1 What is tidal flat?

1.1 Introduction

Wave and current energies are important factors in determining the physico-chemical and biological conditions in coastal ecosystem. Sandy beach develops in the area of very high physical energies facing open ocean where coarse grained sands make beach and sediments are completely oxidized. On the other hand, tidal flat develops under sluggish currents in river mouth and semi-enclosed coastal area where finer particles are trapped in the flat and sediments show strong reducing conditions sometimes to sediment surface.

Tidal flat ecosystem differs from the aquatic ecosystem in the sense that the former is exposed to sunlight directly at ebb tide and is submerged at flood tide. In tidal flat the primary producers are not phytoplanktons but phytobenthos. Pelagic production such as production by phytoplanktons is also supplied from seawater. Filter feeding benthic organisms such as bivalvia depend on currents to transport oxygen and pelagic productions and carry away wastes. There are other benthic organisms, which move through the sediment and take food from the sediment itself. They are called deposit feeders and include worms and amphipods. Tidal flat ecosystem is not a uniform system. Physico-chemical gradients are observed along the depth such as oxidizing and reducing conditions in the sediment, fluid condition and salinity in overlaying water. These variations produce rich benthic systems.

As a result of industrial and urban developments of coastal area in Japan, tidal flats are endangered. Like natural wetlands in U.S.A, the loss of tidal flats is one of the largest environmental concerns in Japan. According to the Environmental Agency in Japan, the area of natural tidal flats was approximately 82,600 ha during the 1940s. However, by the 1980s, nearly forty percent of the natural ones were lost (Kimura 1994). Currently, many efforts have been made to protect natural tidal flats and wetland ecosystems. In addition, there were many projects aiming to restore damaged tidal flats and create man-made tidal flats to mitigate lost ones (Confer et al. 1992, Miyoshi et al. 1990, Ogura et al. 1995).

Any creation and restoration of tidal flats should recover functions and values of natural tidal flats. Despite increasing restoration and creation projects, only a few studies have been carried out on the functions of man-made ones. For man-made tidal flats to secure the typical functions of natural tidal flats, it is necessary to identify and understand relationships between functions and environmental condition, design criteria, and age of man-made tidal flats.

This chapter deals with the experimental approach to reveal the function and structure of both natural and man-made tidal flats and the factors to determine the function and structure of tidal flat through on-site investigations and laboratory experiments. (Lee J.G et al. 1997, 1998a, 1998b, 1999a, 1999b).

1.2 Function and structure of natural and man-made tidal flats

1.2.1 Physico-chemical characteristics

The study sites were selected in the northern part of Hiroshima Bay, which is located in the western part of the Seto-Inland Sea, Japan (Fig.1.1). The Ohta River flows into the northern part of this bay. Table 1.1 summarized characteristic features of natural and man-made tidal flats. Man-made tidal flats were constructed for various purposes like oyster and clam cultures, bathing resort and compensatory mitigation. The significant difference in water quality in the northern part of Hiroshima Bay was not observed: DO (dissolved oxygen) and COD (chemical oxygen demand) at St.2 located at the middle of the bay and St.8 located at the back of the bay ranged from 10.7 to 12.4 mg l^{-1} and from 0.9 to 1.2 mg l^{-1}, respectively (Maritime Safety Agency 1997). It was presumed that the water quality in the northern part of the bay and, offshore of all the tidal flats was almost the same.

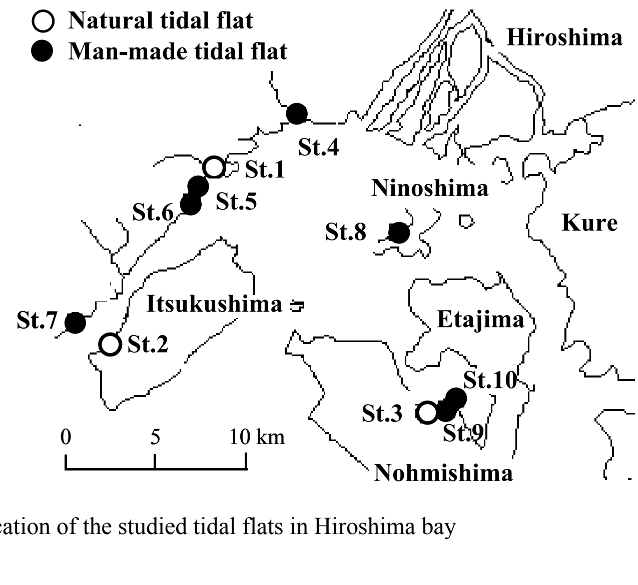

Fig. 1.1. Location of the studied tidal flats in Hiroshima bay

Table 1.1. The studied tidal flats in Hiroshima bay

Site	Origin	Area (ha)	Slope	Constructed year	Purpose
St.1	Natural	24	1.0/100	-	
St.2	Natural	4.7	1.0/100	-	
St.3	Natural	3.3	1.6/100	-	
St.4	Man-made	24	2.5/100	1990	Compensatory mitigation
St.5	Man-made	3.2	0.4/100	1986	Oyster culture
St.6	Man-made	6.7	0.7/100	1973	Oyster culture
St.7	Man-made	1.2	1.5/100	1984	Clam culture
St.8	Man-made	5.0	2.0/100	1987	Clam culture
St.9	Man-made	2.3	4.0/100	1987	Bathing resort
St.10	Man-made	2.3	0.7/100	1987	Oyster culture

Table 1.2. Physico-chemical characteristics of sediment in the tidal flats

Site	Origin	Mean medium (mm)	Silt (%)	Carbon (mg g-dry^{-1})	Nitrogen (mg g-dry^{-1})	Reducing zone (cm)
St.1	Natural	0.49	4.77	10.25	0.93	-2
St.2	Natural	0.39	2.71	3.30	0.33	-2
St.3	Natural	0.57	8.68	5.28	0.52	-2
St.4	Man-made	1.60	0.03	1.50	0.07	ND
St.5	Man-made	0.88	0.85	1.28	0.13	-25
St.6	Man-made	0.42	0.35	1.52	0.10	-15
St.7	Man-made	0.49	0.50	2.08	0.23	-20
St.8	Man-made	0.40	0.87	0.90	0.10	ND
St.9	Man-made	0.80	0.05	1.09	0.10	ND
St.10	Man-made	0.46	2.78	3.78	0.30	-2

Reducing zone: soil depth from the surface showing minus potential.
ND: reducing zone was not detected within core sample of 30 cm.

Fig.1.2 shows vertical profiles of particle size distribution of soils in the typical natural (St.2) and man-made (St.8) tidal flats. Median particle diameters in the natural tidal flat were 0.6 mm in the surface (0 ~ 2 cm) and 0.28 ~ 0.42 mm under 2cm-depth. Median particle diameters in the man-made tidal flat were 0.26 ~ 0.38 mm through all depths. There is no significant difference between the two tidal flats with respect to the median particle diameter. However, silt content indicated large difference between the tidal flats. The natural tidal flat had larger amount of silt (3.5 ~ 6.6 %) compared with the man-made tidal flat (0.4 ~ 1.6 %). The contents of silt for all tidal flats studied are given in Table 1.2. The silt contents in the natural tidal flats were higher than those in the man-made tidal flats except St.10. The silt content at St.10 was the highest among the man-made tidal flats and was almost the same as those in the natural ones. The organic carbon content of soil was in the range of 3.30 to 10.25 mgC g^{-1} in the natural tidal flats and 0.90 to 3.78 mgC g^{-1} in the man-made ones. The organic carbon at St.10 was 3.78 mgC g^{-1}, which was also the highest among the man-made ones and was also similar to those in the natural ones.

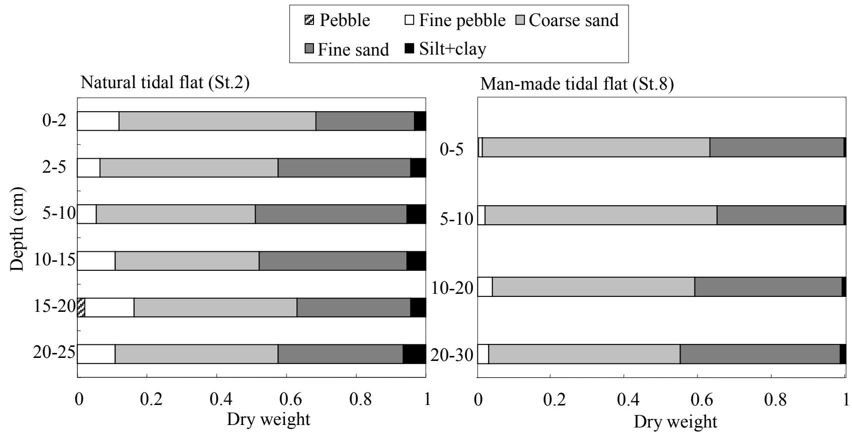

Fig. 1.2. Vertical profiles of particle size distribution of soils in natural and man-made tidal flats. Pebble: >4.75mm, Fine pebble: 2.00~4.75 mm, Coarse sand: 0.425~2.00 mm, Fine sand: 0.075~0.425 mm, Silt+sand: 0~0.075 mm

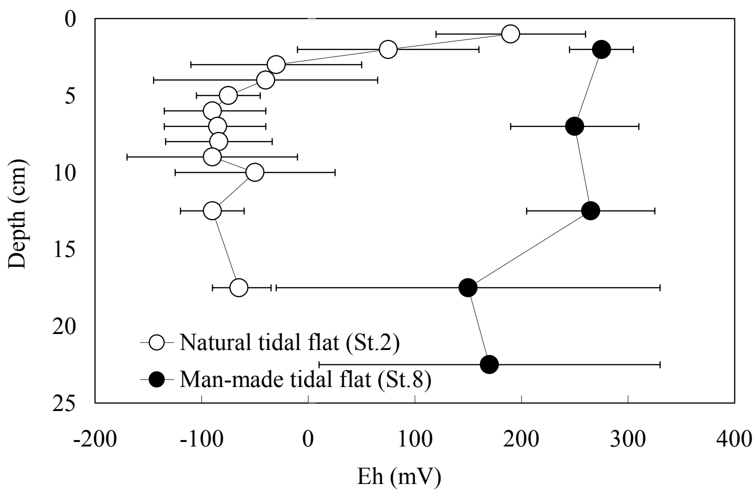

Fig. 1.3. Vertical profiles of ORP in soils of natural and man-made tidal flats

Vertical profiles of ORP (oxidation-reduction potential) at St.2 and St.8 are shown in Fig.1.3. The ORP of soil at St.2 showed positive values from the surface to 4cm in depth and dropped to negative values at zones below 4 cm but negative values were not noted through all depth studied. Other man-made tidal flats except St.10 also showed oxidizing zone in soil shallower than 15 cm in depth. It is clear that there were significant differences in the contents of silt, organic carbon and vertical profile of ORP between the natural and man-made tidal flats. However, the soil at St.10 showed almost the same physico-chemical characteristics with those in the natural ones even though St.10 is a man-made tidal flat.

1.2.2 Hydraulic characteristics

Fig.1.4 shows the diurnal changes of groundwater levels in the natural (St.2) and man-made (St.8) tidal flats. The groundwater level at St.2 did not fall beyond 2 cm even though the seawater level was 135 cm lower than the site studied. On the other hand, the groundwater level at St.8 decreased until 9 cm in depth. These results indicate that seawater and air can be induced into soil every tidal action until 2 cm and 9 cm in depth in the St.2 and St.8, respectively, corresponding to the results of ORP. Those may be the active zones of bacteria and benthic organisms and the responsible zones for the degradation of organic matter in seawater.

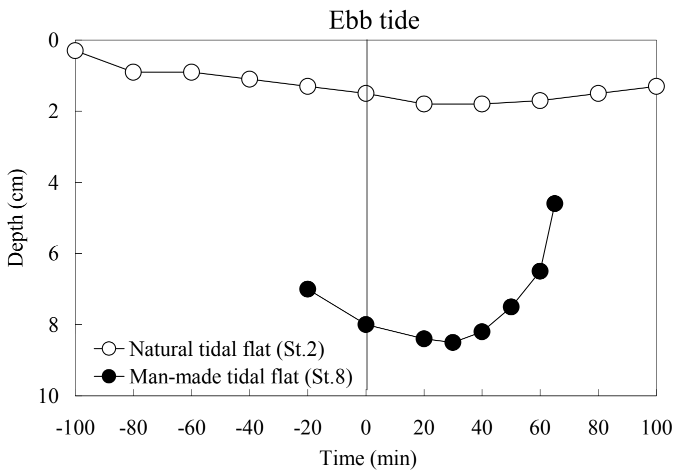

Fig. 1.4. Diurnal changes of groundwater levels in natural and man-made tidal flat

1.2.3 Biomass of bacteria and macrobenthos

Fig.1.5 shows seasonal changes of bacterial population at the surface of the natural (0-2 cm at St.2) and man-made (0-5 cm at St.8) tidal flats. Bacterial population in soils of the natural tidal flat ranged from 1.6 to 3.6 × 10^9 cells $g\text{-dry}^{-1}$ but seasonal change was not observed. Similar result was obtained for bacterial population at the man-made tidal flat. Fig.1.6 shows bacterial populations at the surface of soil in 10 tidal flats. Bacterial populations ranged from 1.6 to 2.5 × 10^9 cells $g\text{-dry}^{-1}$ in the natural tidal flats while the populations in the man-made tidal flats were in the range of 0.07 to 0.38 × 10^9 cells $g\text{-dry}^{-1}$ except for St.10. The bacterial population in soil of the man-made tidal flat was one to two orders of magnitude lower than in soil of the natural one. However, the population at St.10 was 2.3 × 10^9 cells $g\text{-dry}^{-1}$. This was the highest among the samples collected from the man-made tidal flats and was similar to those in the natural tidal flats. Fig.1.7 shows vertical profiles of bacterial population in soils at St.2 and St.8. The bacterial populations did not change by depth at both tidal flats. Organic carbon supplied from seawater must be different between infiltration and non-infiltration zones that were from the surface to 2 cm in depth and below 2 cm at St.2, and the surface to 9 cm and below 9 cm at St.8, respectively. Results indicate that bacterial population is independent of organic carbon supplied.

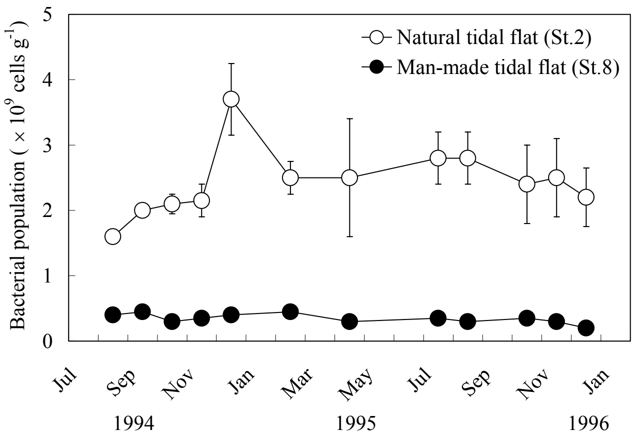

Fig. 1.5. Seasonal change of bacterial population in natural and man-made tidal flats

Fig.1.8 shows the biomass (as wet weight) and population of macrobenthos in the natural and man-made tidal flats. No remarkable difference between the natural and man-made ones was noted in the biomass. The percentages of bivalve to total biomass were extremely high at St.7 and St.8 due to artificial introduction of clam (principally *Ruditapes philippinarum*). Havens et al. (1995) reported that the biomass of macrobenthos in two natural tidal marshes and a man-made one were nearly the same and an apparent difference could not be found among them. The predominant species of macrobenthos in both tidal flats was Polychaeta. At St.10, however, Mollusca was the predominant species. Significant differences in both species and population of macrobenthos were not observed between the natural and the man-made tidal flats.

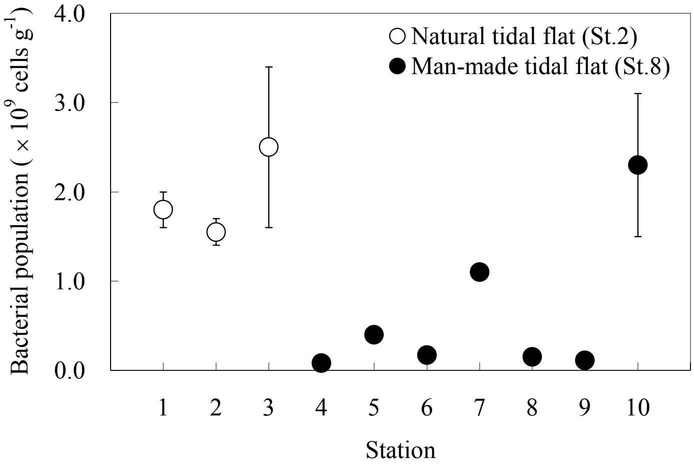

Fig. 1.6. Bacterial population in 10 tidal flats

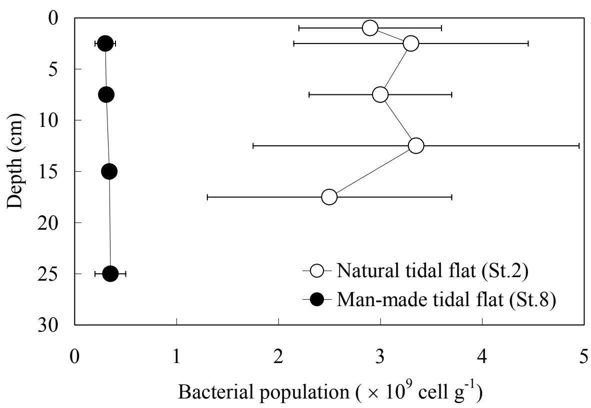

Fig. 1.7. Vertical profiles of bacterial population in soils of natural and man-made tidal flats

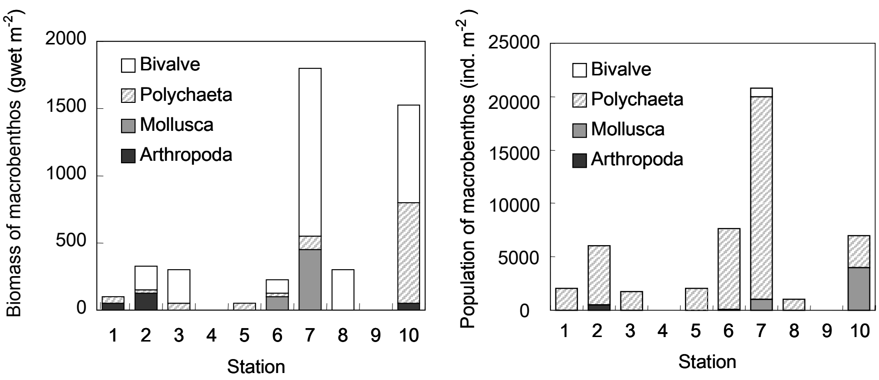

Fig. 1.8. Biomass and population of macrobenthos in natural and man-made tidal flats

1.2.4 Respiration rates of microorganisms

Respiration rates of microorganisms including bacteria, meiobenthos and attached phytoplankton were measured after the removal of macrobenthos from the soil sample. Fig.1.9 shows vertical profiles of microbial respiration rates in soil at St.2 and St.8. The respiration rates at the surface of soil in 10 tidal flats were summarized in Fig.1.10. The respiration rate at the surface of soil was extremely higher than other soil samples below 2 cm at St.2. On the other hand, the difference of the respiration rates between the surface and deeper zones at St.8 was relatively small which may be due to the seawater being supplied to all zones at St.8. The respiration rates below 2 cm were smaller at St.2 than St.8. These results mean that bacterial respiration depends on the supply of seawater with organic carbon and other nutrients. Moreover, bacterial population and organic carbon content in soil were not related to the respiration rate. Middelburg et al. (1996) also reported no correlation between the organic contents and their degradation rates in soils in river tidal flats. These results mean that not all organic contents in soil are utilized by bacteria and the amount of biodegradable organic matter existing in soil and supplied from seawater may determine respiration rate in soil. No significant differences in their rates at the surface of soil were observed between the natural and man-made tidal flats. The respiration rates at different tidal flats with different bacterial population and organic carbon content being almost the same may be due to the similarity of water quality of the tidal flats located in the same bay in terms of biodegradable organic matter content.

1.2.5 Discussion

Both physico-chemical and biological characteristics between natural and typical man-made tidal flats were significantly different on silt and organic carbon contents of soil, groundwater level and bacterial biomass. Vertical profiles of microbial respiration rates and ORP in soil of natural and man-made tidal flats were also different and related to groundwater level, that is, the zone where seawater is supplied keeps oxidative condition and high respiration activity of microorganisms due to organic and inorganic matters and oxygen supplied from seawater. Groundwater level in tidal flat may be determined by soil composition. Large amount of fine particles such as silt keeps water in soil structure and groundwater level does not fall significantly even ebb tide. Therefore, natural tidal flat with high silt content shows development of reducing zone to near the surface of soil and high respiration activity of microorganisms specifically at the surface of soil, whereas typical man-made tidal flat with low silt content shows oxidative condition until the deep zone and high respiration activity at all depths.

The bacterial population in soil of natural tidal flat showed one to two orders of magnitude higher than in soil of the typical man-made tidal flat even though microbial respiration rates were almost the same. Meyer-Reil et al. (1984) and DeFlaun et al. (1983) reported that bacterial population was affected by the size distribution of soil and bacterial population was high in soil at small size. Although organic matter supply from seawater is important to keep bacterial population, spatial habitat may be more important in these tidal flats located at Hiroshima bay.

Accumulation of fine particles such as silt in soil is proven to be very important in determining the physico-chemical and biological characteristics at tidal flat through this experimental approach. If fine particles can be accumulated in man-made tidal flat sediment, the man-made tidal flat may be a natural like tidal flat. The existence of St.10, which has almost the same characteristics as natural tidal flat, show man-made tidal flat can be made like natural one.

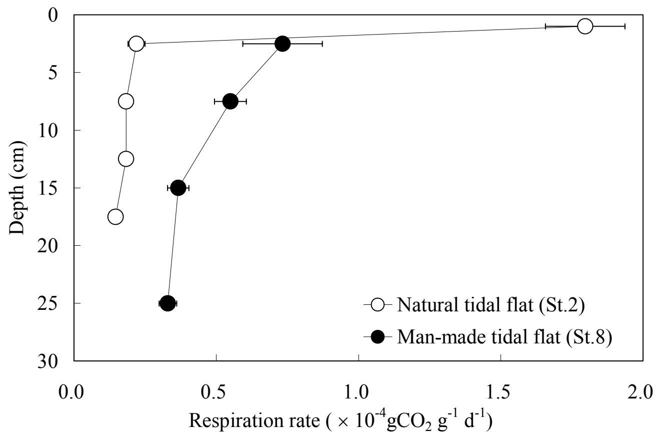

Fig. 1.9. Vertical profiles of microbial respiration rates in soil of natural and man-made tidal flats

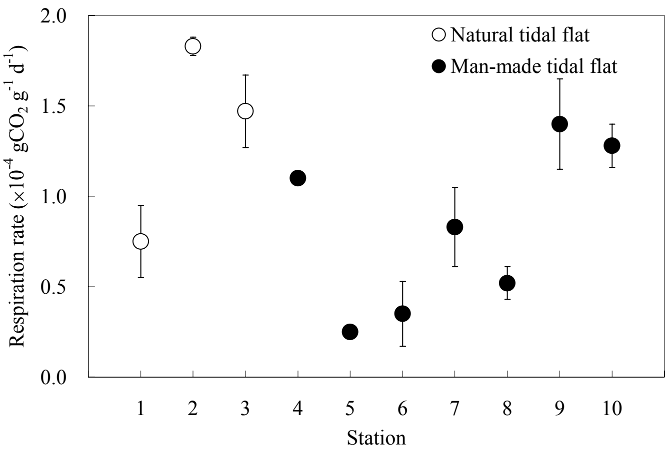

Fig. 1.10. Microbial respiration rates at the surface of soils in 10 tidal flats

1.3 Key factors in determining a tidal flat characteristic

1.3.1 Transfer experiments

The soil in a man-made tidal flat (St.8) was transferred to a natural one (St.2) and vice versa was conducted to find out controlling factors of tidal flat ecosystems. These two tidal flats had almost the same area (47,000 m^2 at St.2 and 50,000 m^2 at St.8). The site transferred was + 1.2 m datum level. The portions of the soil surface to 10 cm in depth were collected from each tidal flat for transfer and macrobenthos in the soil was removed. The soil in the transfer site was previously removed in the area of 60 cm × 60 cm × 10 cm in depth. Before the soil was transferred, nylon mesh with 1 mm in pore size was used to cover the surface of the hole to prevent invasion of macrobenthos.

Silt content, bacterial population and ignition loss were traced after the transfer of each soil. Fig.1.11(a) shows variation in each parameter in soil of the man-made tidal flat transferred into the natural one. All parameters increased gradually after transfer and reached steady state at day 44. The silt content changed from 0.4% at start to 2.9% at day 44, which was the comparable value as the silt content in soil of the natural tidal flat nearby shown in Table 1.2. Bacterial population and ignition loss also indicated almost the same values as those in soil of the natural one. Fig.1.11(b) shows variation in each parameter in soil of the natural tidal flat transferring to the man-made one. The silt content rapidly decreased after transfer into the man-made one and reached less than 1% within 2 weeks. Both bacterial population and ignition loss indicated rapid decrease as well. As a result, three parameters in the transferred soil of the natural tidal flat reached almost the same values as those of the man-made tidal flat nearby. These results suggest that accumulation or loss of silt and organic matter expressed by ignition loss in soil easily changes with environmental condition on site. It is difficult to think that organic matter and nutrient supply from seawater for bacteria are different in both tidal flats since the water quality in offshore water in both tidal flats are almost the same (Maritime Safety Agency 1997). Furthermore, the change in bacterial population along with the changes of silt and ignition loss strongly indicates that bacterial population is related to silt and organic matters content of soil.

Fig.1.12 shows vertical profiles of ORP of soils transferred between the natural and man-made tidal flats at day 78. ORP at all layers of the original soil in the man-made tidal flat showed at positive values, whereas, in the natural one, ORP showed negative values except the surface. However, the transferred soil from man-made tidal flat showed the same vertical profile of ORP as the soil in the natural one after day 78 and the transferred soil from the natural one showed the same vertical profile of ORP as the soil in the man-made one. The change in ORP by transfer might have been induced by accumulation or loss of silt and organic matter, which are related to infiltration of seawater with oxygen into sediment.

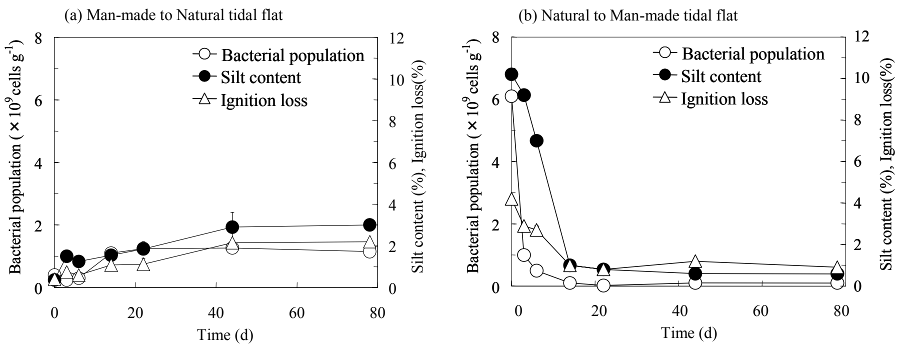

Fig. 1.11. Variation in bacterial population, silt content and ignition loss in (a) soil of man-made tidal flat transferred into natural one and (b) soil of natural tidal flat transferred into man-made one

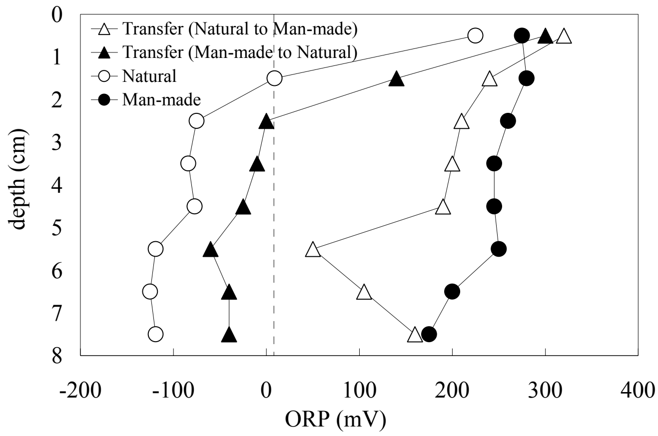

Fig. 1.12. Vertical profiles of oxidation-reduction potential of soils transferred between natural and man-made tidal flats

1.3.2 Relationship between silt content and bacterial population

Relationship between silt content, bacterial population and ignition loss for soil samples during transfer between the natural and man-made tidal flats was evaluated in Fig.1.13. Fig.1.13 indicates that bacterial population and ignition loss increase with increasing silt content in soil. Silt content in soil is determined by the balance of inflow and outflow of silt into and from a tidal flat. Small particles such as silt carried from offshore accumulate on a tidal flat under a calm fluid condition, whereas small particles in soil are carried off into seawater under a turbulent condition. The change of silt content after transfer can be easily explained by the difference of fluid condition between the origin of the transferred soil and the destination. For instance, silt in soil of the natural tidal flat transferred into the man-made one was carried off into seawater due to the strong fluid of seawater on the man-made one. The organic particles such as detritus may accumulate on or be carried off from a tidal flat by the same phenomenon as silt.

However, change of bacterial population in soil cannot be explained by the same phenomenon since the specific gravity of bacteria is almost the same as seawater. Increase of surface area with the increase of silt content in soil, which can cause an increase of bacterial attachment place, or increase of organic matters, which is food for bacterium, may result to the increase of bacterial population.

Transfer experiment suggested that bacterial population is related with silt content in soil. The relationship was confirmed in a simplified tidal flat system (Fig.1.14), which only contained organic matter free soil of various amounts of silt and seawater without suspended matter. Bacteria were removed from the soil before usage to unify the experimental condition on each soil. The seawater with bacteria was induced to the tidal flat system. The equipment was operated with a tidal fluctuation of 12 h cycle at 20 ^{o}C in a dark condition. The highest water level reached the top of the column and the lowest water level reached the bottom of the column.

Bacterial population became stable after 40 to 55days of operation. The population showed a strong relationship with the silt content in soil (r=0.99) as shown in Fig.1.15. Meyer-Reil et al. (1978) and Weise and Rheinhe-imea et al. (1978) reported that most of the bacteria in a tidal flat and sandy beach attached on the surface of soil. Meyer-Reil et al. (1984) and DeFlaun et al. (1983) also reported that bacterial population was affected by the size distribution of soil and as an effect, bacterial population was high in soil with small size. The increase of silt content in soil implies an increase in the surface area of soil per unit weight or volume. Effect of organic matter on bacterial population in soil can be neglected in this experiment since organic matter free soil and seawater without suspended matter were used. Therefore, bacterial population in soil depended on silt content.

Glucose was added to seawater to clarify the effect of food on bacterial population. Bacterial population also showed a strong relationship with the silt content (r=0.99) under rich food condition as shown in Fig.1.15. However, bacterial population with glucose addition showed one to three orders of magnitude higher than that without glucose addition.

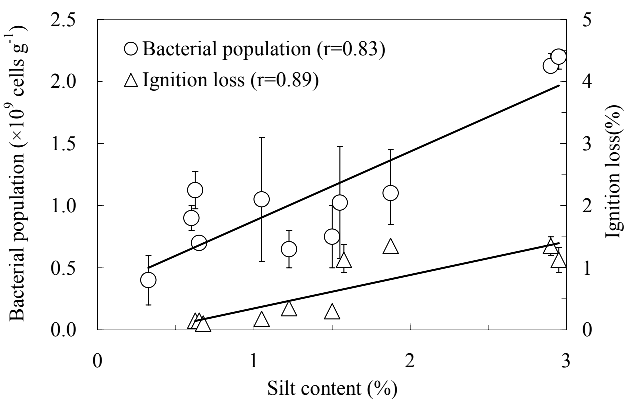

Fig. 1.13. Relationship between bacterial population, ignition loss and silt content for soil samples during transfer between natural and man-made tidal flats

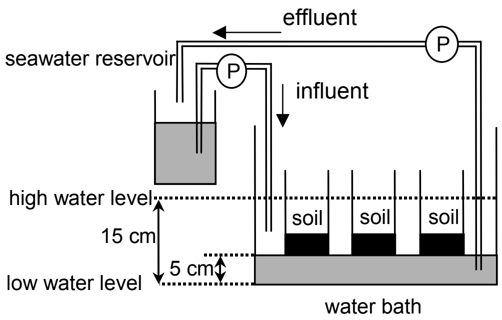

Fig. 1.14. Schematic diagram of experimental setup

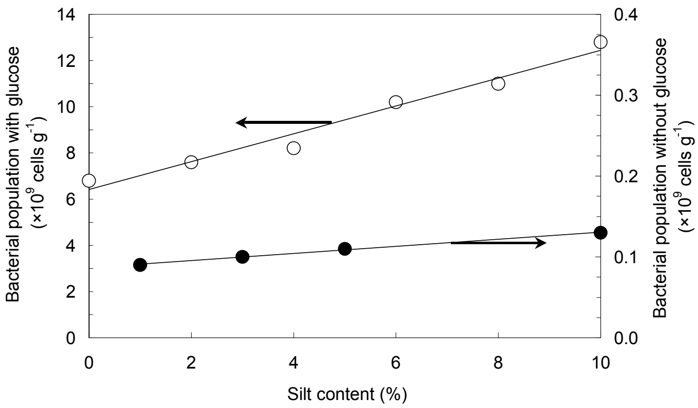

Fig. 1.15. Relationship between bacterial population, ignition loss and silt content in soil samples taken at the end of experiments with or without the addition of glucose

High amount of ignition loss in soil of a tidal flat does not directly mean that high amount of food is supplied for the bacteria in the tidal flat. Most of the organic matter for bacteria must have been supplied from seawater and ignition loss just shows that organic matter accumulated in soil which contains much refractory organic matter to bacteria. However, high amount of ignition loss in soil may mean that high amount of organic particle deposits in the tidal flat which may increase food for bacteria. Therefore, bacterial population in soil depends on surface area of soil for habitat and food. Food for bacteria may become rich by deposition of organic particles in tidal flat under calm fluid condition compared with that under strong fluid condition even though the quality of seawater flowing in the tidal flat is the same.

1.4 Fluid flow on a tidal flat

1.4.1 Outline of study sites

The study sites were selected at St.9 and St.10 in Fig.1.1. Both sites are man-made tidal flats bordering each other. Therefore, fluid condition and water quality of offshore are almost the same. However, the soil structure was quite different between two tidal flats as shown in Table 1.1 and 1.2. Bacterial populations at St.9 and St.10 were 0.11 and 2.32×10^9 cells g^{-1}, respectively. St.9 was typical man-made tidal flat, whereas St.10 was natural-like man-made tidal flat, that is, bacterial population, organic matter content and silt content of soil in St.10 were much higher than those in St.9.

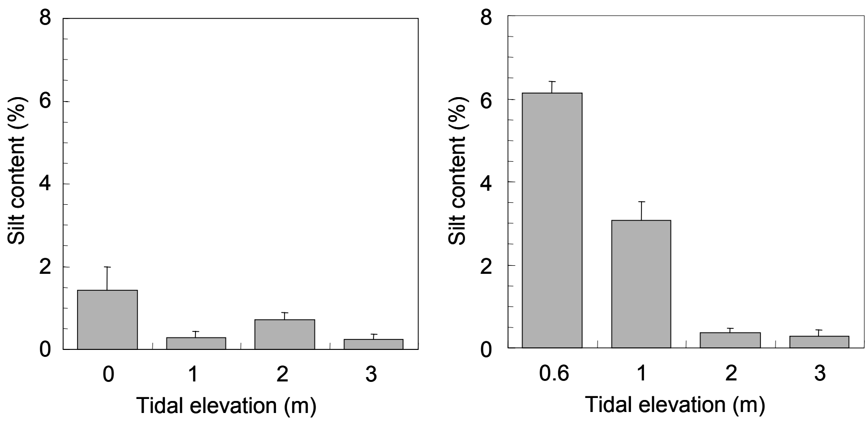

Fig. 1.16. Accumulation of silt particles at different tidal elevation at St.9 (right) and St.10 (left)

Fig.1.16 shows the accumulation of silt particles at different tidal elevation. Silt contents at + 3 m from the datum level was low and almost similar for both tidal flats. It is most likely that both tidal flats were constructed with soil of low silt content because it has little time to be flooded at + 3 m. However, silt contents at + 0.6 m and + 1.0 m in St.10 were very high indicating the accumulation of silt after construction. The only possible source of silt for St.9 and St.10 is seawater because river water does not flow into these tidal flats. The qualities of seawater at both stations are considered to be the same because of their proximity.

1.4.2 Shear stress

Fluid condition was analyzed in both tidal flats to clarify the difference of soil structure. Current velocity in overlaying seawater was measured at 5 cm from soil surface and +1.5 m. Velocity was measured at 10 Hz of frequency using acoustic Doppler current meter (ADV-field, NORTEK, INC., Norway). Two horizontal (*u* and *v*) and one vertical (*w*) components of velocity were obtained; *u* is the velocity from land to sea and *v* is an orthogonal velocity to *u*. Average horizontal velocity ($\overline{U}$) was determined from the average of each horizontal velocity for 10 min:

$$\overline{U} = \sqrt{u^2 + v^2} \tag{1.1}$$

Where:

u, v: horizontal current velocity (cm s^{-1})

$\overline{U}$: average horizontal velocity (cm s^{-1})

The measurement of current velocity in both tidal flats was carried out at flood and ebb tides for one tide simultaneously. Fig.1.17 shows temporal variations of mean velocity at flood tide (21 Oct. 1997). Mean velocities in both tidal flats were less than 3.0 cm s^{-1}. Compared with the average, mean velocity from ebb to high tides at St.9 was 1.5 times higher than that at St.10 and mean velocity from high to ebb tides at St.9 was 2.0 times higher than that at St.10. Fig.1.18 shows temporal variations of mean velocity at ebb tide (21 Nor. 1997). Mean velocity in both tidal flats ranged from 0.5 to 2.5 cm s^{-1} and there was no significant difference.

Shear stresses near the surface of tidal flat were calculated based on the data shown in Fig.1.17.

$$u' = u - U \tag{1.2}$$

$$v' = v - V \tag{1.3}$$

$$w' = w - W \tag{1.4}$$

$$\tau_{UW} = -\rho u'w' \tag{1.5}$$

$$\tau_{vw} = -\rho v'w' \tag{1.6}$$

$$\tau_{total} = \sqrt{\tau_{uw}{}^2 + \tau_{vw}{}^2} \tag{1.7}$$

Where:

u', v', w' : fluctuation current velocities (cm s^{-1})

U, V, W : average velocities (cm s^{-1})

τ_{uw}, τ_{vw} : 2-dimension shear stresses (N m^{-2})

τ_{total} : combined shear stress of τ_{uw} with τ_{vw} (N m^{-2})

ρ : density of seawater (kg m^{-3})

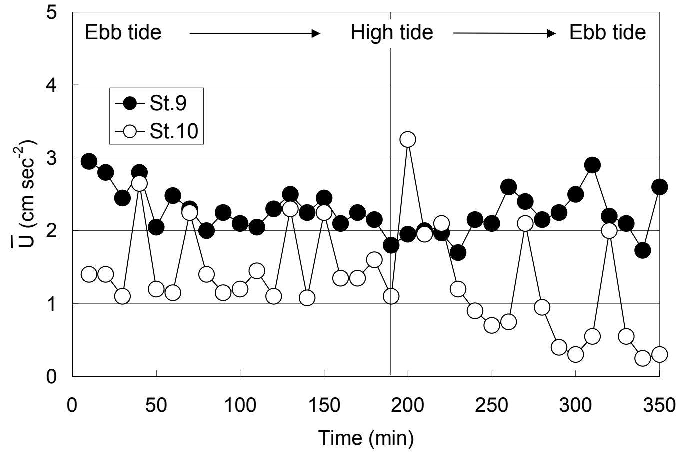

Fig. 1.17. Temporal variations of mean velocity at flood tide (30 Oct. 1997)

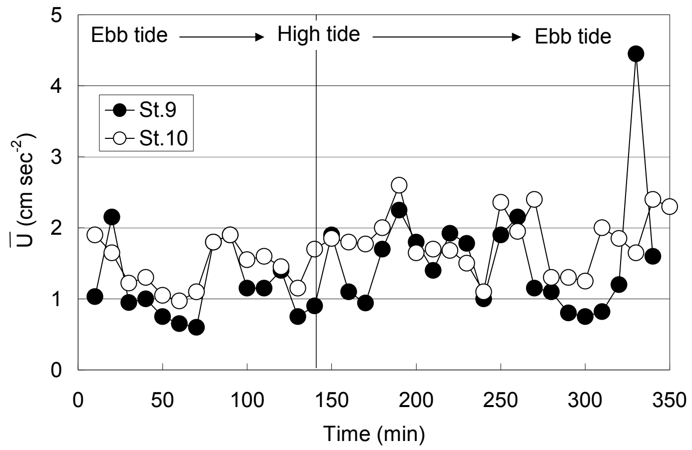

Fig. 1.18. Temporal variations of mean velocity at ebb tide (21 Nor. 1997)

Cumulative distributions of shearing stress for 10 min at high tide, 1h and 2h after high tide and 1h and 2h before high tide are shown in Fig.1.19. Although shear stress at high tide was the same between two stations, shear stress at St.9 was higher than that at St.10 at another calculated periods. The critical shear stress for suspension of silt particles was calculated as 0.1 N m^{-2} based on the experimental data by Mehta *et al.* (1982) using equation proposed by Iwagaki (1985). The rate over 0.1 N m^{-2} of shear stress was small at both tidal flats. However, shear stress at St.9 exceeded 0.1 N m^{-2} in 0.5 to 3 min during 10 min in all calculated periods, whereas shear stress over 0.1 N m^{-2} was found at only two periods in 5 calculated periods. The rate over 0.1 N m^{-2} of shear stress at St.9 was higher than that at St.10 except 2h before high tide.

These results indicate that bottom shear stress at St.10 is smaller than that at St.9 and, therefore, silt easily accumulates in soil at St.10 compared with St.9 despite the proximity of the two tidal flats.

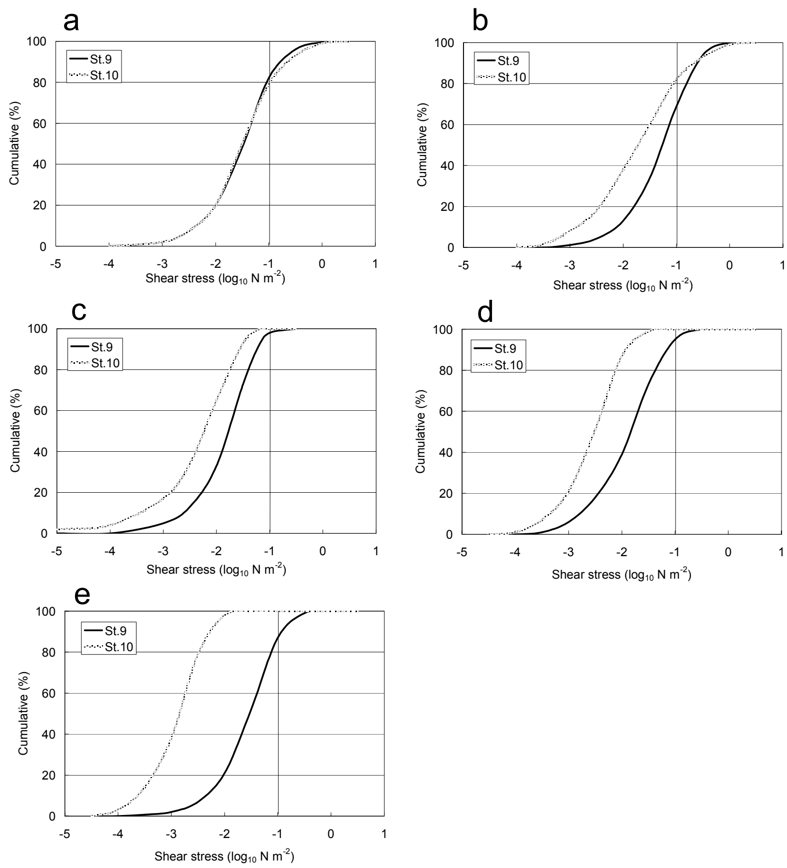

Fig. 1.19. Temporal variation of shear stress at 30 Oct. 1997, (a) before 2 h from high tide, (b) before 1 h from high tide, (c) high tide, (d) after 1 h from high tide, (e) after 2 h from high tide

1.4.3 Sedimentation of sand

To clarify the difference of resuspension of sand between St.9 and St.10, a sediment trap was set at + 1.2 m of elevation for one tide. The amount and particle size distribution of resuspended and trapped sediment at both tidal flats are shown in Fig.1.20. The amount of trapped sediment at St.9 was 133 g m^{-2} and was 2.3 times larger than that at St.10 (59 g m^{-2}). Furthermore, the particle distributions of trapped sediment between St.9 and St.10 were quite different and relatively big particles were trapped at St.9. Over 1000 μm of particles were not trapped at St.10, whereas about 50 g m^{-2} was trapped at St.9. Large amount of silt (less than 75 μm) trapped at St.10 indicates that silt undergoes sedimentation and resuspension in the tidal flat.

Since large particles were trapped only at St.9 and the amount of trapped sediment was larger than that at St.10, the bottom shear stress at St.9 is larger than that at St.10. This conclusion from sediment trap investigation is coincident with the conclusion from shear stress analysis. The difference of bottom shear stress between the two tidal flats results to differences in not only physico-chemical but biological characteristics because biological structures are strongly dependent on silt content in soil as mentioned in 1.3.2.

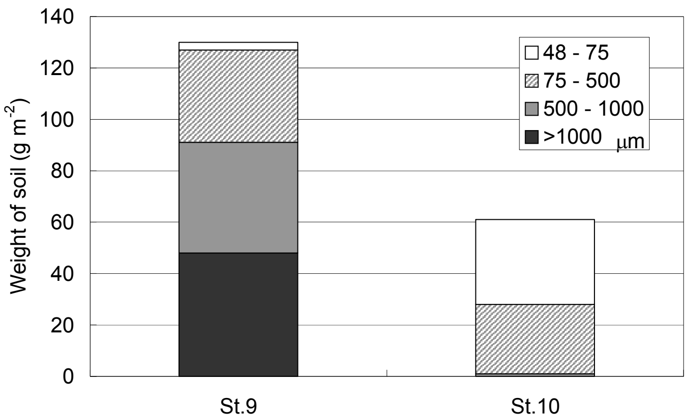

Fig. 1.20. Particle size distribution of trapped sediment at St.9 and St.10

Why is fluid condition different between the two tidal flats in proximity? The differences of construction characteristics between two man-made tidal flats are slope and existence of submerged bank. The slope of St.10 was 0.7/100 and was quite smaller than that of St.9 (4/100), as shown in Table 1.1. The slope of St.10 was smaller than those of natural tidal flats (1/100 to 1.6/100) as shown in Table 1.1. At St.10, submerged bank has been constructed to prevent erosion by current and wave and to maintain moderate slope. Submerged bank and moderate slope reduce the wave and current energies into tidal flat. Hence, bottom shear stress in tidal flat is reduced and silt was accumulated in soil at St.10.

1.4.4 Discussion

Most man-made tidal flats studied showed different physico-chemical and biological characteristics from natural ones. Low silt and organic carbon contents, low groundwater level, oxidative soil condition and low bacterial biomass were observed in man-made tidal flat. The different characteristics were explained by the difference of accumulation of silt and organic matter between man-made and natural tidal flats indicating fluid conditions of both tidal flats were quite different. Man-made tidal flat is constructed at a shoreline where natural tidal flat is not developed indicating that fluid condition in the site is not suitable for tidal flat development primarily due to the strong wave and/or current. Even if tidal flat is constructed using the same soil with large amount of fine soil as natural tidal flat, fine soil may be carried off into seawater and the tidal flat consequently becomes coarse grained sandy beach. Therefore, controlling the fluid condition in overlying seawater in tidal flat becomes very important to make natural-like man-made tidal flat. The investigation of natural-like man-made tidal flat, St.10, gave relevant information to control fluid condition. Constructing tidal flat with moderate slope and setting submerged bank to maintain moderate slope were the key factors to reduce wave and current energies and produce natural-like man-made tidal flat.

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Waves and Tidal Flat Ecosystems
Baba, E.; Kawarada, H.; Nishijima, W.; Okada, M.; Suito, H.
2003, X, 165 p., Hardcover
ISBN: 978-3-540-00442-4