Macrobenthic faunal change after dike construction in Saemangeum Lake, South Korea, with special emphasis on mollusks

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Abstract: The world’s largest Saemangeum Dike was completed on April 21, 2006; however, the water gates were intermittently opened to dilute the polluted water inside the dike with seawater outside the dike. We investigated the macrobenthic faunal change after dike construction in Saemangeum Lake, South Korea, in the summer season. From July 2008 to August 2012, many individuals of bivalve species, such as Arcuatula senhousia, Potamocorbula sp., and Ruditapes philippinarum, were collected from the subtidal zone inside the dike, although the dissolved oxygen content in the bottom water was less than 1 mg/L at many stations, where the water depth was more than 2.7 m. In August 2016 and August 2018, however, most macrobenthic animals disappeared from Saemangeum Lake, because the water became more hypoxic than it was in August 2012. These facts suggest that the Saemangeum Dike negatively affects the water quality and macrobenthic animals inside the dike because of the long closure of sluices.

Key words: bivalves, embankment, hypoxia, macrobenthos, reclamations

Introduction

Since the late 20th century, huge coastal wetland reclamation and dike construction projects have resulted in tremendous negative impacts on the natural environment around the coasts of South Korea and Japan (Fig. 1). In South Korea, the dikes of Shihwa (Fig. 1A; 12.7 km long) and Saemangeum (Fig. 1B; 33 km long) were built in 1994 and 2006, respectively (Hong et al. 1997, Ryu et al. 2014, Lee et al. 2018). In Japan, the inner part of Ishahaya Bay (Fig. 1C) was also isolated by the construction of a dike in April 1997, and most areas (ca. 29 km²) of mud tidal flats have been lost (Sato 2006). Such anthropogenic effects are especially remarkable in tidal flats and estuarine environments, in which many benthic animals are threatened with extinction (Wada et al. 1996, Hong 2000, Sato & Koh 2004, Japanese Association of Benthology 2012). Here, we studied the world’s largest dike construction project, the Saemangeum Dike Construction Project, mainly focusing on its negative effects on the coastal environment and ecosystem.

The Saemangeum Dike is located in the middle of the western coast of South Korea (Fig. 1). The length of the dike is the largest in the world (33 km), and the reclamation area inside the dike is 401 km² (Hong et al. 2007, Sato et al. 2007). The dike construction began on November 28, 1991, and was completed on April 21, 2006. Although the water gates have been intermittently opened to dilute the polluted water inside the dike with seawater outside the dike, the tidal range inside the dike almost disappeared and the intertidal zone dried out within several months after the completion of the dike (Sato et al. 2007). As a result, many macrobenthic animals, including unique mollusk species, such as Koreamya arcuata, Meretrix petechialis, Umbonium (U.) thomasi, and Bullacta exarata, have already disappeared from the Saemangeum tidal flats because of their drying out (Hong et al. 2007, Lützen et al. 2009, Sato et al. 2011).

Many researchers have studied macrobenthic animals collected from the intertidal zone in the Saemangeum area (e.g., An & Koh 1992, Je 2000, Sato 2002, 2005, 2006,
Hwang & Kim 2003, Kim & Hwang 2003, Hong et al. 2007, Koo et al. 2007, 2008a,b, Sato et al. 2007, Ryu et al. 2011a,b, 2014). An & Koh (1992) found 64 species of benthic animals from the Saemangeum tidal flats in July 1988. Je (2000) collected 45 species of benthic animals from the areas similar to those used by An & Koh (1992) in July 1996 and concluded that the species numbers and densities of benthic animals had decreased during dike construction between 1988 and 1996.

The Japan/Korea Tidal-flats Joint Survey Group has also continued to study waterfowls, benthos, and tidal-flat cultures in the Saemangeum area since May 2000 (Japan/Korea Tidal-flats Joint Survey Group, 2001, 2003, 2006, 2008). In our joint research project, we examined the macrobenthic animals collected from 18 fixed stations on the tidal flats of the northern and middle sites in the study area 10 times between May 2000 and September 2006 (Sato et al. 2007). However, after the completion of the dike construction in April 2006, the tidal flats in this area gradually dried out, and a huge amount of dead shells of mollusks and other benthic animals were exposed on the dried tidelands in June 2006 (Hong et al. 2007, Sato et al. 2007). Therefore, we conducted quantitative surveys of macrobenthic communities from the subtidal zone inside the Saemangeum Dike in the summer season on July 11, 2008; August 14, 2011; August 23, 2012; August 16, 2016; August 11, 2017; and August 19, 2018 (Table ES1). The sampling stations were often moved owing to the inner-dike construction and topographical changes of the sea bottom (Table ES1). The present study also compiles these data and discusses the common and different features of these faunal changes caused by the dike construction.

Materials and Methods

Sediment samples were collected from the subtidal zone around six fixed stations (black circles A1–A6 in Fig. 2) and 10 extra stations (white circles; B1–B10). Light gray areas represent dried tidal flats, and dark gray areas represent land. Solid lines are inner dikes completed until August 2018. Dashed lines indicate bathymetric lines.

Fig. 1. Location of the huge reclamation projects in Korea and Japan (modified from Sato 2002). (A–C) Location of the reclamation area in Shihwa (A), Saemangeum (B), and Isahaya Bay (C). Black bars represent the dike completed in each area. Maps from A to C were drawn using the same scale.
using a global positioning system (GPS) receiver (Empex Instruments, Inc., Tokyo, Japan; Pocketnavi Mini). Temperature, salinity, and dissolved oxygen (DO) of the bottom water (less than 50 cm above the bottom sediment) were measured using a water quality meter (YSI Inc., Ohio, USA; Model 85) at each sampling station. Finally, three to four replicate samples were taken at each station using an Ekman-Berge grab (sampling area: 0.02 m²) (Table ES1). The faunal samples were sieved using a mesh with a 2-mm opening. The remnants were preserved in 10% formalin, and the macrobenthic animals were taken from the debris and identified in the laboratory. Among the macrobenthic animals, bivalves and polychaetes were identified to the species level. The other taxa were identified to higher taxonomical levels, such as class or order.

Results

In the Saemangeum area, the temperature of the bottom water was usually more than 25°C at all stations, except for the stations where the water depth was more than 3 m (Table ES1); however, the salinity and DO of the bottom water drastically changed in the summer season between July 2008 and August 2018 (Figs. 3, 4). In July 2008, the salinity was more than 20 at most of the stations near the dike, and the DO was less than 1 mg/L at the four stations (A1, A4, B7, and B8), where the water depth was more than 3.6 m (Table ES1, Figs. 3, 4). The salinity decreased to less than 3 in August 2011, but increased to more than 10 at all stations in August 2012 (Table ES1, Fig. 3). The DO was more than 4 mg/L at all stations in August 2011, but became less than 2 mg/L at stations A1 and A3, where the water depth was more than 2.6 m in August 2012 (Table ES1, Fig. 4). In August 2016, the salinity was less than 10 at the three stations around the river mouth (A6, B5, and B6; Fig. 3), and the DO decreased to less than 1 mg/L at the five stations near the dike (A1, A5, B1, B2, and B4), where the water depth was more than 4.5 m (Fig. 4, Table ES1). In August 2017 and August 2018, the distributions of salinity and DO were similar to those in August 2016, but the salinity gradually increased and the DO decreased around the river mouth (Figs. 3 and 4).

Macrobenthic animals were relatively abundant in July 2008, August 2012, and August 2017, but their number decreased in August 2011, August 2016, and August 2018 (Fig. 5, Table ES2). In July 2008, crustaceans (amphipods and crabs) were collected in abundance (>100 individuals/m²) from stations A1, A2, A6, and B6, but disappeared from all the stations in August 2011 (Fig. 6). In July 2008, a brachiopod, Lingula anatina was also collected from station B6, and three gastropod species Reticunassa festiva, Bullacta exarata, and Laguncula pulchella were found from stations A2, A3, and B8, respectively (Fig. 6). However, in August 2011, no macrobenthic animals were collected from stations A1, A3, A5, and B8, but only polychaetes and bivalves were collected in small numbers from stations A2, A4, A6, and B9 (Fig. 6). In August 2012, many individuals of polychaetes and bivalves (> 50 individuals/m²) were collected at all stations, but only a few were observed in August 2016 (Figs. 5, 6). In August 2017 and August 2018, polychaetes, bivalves, and crustaceans (seven individuals of amphipods and 83 individuals of bar-
nacles) were found from the stations near the river mouth, and especially bivalves were abundant (3500 individuals/m²) in station A4 in August 2017 (Fig. 6, Table ES2).

The dominant species of bivalves were Arcuatula senhousia and Potamocorbula sp. in July 2008 and Potamocorbula sp. in August 2011, and R. philippinarum first increased in August 2012 and then almost disappeared in August 2016 (Fig. 7, Table ES3). In July 2008, many individuals of A. senhousia (>1000 individuals/m²) were collected from the stations near the river mouth, but this species disappeared temporarily in August 2011 (Fig. 8). All bivalves collected from the six fixed stations (A1–A6) in August 2011 were Potamocorbula sp. (Fig. 8, Table ES3). In August 2012, Potamocorbula sp. was still dominant (>50 individuals/m²) at stations A3 and A4, where the salinity was less than 20, whereas A. senhousia increased at stations A1 and A5, where the salinity was more than 20 (Fig. 8). Moreover, many individuals of R. philippinarum (>350 individuals/m²) were found in August 2012 from stations A2 and A6, where the water depth was less than 1.7 m (Table ES1). In August 2016, only one individual each of A. senhousia and Potamocorbula sp. was collected from station A4, besides two individuals of other bivalve species from station A6. In August 2017 and August 2018, A. senhousia was abundant (3367 individuals/m²) in station A4 (Fig. 8, Table ES1).

The number of bivalve species collected from the six fixed stations (A1–A6) first decreased from July 2008 to August 2011 and then increased in August 2012, but most of them disappeared in August 2016 (Fig. 7). In July 2008, in addition to the above-mentioned three species, Theora lubrica, Moerella rutila, and Raeta pulchella were collected from the stations near the dike (Fig. 8). These bivalve species disappeared in August 2011, until they were found again in small numbers at station A5 in August 2012. In August 2016, only four individuals of bivalves (Potamocorbula sp., A. senhousia, and two juveniles belonging to the family Pisidiidae) were collected from stations A4 and A6, and no bivalves were found from the other 10 stations (Fig. 8). Arcuatula senhousia suddenly increased in number in August 2017 and then decreased in August 2018, but the number of bivalve species was still three, the same as that in August 2016 (Fig. 7).

The polychaetes collected in July 2008 were 37 individuals (617 individuals/m²) representing 11 species, but in August 2011, their number decreased to four individuals (67 individuals/m², Table ES4) belonging to only one species (Neanthes succinea). In August 2012, their number increased to 65 individuals (1083 individuals/m²) representing five species, but in August 2016, it decreased to 13 individuals (196 individuals/m², Table ES4) representing two species (N. succinea and Pseudopolydora kempfi). Among these species, N. succinea was the most dominant, and 43 individuals (717 individuals/m²) were collected.

Fig. 4. Temporal change of the distribution pattern of the dissolved oxygen (DO) of bottom water at 6–12 stations inside of the Saemangeum Dike from July 2008 to August 2018.
from all six fixed stations in August 2012 (Table ES4). Five individuals of *L. longifolia* were found only from station A5 in August 2012. In August 2016, only one individual of *P. kempi* was found from station A4, and one to six individuals of *N. succinea* were collected from stations A2, A4, B3, and B6, where the DO was more than 4 mg/L (Tables ES1, ES4). *Neanthes succinea* comprised >70% of all macrobenthic animals collected in August 2016 (Tables ES2, ES4). In August 2017, *N. succinea* increased to 81 individuals (1350 individuals/m²) at stations A3, A4, and B6, and three individuals of *Polydora* sp. were found from station A4. *Neanthes succinea* decreased to 30 individuals (500 individuals/m²) in August 2018, and one individual, each of *Polydora* sp. and *Heteromastus filiformis*, was collected from stations B1 and B6, respectively (Table ES4).

**Discussion**

Previously, some ecological studies have been carried out on the macrobenthic animals from the subtidal zone inside the Saemangeum Dike. For example, Choi & Koh (1994) investigated the macrobenthic fauna in the subtidal zone around the Saemangeum area in June–July 1988, before the dike construction. They collected a total of 5636 macrobenthos individuals representing 61 species from 39 stations, including the estuary of the nearby Geum River and outside the future dike area, using a van Veen grab (sampling area: 0.1 m²). Je (2000) reported the macrobenthic fauna in the subtidal zone inside the dike from October 1999 to March 2000, after the beginning of the dike construction. He found 5065 macrobenthos individuals representing 120 species from 35 stations using the van Veen grab, and concluded that the distribution area of major dominant species, such as *Potamocorbula* sp. and *H. filiformis*, moved from the estuary of the Mangyeong and Dongjin rivers to the subtidal zone near the dike from 1988 to 2000.

Ryu et al. (2014) compiled the data on macrobenthic...
animals collected from the subtidal zone inside the dike in 2002–2005 (An et al. 2006) and 2006–2007 (Lee 2012), and pointed out that the increase in the numbers of *T. lubrica* and *Sternaspis costata* after the dike completion might indicate the accumulated environmental changes in this area. Moreover, they suggested that several opportunistic species, such as *H. filiformis*, were found in this area over the past 20 years, reflecting vulnerable benthic habitats during the dike construction.

In the present study, crustaceans (amphipods and crabs) were collected in abundance (mean density: 263.8 individuals/m²) in July 2008, but their number decreased in most stations in August 2011 (Fig. 5). Choi & Koh (1994) collected 360 individual crustaceans (amphipods, isopods, cumaceans and crabs) with a mean density of 92.3 individuals/m² in 1988 before the dike construction. After the dike construction began, the mean individual density of crustaceans (except for barnacles) was 30.0 individuals/m² in 1999–2000 (Je 2000), and it ranged from 12 to 54 individuals/m² in 2002–2005 (An et al. 2006). Thus, the number of crustaceans, except for barnacles, increased temporarily in 2008 and then decreased after 2011. In the Saemangeum tidal flats, the gammaridean amphipods, especially *Corophium* spp., increased temporarily from May 2005 to March 2006, just before the dike completion (Sato et al. 2007), and a similar situation might have occurred in the subtidal zone after the dike completion.

The dominant bivalve species included a mytilid *A. senhousia* and a corbulid *Potamocorbula* sp. in July 2008 and August 2011, and a venerid *R. philippinarum* increased in number in August 2012 and then almost disappeared in August 2016 (Fig. 7, Table ES3). Especially, *A. senhousia* individuals were collected abundantly (>1000 individuals/m²) from the stations near the river mouth, where the water depth was less than 2.3 m in July 2008 and August 2017 (Fig. 8; Table ES1). The previous studies indicated that *A. senhousia* individuals were collected from the subtidal zone in the estuary of the Geum River in 1988 (Choi & Koh 1994), but very few were found inside the Saemangeum Dike (only one individual was collected in 1999–2000; Je 2000). Furthermore, no data on this species...
from the intertidal zone of the Saemangeum area are available from the years 1988 (An & Koh 1992), 1996 (Je 2000), 2000–2006 (Sato et al. 2007, Koo et al. 2008a, b, Ryu et al. 2011), except for 2002 (Yamashita et al. 2006). *Arcuatula senhousia* was considered to appear suddenly in the subtidal zone of this area in 2008 after the dike completion as it was not present in August 2007 in 10 stations, including the two fixed stations in the present study (A4 and A6) inside the Saemangeum Dike (Sato 2014). This species then disappeared temporarily in August 2011, when the salinity decreased to less than 3 at all stations (Fig. 8).

In the subtidal zone of Isahaya Bay (Fig. 1D), *A. senhousia* suddenly increased in May 1997, a month after the dike completion, and then disappeared in August 1997 simultaneously when the salinity of the bottom water decreased below 5 (Sato et al. 2001, Sato & Azuma 2002). In the present study, this species was mainly distributed in July 2008 and August 2012 at the stations, where the salinity was more than 20, and disappeared temporarily in August 2011 when the salinity decreased to less than 10 (Fig. 8). Exceptionally, this species also increased in August 2017 at station A4, where the salinity was 12.0 (Fig. 8, Table ES1). This species is considered an opportunistic species (Crooks 1996, Gofas & Zenetos 2003, Hiratsuka et al. 2007, Nishijima et al. 2013), and its number was observed to increase immediately around the upper subtidal zone in Miyagi Prefecture, after the Great East Japan Earthquake and Tsunami in 2011 (Okoshi 2016, Sato & Chiba 2016a, b). These facts suggest that *A. senhousia* suddenly increased in number as an opportunist when the salinity was more than 20 and disappeared when the salinity decreased to less than 10, aside from one exception in August 2017 at station A4.

Theora lubrica, a semelid bivalve, was collected from the subtidal zone near the dike in 1999–2000 (Je 2000), and the permanently submerged zone in 2006 just after the dike's completion (Koo et al. 2008a). In the present study, this species was dominant at the stations near the dike in July 2008, disappeared in August 2011, and then appeared again at the stations near the dike in August 2012 (Fig. 8). After 2016, this species was not collected at all stations. In Isahaya Bay, *T. lubrica* increased in number in the subtidal zone outside the dike in May 2002, just after the temporary opening of the water gates (Yamamoto et al. 2015). This species was also considered an opportunistic species (Kikuchi & Tanaka 1976, Lim et al. 2006, Seo et al. 2012), but Saito et al. (1998) mentioned that this species was not classified as a true opportunistic species because its initial response to disturbed conditions was not predictable.

In August 2011, macrobenthic animals drastically decreased in number in the subtidal zone of the Saemangeum area because of the low salinity (less than 5; Table ES1), and only polychaetes and one bivalve species, *Potamocorbula* sp., were collected (Figs. 6, 8). After 2012, *Potamocorbula* sp. was still collected from the stations, where the salinity was less than 20 (Fig. 8). *Potamocor-
Among the mollusks, *A. senhousia* and *T. lubrica* were reported to be typical dominant species in the Korean coastal areas, such as harbors and semi-enclosed regions, where the sediments were enriched with organic matter and summer hypoxia occurred (Seo et al. 2013). However, it is interesting to note that in the waste dumping areas located in the Yellow Sea and southeastern shelf, *R. pulchella* and the thyasirid *Thyasira tokunagai* were typical opportunistic species (Seo et al. 2013). The present study revealed that these two species were not dominant in the Saemangeum area before and after the dike completion.

In July 2008, the macrobenthic fauna collected were dominated by the three major zoological groups—mollusks, crustaceans, and polychaetes, but many of the crustaceans, except for barnacles, decreased in number after August 2011. However, the polychaetes showed their environmental resistance with especially high abundance in August 2012 and remained dominant until August 2018. The presence of the species that are euryhaline and tolerant of organic pollution, such as *Prionospio* (*Minospio*) *japonica*, *Lumbrineris longifolia*, and *P. kempi*, is noteworthy. However, it should be noted that numerically, the most important polychaete was a nereid, *N. succinea*, which is well-known as an invasive species. This species is already widely distributed in the oceans worldwide, but seems to widely occupy estuarine habitats like *Hediste diversicolor* in Europe and *H. japonica* in Asian waters (Sato 2013). The present study showed that *N. succinea* comprised >70% of all macrobenthic animals collected within August 2016 (Tables ES2, ES4), showing that this species is highly resistant to hypoxic conditions. According to Sato (2013), in Nagoya Port, located at the innermost part of Ise Bay, *N. succinea* commonly inhabited interstitial spaces within sessile organisms, including exotic bivalves (*Xenostrobus secures*, *Perna viridis*, and *Mytilopsis sallei*) and barnacles (*Balanus eburneus*, *Balanus improvisus*, and *Balanus amphitrite*) (Kimura & Horii 2004). Interestingly, the spionid polychaete *P. kempi* and *N. succinea* were also abundant and dominant inside Shihwa Lake right after the dike construction (Hong et al. 1997). Therefore, the monitoring of these exotic invaders and their impact on coastal ecosystems is strongly suggested.

Changes in macrobenthic fauna were confirmed not only inside the dike, but also outside the dike, in Isahaya Bay and Shihwa Lake (Sato et al. 2007). In Isahaya Bay, the red tides and hypoxic water conditions have been observed frequently, and many bivalve species have decreased in number rapidly after the dike completion (Tsutsumi 2006). Kanazawa et al. (2005) and Uesugi et al. (2012) pointed out that the temporal changes in bivalve fauna were strongly affected by environmental changes, such as the occurrence of hypoxic water and changes in the grain size of bottom sediments, and those that were caused by the dike completion of Isahaya Bay. Moreover, the Shihwa Reclamation Project was halted in 1996 because of its negative effects on the environment, and the sluice gates were opened to introduce seawater into the dike (Lee et al. 2014). These facts suggest that the Saemangeum Dike might negatively affect not only the nearby coastal areas, but also the entire Yellow Sea ecosystem, in the long-term. To confirm this, future studies need to monitor the long-term changes of tidal flow, water quality, bottom sediments, and community structures of benthic animals outside of the Saemangeum Dike.

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Table ES1
Table ES2
Table ES3
Table ES4

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