{br} + f_3 \frac{L_3}{D_3}) \frac{Q_3^{\,2}}{2gA_3^{\,2}} \qquad (1)$$

$$H = (f_e + f_1 \frac{L_1}{D_1}) \frac{Q_1^{\,2}}{2gA_1^{\,2}} + (f_o + f_{br} + f_2 \frac{L_2}{D_2}) \frac{Q_2^{\,2}}{2gA_2^{\,2}} \qquad (2)$$

$$Q_1 = Q_2 + Q_3 \qquad (3)$$

where H is the head different (m), Q is the discharge (m3/s), g is the acceleration due to gravity (m/s2), D is the diameter of pipe (m), L is the pipe length (m), A is the area of pipe (m2), and f is the friction factor. The subscripts 1, 2 and 3 are for the three branches, see Fig. 3. The entrance head loss factor (fe), the exit factor (fo) and the branch factor (fbr) are 0.6, 1.0 and 0.9 respectively. Each outlet is 1.5m in diameter and the head difference of two reservoirs is provided as a sinusoidal function. The correlation coefficient is estimated Cq=0.11 in comparison with the calculated discharge (Qs). The discharges for applying the numerical modeling system (Qc) were calculated using the correlation coefficient to the values of other channels for two cases, see Table 2.

Table 2. The Discharges Computed Using the Correlation Coefficient

Length of pipe (m)		Qs (m3/sec)	Qc=Qs*Cq (m3/sec)
CASE 1	203.6	0.7641	0.0916
	578.3	0.2577	0.0309
CASE 2	586.7	0.4577	0.0549
	195.2	0.2234	0.0268

The total length of the multi-outlets is 781.9 in meters. In CASE 1, the calculated seawater being at the point of 203.6 m was 0.0916 m3/s, and the end of the pipe was 0.0309 m3/s. In CASE 2, the calculated seawater being at the point of 586.7 m was 0.0549 m3/s, and the end of the pipe was 0.0268 m3/s.

4. The Numerical Modeling System

The discharges (Qc) were applied to the numerical modeling system in order to compare the effects of seawater circulation in case by case. As shown in Fig. 8, study area was split into as three zones, HEAD (inner section of the harbor), BODY (middle section of the harbor) and TOTAL (total space of the harbor) to evaluate the effectiveness of each scheme.

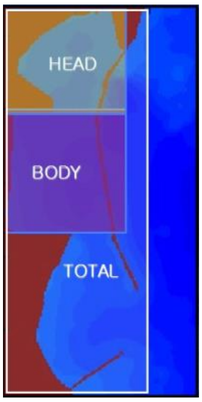

Fig. 8; Three Sections Classified for Concentration Distribution

For this study, advection and diffusion equation in terms of concept of mass conservation for concentration is below as,

$$\frac{\partial}{\partial t}(dC)+\frac{\partial}{\partial x}(UdC)+\frac{\partial}{\partial y}(VdC)=\frac{\partial}{\partial x}[d(D_{xx}\frac{\partial C}{\partial x}+D_{xy}\frac{\partial C}{\partial y})]+\frac{\partial}{\partial y}[d(D_{xy}\frac{\partial C}{\partial x}+D_{yy}\frac{\partial C}{\partial y})] \quad (4)$$

$$D_{xx}=v_T+D_S\cdot U^2/q^2 \quad (5)$$

$$D_{yy}=v_T+D_S\cdot V^2/q^2 \quad (6)$$

$$D_{xy}=D_S\cdot U\cdot V/q^2 \quad (7)$$

$$q^2=U^2+V^2 \quad (8)$$

$$v_T=0.07du_* \quad (9)$$

$$D_s \approx 5.86du_* \tag{10}$$

where, C means depth averaged concentration (kg/m3). U and V are the depth-mean velocities in the x, y direction respectively. Dxx, Dxy, Dyy are the diffusion coefficients in the x, y direction, respectively. VT is the diffusion coefficient in the horizontal direction. Ds is the dispersion coefficient in the flow direction. U* is the shear velocity (Elder, 1959).

The numerical modeling system is calculated seawater exchange rate each 1 day, total 15 days. Fig. 9, Fig. 10, and Fig. 11 show they express when seawater has supplied for 15 days and they were distinguished the seawater exchange rate which was expressed the value of between 1 and 0. If the seawater exchange rate is high, the color can be estimated nearby number 1 or red. In contrast, number 0 or nearby blue appear that seawater exchange rate is low. CASE 0 for the SEB, cannot supply clean water to some dead zones, see Fig. 9.

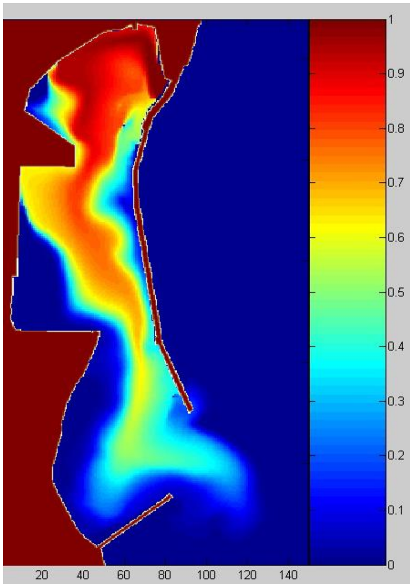

Fig. 9; The Concentration Distribution of CASE 0 for 15 Days

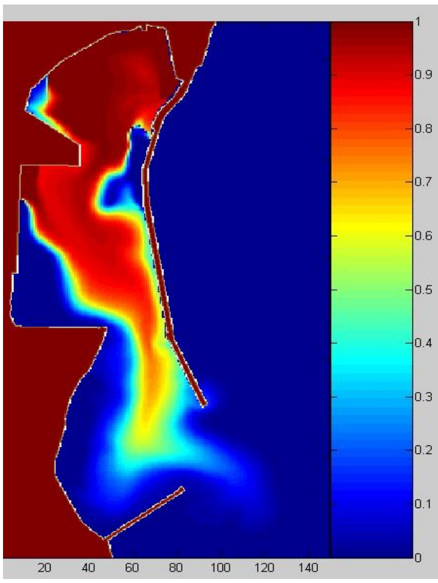

Fig. 10; The Concentration Distribution of CASE 1 for 15 Days

CASE 1 for the WSES, shows much better capability, see Fig. 10. The dead zones are mostly treated, and zone HEAD shows almost perfect replacement by clean water by the given time. However, this scheme still leaves some small dead zones. HEAD and BODY are filled with clean seawater. Especially, zone HEAD is almost clean. CASE 2 for the WSES, shows best performance in refreshing zone HEAD within a fixed time frame, see Fig. 11.

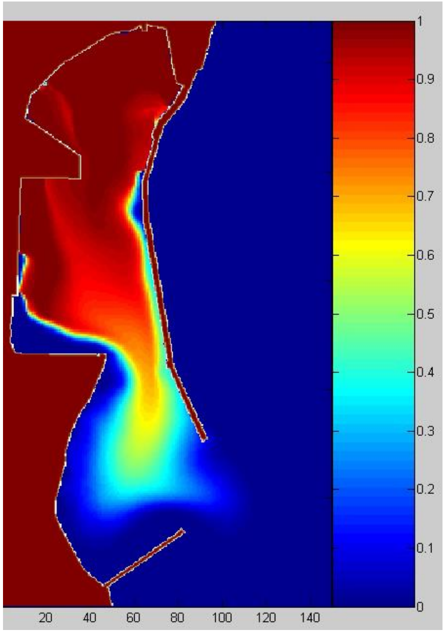

Fig. 11; The Concentration Distribution of CASE 2 for 15 Days

5. Quantitative Estimation

In order to compare the value exactly, quantitative estimation was installed at 3 Zones (HEAD, BODY and TOTAL). As shown in Fig. 12, Fig. 13, and Fig. 14 show the seawater exchange rate for 15 day. According to Fig.8, seawater exchange rate of CASE 2 was 0.97 which is the highest other case at zone HEAD. As shown in Fig. 9 and Fig. 10, other zone also was estimated highly better than others. On the other hand, although CASE 0 shows that the rate at zone HEAD was 0.82. Total rate is the lowest other cases.

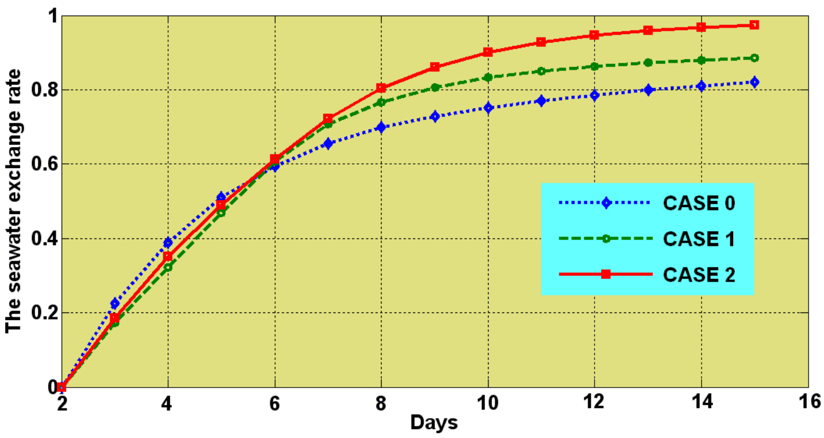

Fig. 12; Time Series of the Seawater Exchange Rate Difference at HEAD

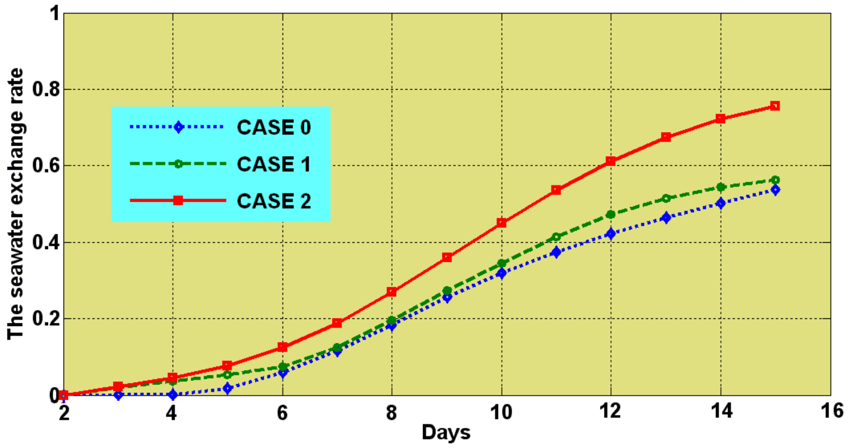

Fig. 13; Time Series of the Seawater Exchange Rate Difference at BODY

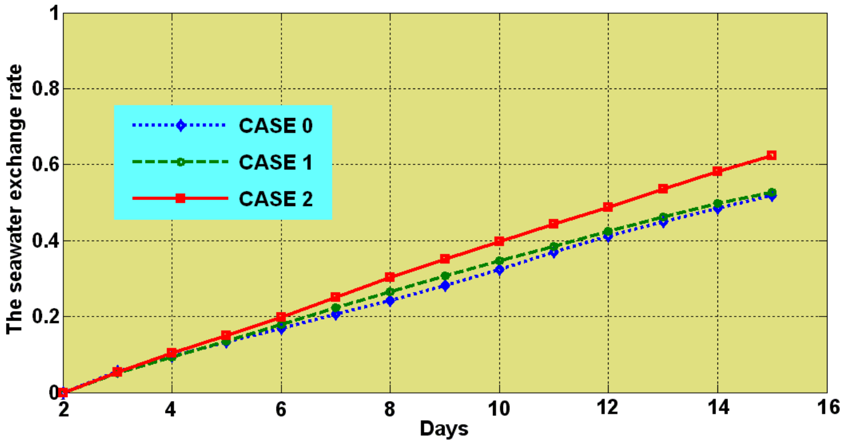

Fig. 14; Time Series of the Seawater Exchange Rate Difference at TOTAL

Table 3. Comparison of the Seawater Exchange Rate

	CASE 0	CASE 1	CASE 2
HEAD	0.82	0.89	0.97
BODY	0.54	0.56	0.76
TOTAL	0.52	0.53	0.62

6. Conclusions

It turned out that CASE 0 for the SEB is not effective enough to guarantee clean water in HEAD and BODY. Especially, the flow at the inner section to the west of the harbor was not effective enough for complete circulation of seawater (Fig. 9). In CASE 1 for the WSES, although the seawater flow was effective considerably, it is hard to expect the effects as much as CASE 2 since the level of discharge at the western section was low (Fig. 10). In CASE 2 for the WSES, seawater flow in the harbor was effective. Especially, HEAD and BODY show better water quality than CASE 1 (Fig. 11). Total seawater exchange rate also was higher than different area (Table. 3). The model results demonstrate that the WSES with transit pipeline and multi-outlet are more effective than direct, the SEB with single outlet in spite of reduced influx rate due to long transit line, and consequent increment of head loss.

CASE 2 is recommended for future development at the harbor, because it shows faster circulation at some presently dead zones.

7. Acknowledgements

This work was supported by the Daejin University Research Grants in 2022

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