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Research Article

Fundamental issues in Japan's coastal management system for the prevention of beach erosion

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Abstract

When an offshore or port breakwater is constructed on a coast, beach erosion often occurs on nearby beaches of the breakwater, due to the wave diffraction effect of the breakwater; this is associated with the formation of a wave-shelter zone, because longshore sand transport is triggered from outside to inside the wave-shelter zone. Similarly, when unidirectional longshore sand transport is blocked by a breakwater, beach erosion will occur downcoast. In these cases, longshore sand movement is the key factor; However another aspect has arisen from the management system of the land near a coast subject to such longshore sand movement. In Japan, the management of coastal land is under the jurisdiction of several agencies. When sand is transported alongshore across 2 management areas, the sand rights belong to the agency administrating the area to which the sand is deposited, and the agency administrating the area from which the sand originated has no rights. Thus, this leads to uncoordinated solutions to erosion problems, because longshore sand can freely move across the boundaries of coastal management areas. In this study, these issues were studied through real examples. Even though the accuracy of the predictive model of beach changes was increased, implementing fundamental changes for coastal conditions is difficult when this issue is as unsolved as it is.

1. Introduction

Beach erosion is mainly caused by an imbalance in the sediment budget of a coast. The fundamental processes of beach changes that result in beach erosion are described in detail in a textbook of coastal engineering (Dean & Dalrymple, 2002). The present author categorized beach erosion into 7 types on the basis of real cases (Uda, 2017). One type concerns the beach changes associated with the formation of a wave-shelter zone; when an offshore or port breakwater is extended, a wave-shelter zone is formed behind the breakwater concurrently with wave diffraction at the offshore tip of the breakwater, inducing longshore sand transport from outside to inside the wave-shelter zone, resulting in beach erosion outside the wave-shelter zone (Uda, 2017). Similarly, when unidirectional longshore sand transport is blocked by a port breakwater, beach erosion will occur downcoast. These are well-known phenomena, with many examples not only in Japan but also in Asian countries; in Taiwan, the Dawu fishing port breakwater had been extended since 1956,

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and southward longshore sand transport was blocked by the breakwater, resulting in severe downcoast erosion (Kumada et al., 2012). In the western part of Bali Island, Indonesia, prevailing north-westward longshore sand transport was blocked by the Pengambengan fishing port breakwater, resulting in the same downcoast erosion (Uda et al., 2015). As a measure, a seawall had been constructed, which caused further downcoast erosion. In Phan Thiet, Vietnam, land reclamation was carried out for port development; then, downcoast erosion occurred, increasing the necessity of successive measures against beach erosion (Noshi et al., 2019). In all cases, longshore sand movement was the key factor in determining the beach changes.

Although study of the mechanisms involved in each case is interesting for coastal engineering, there is another important issue which is deeply related to the management system of coastal land. In Japan, the management of coastal land is under the jurisdiction of several agencies, and each agency is set up in accordance with the provisions of relevant laws. When sand is transported alongshore across 2 management areas, the right to manage the sand belongs to the agency administrating the area to which the sand is deposited. This leads to uncoordinated solutions to erosion problems. In this study, this issue is investigated through several examples: Oharai Port, where sand deposition occurred owing to the formation of a wave-shelter zone of the port breakwater; Fukude Fishing Port, where beach changes occurred owing to the blockage of longshore sand transport; and issues arising from the management system used on the Ichiki and Kushikino coasts facing the East China Sea. Beach erosion in Japan is not just a simple technological problem but is deeply related to the fundamental management system defined by the relevant laws. A drastic reform of the legal and social systems is necessary to solve the beach erosion problem.

2. Beach changes associated with the extension of port breakwaters

2.1 Beach changes around port breakwaters

When a port breakwater is constructed offshore of a shoreline, a wave-shelter zone is formed on the lee of the structure, inducing longshore sand transport from outside to inside the wave-shelter zone due to the wave diffraction effect. As a result, beach erosion occurs outside the wave-shelter zone, whereas sand is deposited inside the wave-shelter zone, as schematically shown in **Figure 1** (Uda, 2017). Beach changes of this category have occurred at many beaches; the beach near Kashiwazaki Port in Niigata Prefecture, the coasts adjacent to Ohtsu fishing port, and Oharai Port in Ibaraki Prefecture in Japan (Uda, 2017).

This longshore sand transport continues to develop until the shoreline reaches a stable form behind the breakwater, as described by the concept of headland and equilibrium bay beaches (Silvester & Hsu, 1993). However, sand deposited inside the port is removed, because there is a navigation channel inside the port, and it is difficult for the shoreline to attain a stable form without sufficient measures, such as a jetty to block longshore sand transport. Erosion outside the wave-shelter zone and accretion inside the wave-shelter zone, therefore, continue to occur. At the final stage, the erosion zone, shown in **Figure 1**, is not restricted locally, but extends to a solid boundary, such as a headland or an artificial structure, far from the port breakwater, resulting in the formation of an artificial coastline protected by a seawall, together with concrete armor units installed against shoreline recession, because the houses and coastal facilities built along the coast far from the port breakwater must also be protected.

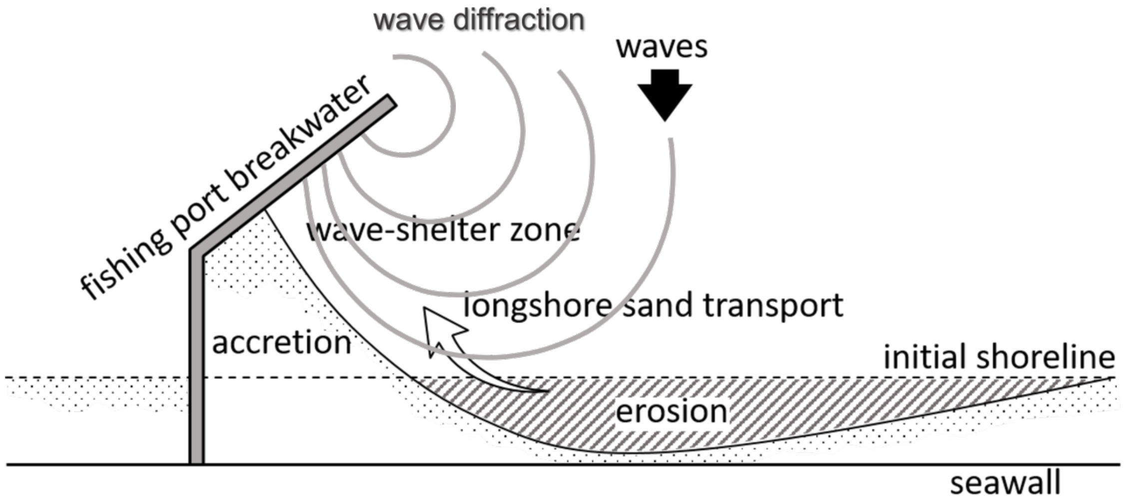

Figure 1 Schematic explanation of beach changes associated with formation of wave-shelter zone.

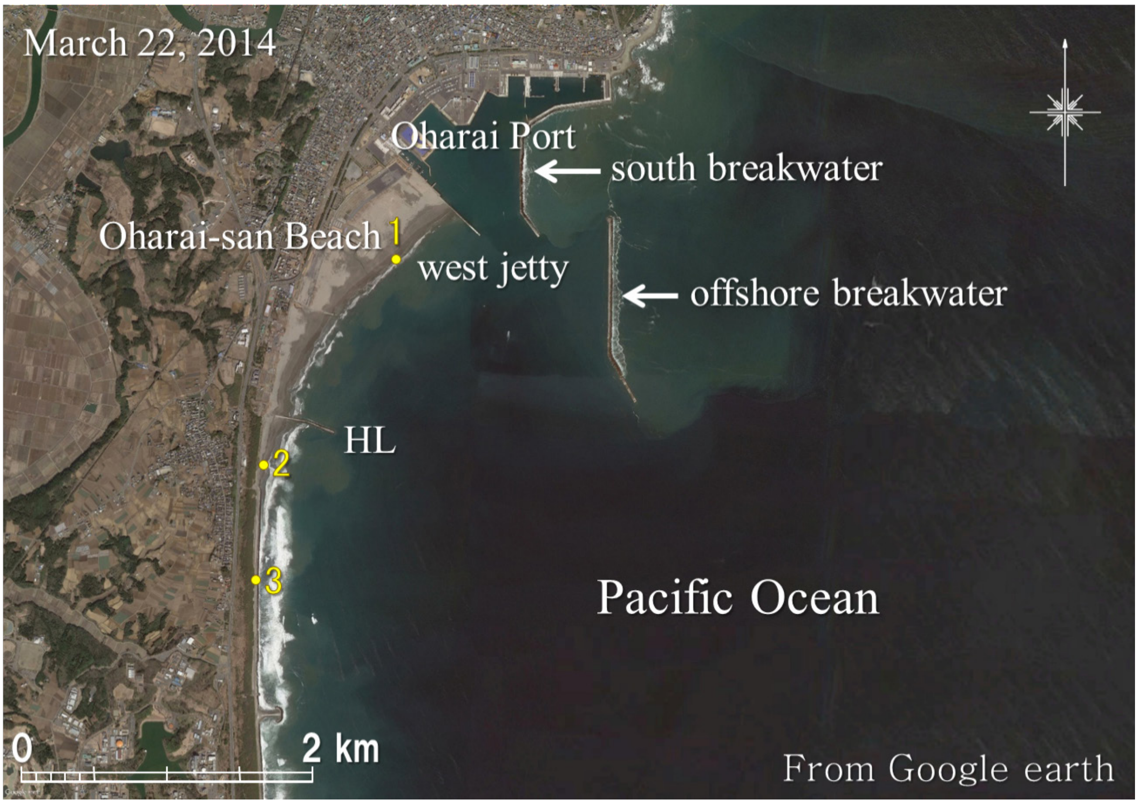

Figure 2 Satellite image of Oharai Port and nearby coasts.

Figure 3 Foreshore at south end of sandy beach in wave-shelter zone.

Figure 4 Sand deposition at boundary between accreted and eroded beaches.

2.2 Example of Oharai Port

A typical example of beach changes of this category can be observed around Oharai Port, facing the Pacific Ocean (Uda, 2017). **Figure 2** shows a satellite image of Oharai Port taken on March 22, 2014, where an offshore breakwater of 1.26 km length, a south breakwater, and a west jetty for preventing the deposition of sand into the port have been constructed. The locations (Nos. 1 - 3), whose photographs were taken on May 6, 2016, are also shown in **Figure 2**. The breakwaters of this port were constructed at the corner of a 40-km-long coastline. The predominant direction of waves of this coast is easterly; thus, a wide wave-shelter zone was formed on the lee (west side) of the port breakwater, which induced longshore sand transport from outside to inside the wave-shelter zone due to the wave diffraction effect. Owing to this effect, a large amount of sand was deposited in the wave-shelter zone, whereas the beach south of the port was severely eroded, and the coastline was covered with concrete blocks. The shoreline advanced up to 750 m relative to the original shoreline position before the construction of the port. The rate of longshore sand transport was estimated to be 2.8×10^5 m^3/yr between 1979 and 2004 (Uda, 2017) owing to the analysis of the bathymetric data. Now a wide sandy beach, Oharai-san Beach is used for recreation, but the coast south of the beach has been devastated, and all the sandy beach has disappeared and has been covered by the seawall and concrete armor units.

Figure 5 Artificial coastline protected by seawall and a number of concrete blocks.

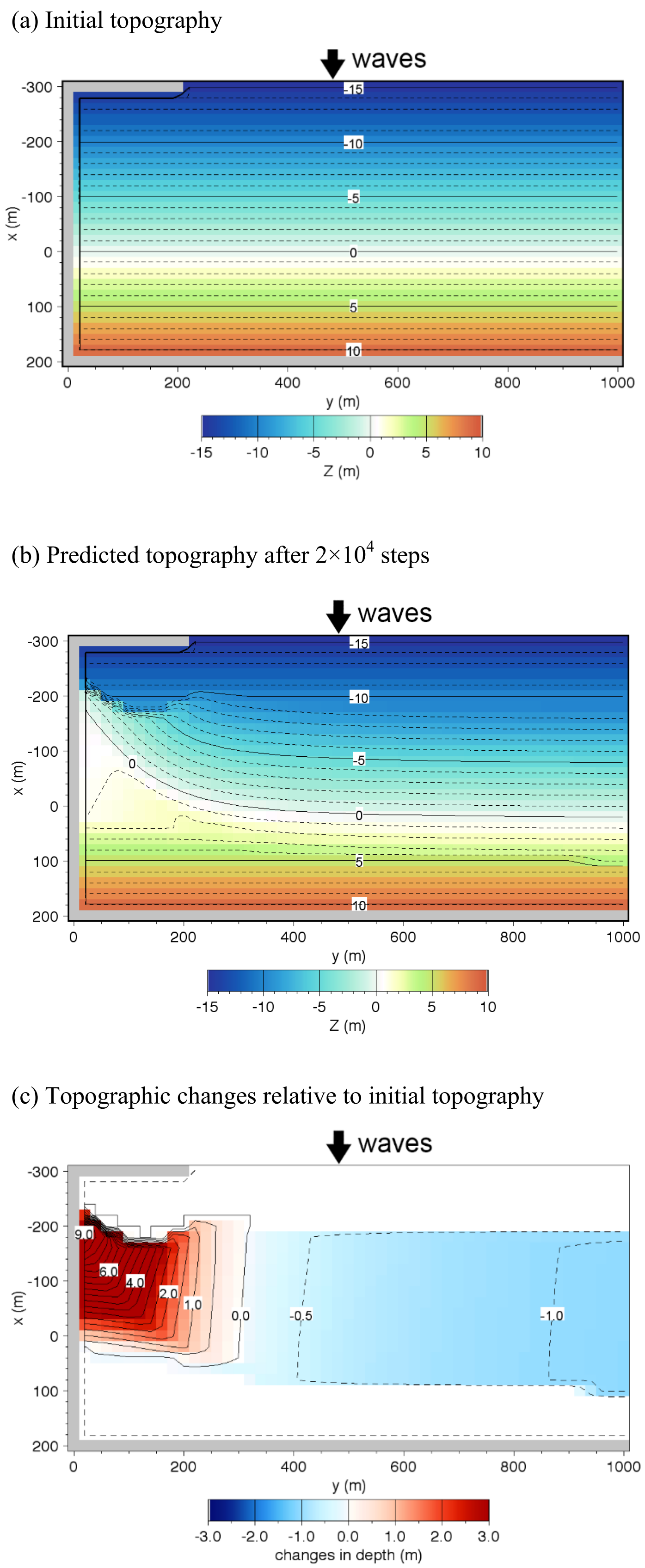

Figure 6 Initial and topographic changes after 2×10^4 steps of calculation in simulating beach changes on lee of a breakwater (Uda, 2017).

The changes in coastal conditions inside and outside the wave-shelter zone can be well documented from the differences in coastal conditions at 3 points, as shown in **Figure 2**. First, **Figure 3** shows a photograph of the beach at St. 1 at the northern end of Oharai-san Beach, taken on July 6, 2015, facing southwest. A large amount of fine sand of median diameter of 0.19 mm (Uda et al., 2020) had been deposited in the wave-shelter zone, forming a very gentle foreshore slope. The coastal conditions at St. 2 south of artificial headland No. 40 are shown in **Figure 4**. The sandy beach ended here, and the coast covered with the seawall and concrete blocks began. Further south, the coastline was heavily protected by a number of rocks and concrete blocks at St. 3 (**Figure 5**) for a long stretch of coastline, which contrasted well with the north coast at St. 1, and it was difficult for beach users or fishermen to approach the shoreline, owing to the blockage by concrete blocks. Despite the protection, a cave-in was found immediately behind the seawall because of the discharge of fill material underneath the seawall, and subsidence of the blocks had occurred.

The very gentle slope inside the wave-shelter zone was in strong contrast with the eroded coast, as shown in **Figures 3** and **5**. A beach was formed by the deposition of a large amount of fine sand in the wave-shelter zone, whereas an eroded and devastated coastline was left over a distance of 5 km south of the port.

2.3 Numerical simulation

The deposition of sand due to the wave diffraction effect behind a wave-shelter zone can be successfully predicted using the BG model (a model for predicting 3-dimensional beach changes, based on Bagnold's concept) (Uda, 2017; Uda et al., 2018). Consider a simple case schematically shown in **Figure 6(a)**, in which a straight offshore breakwater has been built at the left end of the calculation domain with an initial uniform beach slope of 1/20 (Uda, 2017). In the BG model, beach changes are assumed to occur in the depth zone between the berm height, h_R, and the depth of closure, h_c, at a given breaker height. In this study, the breaker height, h_c, h_R, and the critical slopes on land and on the seabed were simply assumed to be 3, 10, 3 m, and 1/2, respectively, as a model case, considering beaches facing the Pacific Ocean in Japan. On such a coast, the breaker height, with the occurrence of several times a year, ranges between 2 and 3 m, and h_c and h_R are approximately given by 10 and 3 m, respectively. Furthermore, we set $\Delta x = \Delta y = 10$ m, and $\Delta t = 0.05$ h.

Figure 6(b) shows the predicted topography around the offshore breakwater after 2×10^4 steps (10^3 h) of the calculation. Because of the wave-sheltering effect of the breakwater, longshore sand transport toward the wave-shelter zone was induced, and sand was deposited on the lee of the offshore breakwater concurrently with erosion on the nearby coast. The changes in depth in the calculation domain are shown in **Figure 6(c)**. Erosion occurred over a wide area, even far from the offshore breakwater, with a maximum change in depth of 1 m, whereas a large amount of sand accumulated behind the breakwater. This calculation result explains why sand accumulated on the lee of the offshore breakwater in Oharai Port.

3. Beach changes due to blockage of longshore sand transport

3.1 Example of Fukude Fishing Port

When a long breakwater is extended on a coast with predominant longshore sand transport, the shoreline advances upcoast and recedes downcoast (Dean & Dalrymple, 2002). Beach changes of this category have also occurred along many coasts in Japan (Uda, 2017). A typical example can be seen around Fukude Fishing Port, facing the Pacific Ocean and located 9.4 km downcoast of the Tenryu River mouth (**Figure 7**) (Kainuma et al., 2018). Along this coast, port breakwaters were constructed at the Ota River mouth, where eastward longshore sand transport prevails. Soon after the construction, sand started to deposit west of the breakwater, whereas erosion occurred downcoast. After the extension of the breakwater, a large amount of sand was deposited inside the port, making it necessary to carry out dredging for maintenance every year. The cost of the dredging and the erosion downcoast increased over time, which forced the fishing port authority to construct a sand-bypassing system across the port.

With this system, the sand deposited immediately west of the port was artificially transported downcoast through a pipeline. The intake pipe for dredging which was attached to the pier extended from the west breakwater of the fishing port, as shown by a circle in **Figure 7**, and sea water containing approximately 10 % of sand was discharged from the pipe downcoast of the fishing port. Sand-bypassing was started at a rate of 8×10^4 m^3/yr in March 2014. The intake pipe, however, was frequently blocked, because of the entanglement of floating debris such as driftwood, which were transported from the Tenryu River mouth west of the fishing port. Thus, the planned transport of sand still has difficulty in practice.

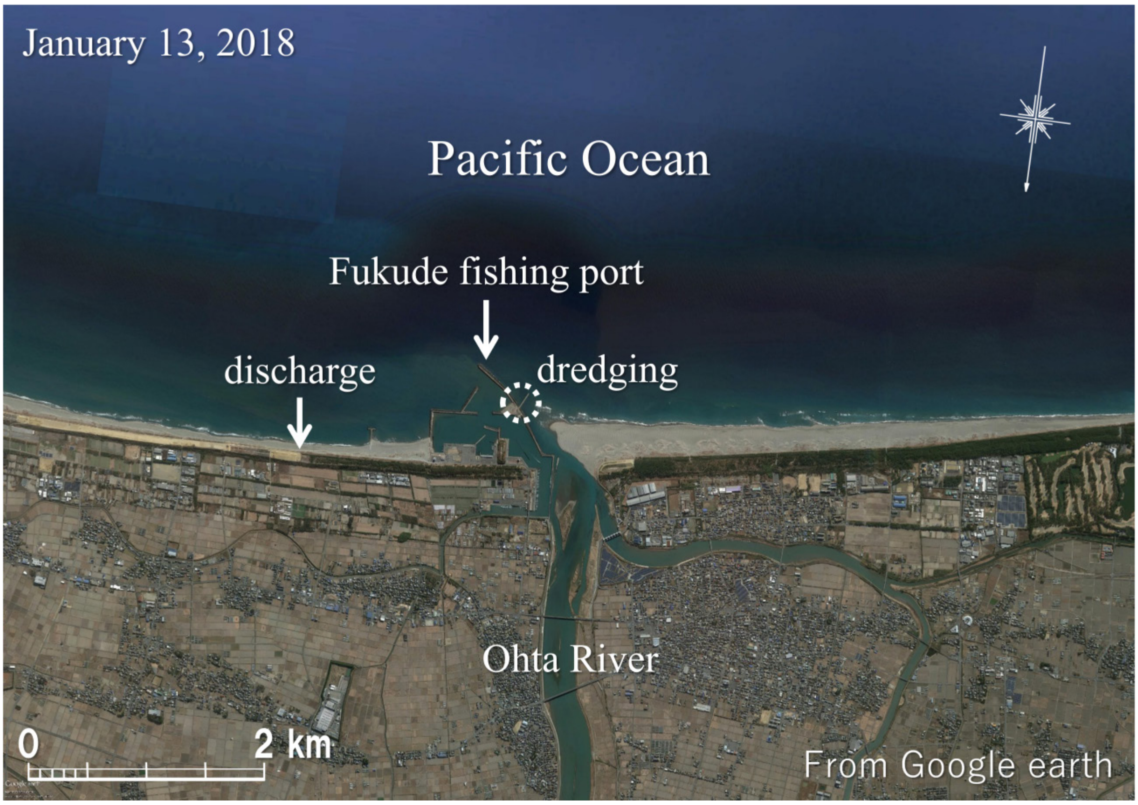

Figure 7 Satellite image of Fukude Fishing Port facing the Pacific Ocean.

3.2 Beach changes around Fukude Fishing Port

Beach changes over time around this port can be effectively compared using the bathymetries measured at 100 m intervals alongshore by a single beam depth meter in 1993, 2004, and 2016 (**Figure 8**). By February 1993, the west breakwater had been extended by 920 m southeastward from the shoreline, whereas the east breakwater was under construction (**Figure 8(a)**). At this stage, a wide sandy beach extended west of the port, whereas the beach width was narrow east of the port owing to the partial blockage of eastward longshore sand transport by the breakwater. The predominance of eastward longshore sand transport can be recognized from the fact that the 5-m-depth contour shows asymmetry near the breakwater. The 5-m-depth contour acutely intersects with the breakwater on the west side, whereas it has a concave shape on the east side, implying blockage of the eastward longshore sand transport near the location of 5 m depth.

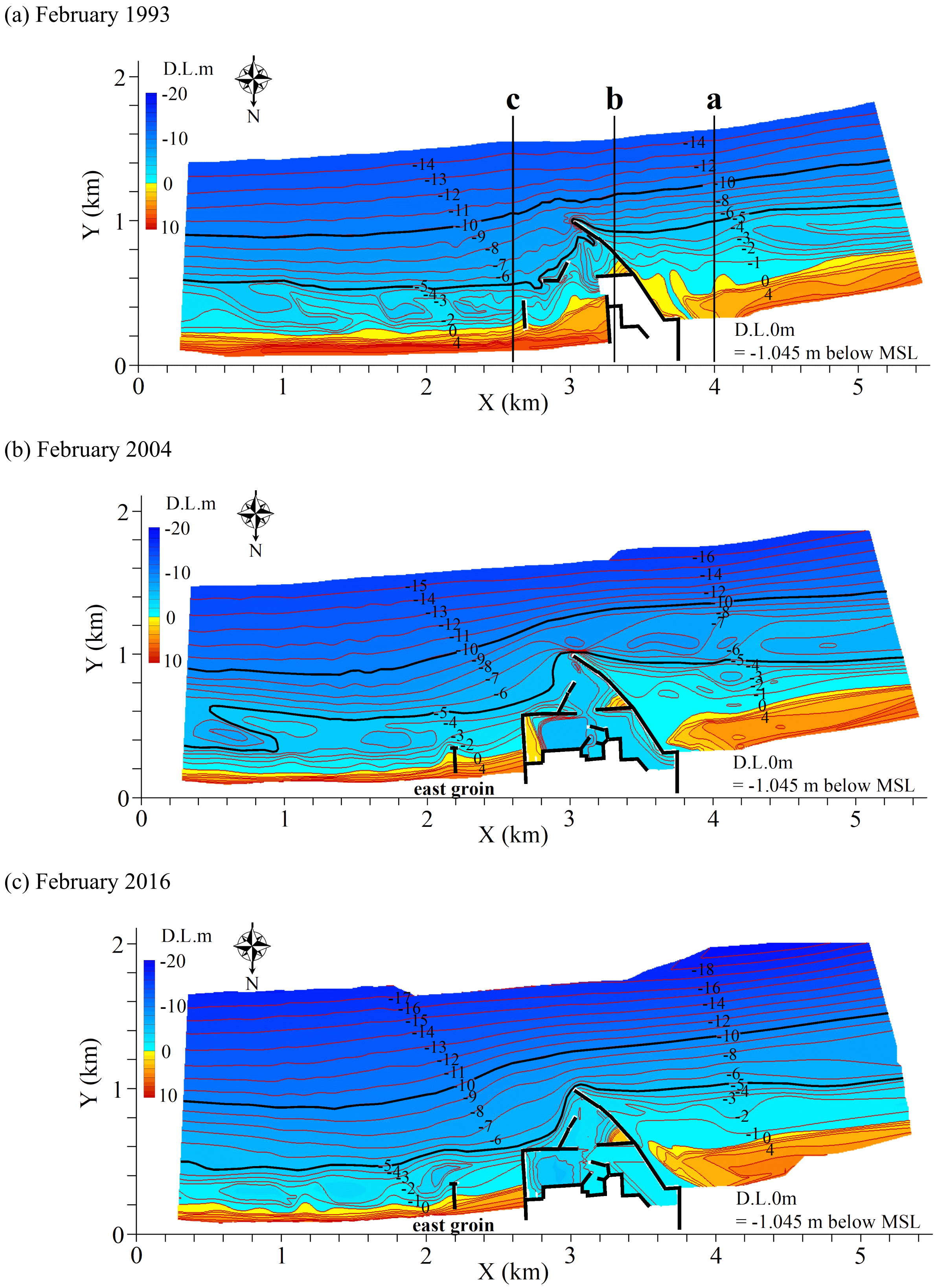

Figure 8 Bathymetries around Fukude Fishing Port measured in 1993, 2004, and 2016.

Figure 8(b) shows the bathymetry in the same area as that in **Figure 8(a)** in February 2004. The fishing port breakwater was completed in 2004, and water depth in the port increased owing to the dredging and extension of the east groin at a location 500 m east of the fishing port. At this stage, 5-m-depth contour exhibited strong asymmetry with respect to the west breakwater, with the depth of closure given by approximately 10 m depth. Moreover, the sandy beach was eroded east of the east groin. In February 2016, the 5-m-depth contour significantly meandered at the tip of the west breakwater, and a concave contour was formed downcoast of the fishing port (**Figure 8(c)**).

The topographic changes around this fishing port were further investigated on the basis of the bathymetric changes until 2004 and 2016, with reference to those in 1993. **Figure 9(a)** shows the bathymetric changes in eroded and accreted areas occurring between 1993 and 2004. By 2004, sand was deposited west of the port, whereas the east side of the port beach was eroded because of the predominance of eastward longshore sand transport. West of the fishing port, the accretion zone extended to a depth of 13 m and covered the entire fishing port facility. In contrast, east of the east groin, severe beach erosion occurred in a zone shallower than 5 m in depth. **Figure 9(b)** shows the topographic changes occurring between 1993 and 2016. The topographic changes were more intense because of the longer comparison period than that shown in **Figure 9(a)**.

(a) February 1993 → February 2004

(b) February 1993 → February 2016

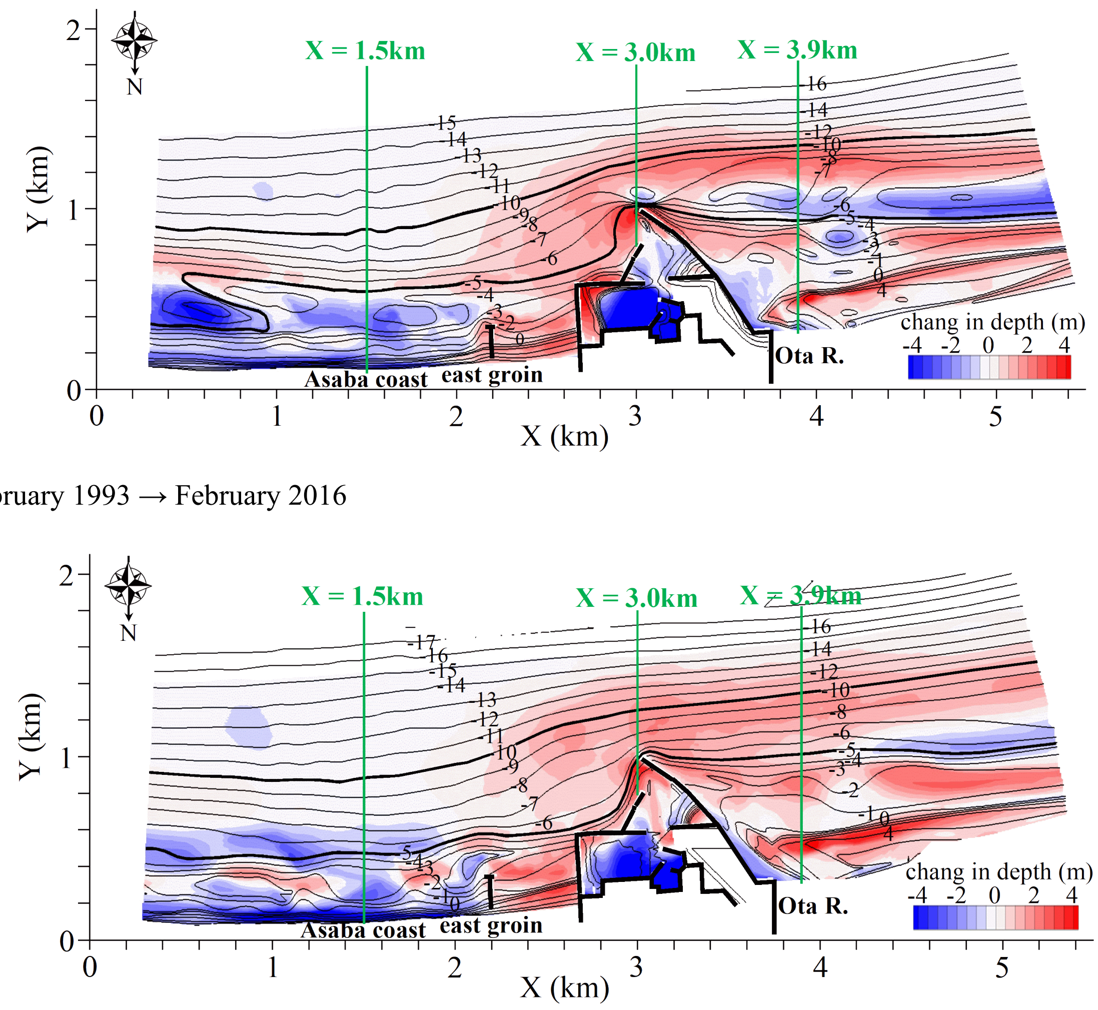

Figure 9 Bathymetric changes around Fukude Fishing Port.

In this case, the shore protection of the eroded area downcoast of the east groin is under the jurisdiction of another agency, not the fishing port agency. Therefore, comprehensive measures against beach erosion are difficult to adopt, similar to the cases in Oharai Port and nearby areas.

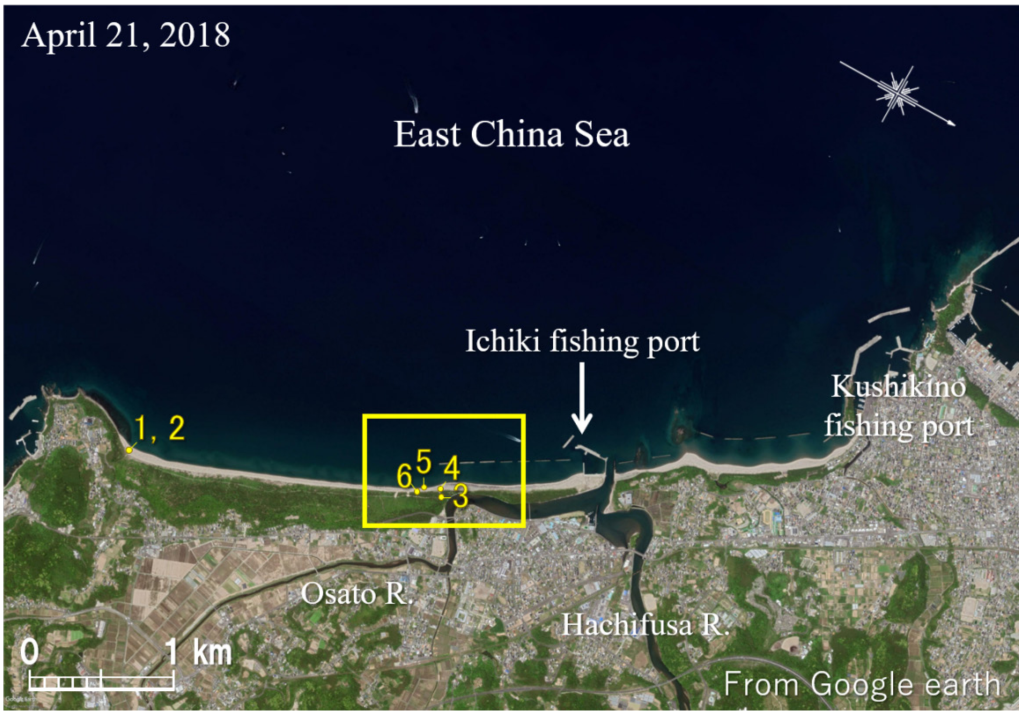

Figure 10 Satellite image of Ichiki and Kushikino coasts in Kagoshima Prefecture, Japan.

Figure 11 Photograph of sand dune and backshore taken at St. 1.

4. Structural problems arising from management system of coast

4.1 Example of Ichiki and Kushikino coasts

A typical example can be found on the Ichiki and Kushikino coasts, located in Satsuma Prefecture in Kyushu (**Figure 10**). A pocket beach of a 5 km stretch, with a sand dune behind, extends along the coastline. South of Ichiki Fishing Port, 7 detached breakwaters were constructed parallel to the coastline to prevent sand from depositing inside the fishing port. In this area near Ichiki Fishing Port, the coastal zone is separated into 3 areas for management: the fishing port area extends between the river mouth and the south end of the detached breakwaters, the shore protection area is immediately south of the fishing port area, and the area behind the coastline is controlled as a coastal forest area. These areas are designated as provided by 3 relevant laws.

On December 7, 2019, field observation was carried out; the coasts at the south end of the pocket beach and near the south end of the detached breakwaters south of Ichiki Fishing Port. In the satellite image of this area (**Figure 10**), the numbers of sites where photographs were taken are shown. **Figure 11** shows the photograph of St. 1 in the backshore area at the south end of the pocket beach, facing the north. A gentle slope extended from the sand dune to the shoreline, with a backshore covered with low coastal vegetation. In front of the vegetation, a wide, natural sandy beach of 50 m width extended (**Figure 12**).

Figure 12 Sandy beach of approximately 50 m width, extending northward, without artificial structures.

Figure 13 Photograph of coastal conditions at south end of detached breakwaters taken at St. 3.

Figure 13 shows the coastal conditions at St. 3, close to the Osato River mouth. In the offshore area, detached breakwater Nos. 4, 5, and 6 can be seen, with the formation of a sandy beach behind each detached breakwater. The beach conditions south of St. 4 is shown in **Figure 14**. Although the seaward slope of the sand dune was densely covered with coastal vegetation, it was found that coastal forest disappeared at the location encircled in **Figure 14**, and a protection facility is seen in the distance in front of the coastal forest. **Figure 15** shows the shoreline at St. 5, facing the south. Around the protective structures, the slope covered with vegetation in front of the coastal forest disappeared, and the earth surface was bare owing to erosion. Furthermore, the shoreline markedly retreated in front of the area, resulting in a reduction in the beach width.

These findings imply that the beach was eroded in this vicinity, forming a scarp, and shore protective facilities were installed to prevent further erosion. **Figure 16** shows a close-up view of the facilities; many filter units with gravel inside were placed along the coastline, and extremely unnatural conditions were produced, in strong contrast to the natural conditions shown in **Figure 11**, taken at the south end of the coastline. Because this coast is a pocket beach, a natural beach can be maintained as it is, unless artificial alteration is made. In this case, as a result of the construction of detached breakwaters immediately north of the study area, longshore sand transport toward the lee of the detached breakwaters was triggered, which was the fundamental reason for the beach erosion.

Figure 14 Protective structures, such as filter units, were seen at the location shown by a circle in front of the coastal forest.

Figure 15 View of protection facilities and shoreline from St. 5.

Figure 16 Close-up view of filter units taken at St. 6.

4.2 Reason behind the formation of artificial coast

The agency administering Ichiki Fishing Port constructed detached breakwaters, on the basis of the Fishery Law, to prevent sand from being deposited in the port. However, the breakwaters triggered the longshore movement of sand from the south coast to the lee of the detached breakwaters, resulting in erosion of the shore and coastal forest, which had been designated as protected areas in accordance with the Seacoast Law and the Forest Law, respectively. Since sand deposited in these designated areas is transported alongshore across their boundaries, national land management under this static condition has limitations for variable conditions, as in coastlines.

In Japan, the right of management of sand deposited in a designated area belongs to the designated management agency. Sand movement, however, occurs independent of this management system. Because sand management is undertaken by each independent management agency, disharmony will occur in this management unless proper coordination is taken among the relevant agencies.

In the present case, the agency administering the coastal forest, where severe beach erosion occurred, was forced to protect the forest land on the basis of the Forest Law, and filter units were placed to prevent beach erosion in the eroded area, as shown in **Figure 16**. **Figure 17** shows an enlarged aerial photograph of the rectangular area shown in **Figure 10**. Sand was transported to the lee of the detached breakwaters across the boundary between the natural coast and the area protected by detached breakwaters, forming a salient, whereas the shoreline retreated and the beach width decreased south of the detached breakwaters. Although a large salient developed behind detached breakwater Nos. 7 and 6, the size of the salient significantly decreased northward.

Point A was set at a location where the original shoreline was maintained because there was no marked sand deposition behind detached breakwater No. 4, and point B was set 430 m south of detached breakwater No. 7, where the effect of the installation of the detached breakwaters was assumed to be minimal. Therefore, it is considered that sand was deposited where the shoreline advanced from this solid line, and vice versa.

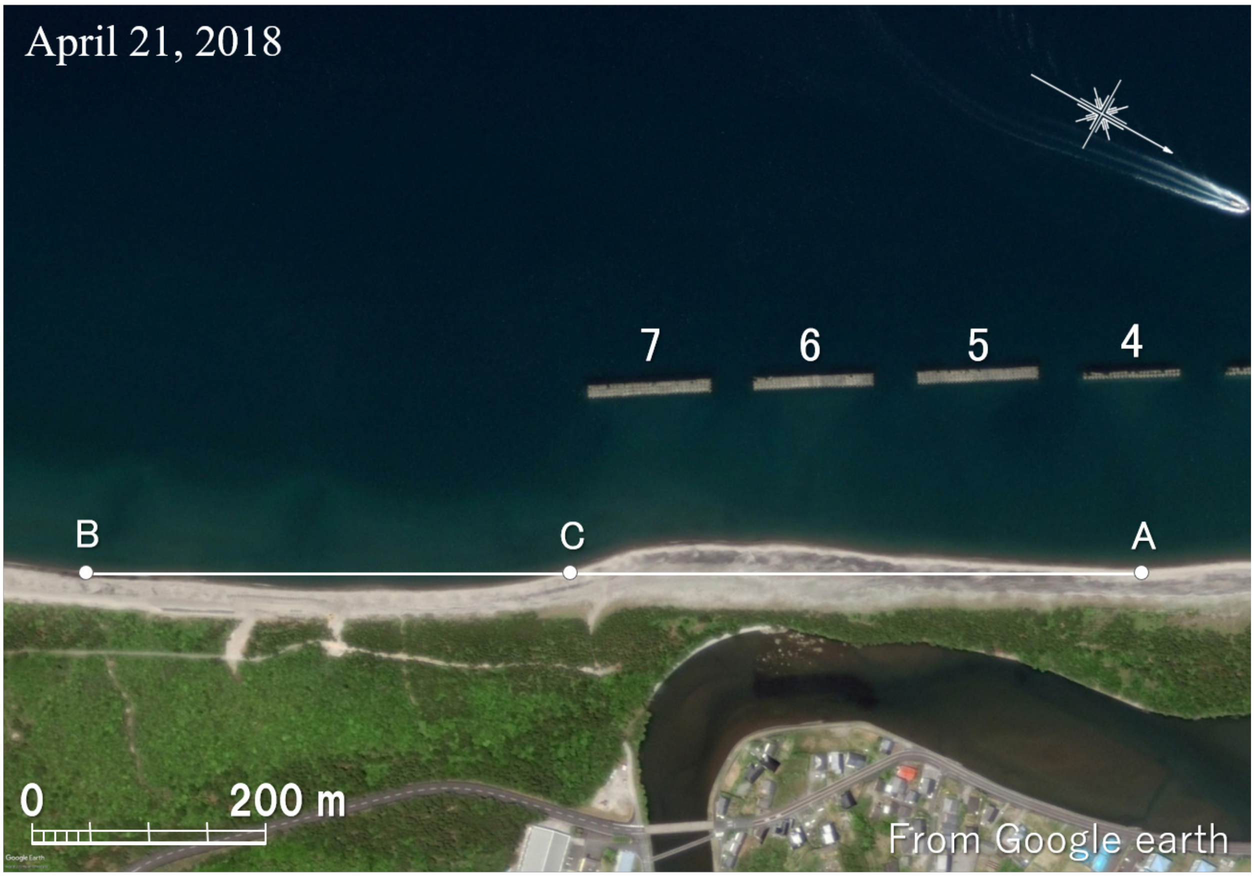

Figure 17 Enlarged satellite image of south end of detached breakwaters.

In **Figure 17**, the shoreline retreated between points B and C south of the detached breakwaters, and the shoreline advanced between points C and A behind the detached breakwaters at this stage. This is a natural phenomenon after the construction of a wave-sheltering structure, and beach changes triggered by the construction of coastal structures can be predicted by using a numerical model, such as the BG model (Uda et al., 2018). Even though prediction is possible, the reason why the issue cannot be solved is the separation of the agencies managing the coastal areas. The preventive measures against sand movement across the different management areas is difficult to implement because of this separation. In fact, measures have always been taken after the erosion has occurred.

In general, the management of coastal land has been carried out on the basis of several relevant laws in Japan. For example, port and fishing port constructions are subject to the Port Law and the Fishing Port Law, respectively, to develop coastal areas. Shore protection and the protection of coastal forests are respectively controlled by the Coast Law and the Forest Law to conserve coastal lands (Uda, 2017). The areas designated in accordance with the laws are clearly separated by a line between them. Even though the shoreline will change over time, owing to the movement of sand, various issues have arisen because the boundary between the areas of management is fixed.

These conditions are schematically shown in **Figure 18**. In the present case, the coastal zone in the sea is separated into the shore protection area and the fishing port area, and each area is controlled by independent management agencies. In contrast, the shore protection area of a certain width is designated in accordance with the Coast Law, and the coastal forest area extending landward of the shore protection area to block wind and salinity is designated in accordance with the Forest Law.

When the shoreline recedes with erosion, as shown in **Figure 18**, not only the land in the shore protection area, but also the land in the coastal forest zone, is eroded. Sand is transported toward the lee of the detached breakwaters constructed in the fishing port area by longshore sand transport. However, the management agencies have no right to manage the transported sand, and they only carry out damage restoration work on the eroded beach using protection facilities after the erosion has occurred. In fact, sand does not disappear from the area, but all the sand is deposited in the adjacent area, managed by a different agency.

Under the present system, however, a measure to compensate for the imbalance cannot be adopted, and concrete armor units or filter units are temporarily adopted as cheap, stopgap measures, taken after the damage has occurred and without coordination among the agencies relevant to shore protection, coastal forest, and fishing port authorities. Since the present situation remains as it is, the length of the artificial coastline, covered with many structures, increases over time.

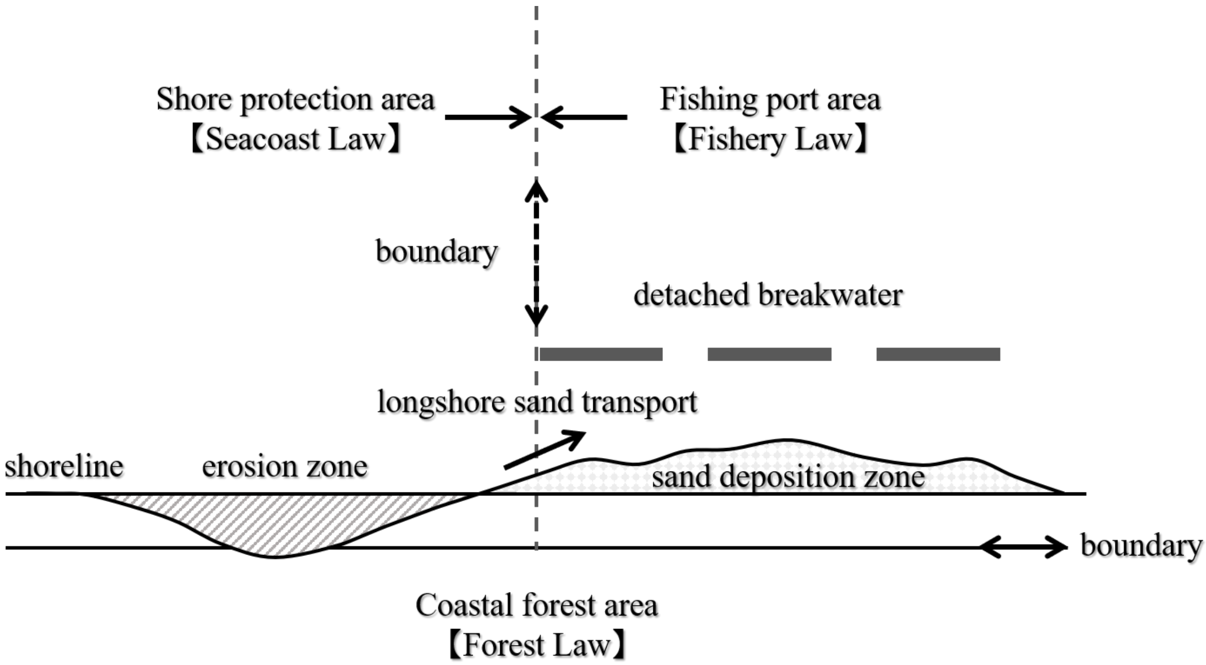

Figure 18 Management areas near coastline.

5. Conclusions

Longshore sand can freely move across the boundaries of coastal management areas artificially set by human beings. Sand transported away from the coastal forest area and deposited in the shore protection and coastal forest areas is an important resource involving national land. When it is transported into the fishing port and deposited in the navigation channel, however, it becomes an obstacle. Accordingly, the proper adjustment of this relationship is required. Among the relevant administration areas, the occurrence of sand movement across their boundaries should be acknowledged, and after taking measures to reduce sand movement as much as possible, a system for sand back-passing, by which sand is returned to the original coast, must be established cooperatively among the relevant agencies, using an appropriate cost allocation method.

This author has believed that natural coasts can be well preserved when a method of accurately predicting future beach changes is established. In this study, however, it was definitely recognized that the most fundamental barrier to the solution of beach erosion problems in Japan is the coastal management system itself, established on the basis of relevant laws. In this case, even though the accuracy of the predictive model is increased, implementing fundamental changes in the coastal conditions is difficult.

In recent years, a comprehensive management of sand has been proposed in Japan, but fundamental changes in sector-by-sector thinking must be considered, in order to drastically change the present conditions of coasts in Japan.

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