Article

Changes in Marine Environment by a Large Coastal Development of the Saemangeum Reclamation Project in Korea

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Abstract : The word ‘Saemangeum’ indicates an estuarine tidal flat in the southwestern part of the Korean peninsula. The Saemangeum Reclamation Project was launched as a national project in 1991 to reclaim a large coastal area of 401 km² by constructing a 33-km long dyke. The final dyke enclosure in April 2006 has transformed the tidal flat into lake and land. An integrated oceanographic study has been conducted since 2002 as a part of the Government Action Plan to monitor and assess changes in the marine environment. Prior to the dyke enclosure, the coastal environment in the Saemangeum was a complex system governed by tidal motion, estuarine processes, and coastal circulation of the Yellow Sea. The dyke construction has radically changed not only the estuarine tidal system inside the dyke, but also the coastal marine environment outside the dyke. Post to the dyke enclosure, subsequent changes such as red tide, hypoxia, and coastal erosion/deposition occur successively. Red tides appear almost the year round in the inner area. Even under the condition that the sluice gates are fully open, the water quality does not improve as much as the developers would expect, mainly due to the critical reduction of the hydrodynamic stirring power. We will introduce details of our monitoring program and significant changes in the Saemangeum marine environment, based on observations and model results.

Key words : Saemangeum, marine environment, reclamation, dyke, hypoxia

1. Background of the Marine Environmental Study

‘Saemangeum’ indicates a tidal flat in Jeollabukdo Province in the southwestern part of the Korean peninsula. The Saemangeum Reclamation Project is a national project which reclaims the Saemangeum area mainly for the agriculture use. Fig. 1 shows the Saemangeum coastal area on a satellite image. Saemangeum is located between the Geum River to its north and the Byunsan peninsula to its south. The area itself contains two estuaries, of the Mangyung and Dongjin Rivers, and well-developed tidal flat. As seen in Fig. 1, a 33-km long dyke starts at Bieung Island to the north and extends southward to Daehang-ri

to the south through Sinsi Island mid-way.

The dyke construction has finally enclosed the coastal area of 40,100 ha (401 km²) corresponding to 60% of the size of Singapore or two thirds of Seoul’s area. According to the initial plan, the inner coastal area in the dyke will be transformed into land (283 km²) for rice field and lake (118 km²) for water reservoir. The project was scheduled to be completed around 2030; however, in 2008 the Korean government has newly proposed a change of the original purpose of farming to industrialization. The government is apparently dreaming of a Koreanized ‘Dubai’ in Saemangeum (Cheong Wa Dae 2008).

The dyke construction started in 1991 and progressed smoothly through the late 1990s, before the water quality in the lake of Siwha reclaimed area near Seoul became a grave nationwide issue. The water color in the lake

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Fig. 1. Saemangeum area. The dyke starting at Biung Island extends southward to Daehang-ri through Sinsi Island at the mid position. The 4th dyke was closed on 10 June 2003, and two opening gaps (Gaps 1 and 2) with the total length of 2.7 km were closed on 21 April 2006.

became brown within a few months after the gate closure (Huh and Oh 1997). This issue served as a bridge connecting to the bleak future of water quality in Saemangeum. Environmental groups in Korea strongly requested cancellation of the Saemangeum project, for they were worried that the project, much bigger than the Siwha project (dyke length: 11.2 km) would carry more serious environmental risk.

In 1999, the Office of Premier organized a special committee in order to re-evaluate water quality, environmental changes, and economical value. Based on the committee's recommendation, the Office made the following decision for an environment-friendly development: the dyke construction would continue as planned, but the development of the northern part of the inner area (Mangyung area) would be suspended by time when the water quality in it is ensured against the water pollution. At the same time, the Ministry of Maritime Affairs and Fisheries (MOMAF) promoted an action plan consisting of a monitoring program for the marine environment as part of the follow-up measures of the government decision. The program is named 'Integrated preservation study on the marine environment in Saemangeum' and will continue through the year 2011 (MOMAF 2007).

Korea is a highly populated country, so a number of reclamation projects have been pushed as an effective way to ensure a continuous food supply. Even at present, high-level decision makers are strongly tempted to promote the

coastal development projects rather than to reserve /or preserve the tidal flats, since potential value in future from the natural marine environment is always much underestimated as compared to monetary value under one's very nose of land use for food supply or industrialization. Researchers involved in the Saemangeum monitoring program are realizing that the coastal environment responds immediately to the coastal development and reacts negatively against the development. The main purpose of this presentation is to give an overview of remarkable changes in the marine environment by the dyke enclosure and to share our experience acquired through this study with experts in the field of marine environment.

2. Outline of Marine Environment Study

We briefly introduce the outline of the MOMAF monitoring program for the marine environment preservation (Korea Ministries of Agriculture and Forestry, Environment, and Maritime Affairs and Fisheries, and Jeollabukdo Province 2001). The final goal of the MOMAF action plan is to minimize impacts of the reclamation project on the marine environment and to effectively manage/utilize the offshore area off the dyke (the program is directed under a new ministry of Land, Transport, and Maritime Affairs from February 2008).

At the time that the environmentalists were stressing the importance of environmental preservation in response to the Saemangeum project, little attention had been paid to the impact of the dyke construction on the marine

Fig. 2. Flow chart of the marine environment study for the Saemangeum project.

Fig. 3. Stations for seasonal surveys of hydrography and water quality (a) and real-time monitoring networks at selected reference sites (b).

environment comprehensive oceanographic measurements had not been conducted, except for a preliminary study on the marine environment to meet the minimum level of the legal requirements. Therefore, the action plan mainly focused on (1) implanting a monitoring network for changes in the Saemangeum marine environment, (2) developing numerical models for assessment of the environmental changes in the course of the dyke construction, and (3) considering countermeasures and/or alternatives necessary for the environment preservation and protection.

The 10-years long study (2002~2011) may be divided into three steps according to the progress of the reclamation project; before completion of the dyke construction, during the development of the southern inner area, and during the development of the northern inner area. During 2002~2008, we have been continuously monitoring hydrography, water movement, water quality, planktons and benthic animals, and geomorphology. The monitoring program is composed of seasonal surveys by ships for spatial distributions of the major parameters and real-time monitoring of basic oceanographic and meteorological parameters at selected reference points. Fig. 3 presents station maps for the seasonal surveys and real-time monitoring stations. At about 10 stations located in the inner area, CTD castings were regularly conducted at least once a month during 2002~2006. We are also making an effort to collect more data in summer, when river discharge increases significantly, and to measure hourly variations of physical and chemical parameters in response to tides. For the continuous real-time monitoring, we are building up a monitoring network

using small-size data buoys or tower at selected reference points. Data observed at the buoy and tower stations are transmitted to laboratory on the real-time base via satellite. We are also watching changes in the bottom environment including benthic animals, surface sediment, and bottom topography. Besides the monitoring work, numerical models are also developed for water circulation, water quality, ecosystem, and sediment transport. It is strongly suggested that each discipline interact with other disciplines to better understand the major processes associated with the environmental changes in the area.

3. Subdivision of Coastal Environment System by Dyke

In Saemangeum, tidal range at spring tides is about 6 m, and two rivers, Mangyung and Dongjin, supply freshwater and land-based materials, although discharge from the rivers is mainly concentrated in summer when flooding occurs. Therefore, the marine environment prior to the dyke construction could be classified as a tide-dominated estuarine system. Tidal flat is well-developed all along the coast and the bottom topography is gently sloping (Fig. 4). Tidal channels are generally distributed in the east-to-west direction. Water circulates mainly through the tidal channels and strong tidal currents play a role as a long-distance transporter of materials between near-shore and offshore.

The dyke construction has not only geographically divided the area into the inner area in the dyke and the outer area off the dyke, but also has radically transformed

Fig. 4. Satellite image on 8 February 1991 (left) and digital elevation model (DEM) showing altitude of the tidal flat in 1991 (right).

the marine environment system into three subsystems. The archipelagoes of Gogunsan, which are sprinkled in the east-west direction, are now connected to the central part of the dyke, so the offshore area has been eventually divided into the northern and southern parts after the connection. Water exchange between the inner and outer areas is possible only through two sluice gates of Sinsi and Garyeok, both located in the southern part of the dyke. Even under the condition that the gates are fully open, the tidal range in the inner area is decreased to 1m, so that the coastal system of the inner area is no longer the tide-dominated estuarine system.

Before the dyke construction, the water between the northern and southern parts of the archipelagoes was circulated mainly through the coastal area east of the archipelagoes, while, after the dyke construction, the water has circulated through narrow channels between islands and the offshore area west of the archipelagoes. That is, the marine environment in the northern part of the archipelagoes is more directly linked to the Geum River estuary. At the same time, the geometric configuration of the southern offshore area has become a semi-enclosed bay surrounded by the archipelagoes to the north, the Byunsan peninsula to the south, and the dyke to the east. The marine environment in the southern part is partly affected by the outflow from the inner area, when the gates are open. Thus, Saemangeum is divided into three different subsystems in terms of the marine environment: the inner area, the northern outer area, and the southern outer area.

4. Change of Hydrodynamic Regime

In 2002, at the beginning of the study, there were three

opening gaps: one on the northern dyke and two on the southern dyke. The northern gap was plugged up in June 2003 and the southern gaps were closed in April 2006. To sketch the circulation before and in the early stage of the dyke construction, Lie (2006) consulted fragmentary information such as bathymetric charts and visible satellite images. Tidal channels and sand banks were well developed in the southwest-to-northeast direction in the southern part of the inner area and in the west-to-east in the northern part. The characteristic elongation of high turbidity plume reflected the dominance of tidal currents roughly in these directions. All along the west coast of Korea, the coastal current in the sub-tidal frequency bands is very seasonal, flowing southward in winter when strong northerly winds blow but flowing northward in summer (Lie 1985). The regional circulation in Saemangeum is mainly governed by the coastal circulation of the Yellow Sea, although the detailed structure may be modified by complicated coastline and rugged bottom. Therefore, the hydrodynamic regime before and in the early stage of the dyke construction can be classified as a coastal-estuarine complex regime dominated by the large tidal motion (Lie *et al.* 2005; Lie 2006).

Between the dyke construction and the final enclosure of the southern dyke, the hydrodynamic regime must have been continuously changed according to the dyke extension. In general, change in the hydrodynamic regime inevitably gives rise to change in bottom topography and the latter in turn leads to change in tidal and residual currents. Flow passing through opening gap becomes stronger as the gap gets narrower. Outflows both from the Geum River and the northern gap gradually shifted to south until the closure of the northern gap, while flows

Fig. 5. Sea level changes in the inner area around the final enclosure of the southern dyke in April 2006. Vertical bars denote a period when intensive plugging was conducted.

passing through the southern gaps were much strengthened by about 10~15% (Lie 2006). The local circulation in the northern outer area is now closely associated with the Geum River estuary and it is completely independent of the inner circulation.

From the final enclosure of the southern dyke, the inner circulation can be artificially controlled by the gate operation. When the gates are closed, the water in the inner area is almost motionless, except in the river mouths. Provided that the gates are open, the inner circulation is activated by gate inflow which is tide-dependent, whereas the circulation in the southern outer area close to the dyke is in turn sensitive to the gate

control which determines strength of inflow or outflow and water exchange between the inner and outer areas. Thus, the coastal-estuarine circulation regime of before the dyke construction has been transformed into three sub-regimes with weak linkage between them.

The regional tidal regime after the final enclosure is very different from that before the dyke construction. Before the enclosure, tidal waves propagated inward in the inner area through the gates, but the waves are limitedly allowed to propagate inward. Tidal range was about 6 m at spring tides everywhere before the enclosure. After the enclosure, the range has slightly decreased by less than 5% near dyke in the outer area, but it has been

Fig. 6. Reduction of tidal currents by the closure of the 4th dyke (left) and by the final dyke enclosure (right).

largely reduced to 1 m in the inner area, even provided the gates are fully opened.

Tidal currents were greatly modified twice at the closing events (Fig. 6). After the closure of the northern dyke, a significant reduction in tidal currents occurred in the northern area, while the tidal currents in the southern area were strengthened. After the closure of the southern dyke, a drastic reduction occurred in the southern area as predicted by Lee *et al.* (2008). According to a numerical comparison of M_2 currents between before the dyke construction and after the final dyke enclosure, reduction of more than 40% occurs within a short distance of 2 km from the dyke in the northern area, but the reduction occurs almost in the entire southern area.

5. Deterioration of Water Quality

Space-averaged chemical oxygen demand (COD) in the inner area was sharply increased from June 2003 when the northern dyke was closed. In 2002, the value was below 2 mg/l, but from summer of 2003, it has been higher than 5 mg/l in summer. Of particular interest is that the highest value of 7.7 mg/l was observed in autumn of 2007, one year after the final dyke enclosure. The space-averaged COD in the outer area shows a trend similar to that in the inner area. The value was below 1.5 mg/l before June 2002, but has increased to 2~4 mg/l from thereafter. The final enclosure in April 2006 has not yet caused any significant change in COD in the outer areas. The high level of COD after the closure of the northern dyke may be associated with high primary production in

the inner area, although biogeochemical processes remain to be clarified in future.

COD in surface sediment was about 2 mg/g in the inner area during 2002~2005, but in 2007, it was sharply increased to larger than 18 mg/g in the mouth of the Mangyung River and the deep tidal channel close to the Sinsi Gate. The sharp increase after the final enclosure seems to be closely associated with high concentration of organic particles in the surface sediment which may result from sinking of suspended particles due to the drastic reduction of tidal current after the final enclosure. Relatively high value in the tidal channel just in front of the Sinsi Gate may be closely associated with deposition of suspended particles transported from upstream.

Chlorophyll *a* concentration shows a larger time-variation in 2006~2007 after the final enclosure as compared with that in 2004~2005. Blooming has not occurred simultaneously in the inner and outer areas since March 2006 when the final closing started. Blooms were defined as chlorophyll *a* observations deviating significantly from a normal seasonal cycle. In the inner area, blooming occurred in March 2006, March 2007, and October 2007, while in the outer area, it occurred in March and July 2007. Dominant phytoplankton species at the blooming events were also different. For instance, a diatom species, *Eucampia zodiacus*, was dominant everywhere in March 2007, whereas in the inner area, *Prorocentrum minimum*, one of red tide species, was dominant in October 2007 (Fig. 9). Differences in bloom timing and dominant phytoplankton species between the inner and outer areas might be a prelude to segregation of the plankton

Fig. 7. Time series of space-averaged COD in Saemangeum. (a) inner area and (b) outer area. (H) and (L) in x-axis indicate high water and low water, respectively.

Fig. 8. Spatial distribution of COD in the surface sediment during 2002~2007.

Fig. 9. Total phytoplankton and dominant species abundance in March 2007 (left) and October 2007 (right).

ecosystem into the inner and outer sub-systems as a consequence of the dyke construction.

In the inner area, dissolved oxygen (DO) is rich in the surface layer almost the year round, while in the bottom layer, it dropped frequently to below 50% in summers of 2006 and 2007 after the final enclosure. Sometimes, low DO appears both in the Mangyeong River estuary and in the deep channel near the Sinsi gate. High DO in the surface layer is indicative of a good condition for high primary production. On the other hand, low DO in the bottom layer means no sufficient supply of DO from the surface layer and excessive consumption by oxidation in the bottom layer. Intensification of pycnocline (stratification) after the final enclosure plays a role in screening vertical exchange of materials, so that deficit in

oxygen (hypoxia) has at last occurred in the inner area after the final enclosure, especially in warm seasons. Another interesting point is that turbidity is low at times when the hypoxia occurs. Low turbidity reflects calm sea state, so high DO in the surface layer is hard to reach the bottom layer across the strong pycnocline.

6. Change of Bottom Environments

The biggest change in the bottom environments caused by the dyke construction is disappearance of well-developed tidal flats in the inner area due to a large reduction of tidal range. The tidal flats of 231 km² before the dyke construction have been transformed mainly into sub-tidal zone (127 km²) and partly into supra-tidal flat

Fig. 10. Time series of turbidity and DO near bottom at station M1 in the inner area.

Fig. 11. Grain size of surface sediments along line SA in the inner area and a sediment core sample with diameter of 6 cm taken one month after the closure of the 4th dyke. Surface deposition of fine mud 10 cm thick above the sandy mud.

(53 km²). Only 22% of the tidal flats could remain as natural tidal flat under the condition that the sluice gates are fully opened without gate control.

Bottom topography has been continuously changed according to the progress of the dyke construction. Tidal channels near the opening gaps were forced to be modified both in shape and depth, deepening by strong flow passing through the gaps before the dyke closure and stuffing with new sediment after the dyke closure. Sediments in the inner area originating from rivers during flooding are blocked from moving to the outer area after the final enclosure. Only part of suspended sediments may come out of the inner area on riding the gate outflow. Surface sediment texture is being also adjusted to the

hydrodynamic system and sedimentary processes under the new dynamic system (Lee *et al.* 2006). In general, surface sediments become coarser in areas where erosion is dominant, but becomes finer in areas where deposition is dominant. In the inner area, the sand-dominant texture before the dyke closure is being gradually replaced by a mud-dominant texture after the final enclosure.

Changes in bottom topography and sediment texture are followed by changes in benthic ecosystem. The dyke closing events gave rise to remarkable changes in macrobenthic community structure. In the inner area, fining of sediment grain size as well as transformation of inter-tidal zone into supra-, inter-, and sub-tidal zones decisively affected survival and population of the

Fig. 12. Variations of species number of benthic animals in the sub-tidal zone. Upper : inner area and lower : outer area. Error bar represents standard error (SE) among sampling stations. Dotted line shows mean value. Black and red arrows indicate the 4th dike closure and the final enclosure, respectively.

macrobenthos. In the supra-tidal zone, all macrofauna died off within 120 days, mainly due to high temperature after their exposure to air, whereas in the inter-tidal zone, the abundance was largely diminished due to a big reduction of the area. In the newly transformed submerged zone, species were tolerant under the similar habitat environment, but opportunistic species, such as *Sinocorophium sinensis*, *Theora fragilis* and *Pseudopolydora Kemp*i, were massively recruited. In the sub-tidal zone, the number of macrobenthic species tends to decrease during 2002~2004, but recover after 2005. The trend continued in 2006 and 2007 (Fig. 12).

In the outer area, the macrofaunal group in the tidal flat sustains its specific benthic faunal assemblages. The species number does not show any trend of temporal variation, but the similarity of community structure is gradually evolving after the final enclosure. On the other hand, in the sub-tidal zone, the species number and mean density tend to gradually decrease from 2002. The decreasing trend may be closely associated with disturbances in habitat in the vicinity of the dyke and the deep channels. The disturbances are represented by redistribution of surface sediment structure and evolution of the regional hydrodynamic regime.

7. Summary and Concluding Remarks

In this study, we briefly presented the background of the Saemangeum marine environment study and the major

Fig. 13. The Simpson-Hunter mixing parameter around the final dyke enclosure during January - July 2006. Stations are marked in Fig. 3b.

changes in the marine environment, mainly based on observed data collected over the last 6 years. The marine environment in the Saemangeum area maintained a coastal-estuarine complex system before the closure of the 4th dyke in June 2003, although it had been gradually modified since the commencement of dyke construction. Drastic transitions in the marine environment regime appeared immediately after the two closing events in June 2003 and April 2006. The dyke enclosure ruptured the preexisting environmental regime including fishes and migratory birds. The final dyke enclosure has not only

transformed the large tidal flats of the inner area into supra-, inter-, and sub-tidal zones, but also blocked the free exchange between seawater and freshwater.

As a proverb says 'stagnant water is bound to corrupt': water in the inner area is almost motionless and its quality tends to get worse and worse. Subsequent changes such as intensification of vertical stratification, occurrence of red tide, oxygen depletion, and coastal erosion/deposition occur successively. In 2007, red tides appeared almost the year round in the inner area. What is responsible for the stagnant state of water motion in the inner area and in the vicinity of the dyke? The dyke not only blocks the exchange of water and materials between the inner and outer areas, but also reduces the tidal current. The Simpson-Hunter mixing parameter (Simpson and Hunter 1974) is an indicator showing the vertical mixing power of water column which is proportional to H/U^3 , where H is the water depth and U is the current speed. Fig. 13 shows time variation of the mixing parameter at four points around the final enclosure. The power was drastically reduced at point B in the inner area and at C in front of Sinsi Gate after the final enclosure.

Are there any countermeasures to enhance the water quality? At the planning stage for the Saemangeum project, the concerned authority did not pay attention to the water quality or to the marine environment. Sewage treatment plants and sewer pipe lines to reduce pollutant input have not yet improved the water quality in the inner area. Even provided that the sluice gates are fully opened, the water quality does not improve as much as expectations of the developers' thinking, mainly due to the critical reduction of the hydrodynamic stirring power. Filthy water is discharged through the sluice gates and the drained water in turn affects the marine environment in the outer area, since it does not mix quickly with surrounding seawater due to the reduced mixing power. A large coastal development as the Saemangeum reclamation project will be inevitably accompanied by destruction of our nature as two sides of a coin. Our deep agony is how to keep the marine environment as healthy and clean as before the development and how to effectively persuade decision makers who drive coastal development projects.

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