THE EFFECT OF TIDAL CURRENTS AND STORM SURGE TO SEDIMENT TRANSPORT IN THE NORTH ARIAKE SEA, JAPAN

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by

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A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Engineering

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ABSTRACT

Sedimentation process influences many situations that are important to humanity. Any deposition reduces the capacity of reservoirs, interferes with harbor operation and closes or modifies the path of water course in rivers or coast line.

The Ariake Sea in Japan is a typical semi-enclosed shallow sea being rich in fishery products. It supports the local economy through fishing and the cultivation grounds of fish and shellfish. The amount of fishery products have decreased in recent years. One of the reasons is that the seabed deposit has been being deteriorated. It is considered that the decline in the shellfish production is the most serious signal of the environmental degradation of Ariake bay.

The research presented in this dissertation as the prediction of tidal flow, wind effect and suspended sediment transport are simulated to be accordant to natural occurrence by using 3-D hydrodynamic and mud transport models. The objective of this study is to evaluate the condition of sediment concentration and its transport on the aquatic environment of the north Ariake Sea caused by tidal currents, storm surge and the assessment to sediment transport rates, pathways and as references in the northern Ariake Sea.

Model simulations were undertaken with applying tide at Nagasaki and storm surge based on the typhoon Songda 200418 which was simulated from 28 August to 7 September, 2004. There are two scenarios; the first scenario is the sediment changes which is affected by the tide alone, and the second scenario is affected by the tide and wind concurrent took place. In the first set of simulation only tidal current was considered. Applying with tidal forcing or tidal currents concurrent with storm surge, an established morphology in the estuaries of the Chikugo and the Kase Rivers shows
typical characteristics of the mouths of both rivers, with tidal flats existence in those places. Model simulation shows the area where higher or lower suspended sediment concentration appears in the north Ariake Sea as well. The condition of sediment concentration can influence the transparency so that it might disturb the fish and shellfish cultivation in the north Ariake Sea in general.

The intrusion of salt water to the upstream of the Chikugo and Kase Rivers supported the generation of suspended sediment concentration in around the mouth of river, because the intrusion of saltwater can create the disturbance of water in this area. The highest suspended sediment concentration location is near the river mouth affected by flooding and behavior of suspended sediment concentration from north to south at spring and neap tides. Storm surge affected the erosion taking place at most areas in the north Ariake sea and influenced the most to suspended sediment during strong wind period.

**Keywords:** North Ariake Sea, Sediment transport, Tidal currents, Storm surge.
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1.1 Background

Sedimentation processes include erosion, transport, deposition and compaction of sediment which external agents and forces driving these processes may include water, wind and gravity. Human activities also affect these sediment processes. Sediment transport cannot be separated from beach process and, in a broader sense also coastal processes are controlled predominantly by wind waves, tidal waves, and wave generated currents. Waves are the result of mechanical energy transferred from the wind onto the water surface. The large surface of an ocean can absorb much more energy from the atmosphere than that of a small lake. Areas with a long wind fetch can create much larger waves than water bodies of limited length parallel to the wind direction. Waves do not transport water and therefore do not induce currents, which this is a secondary effect taking place in shallow water where deep water waves are transformed into shallow water waves and finally dissipate.

Storm surge is the way of causing damages in the sea basin as well as in the land by typhoon. In the sea basin the most involve to its effect is the agitation of sediment existence in the nearshore as well as offshore. The Ariake Sea especially in north part where tidal flats exist is a risk place for the sediment agitation. The wind is one of the most obvious effects of typhoon while storm surge can be one of the most destructive. Storm surge is simply a behavior of water that is pushed toward the shore by the force of the winds swirling around the storm. Wind waves are superimposed on the storm tide. The rise of water level can cause severe flooding in coastal areas. The southern and eastern part of the Kyushu island are regularly affected by typhoon every year.
Characteristics of the typhoon is a high wind speed with wind direction changing and the higher the wind speed is accompanied by lower air pressure. The wind speed causes sea levels rise causing storm surges. The changing of wind direction can cause a change of water flow therefore can changes the existence of sediment in the sea basin offshore and nearshore.

Depending on grain sizes and sediment material density, fluid density and viscosity, and the strength and turbulence of the flow, sediment transport may occur in variety of modes involving different size classes at the same time or the same classes at different times. In rivers and channels with moderate gradient, there are two overlapping systems of classifying transport modes: (1) as bed load plus suspended load or (2) as bed-material load plus wash load. Under the first system, suspended load consists of the finer sediment maintained in suspension by turbulence, whereas bed load consists of the coarser particles transported along the bed intermittently by rolling, sliding or saltating. Under the second system bed material load comprises all sizes normally found in the bed, whether transported as bed load or in suspension, whereas wash load consists of fine sizes that always travel in suspension and are not found in significant quantities in the bed.

Bed load transport may take place similarly to a conveyor belt or moving layers by evolution and migration of various bed and channel form like dunes, bars or bends. Suspended load is generally transported within and at the same velocity as the water, whereas bed load transport may occur only occasionally during high flow events. The boundary between suspended sediment and bed load transport is not precise and may vary with the flow strength. The higher the flow, the coarser the sediment that can be suspended by turbulence. Suspended load plus bed load, or wash load plus bed material
load, together compose the total sediment load.

Sedimentation process influences many situations that are important to humanity. Deposition reduces the capacity of reservoirs, interferes with harbor operation and closes or modifies the path of water course, and in rivers or coast line.

The Ariake Sea is a typical semi-enclosed shallow sea being rich in fishery products. It supports the local economy through fishing and the cultivating grounds of fish and shellfish. The amount of fishery products has decreased in recent years. One of the reason is that the seabed deposit has been deteriorated. Considering that the decline in the shellfish production was the most serious signal of the environmental degradation of Ariake bay (Nakata et al., 2010). For this reason, the prediction of tidal flow, wind effect and suspended sediment transport is important in coastal related areas. Kyushu island is often passed by typhoons. In the west of this island there is the Ariake Sea characterized by a macro tidal range (3-6m) which is the largest tidal range in Japan (Kato and Seguchi, 2001; Hiramatsu et al., 2005; Tsusumi, 2006). The influence of typhoon on the sea basin as general strongly depends on its tracks and wind speed. Typhoon Songda space 200418 is the one of the most serious typhoon which effects to the Ariake Sea area.

Several previous studies express : Tidal currents play an important role in the sediment resuspension in the tidal flat area (Cao Don, 2007); The mixing of fresh and saline waters in relatively shallow depths in those areas can create not only an extremely productive ecosystem but also a region having high concentrations of suspended sediment that can limit light penetration and decrease algal production or suspended sediment can affect water quality, other productions and the aesthetics of coastal areas (Nguyen, 2008); The Ariake Sea was divided into zones on the basis of water quality
parameters like salinity, water temperature, etc. (Sonoda, 2011)

1.2 Objective

The objectives of this research are to investigate and to predict the conditions of sediment concentration and its transport on the aquatic environment in the north Ariake Sea in response to tidal currents, storm surge and the assessment to sediment transport rates, pathways and its relative contributions in the northern Ariake Sea.

1.3 Outline of Dissertation

This dissertation is comprised of six chapters.

Chapter 1: Introduction of this study is discussed in this chapter. The background of sedimentation transport as a core in this study and its existence with background to the Ariake Sea as the study area, are presented in this chapter as well.

Chapter 2: Literature review is summarized in this chapter regarding to various sedimentation models as the support to the core of this study. An overview of MIKE3 FM Hydrodynamic and MT mud transport model and how to use the tools to simulate the model are described.

Chapter 3: The calculation method, model setting and the types of necessary data are presented for the computational tools and calculation in the previous chapter as well.

Chapter 4: This chapter presents salinity condition in general and specific to Chikugo and Kase River estuaries from the simulation results of MIKE3 Hydrodynamic model,
affected by tide and tide-wind concurrent. The intrusion of saltwater to both rivers can be measured by placing some of stratification checking points from the mouth to upstream of the rivers. This case is discussed in this chapter as well.

Chapter 5: The simulation results of the tools MIKE3 FM Hydrodynamic and Mud Transport models affected by tide and tide-wind concurrent to the north Ariake Sea are discussed in this chapter. The existences of sediment concentration in nearshore as well as offshore are discussed as well.

Chapter 6: The finding of the previous chapters and the suggestion for future research are summarized and discussed in this chapter.
2.1 Sediment Transport Model

The field of sediment transport might just as well be called transport of granular particles by fluids. There is a type of two phase flow, in which one phase is fluid and the other phase is solid. The prototype for the field is the river or sea water. The fluid phase is river water or sea water and the solid phase is sediment grains.

The sediment transport modes as general are divided into three parts:

- Bed load
- Suspended load
- Wash load

The wash load consists of very fine particles which are transported by the water and which normally are not represented in the bed. The wash load is neglected when the term of total sediment discharge is applied. The total sediment load can distinguish into two categories, the bed load and the suspended load. The basic idea of splitting up the total sediment load into two parts is that two different mechanisms are effective during the transport. The bed load is defined as the part of the total load that is in more or less continuous contact with the bed during the transport. It primarily includes grains that roll, slide or jump along the bed, and never rise too far above the bed. The suspended load is the part of the total load that is moving without continuous contact with the bed as a result of the agitation of fluid turbulence. In both cases, the driving force for sediment transport is the action of gravity on the fluid phase, this force is transmitted to the particles through drag. Whether the mode of transports is saltation or suspension, the volume concentration of solids anywhere in the water column tends to be rather dilute.
in rivers.

The sediment transported in the coastal zone usually contains particles ranging from gravel or sand down to very small particles classified as silt or clay. The very fine fractions are carried as wash load.

Theoretical approaches to the problem of predicting the rate of bed load transport was presented by Einstein(1950). The analysis was led to the application of the theory of probability to account for the statistical variation of the agitating forces on bed particles caused by turbulence.

If the magnitude of the instantaneous agitating forces on a certain bed particle exceeds the stabilizing forces on the particle, the particle will begin to jump, roll, or slide along the bed until it becomes deposited downstream at a location where the magnitude of the instantaneous forces is smaller than stabilizing forces. Based on experimental observations, Einstein (1950) assumed that the mean distance travelled by a sand particle between erosion and subsequent deposition, is simply proportional to the grain diameter and independent of the hydraulic conditions and the amount of sediment in motion.

The bed load as that part of the load which is more or less in continuous contact with the bed during the transport. At small transport rate, this transport occurs in one single layer of particles moving over the fixed bed as in Figure 2.1. At larger transport rates, some of the particles either go into suspension or the particles move as bed load in several layers.

The behavior of particle sediment coarse-grained or fine-grained on moving as sediment transport depend on sorting processes in sediment. Coarse or fine grained is different in priority in moving. Figure.2.2 depicts the sorting processes of particle as
sediment transport.

**Figure 2.1** Modes of sediment transport, A: bed load at small shear stresses, B: sheet flow, C: suspended sediment (Fredsoe & Deigaard, 1992)

Dynamic Equivalence and Sorting processes:

**Figure 2.2** Schematic illustration of sorting processes and possible dynamic equilibrium acting on sediments (A) Settling equivalence, (B) Entrainment equivalence (Selective entrainment), (C) Transport equivalence (Transport sorting) (D) Dispersive-pressure equivalence (Shear sorting), (Kennis, 2001)

Sediment in its action of transport, more or less to be influenced by system of coastal morphodynamic. From sediment itself as fluvial sediment input, from nature environment as atmospheric, astronomical, and oceanic forcing, and from external
action as tectonic effect. Figure 2.3 depicts the position of sediment transport around many factors of environment.

**Figure 2.3** Flow diagram depicting the idealized elements and linkages in a coastal morphodynamic system (Kennish, 2001, from Wright L.D, 1995)

The sediment cycle starts with the process of erosion, whereby particles or fragments are weathered from rock material. Action by water, wind, plant and animal activities, contributes to the erosion of the earth’s surface. Fluvial sediments are the term used to described the case where water is the key agent from erosion. Natural or geological erosion takes place slowly, over centuries or millennia. Erosion that occurs as a result of human activity may take place much faster. Any material that can be dislodged is ready to be transported.
Transport sediment processes is initiated on the land surface when raindrops result in sheet erosion. Rills, gullies, streams and rivers then act as conduits for sediment movement. The greater the discharge, or rate of flow, the higher the capacity for sediment transport. Mass sediment transport can also occur through landslides, debris flows and mud flows.

The final process in the sediment transport cycle is deposition. When there is not enough energy to transport the sediment, the process comes to rest. Sinks or depositional areas, can be visible as newly deposited material on a floodplain, bars and islands in a channel and deltas. Considerable deposition occurs that may not be apparent, as on lake and river beds. Alluvial fans are depositional environments typically encountered at the base of a mountain front. Flooding processes occurring on alluvial fans are considerably different from those occurring along single thread rivers with well defined floodplains (Garcia, 2008).

Environmental sedimentology itself as the study of the effects of both man and environmental changes upon active surface sedimentary systems. Therefore environmental sedimentology can be regarded as the study of how both natural and anthropogenic inputs and events modify the production and accumulation of the physical and biogenic constituents of recent sedimentary deposits. Sedimentological processes and geo-morphological changes that have been operating over short to medium ( >10 yr, <100yr) time scales (Fig.2.4). A short term changes ( <1 yr) within a coastal sedimentary environment include the processes of tidal erosion and deposition, seasonal changes in beach profiles or morphological change due to storm events. In the short to medium- term (< 10yr), mass movement of unstable cliffs, spit progradation, or barrier breaching. In the medium term (up to 100yr), coastal landform progradation
changes in delta morphology or coastal retreat. Superimposed upon these processes may be a range of anthropogenic activities (e.g. sea wall construction, sand dredging or contaminant inputs), which may influence not only the dynamics of the sedimentary system, but also the associated floral and faunal components (e.g. dune plants, mangrove or corals) are often of sedimentological significance in their own right, either as sources of sediment or as agents of sediment trapping and stabilization (Perry & Taylor, 2007).

![Figure 2.4 Time scales of geomorphology processes operate within a hypothetical coastal environment. (Perry & Taylor, 2007, adapted from Woodroffe 1992)](image)

### 2.2 MIKE3 FM Hydrodynamic and Mud Sediment Model

#### 2.2.1 Hydrodynamic Model

The hydrodynamic model calculates the resulting flow and distributions of salt, temperature, subject to a variety of forcing and boundary conditions. The simulation time and accuracy can be controlled by specifying the order of the numerical schemes which are used in the numerical calculations. Both the scheme for time integration and for space discretization can be specified. The time integration of the shallow water
equations and the transport (advection-dispersion) equations is performed using a semi-implicit scheme, where the horizontal terms are treated explicitly and the vertical terms are treated implicitly. Due to the stability restriction using an explicit scheme the time step interval must be selected.

**Domain:**

The MIKE3 Flow Model FM is based on flexible mesh approach. Providing with a suitable mesh is essential for obtaining reliable results from the model. A layered mesh is used. An unstructured mesh is used in the horizontal domain, while in the vertical domain a structured mesh is used. The difference types of mesh can be recognized as in vertically the element can be prisms or bricks (hexahedrals) while horizontal faces are triangles and quadrilateral elements.

**Density:**

The density is assumed to be a function of salinity and temperature, but in this research the temperature was not considered and had been taken as a constant value. The temperature or salinity model is invoked from the specification of the density, provided baroclinic density which density depends on temperature and or salinity. When the density is considered to be a function of temperature and or salinity as baroclinic mode, the transport equation for the temperature and or salinity must be solved. The density is calculated using UNESCO’s standard equation of state sea water. These relations are applicable for temperature ranging from $-2.1^\circ C$ to $40.0^\circ C$ and salinities in the range from 0 to 45 PSU (Practical Salinity Unit).

**Wind:**

It is possible to take into account the effect of the wind on the flow field. The format of the wind data can be specified as:
-Constant, the wind is blowing from the same direction and with the same magnitude for the whole simulation period and over the entire model area.

-Varying in time and constant in domain, the magnitude and direction vary during the simulation period but are the same over the entire model area.

-Varying in time and domain, the magnitude and direction vary during the simulation period and over the model area.

The effect of wind blowing over the model areas:

The surface stress ($\tau_s$) is determined by the wind speed above the water. The empirical relation of the stress,

$$\tau_s = \rho_u c_a |u_a| w_{10}$$ (2-1)

where $\rho_a$ is the density of air, $c_a$ is the empirical drag coefficient of air, and

$u_a$ is the wind speed above the sea surface.

Definition of wind direction that had been given in degrees blowing from relative to true north, can be seen in the Figure 2.5.

The drag coefficient can either be a constant value or depend on the wind speed. The empirical formula for the parameterization of the drag coefficient(Wu, 1994) as follow:

$$c_d = c_a + \frac{c_b - c_a}{w_b - w_a} (w_{10} - w_a) \quad \text{if} \quad w_{10} < w_a$$ (2-2a)

$$c_d = c_a + \frac{c_b - c_a}{w_b - w_a} (w_{10} - w_a) \quad \text{if} \quad w_a \leq w_{10} \leq w_b$$ (2-2b)

$$c_d = c_b + \frac{c_b - c_a}{w_b - w_a} (w_{10} - w_a) \quad \text{if} \quad w_{10} > w_b$$ (2-2c)
where $c_a$, $c_b$, $w_a$, $w_b$ are empirical factors and $w_{10}$ is the wind speed 10m above the sea surface. The default values for the empirical factors are $c_a=1.255 \times 10^{-3}$, $c_b=2.425 \times 10^{-3}$, $w_a=7$ m/s, $w_b=25$ m/s. The value gives generally good results for open sea applications. Field measurements of the drag coefficient collected over lakes indicate that the drag coefficient is larger than open ocean data (Geenaert and Plant, 1990).

![Figure 2.5 Definition of Wind Direction](image)

**Initial conditions:**

The initial value for the hydrodynamic variables can be specified as constant, spatial varying surface elevation, and spatially varying water depth and velocities.

**Boundary conditions:**

The hydrodynamic boundary conditions have some types: Land (zero normal velocity), Land (zero velocity), Specified velocities, Specified fluxes, Specified level, Specified discharge, Flather condition. The Flather (1976) condition is one of the most efficient open boundary condition, which the normal component of the barotropic velocity one option is to radiate out deviations from exterior values at the speed of the external gravity waves. The exterior values are often used to provide tidal boundary conditions to the barotropic mode. The instabilities which are often observed when
imposing stratified density at a water level boundary can be avoided using Flather conditions.

2.2.2 Mud Sediment Transport Model

Mud is a term generally used for fine grained and cohesive sediment in a sediment-water mixture that is less than 63 microns in size exhibits rheological behavior that is viscoelastic when the mixture is particle supported, and is highly viscous and non Newtonian when it is in a fluid like state. Mud is typically found in sheltered areas protected from strong wave and current activity. Occasionally are the upper and mid reaches of estuaries, lagoons and coastal bay, the source of fine-grained sediment may be both fluvial and marine. Fine sediment is brought in suspension and transported by current and wave actions, which is characterized by low settling velocities. Therefore, the sediments may be transported over long distances by the water flow before settling. The cohesive properties of fine sediments allow them to stick together and form larger aggregates or flocs with settling velocities much higher than the individual particles within the floc (Krone,1986; Burt,1986)). The sediments are able to deposit from this way in areas where the individual fine particles would never settle. Depending on the amount of sediment in suspension as well as the turbulence properties of the flow, the formation and destruction of flocs will occur. In non cohesive sediment the particles are transported as single grains.

A zone with high concentration suspension of sediment is called a turbidity maximum and will change its position within the estuary depending on the tidal cycle and the input of fresh water from rivers (e.g.Dyer, 1986).
Table 2.1 Classification of Fine sediment (DHI, MIKE, 2011)

<table>
<thead>
<tr>
<th>Sediment type</th>
<th>Grain size</th>
<th>Flocculation ability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay</td>
<td>&lt; 4(\mu)m</td>
<td>high</td>
</tr>
<tr>
<td>Silt</td>
<td>4-63(\mu)m</td>
<td>medium</td>
</tr>
<tr>
<td>Fine sand</td>
<td>63-125(\mu)m</td>
<td>very low/no flocculation</td>
</tr>
</tbody>
</table>

The mud transport model calculates the resulting transport of cohesive materials based on the flow conditions found in the hydrodynamic calculations. Sediment transport is dependent on the hydrodynamic conditions. In general there are two types of sediment transport. Cohesive and non cohesive. The cohesive is characterized by low settling velocities and long response times for hydrodynamic changes. Therefore the transport is dominated by the advection of the water column. For non-cohesive sediments the settling velocities are in general larger and the concentration profile will therefore quickly adjust to changes in hydrodynamic. As a consequence of this a major part of this transport will take place on or very close to the bed as bed load. The bed is assumed to erode as flakes which means that the distribution of fractions within the bed is also the distribution when eroded. This means also that the erosion formula used in the Mud Transport section controls the maximum erosion of all fractions, after the flakes have been eroded it is assumed that they are destroyed or regrouped by turbulence. Since the sand fractions have no cohesive properties it will be freed by this and behave independently.

In MIKE3 Flow Model FM model, the transport of fine grained material (mud) has been included in the Mud Transport Module (MT) linked to Hydrodynamic module (HD) as
in the Figure 2.6 below:

Figure 2.6 Data flow and physical processes in MIKE3 Flow Model FM-Mud transport calculation (DHI, MIKE, 2011)

**Settling velocity:**

The settling velocity for mud in suspension can be divided into: Constant settling velocity, Flocculation, Hindered settling, Fluid mud.

Constant settling velocity can be selected if the concentrations are assumed not to influence the settling velocity.

The settling velocity is dependent on the size of the particles. The settling velocity of a single free particle can be roughly estimated by the Stokes law.

\[
 w_s = \frac{(\rho_{\text{sediment}} - \rho)}{\rho_{\text{sediment}}} \frac{gd^2}{18\nu_c} \quad (2-3)
\]

in which:

\( \rho_{\text{sediment}} \): sediment density (kg/m³)
In case of fine grained cohesive sediment (<0.006mm), the settling velocity will depend on the rate of flocculation. If the suspended sediment concentration is low the probability for collision between the cohesive particles is low and the settling velocity will be close to the settling velocity for a single grain. With increasing concentration, collision between particles will occur more frequently and formation of flocs takes place from cohesiveness of the particles. Consequently this leads to an increase in settling velocity. The floc size can be increased or decreased by many other factors. High levels of turbulence will decrease the floc size due to destruction of flocs. If sediment concentration increases further, the flocs will eventually interact hydrodynamical so that the effectively of the flocs during settling cause an upward flow of the liquid they displace and hindered settling occurs which leads to a reduction in settling velocity. Further increase in sediment concentration will result in decreasing distance between the flocs, which leads to negligible settling velocity and the mixture will act as fluid mud.
Flocculation is when the concentration of sediment is high enough for sediment flocs to influence each other’s settling velocity. This occurs because collision between flocs will increase floc size leading to higher settling velocities.

Standard flocculation concentrations occur when hindered settling is neglected.

\[
W' = W_{s,t} \left( \frac{C_{floc}}{\rho_{sediment}} \right)^\gamma 
\]

(2-4a)

\[
W' = W_{s,t} \left( \frac{C_{total}}{\rho_{sediment}} \right)^\gamma 
\]

(2-4b)

\[
W' = W_{s,t} \left( \frac{C_{hindered}}{\rho_{sediment}} \right)^\gamma 
\]

(2-4c)
**Figure 2.8** The pattern of applied concentration profile when flocculation selected (DHI, MIKE, 2011)

Where:

- \( \rho_{\text{sediment}} \): density sediment (kg/m\(^3\))
- \( c_{\text{floc}} \): concentration at which flocculation begins (kg/m\(^3\))
- \( c_{\text{total}} \): total concentration of sediment (kg/m\(^3\))
- \( c_{\text{hindered}} \): concentration at which hindered settling begins (kg/m\(^3\))
- \( w_{s,r} \): settling velocity coefficient
- \( w_s \): settling velocity (m/s)
- \( \gamma \): power constant

When the concentration of sediment gets high enough for the flocs to influence each other’s settling velocity, then the hindered settling occurs. This is not fall freely and the results are in a lower settling velocity.
The settling velocity in this regime is given by (Richardson and Zaki, 1954):

a). Single mud fraction,

\[ w_s = w_{s,t} \left( 1 - \frac{c}{c_{gel}} \right)^\gamma \]  \hspace{1cm} (2-5)

b). Multiple mud fractions

\[ w_s = \alpha \left( 1 - \Phi \right)^{\alpha \Phi} \]  \hspace{1cm} (2-6)

where,

\[ \Phi = \min \left( 1.0, \Phi \right) \]  \hspace{1cm} (2-7)

\[ \Phi = \frac{\sum c^i}{c_{gel}} \]  \hspace{1cm} (2-8)

\( w_{s,t} \) is the settling velocity coefficient, \( \gamma \) is the power constant for fraction, \( c_{gel} \) is the gelling point for sediment.
\begin{equation}
    w'_i = w'_{s,r} \frac{(1 - \Phi_s)(1 - \Phi_p)}{1 + 2.5\Phi}
\end{equation}

where,

\begin{equation}
    \Phi_p = \frac{\sum c^i}{\rho_s}
\end{equation}

\[ \rho_s \text{ (kg/m}^3 \text{)} \text{ is the dry density of sediment.} \]

Fluid mud in this model was considered as a bottom layer and the settling velocity for this will be treated as consolidation.

There are different regimes as long settling process as the table below:

\textbf{Table 2.2 Settling regimes (DHI,MIKE,2011)}

<table>
<thead>
<tr>
<th>Sediment stage</th>
<th>Concentration (kg/m$^3$)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suspension</td>
<td>0 - 0.01</td>
<td>No flocculation</td>
</tr>
<tr>
<td>Suspension</td>
<td>0.01 - 10.0</td>
<td>Flocculation may occur</td>
</tr>
<tr>
<td>Suspension</td>
<td>10.0 - 50.0</td>
<td>Void ratio larger than 6. No effective stresses between grains. Hindered settling begins</td>
</tr>
</tbody>
</table>

\textbf{Deposition:}

The deposition of suspended sediment is the transfer of sediment from the water column to the bed. Deposition takes place where the bed shear stress $\tau_{bd}$ is smaller than the critical shear stress for deposition $\tau_{cd}$.

The deposition for the $i$ mud fraction is shown as follow,

\begin{equation}
    D_i = w'_i c'_{nb} p'_b
\end{equation}

where $p'_b$ is a probability ramp function of deposition, $w'_i$ (m/s) is the settling velocity, $c'_{nb}$ (kg/m$^3$) is the near bed concentration of fraction $i$. 
The probability of ramp function,

\[ p^i_b = \max \left( 0, \min \left( 1.1 - \frac{\tau_b}{\tau_{\text{crit}}} \right) \right) \] (2-12)

**Bed parameter:**

One or more bed layers consist in the sediment are considered as the Mud transport model. Each bed layer is defined by the sediment mass contained in the layer and by the dry density and erosion properties of the layer. The sediment mass of a bed layer is comprised by the summation of the mass of each sediment fraction present in the layer. The dry density and erosion properties are considered properties of each of the bed layers and are therefore kept constant in time. The bed layer masses are considered the state variables of the sediment bed, which means that the model during simulation tracks their evolution in space and time.

![Diagram of sediment processes](image)

**Figure 2.10** The mud transport model processes

(DHI,MIKE,2011)

The mass of the i sediment fraction in the j bed layer in a certain horizontal grid point is
updated every time step following the expression:

\[ m_{i,j}^{\text{new}} = m_{i,j}^{\text{old}} + (D_i - E_i) \Delta t + (T_{i,j-1} - T_{i,j}) \]  \hspace{1cm} (2-13)

where, \(m\) (kg/m\(^2\)) is sediment mass, \(D\) (kg/m\(^2\)/s) is a possible deposition in uppermost bed layer, \(E\) (kg/m\(^2\)/s) is a possible erosion from the active bed layer, \(T\) (kg/m\(^2\)/s) is a possible downward transfer of sediment and \(\Delta t\) (s) is simulation time step.

The thickness of the \(i\) bed layer is a derived parameter determined as:

\[ H_j^{\text{new}} = \frac{M_j}{\rho_{d,j}} = \frac{\sum m_{i,j}^{\text{new}}}{\rho_{d,j}} \]  \hspace{1cm} (2-14)

where \(H\) (m) is bed layer thickness, \(M\) (kg/m\(^2\)) is total sediment mass and \(\rho_d\) (kg/m\(^3\)) is dry density.

**Erosion:**

The erosion of a bed layer is the transfer of sediment from the bed to the water column. Erosion takes place from the active bed layer in areas where the bed shear stress \((\tau_b)\) is larger than the critical shear stress for erosion \((\tau_{ce})\). The bed parameters are considered constant for each layer.

The critical shear stress for erosion is exceeded corresponding to the driving forces exceeding the stabilizing forces. Through simulation the critical shear stress is constant.

The erosion rate for a dense consolidated bed for the \(j\) layer (Partheniades, 1965) as follow:

\[ E^j = E_0^j p_{E}^{j_{\text{new}}} \]  \hspace{1cm} (2-15)

where, \( p_{E}^{j_{\text{new}}} \) is a probability ramp function of erosion, \( E_0 \) is the erosion coefficient, \( E_m \) is the power of erosion.
\[ p_E^j = \max \left( 0, \frac{\tau_j}{\tau_{ce}} - 1 \right) \]  

(2-16)

The erosion rate for partly consolidated for a soft bed for the j layer (Parchure and Mehta, 1985):

\[ E_r = E_0^j \exp \left( \alpha \left( \tau_b - \tau_{ce}^j \right) \right) \]  

(2-17)

where, \( \alpha \) is a coefficient.

The following typical values for critical shear stress are given:

<table>
<thead>
<tr>
<th>Mud type</th>
<th>Density (kg/m³)</th>
<th>Typical ( \tau_{ce} ) (N/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mobile fluid mud</td>
<td>180</td>
<td>0.05-0.1</td>
</tr>
<tr>
<td>Partly consolidated mud</td>
<td>450</td>
<td>0.2-0.4</td>
</tr>
<tr>
<td>Hard mud</td>
<td>600⁺</td>
<td>0.6-2</td>
</tr>
</tbody>
</table>

Table 2.3 Critical shear stresses for erosion (DHI, MIKE, 2011)

Density of bed layers:

Each sediment type has different density depending on the previous history as geological, the chemical properties, the content of organic and other factors. It is necessary to obtain knowledge of sediment in spreading out of the interest location in order to generate a representative density map area for each layers. This can be done from either measurements or through researching the geological history of the area. In the vertical the density varies with the degree of compression and with the type of mud. Area that had been covered by glaciers can have very hard layers, while the area that had been sedimentation areas for a long time can be covered by relative loose mud.

The bed density is defined as dry density as follows:
\[ \rho_d = \frac{mass \ of \ grains}{volume \ of \ mixture} \] (2-18)

The range of bed density can be seen in the table below:

<table>
<thead>
<tr>
<th>Sediment stage</th>
<th>General description</th>
<th>Rheological behaviour</th>
<th>Dry density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freshly deposited (1 day)</td>
<td>Fluff</td>
<td>Mobile fluid mud</td>
<td>50-100</td>
</tr>
<tr>
<td>Weakly consolidated (1 week)</td>
<td>Mud</td>
<td>Fluid stationary mud</td>
<td>100-250</td>
</tr>
<tr>
<td>Medium consolidated (1 month)</td>
<td></td>
<td>Deforming cohesive bed</td>
<td>250-400</td>
</tr>
<tr>
<td>Highly consolidated (1 year)</td>
<td></td>
<td>Stationary cohesive bed</td>
<td>400-550</td>
</tr>
<tr>
<td>Stiff mud (10 years)</td>
<td>Stiff clay</td>
<td>Stationary cohesive bed</td>
<td>550-650</td>
</tr>
</tbody>
</table>

**Bed roughness:**

The bed roughness is the resistance against the flow, and included for calculating the bottom shear stress. The bed roughness is independent of the other bed parameters except the shape of the bed likes dunes, ripples, etc.

The bed roughness can be specified as:

- Constant in domain
- Varying in domain

and is defined as Nikuradse roughness \((k_n)\) and the unit is (m).

**Initial conditions:**

The initial conditions are the spatial distribution of the component concentration throughout the computational domain at the beginning of the simulation. The format of the initial concentration in component unit (kg/m³) for each fraction can be specified as constant in domain and varying in domain.
The format of the initial concentration in component unit for each fraction can be specified as,

- Constant in domain
- Varying in domain

The unit of initial concentration is (kg/m$^3$), and the typical background concentration is 0.01 kg/m$^3$.

**Boundary conditions:**

There are three boundary types:

- Land
- Specified values (Dirichlet boundary condition)
- Zero gradient (Neuman boundary condition)

The boundary conditions can be recognized from the initially set up of mesh file for the boundary codes. The format of the fraction concentration at the boundary if specified is selected as follow:

- constant in time and along boundary
- varying in time and constant along boundary
- varying in time and along boundary.

Fraction concentration unit in kg/m$^3$.

For the two cases with values varying in time two types of time interpolation can be selected: linear and piece wise cubic.

In the case with values varying along the boundary two methods of mapping from the input data file to the boundary section are normal and reverse order.
2.3 Conclusion.

The mud transport model calculates the resulting transport of cohesive materials based on the flow conditions found in the hydrodynamic calculations.

The cohesive sediment transport is characterized by low settling velocities and long response times for hydrodynamic changes. Therefore the transport is dominated by the advection of the water column.

The settling velocity for mud in suspension can be divided into: Constant settling velocity, Flocculation, Hindered settling, Fluid mud. Constant settling velocity can be selected if the concentrations are assumed not to influence the settling velocity. The settling velocity will depend on the rate of flocculation of fine grained cohesive sediment and the size of the particles. Flocculation occurred when the concentration of sediment is high enough for sediment flocs to influence each other’s settling velocity, then the hindered settling occurred. Fluid mud was considered as a bottom layer and the settling velocity for this will be treated as consolidation.

Deposition takes place where the bed shear stress is smaller than the critical shear stress for deposition. Erosion takes place from the active bed layer in areas where the bed shear stress is larger than the critical shear stress for erosion. The bed parameters are considered constant for each layer.
3.1 Introduction

The Ariake Sea located in the western part of Japan with about 90 km long, 20 km wide and 20 m in average depth (Kamada, 1985). The north part of this bay is strongly affected by freshwater from several rivers, among them the Chikugo river is the largest river. The Ariake Sea is also one of the major enclosed bay in Japan with various and rich fishery resources. The sea products show a decrease from 1980s to the recent years (The Ministry of Agriculture, Forestry and Fisheries of Japan, 2001). The decrease of this product might be caused by environmental changes in this area. Some of human activities brought severe environmental deterioration, changing the tidal currents and increase in transparency.

From the environmental viewpoints the understanding of transport sediment process is important in the prediction of distribution in contaminants in the coastal area because the chemical materials are likely absorbed into particles sediment.

Figure 3.1 Tidal Flat in the Ariake Sea
3.2 Study area

The Ariake Sea locates in the west of Kyushu Japan. The total area of this sea is approximately 1,700km$^2$. Tidal flats cover 188.40 km$^2$ in this part, receiving flow of some rivers. Among them, the Chikugo river is the largest river in which the estuary connects to the north Ariake bay.

![Figure 3.2 Study Area](image)

3.3 Methodology

3.3.1 Computational Tools

As the computational tools the MIKE3 Flow Model Flexible mesh (MIKE3 FM) HD Hydrodynamic and MT Mud sediment transport by DHI (Denmark Hydraulic
Institute) are used.

The main characteristics of these tools are:

- Dimension work is 3D
- Integral method is Eulerian
- Coordinate vector system is Cartesian
- The cell element used prisms-triangular extrusion
- Method of generation mesh used triangulation-Delaunay
- The finite approximation for transport equation used FVM
- Finite approximation for hydrodynamic equations used FEM/FVM
- Method for resolution for transport equations is explicit UPWIND scheme.
- Method for resolution for dynamic equations is implicit algorithm GMRES.

3.3.2 Calculation method

The model is based on the solution of the three dimensional incompressible Reynolds averaged Navier-Stokes equations, subjected to the assumption of Boussinesq and of hydrostatic pressure.

The equation of continuity:

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = S
\]  
\[(3-1)\]

The momentum equation:

The two horizontal momentum equations for the x and y component, respectively:

\[
\frac{\partial u}{\partial t} + \frac{\partial (u^2)}{\partial x} + \frac{\partial u}{\partial y} + \frac{\partial uw}{\partial z} = f v - \frac{\rho g}{\partial x} + 1 \frac{\partial p}{\partial x} + \frac{g}{\partial x} \int_{y}^{y} \rho \frac{\partial h}{\partial x} \, dz - \frac{1}{\rho h} \left( \frac{\partial s_{xx}}{\partial x} + \frac{\partial s_{xy}}{\partial y} \right)
\]
\[ F_u + \frac{\partial}{\partial z} \left( v_i \frac{\partial u}{\partial z} \right) + u_i S \]  

(3-2)

\[
\frac{\partial v}{\partial t} + \frac{\partial v^2}{\partial y} + \frac{\partial uv}{\partial x} + \frac{\partial wv}{\partial z} = -fu - g \frac{\partial \eta}{\partial y} - \frac{1}{\rho} \frac{\partial p_a}{\partial y} - g \int \frac{\partial \rho}{\partial y} dz - \frac{1}{\rho h} \left( \frac{\partial S_{yx}}{\partial x} + \frac{\partial S_{yy}}{\partial y} \right) +
\]

\[
F_v + \frac{\partial}{\partial z} \left( v_i \frac{\partial v}{\partial z} \right) + v_i S
\]  

(3-3)

where \( t \) (s) is the time, \( x,y \) and \( z \) (m) are the Cartesian co-ordinates; \( \eta \) (m) is the surface elevation; \( h_s \) (m) is the still water depth; \( h = \eta + h_s \) is the total water depth; \( u,v \) and \( w \) (m/s) are the velocity components in \( x,y,z \) direction; \( f = 2 \Omega \sin \phi \) is the Coriolis parameter; \( \Omega \) (deg) is the angular rate of revolution and \( \phi \) (deg) is geographic latitude; \( g \) (m/s\(^2\)) is the gravitational acceleration; \( \rho \) (kg/m\(^3\)) is the density of water; \( S_{xx},S_{yy},S_{xy} \) and \( S_{yx} \) (kg/s\(^2\)) are components of the radiation stress tensor; \( \nu \) (m\(^2\)/s) is the vertical turbulent viscosity; \( p_a \) (Pa) is the atmospheric pressure; \( S \) (kg/m\(^3\)/s) is the magnitude of discharge due to point sources and \((u_s,v_s)\) (m/s) is the velocity by which the water is discharged into the ambient water. In the \( z \) direction the calculation was determined by using transport equation for salt.

The horizontal stress terms are described using a gradient-stress relation, which is simplified to:

\[
F_u = \frac{\partial}{\partial x} \left( 2h_i \frac{\partial u}{\partial x} \right) + \frac{\partial}{\partial y} \left( h_i \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) \right)
\]  

(3-4)

\[
F_v = \frac{\partial}{\partial x} \left( h_i \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) \right) + \frac{\partial}{\partial y} \left( 2h_i \frac{\partial v}{\partial y} \right)
\]  

(3-5)

where \( h_i \) (m\(^2\)/s) is the horizontal eddy viscosity.

The surface and bottom boundary condition for \( u, v \) and \( w \):
at \( z = \eta \):
\[
\frac{\partial \eta}{\partial t} + u \frac{\partial \eta}{\partial x} + v \frac{\partial \eta}{\partial y} - w = 0, \quad \left( \frac{\partial u}{\partial z}, \frac{\partial v}{\partial z} \right) = \frac{1}{\rho_0 v_j} \left( \tau_{sx}, \tau_{sy} \right) \tag{3-6}
\]

at \( z = -d \):
\[
u \frac{\partial d}{\partial x} + v \frac{\partial d}{\partial y} + w = 0, \quad \left( \frac{\partial u}{\partial z}, \frac{\partial v}{\partial z} \right) = \frac{1}{\rho_0 v_j} \left( \tau_{bx}, \tau_{by} \right) \tag{3-7}
\]

where \( (\tau_{sx}, \tau_{sy}) \) and \( (\tau_{bx}, \tau_{by}) \) are the x and y components of the surface wind and bottom stresses in (Pa).

The total water depth \( h \) (m) can be obtained from the kinematic boundary condition at the surface, once the velocity is known from the momentum and continuity equations.

The vertical integration of the local continuity equation:
\[
\frac{\partial h}{\partial t} + \frac{\partial hu}{\partial x} + \frac{\partial hv}{\partial y} = hS + \bar{P} - \bar{E} \tag{3-8}
\]

where \( \bar{P} \) (mm/day) and \( \bar{E} \) (mm/day) are precipitation and evaporation rates respectively and \( \bar{u} \) and \( \bar{v} \) (m/s) are the depth averaged velocities.

\[
\bar{h}u = \int_{-d}^{\eta} u \partial z, \quad \bar{h}v = \int_{-d}^{\eta} v \partial z \tag{3-9}
\]

The fluid is assumed to be incompressible, the density \( \rho \) does not depend on the pressure, but only on the temperature \( T \) and salinity \( s \) through the equation:
\[
\rho = \rho(T, s) \tag{3-10}
\]

Here the UNESCO equation of state is used.

Transport equation for salt:
\[
\frac{\partial s}{\partial t} + \frac{\partial us}{\partial x} + \frac{\partial vs}{\partial y} + \frac{\partial ws}{\partial z} = F_s + \frac{\partial}{\partial z} \left( D_s \frac{\partial s}{\partial z} \right) + s_j S \tag{3-11}
\]
The diffusion coefficients can be related to the eddy viscosity:

\[
F_i = \left[ \frac{\partial}{\partial x} \left( D_h \frac{\partial}{\partial x} \right) + \frac{\partial}{\partial y} \left( D_h \frac{\partial}{\partial y} \right) \right](s)
\]  

(3-12)

The diffusion coefficients can be related to the eddy viscosity:

\[
D_h = \frac{A}{\sigma_T} \quad D_v = \frac{v_t}{\sigma_r}
\]  

(3-13)

Where \( D_v \) (m²/s) is vertical turbulent (eddy) diffusion coefficient, \( s_s \) (PSU) is salinity of the source, \( F \) (m²/s) is horizontal diffusion terms, \( D_h \) (m²/s) is horizontal diffusion coefficient, \( \sigma_T \) is Prandtl number.

The transport of the mud:

The transport of the mud is generally described by the equation (e.g. Teisson, 1991):

\[
\frac{\partial c}{\partial t} + \frac{\partial uc}{\partial x} + \frac{\partial vc}{\partial y} + \frac{\partial wc}{\partial z} - \frac{\partial w_c}{\partial z} = \frac{\partial}{\partial x} \left( \frac{\nu_{T_x}}{\sigma_{T_x}} \frac{\partial c}{\partial x} \right) + \frac{\partial}{\partial y} \left( \frac{\nu_{T_y}}{\sigma_{T_y}} \frac{\partial c}{\partial y} \right) + \frac{\partial}{\partial z} \left( \frac{\nu_{T_z}}{\sigma_{T_z}} \frac{\partial c}{\partial z} \right) + S
\]  

(3-14)

Where \( t \) (s) is the time, \( x, y \) and \( z \) (m) are Cartesian co-ordinate, \( u, v \) and \( w \) (m/s) are flow velocity component, \( c \) (kg/m³) is mass concentration, \( w_c \) (m/s) is settling velocity, \( \sigma_{T_x} \) is turbulent Schmidt number, \( \nu_{T_x} \) (m²/s) is anisotropic eddy viscosity, \( S \) is source term.

**Settling velocity:**

The settling velocity for mud in suspension can be divided into: Constant settling velocity, Flocculation, Hindered settling and Fluid mud. The settling velocity of the suspended sediment may be specified as a constant value. Constant settling velocity can be selected if the concentrations are assumed not to influence the settling velocity. Flocculation is described as a relationship with the suspended sediment concentration (Burt, 1986). Hindered settling can be applied if the suspended sediment concentration exceeds a certain level. Fluid mud is most involved with consolidation behavior of the
bed layer. To distinguish between three different settling regimes, two boundary are defines, \( c_{floc} \) and \( c_{hindered} \), which are the concentrations where flocculation and hindered settling begins, respectively.

In case of fine grained cohesive sediment (<0.006mm), the settling velocity will depend on the rate of flocculation. If the suspended sediment concentration is low the probability for collision between the cohesive particles is low and the settling velocity will be close to the settling velocity for a single grain. With increasing concentration, collision between particles will occur more frequently and formation of flocs take place from cohesiveness of the particles. Consequently this leads to an increase in settling velocity. High levels of turbulence will decrease the floc size due to destruction of flocs. If sediment concentration increases further, the flocs will eventually interact hydrodynamical so that the effectiveness of the flocs during settling cause an upward flow of the liquid they displace and hindered settling occurs which leads to a reduction in settling velocity. Further increase in sediment concentration will result in decreasing distance between the flocs, which leads to negligible settling velocity and the mixture will act as fluid mud.

Flocculation is when the concentration of sediment is high enough for sediment flocs to influence each other settling velocity. This occurs because collision between flocs will increase floc size leading to higher settling velocities. Standard flocculation concentrations occur when hindered settling is neglected.

The concentration of sediment is defined such as concentration of floc or concentration of hindered, can be seen in Table 2.2. The sediment stage as suspension with concentration about 0.01-10.0 kg/m\(^3\), the flocculation may occur and if the concentration about 10.0-50.0 kg/m\(^3\), hindered settling begins. To determine where the
sediment is classified as floc concentration or hindered concentration, physical laboratory assessment should be undertaken. Based on the flocculation and hindered phenomena, the quantity of floc concentration and hindered concentration can be determined. Settling velocity in the model setting were preset in the range varied between 0.001-0.005 m/s.

**Constant settling velocity:**

The flocculation may be negligible while suspended sediment concentration is below a certain value, and constant settling velocity can be applied:

\[ w_s = k \left( \frac{c}{\rho_{s}} < c_{floc} \right) \]  \hspace{1cm} (3-15)

Where \( w_s \) (m/s) is the settling velocity and \( k \) is the constant.

**Flocculation:**

The sediment will begin to flocculate after reaching \( c_{floc} \). The relationship between settling velocity and sediment density (Burt, 1986):

\[ w_s = k \left( \frac{c}{\rho_{s}} \right)^r \quad c_{floc} > c > c_{hindered} \]  \hspace{1cm} (3-16)

Where \( k \) is a constant, \( \rho_{s} \text{ (kg/m}^3\text{)} \) is the sediment density, \( r \) is a coefficient termed settling index.

**Hindered settling:**

The settling column of flocs begins to interfere after a relatively high sediment concentration \( c_{hindered} \) is reached and hereby reduces the settling velocity.

The relationship between salinity and flocculation is not considered in the model due to time of simulation should be longer in order to obtain the stability of graph.
**Deposition:**

The relationship within the deposition as (Krone, 1962)

\[ S_D = w_s c_b P_D \]  

(3-17)

where \( w_s \) is the settling velocity of the suspended sediment (\( \text{ms}^{-1} \)), \( c_b \) is the suspended sediment near the bed, \( P_D \) is the probability of deposition.

\[ P_D = 1 - \frac{\tau_b}{\tau_{cd}} \]  

(3-18)

In the three-dimensional model, \( c_b \) is simply equal to the sediment concentration in the water cell just above the sediment bed.

**Erosion:**

**Erosion for hard-bed:**

The erosion rate for a consolidated bed can be written as (Partheniades, 1965):

\[ S_E = E_r \left( \frac{\tau_b}{\tau_{ce}} - 1 \right)^{Em} \quad \tau_b > \tau_c \]  

(3-19)

Where \( E_r \) is the rate of erosion (kg m\(^{-2}\) s\(^{-1}\)), \( n \) is the power of erosion, \( \tau_b \) is the bed shear stress (N m\(^{-2}\)) and \( \tau_{ce} \) is the critical shear stress for erosion (N m\(^{-2}\)). \( S_E \) is the erosion rate for a consolidated bed (kg m\(^{-2}\) s\(^{-1}\)).

**Erosion for soft-bed:**

The erosion rate of the partly consolidated bed can be written as (Parchure and Mehta, 1985):

\[ S_E = E_r \left( e^{\alpha(\tau_b - \tau_c)} \right) \quad \tau_b > \tau_c \]  

(3-20)

Where \( \alpha \) is the coefficient for erosion.

3.4 Model setting and data:

In the model setting, a finite difference grid was developed as the model domain.
with the size of the triangular mesh option which each element maximum area is 1,000,000 m$^2$. The vertical direction z is divided into 10 layers. The horizontal grid mesh contains 256,250 element with 152,196 nodes (Figure 3.3, Figure 3.4).

![Unstructured Mesh of the Ariake Sea in Mesh file](image)

**Figure 3.3** Unstructured Mesh of the Ariake Sea in Mesh file

Simulation period consists the number of time step which is 946800 time step and interval of time step which is 1 second.

The model was calibrated with using observed data from August to September, 2004. During calibration the parameter of hydrodynamic and sediment characteristics of the sea were adjusted until a satisfactory correspondence between the model results and observed field data was obtained.
The critical shear stress $\tau_{ce} = 0$ to 0.4 Pa, was used for start the sediment resuspension value. The rate of erosion ($E_r$) is a factor used to control the overall level of the erosion (Eqs.3-19,3-20). The calibrated rate of erosion $E_r=0.00001$ kg m$^{-2}$ s$^{-1}$. The empirical constant for erosion $\alpha=1$, the power of erosion $E_m=1$. Bed roughness, $z_0= 0.001$ to 0.005 m.

Figure 3.4 Unstructured Mesh and Element of Triangular of north part of the Ariake Sea in Mesh Generator file
Table 3.1 Information of Mesh

<table>
<thead>
<tr>
<th>Item of Mesh</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of elements</td>
<td>256250</td>
</tr>
<tr>
<td>Number of faces</td>
<td>676525</td>
</tr>
<tr>
<td>Number of nodes</td>
<td>152196</td>
</tr>
<tr>
<td>Number of sections</td>
<td>6</td>
</tr>
<tr>
<td>Min. x coordinate</td>
<td>569591.77</td>
</tr>
<tr>
<td>Max. x coordinate</td>
<td>672318.943</td>
</tr>
<tr>
<td>Min. y coordinate</td>
<td>3545554.25</td>
</tr>
<tr>
<td>Max. y coordinate</td>
<td>3680341.75</td>
</tr>
<tr>
<td>Min. z coordinate</td>
<td>-130.90236</td>
</tr>
<tr>
<td>Max. z coordinate</td>
<td>9.961558</td>
</tr>
</tbody>
</table>

The data needed as input are:

Bathymetric data obtained from the Ariake Sea Project of Saga University in the form of water depth in the Ariake Sea and other areas in the southern of Kyushu Island in longitude 129° - 130° and latitude 32° - 33°. The topographic data are obtained from 50 m DEM of Japan supplied by Geospatial Information Authority of Japan. The discharge data of Chikugo, Yabe, Rokkaku and Kase river are obtained from Japan Water Information System. The high intensity of rainfall effect to the river can be shown in the data as high discharge (flooding). The suspended sediment concentration loading from river basins is not consider because the boundary condition of sediment in the model is confined with fine grained sediment (silt) with diameter of particle <0.063mm. The tidal current considered is Nagasaki Tide. The data are obtained from Japan Oceanographic Data Center. The Storm Surge is Typhoon Songda200418 from 28 August to 7 September 2004 in the form of wind speed and direction, obtained from Japan Meteorology Agency.

In Figure. 3.5 denotes that the discharge of Chikugo river is higher than the three other
rivers; Kase, Rokkaku and Yabe river.

Figure 3.5 Chikugo, Kase, Rokkaku, Yabe river discharge

Figure 3.6 Tide level at Nagasaki Station
Figure 3.7 Tide level at Kuchinotsu Station

Figure 3.8 Tide level at Misumi Station
Figure 3.9 Tide level at Oura Station

Wind data:

Wind data had been taken from the data of typhoon SONGDA200418 which the basic information of this typhoon is as follow:

Birth : 2004-08-28 00:00:00 UTC
Death : 2004-09-08 00:00:00 UTC

Life Time : 264 hours

Minimum pressure: 925 hPa

Maximum wind : 95 knots

Largest radius of storm wind : 370 km

Largest diameter of storm wind : 520 km

Average speed : 25.4 km/h

In the simulation, typhoon space Saga SONGDA200418 are used.
Figure 3.10 The Track of Typhoon SONGDA200418 (Japan Meteorological Agency)

Figure 3.11 Speed and direction of Typhoon Saga SONGDA200418 in the north of Ariake Sea (2004/09/07 10:03:20)
Figure 3.12 Speed and direction of Typhoon Saga SONGDA200418 in the Ariake Sea (2004/09/07 10:03:20)
Figure 3.13  Wind SagaSONGDA200418 28agt-7sept 2004   at Saga station
Initial Conditions and Boundary Conditions

The hydrodynamic initial condition is a form of surface water level data on 28 August, 00:00:00, 2004 which is interpolated by using data from several station Nagasaki, Kuchinotsu, Misumi and Oura. The salinity initial condition is a data file containing initial salinity value (PSU) where the data is varying in domain. The salinity data value was preset in the range 25 to 32 PSU (Fig.3.15). The temperature was not considered in this study and had been taken as constant value. The mud transport initial condition was preset as suspended sediment concentration constant value in domain, in the range 0 to 0.024 kg m$^{-3}$.
The hydrodynamic boundary condition is a form of time series discharge of Chikugo (Senoshita station), Yabe (Funakoya station), Rokkaku (Mizonoue station) and Kase river (Kawakami station) from 28 August, 00:00:00 to 7 September, 23:00:00, 2004 and tidal level at Nagasaki as boundary condition at open sea of the Ariake Sea. The salinity boundary condition is specified value as varying in time and along boundary at open sea of the Ariake Sea, is taken in the range 31 to 33 PSU (Fig.3.16, ref.50). For the rivers, salinity value was preset at 0 PSU with assumption that at the start of simulation the water from river is still fresh water. The mud transport boundary condition for rivers and the open sea were preset in the range 0.001 to 0.02 kg m$^{-3}$.

![Figure 3.15 Salinity Initial Condition as MIKE3dfs3 file varying in domain](image-url)
In Figure 3.15 it can be seen that around the open sea of the Ariake Sea (south part), salinity value is taken about 32 PSU. Conversely in the north part of Ariake Sea salinity value is taken lower than the open sea value and about more than 28PSU. This graph had been gotten after interpolation of available data.

![Salinity Boundary Condition as MIKE3 dfs2 file](image)

**Figure 3.16** Salinity Boundary Condition as MIKE3 dfs2 file at 28 August, 2004 (0:00:00)

Figure 3.16 depicts that the variation value of salinity around and along open boundary of the open Ariake Sea after horizontal and vertical interpolation of the data.
3.5 Model calibrations

The predictions from the numerical models will instead be validated against available observation data that had been informed in the reference. Calibration of water level had been done based on the tide data of Nagasaki and Kuchinotsu.

Calibration of suspended sediment concentration (SSC) based on the monthly data in year 2004 from Station S6, S1 and S5 (Figure 3.17).

Calibration of salinity based on the monthly mean value data between August to September 2004 from Sea Area Division A,B,C,D,E and F (Figure 3.18).

Figure 3.19 to Figure 3.30 show that the distribution of water level, salinity and suspended sediment concentration are consistent with the measured values. Therefore, this model can be used to calculate salinity and sediment transport change resulting from tidal currents or combined with wind effect.

Figure 3.17 Station S1, S5 and S6 (Cao Don et al.,2007)

Figure 3.18 Sea Area Division (Sonoda et al.,2011)
Figure 3.19 Calibration of water level at Station Nagasaki

Figure 3.20 Calibration of water level at Station Kuchinotsu
Figure 3.21 Calibration of SSC at Station S6

**Figure 3.22** Calibration of SSC at Station S1

**Figure 3.23** Calibration of SSC at Station S5

Figure 3.21 shows the trend of suspended sediment concentration at station S6 which the location near river mouth. The comparison of SSC quantity with other location S1 and S5 implies that suspended sediment concentration gathers more in near river mouth than offshore.
Figure 3.24 Calibration of Salinity at A area

Figure 3.25 Water level at A area

Figure 3.26 Calibration of Salinity at D area

Figure 3.27 Calibration of Salinity at E area
Figure 3.25 shows the water level at A area which the trend follows the trend of tide in Figure 3.9. The salinity in this area (Figure 3.24) tend to increase or decrease with water level amplitude and the value is in the range of salinity measurement data. The value of salinity that had been shown in Figure 3.26 to Figure 3.30 is still in the range of measurement data but different in trend. This might be caused of factor like wind induce sea wave and gravity current due to difference of density of water which were not consider in this study. The comparison of salinity value of area A to F implies that salinity more to the open sea is higher than to nearshore.

Some of the stations or areas of data observation which used in calibration reside
near to the location of the Chikugo and Kase estuaries, therefore calibration for estuaries is not undertaken. Table 3.2 shows the parameters that are used in the simulation. The others parameter are default parameter and are not shown in this table.

**Table 3.2 Parameters used in calibration**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Quantity</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hydrodynamic:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>eddy viscosity</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>horizontal</td>
<td>$h_t$</td>
<td>0.002</td>
<td>m²/s</td>
</tr>
<tr>
<td>vertical</td>
<td>$v_t$</td>
<td>0.002</td>
<td>m²/s</td>
</tr>
<tr>
<td><strong>Salinity:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>horizontal dispersion</td>
<td>$D_{isp.hor}$</td>
<td>0.01</td>
<td>m²/s</td>
</tr>
<tr>
<td>vertical dispersion</td>
<td>$D_{isp.vert.}$</td>
<td>0.01</td>
<td>m²/s</td>
</tr>
<tr>
<td><strong>Mud transport:</strong></td>
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<td><strong>Water column parameter:</strong></td>
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<tr>
<td>settling:</td>
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<td></td>
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<tr>
<td>density sediment</td>
<td>$\rho_{sediment}$</td>
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<td>kg/m³</td>
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<tr>
<td>concentration for flocculation</td>
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<td>kg/m³</td>
</tr>
<tr>
<td>(default)</td>
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<td></td>
</tr>
<tr>
<td>concentration for hindered settling</td>
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<td>kg/m³</td>
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<tr>
<td>(default)</td>
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<td></td>
<td></td>
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<td>settling velocity</td>
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<td>critical shear stress</td>
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<td><strong>Bed parameter:</strong></td>
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<tr>
<td>erosion:</td>
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<tr>
<td>rate of erosion</td>
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<tr>
<td>critical shear stress</td>
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<tr>
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<td>kg/m³</td>
</tr>
<tr>
<td>bed roughness</td>
<td>$R_b$</td>
<td>0.002</td>
<td>m</td>
</tr>
</tbody>
</table>
3.6 Conclusion

The pattern distribution of suspended sediment concentration in the location of station S6 differs with the pattern in S1 and S5. The location S6 is near the mouth of river which much be influenced by water flow from the river that picks up sediment from upstream of river, while S1 and S5 are little far from the river of mouth. This conditions will influence the distribution pattern of suspended sediment concentration.

The value of salinity average still in the range of measurement data but the trends differ with the measurement data trend, this might be caused by some factor there were not consider in the study like effect of the seawater wave generated by wind and other like gravity current.

Boundary condition of salinity in open the Ariake Sea is varying in time and along boundary. Initial condition as varying in domain. The model had been calibrated against water level, salinity and suspended sediment concentration (SSC), which its distribution has the good results to measurement value. The parameters of hydrodynamic and sediment characteristics of the Ariake Sea were calibrated until a satisfactory correspondence between the model results and observed field data was obtained. The parameters used in the calibration are denoted in Table 3.2
4.1 Introduction

An estuary is defined as a semi enclosed coastal body of water that is either permanently or periodically open to the sea and within which seawater is measurably diluted with seawater derived from land drainage (Kennish, 2001). The existence of tidal and non tidal components results in water circulation in estuaries from extrinsic forces, that are tide producing forces of the sun and moon, which are responsible for the periodic vertical displacement of estuarine water and the associated horizontal movement of tidal currents. The non tidal component originates from factors independent of astronomical forces, specifically water movements induced by the interaction of fresh and saline water of different densities. The intensity of tidal currents relative to river flow, in combination with geometric configuration of the estuary largely determines circulation patterns. While tides and tidal currents provide the ultimate driving force for much of the turbulence and mixing in most stratified and well-mixed estuaries. Other mechanisms like surface wind stress and other meteorological forcing can be important modifying factors, especially in shallow coastal bays. The non tidal forcing induced changes in estuarine circulation, storm surges and variability in the neap-spring tidal cycle.

Seawater density (about 1.025 g/cm³) is more dense than freshwater (1.0 g/cm³), this difference makes two fluids tend to form separate water masses in estuaries, with fresh water overlying seawater. Although water temperature influences the density values of both freshwater and seawater, it has a much smaller effect than the
concentration of dissolved salts on density levels. The mixing between freshwater and seawater masses in a density stratified system lacking currents is ascribed to diffuse and advection processes. Diffusion in estuarine water is defined as a flux of salt and advection as a flux of salt and a flux of water. Vertical advection, the upward breaking of internal waves at the interface between the freshwater and seawater layers, is the primary mixing agent in the absence of currents, causing a diffuse boundary layer between the two water masses and a gradual increase in salinity in the freshwater layer down estuary. Although the upward flux of salt by diffusion does not produce the mass flux of water and salt as advection, it plays an important role in the mixing of waters along the vertical, lateral and longitudinal axes of estuaries.

The mixing of estuaries waters is facilitated by current action. The interaction of tidal currents, wind stress, internal friction and bottom friction can reduce or eliminate density stratification of the water column. The turbulence produced by both internal shear and bottom friction is a critical factor for estuaries mixing. In well-mixed systems, turbulence generated by bottom friction predominates whereas in highly stratified estuaries, turbulence produced by internal shear is premier. Both internal shear and bottom friction are important in the mixing of partially stratified systems.

Four types of estuaries are recognized based on water circulation(Kennish,2001):

1. Type a, vertically homogeneous estuaries, which have a lateral salinity gradient and are characterized by greater tidal action relative to river inflow.
2. Type b, partially mixed estuaries, which are moderately stratified and characterized by less dominating river inflow.
3. Type c, sectional homogeneous estuaries, which are both laterally and vertically homogeneous and characterized by tidal flow that greatly exceeds river discharges.
4. Type d, salt wedge estuaries, which are highly stratified and characterized by river inflow that completely dominates the circulation system.

The river water entering the estuaries mixes to some extent with the denser sea water but eventually flows out in the form of a surface current into the open sea. The inflowing seawater in turn enters the estuary as a bottom current and later mixes with out flowing freshwater. This type of water exchange is referred to as estuaries circulation.

The models in Figure 4.1 show the four principal cases identified in nature. In a shallow estuary, the entering river water and seawater may become completely mixed and therefore unstratified (Fig.4.1b) but salinity increases from the river inlet toward the open sea. If mixing of seawater and freshwater is less effective, which occurs particularly in deep estuaries with a sill, the water body displays a more or less pronounced and stable density stratification (Fig.4.1c and d)

Mud suspended sediment plays an important role in the estuary environment. In estuaries, the transport mechanism (settling and scour lag) acting on the fine-grained material tend to concentrate and deposit the fine-grained material in the inner sheltered parts of the area (Van Straaten & Kuenen, 1958; Postma, 1967; and Pejrup, 1988).

A zone with high concentration of suspension is called turbidity maximum and will change its position within the estuary depending on the tidal cycle and the input of fresh water from river. In this condition the salinity around the area also is important.

Clay particles have a plate like structure and an overall negative ionic charge due to broken mineral bonds on their faces.
In saline water the negative charges on the particles attract positively charged cations and a diffuse cloud of cations is formed around the particles. In this way the particles tend to repel each other (Van Olphen, 1963). Still particles in saline water flocculate and form large aggregate or flocs in spite of the repulsive forces. This is because in saline water the electrical double layer is compressed and the attractive van der Waals force acting upon the atom pairs in the particles becomes active.

Studies of spatial variability in circulation have concentrated on flow in the longitudinal sense, along the estuary and its changes in the vertical plane with increasing depth. Little or no consideration is often given to the variation of flow across the estuary in a lateral direction. In many cases, lateral differences in velocity or density

**Figure 4.1** Estuary in plan view (at top) and model of estuaries water circulation in cross section (Einsele, 2000)
fields produce transverse effects that can be large compared with vertical variations. Secondary flows may arise where circulation is not evenly distributed across the estuary because of the lack of consistency in the cross-sectional form of the basin in a longitudinal direction, the effect of the Coriolis force, and difference in lateral density field. In many stratified and well-mixed estuaries, longitudinal density gradient circulation and mixing are common. The longitudinal surface slope, which acts in a down estuary direction, and the longitudinal density gradient force which acts in an up estuary direction, drive this type of circulation. When river discharge is low, the surface slope force dominates in the upper part of the water column, with a net flow down estuary. Conversely, the density gradient force dominates in the lower part of the water column with a net flow up estuary. The circulation pattern may be obscured by lateral effects, surface wind stress, meteorological forcing and the basin geometry, at least for certain period of time, particularly in large estuaries. Wind stress interacting with tidal and river flows often governs the degree of turbulent mixing and controls the vertical salinity and velocity structure of estuaries.

**Table 4.1** General Estuary Physical Characteristic (Kennis, 2001)

<table>
<thead>
<tr>
<th>Estuary Type</th>
<th>Dominant Mixing Force</th>
<th>Width/depth Ratio</th>
<th>Salinity Gradient</th>
<th>Probable Topographic Categories</th>
</tr>
</thead>
<tbody>
<tr>
<td>Highly stratified</td>
<td>River flow</td>
<td>Low</td>
<td>Longitudinal</td>
<td>Fluvial</td>
</tr>
<tr>
<td>Moderately stratified</td>
<td>River flow</td>
<td>Low, Moderate</td>
<td>Longitudinal</td>
<td>Deltaic</td>
</tr>
<tr>
<td>Vertically homogeneous</td>
<td>Tide, wind</td>
<td>High</td>
<td>Vertical</td>
<td>Fjord</td>
</tr>
<tr>
<td>Vertically and laterally homogeneous</td>
<td>Tide, wind</td>
<td>Very high</td>
<td>Longitudinal</td>
<td>Coastal plain Bar built Bar built</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Lateral</td>
<td>(Lagoon) Coastal plain</td>
</tr>
</tbody>
</table>
4.2 Salinity and Application of MIKE3 Hydrodynamic (HD)

To calculate the saltwater intrusion within the study area with the MIKE3 tools, consider the time simulation which be taken from 28 Aug. to 7 Sept. 2004. Hydrodynamic boundary condition used the discharge of Chikugo, Yabe, Rokkaku, Kase river and the tide of Nagasaki. For the tide and wind concurrent, boundary condition used wind Saga SONGDA200418. The points of checking had been taken as the random points from mouth to more south direction P1 to P2 (Figure 4.2) and IP1 to IP4 from the mouth of river to upstream direction (Figure 4.8) to predict the intrusion of salt water to upstream of Chikugo river. Points IP1 to IP5 from the mouth of Kase river to upstream direction had been predicted as well (Figure 4.20).

Tide effects to salinity:

Figure 4.2 Salinity horizontal distribution P1-P2 effected by tide in the Ariake Sea at surface layer
**Figure 4.3** Salinity vertical distribution P1-P2 effected by tide in the Ariake Sea

The simulation results in Figure 4.2 and Figure 4.3 show the distribution and mixing as horizontal and vertical of salinity which are prevalent distribution due to the nature action of tidal currents, but in Figure 4.6 and Figure 4.7 the simulation results of the distribution horizontal and vertical of salinity much be influenced by effect of wind influences the propagation of saltwater to upstream of river. It can be compared from Figure 4.3 and Figure 4.7 which denotes that there is a change in salinity distribution from P2 to upstream caused by wind which direction to upstream.

In Figure 4.3 vertical profile of salinity as the salt wedge pattern of estuary (Figure 4.1.d) which in the point intersection of fresh water and salt water, in surface layer fresh water more towards offshore, while in bottom layer salt water more towards upstream of river. In the Figure 4.7 the pattern of distribution is different caused by interference of wind to tidal currents. Figure 4.4 and Figure 4.5 at the time which water level from river is lower, saltwater propagates more to upstream in the bottom layer.
Figure 4.4 Salinity horizontal distribution P1-P2 in surface layer effected by tide in the Ariake Sea at low level water from river.

Figure 4.5 Salinity vertical distribution P1-P2 effected by tide in the Ariake Sea at low level water from river.
Tide-wind concurrent effect to salinity:

**Figure 4.6** Salinity horizontal distribution PI-P2 effected by tide-wind concurrent in the Ariake Sea at surface layer

**Figure 4.7** Salinity vertical profile P1-P2 effected by tide-wind concurrent in the Ariake Sea
4.2.1 Salt water intrusion to Chikugo river:

The trend of salt water intrusion from the mouth of Chikugo river to upstream of river, had been determined by put the checking point IP1, IP2, IP3 and IP4, where the distance from IP1 to IP4 is about 4,200 m. Point IP1 resides at the mouth of Chikugo river. The location of point IP1,IP2, IP3 and IP4 can be seen in horizontal view of north Ariake Sea in Figure 4.8.

**Figure 4.8** Horizontal view of IP1 to IP4 Chikugo river salinity checking points at surface layer.

**Figure 4.9** Salinity vertical profile of IP1-IP4 in Chikugo river at spring-tide
**Figure 4.10** Salinity vertical profile of IP1-IP4 in Chikugo river at neap-tide

The point IP4 is not the most upstream point of saltwater intrusion, these only show the trend of saltwater intrusion to upstream. Figure 4.9 shows the vertical distribution of salinity of point IP1 to IP4. It denotes that in spring tide which seawater is moving up then saltwater from offshore propagates to upstream causes the higher salinity in bottom between IP3 to IP4 more to upstream. Conversely in surface freshwater from river propagates more to offshore causes the salinity is lower. Figure 4.10 the condition of salinity in surface between IP1 to IP4 is more influenced by flowing of freshwater to offshore due to effect of neap tide and water flows from river.

The stratification of salinity can be depicted the point stratifications for all layer. Figure 4.11, Figure 4-12, Figure 4.13 and Figure 4.14 denote the distribution of salinity value in all layer of the checking point effected by tide in spring tide which the peak of intrusion of saltwater probably occur. The vertical distribution of salinity in neap tide can be seen in Figure 4.10 which the condition of salinity much be influenced by water flowing to offshore due to river flow to downstream and moving down of seawater at
neap tide.

**Figure 4.11** Salinity stratification IP1 in spring tide (Chikugo river)

**Figure 4.12** Salinity stratification IP2 in spring tide (Chikugo river)

**Figure 4.13** Salinity stratification IP3 in spring tide (Chikugo river)
Salinity stratification effected by spring tide, in point IP1 at surface layer of salinity about 28.40 PSU, IP2 about 28.02 PSU, IP3 about 23 PSU, and IP4 about 2 PSU. The value of salinity seems gradually decreases by the time the water flows to upstream. In bottom layer IP1 about 28.37 PSU, IP2 about 27.94 PSU, IP3 about 26.0 PSU, and IP4 about 10 PSU. Same with the condition at surface layer which the salinity gradually decrease while the water flows to upstream. IP1 and IP2 are the area that the salinity is most influenced by the saltwater from bottom to surface, while in IP3 and IP4 are the area that gradually mix between saltwater and freshwater, therefore the patterns of salinity distribution in IP1 and IP2 are different from IP3 and IP4. The results indicate that until more than point IP4 or about 4,200 m from IP1 or the mouth of Chikugo river the salinity is lower. In IP4 at surface layer the salinity less than at the bottom layer, this phenomena indicates that the vertical profile of the mix between fresh water and salt water like salt wedge estuary pattern (Fig.4.1 d). The salt water effectively dominates the fresh water of river in bottom layer, while in surface layer the salt water less dominates the fresh water of river.
Table 4.2 Salinity at checking point IP1, IP2, IP3 and IP4 in Chikugo river at spring tide

<table>
<thead>
<tr>
<th></th>
<th>IP1</th>
<th>IP2</th>
<th>IP3</th>
<th>IP4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salinity (PSU) (surface layer)</td>
<td>28.40</td>
<td>28.02</td>
<td>23.00</td>
<td>2.00</td>
</tr>
<tr>
<td>Salinity (PSU) (bottom layer)</td>
<td>28.37</td>
<td>27.94</td>
<td>26.00</td>
<td>10.00</td>
</tr>
</tbody>
</table>

The peak of discharge of the Chikugo river produce flooding more than the other three rivers; Yabe, Rokkaku as well as Kase river. Flooding of Chikugo river for the sake of time simulation occurs the most at about 7 September 2004.

Figure 4.15 Salinity stratification IP1 in flooding tide (Chikugo river)

Figure 4.16 Salinity stratification IP3 in flooding tide (Chikugo river)

Effect of flooding in point IP1 based on Fig.4.15 indicates that in point IP1 by the
time of flooding, in surface layer it dominates by fresh water from flooding which salinity about 0.5 PSU, and in bottom layer it still dominates by salt water which salinity about 23 PSU. In Figure 4.16 the distribution of salinity becomes small, it indicates that the influence of saltwater from offshore until about IP3. The pattern of salt intrusion is salt wedge which the large inflow from river leads the fresh water to offshore.

Effect of tide if concurrent wind takes place in the Ariake Sea can be evaluated by stratification point in IP1 to IP3. It can be seen in the Fig.4.17 to Fig.4.19.

**Figure 4.17** Salinity stratification at point IP1 effected by tide-wind(Chikugo river)

**Figure 4.18** Salinity stratification at point IP2 effected by tide-wind(Chikugo river)
Figure 4.19 Salinity stratification IP3 effected by tide-wind (Chikugo river)

The effect of tide when concurrent wind occurrence can be indicated that in point IP1 salinity is keep a little higher in bottom layer and gradually decrease to upstream direction, but in the surface layer the salinity is low. In IP2 and IP3 the salinity become small at surface and bottom layer, indicates that the influence of saltwater from offshore until about IP1 (Figure 4.17 to Figure 4.19).

4.2.3 Salt water intrusion to Kase river:

Figure 4.20 Horizontal view of IP1 to IP5 salinity checking points in Kase river
The trend of salt water intrusion from the mouth of Kase river to upstream of river, had been determined by put the checking point IP1, IP2, IP3, IP4 and IP5, where the distance from IP1 to IP5 is about 1,260 m. Point IP1 resides at the mouth of Kase river. The location of point IP1, IP2, IP3, IP4 and IP5 can be seen in horizontal view of the north Ariake Sea in Figure 4.20.

**Figure 4.21** Salinity vertical profile of IP1-IP5 in Kase river at spring-tide

**Figure 4.22** Salinity vertical profile of IP1-IP5 in Kase river at neap-tide
The stratification of salinity can be depicted the point stratifications for all layer. Figure 4.23 to Figure 4.27 denote the distribution of salinity value in all layer of the checking point effected by tide in spring tide which the maximum of intrusion of saltwater probably occur. The vertical distribution of salinity in neap tide can be seen in Figure 4.22 which the condition of salinity much be influenced by water flowing to offshore due to river flow to downstream and the moving down of seawater at neap tide.

**Figure 4.23** Salinity stratification at IP1 Kase river in spring tide

**Figure 4.24** Salinity stratification at IP2 Kase river in spring tide
Figure 4.25 Salinity stratification at IP3 Kase river in spring tide

Figure 4.26 Salinity stratification at IP4 Kase river in spring tide

Figure 4.27 Salinity stratification at IP5 Kase river in spring tide
The changes of salinity from point IP1 to IP5 in the mouth of Kase river can be seen in Fig.4.23 to Fig.4.27. In surface layer from IP1 to IP5 the results of salinity are 26.75 PSU, 26.14 PSU, 20 PSU, 8 PSU and 1.00 PSU in IP5, indicates that in IP5 salinity was dominated by fresh water. While in bottom layer the results of salinity from IP1 to IP5 are respectively 26.6 PSU, 25.975 PSU, 24 PSU, 15 PSU and 4 PSU, indicates that in IP5 salinity was still a little mix between fresh and salt water. the profile of salinity in Kase river estuary like profile salt-wedge estuary. The distance of intrusion about 1,200 m from the mouth of Kase river at spring tide. IP1 and IP2 are the area that the salinity is most influenced by the saltwater from bottom to surface, while in IP3 to IP5 are the area that gradually mix to upstream between saltwater and freshwater, therefore the patterns of salinity distribution in IP1 and IP2 are different from IP3, IP4 and IP5.

Table 4.3 Salinity at checking point IP1,IP2,IP3, IP4 and IP5 in Kase river at spring tide

<table>
<thead>
<tr>
<th></th>
<th>IP1</th>
<th>IP2</th>
<th>IP3</th>
<th>IP4</th>
<th>IP5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salinity (PSU)</td>
<td>26.75</td>
<td>26.14</td>
<td>20.00</td>
<td>8.00</td>
<td>1.00</td>
</tr>
<tr>
<td>(surface layer)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Salinity (PSU)</td>
<td>26.60</td>
<td>25.97</td>
<td>24.00</td>
<td>15.00</td>
<td>4.00</td>
</tr>
<tr>
<td>(bottom layer)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Effect of flooding in point IP1 and IP3 based on Figure 4.28 and Figure 4.29 denotes that in point IP1 by the time of flooding, in surface layer and bottom layer value of salinity is gradually decrease until IP3. It indicates that in flooding time, the influence of saltwater from offshore until about IP3.
**Figure 4.28** Salinity stratification IP1 in flooding tide (Kase river)

**Figure 4.29** Salinity stratification IP3 in flooding tide (Kase river)

Effect of tide if concurrent wind takes place in the Ariake Sea to the Kase river estuary can be evaluated by stratification point in IP1. It can be seen in Figure 4.30 that salinity distribution in IP1 is very small at surface and bottom layer and same like freshwater, indicates that the influence of saltwater from offshore before the location of pointIP1.
4.3 Conclusion

The Chikugo and Kase river are the rivers in the north Ariake Sea which contribute sediment from the river to the sea by flow of the river from upstream. Tidal flat is exist in the estuary of the Chikugo and Kase river. Tide is responsible to vertical displacement of estuary waters and the associated horizontal movement of tidal currents. Water movements induced by the interaction of fresh and saline waters of different densities.

The mixing of estuaries waters is facilitated by current action. The interaction of tidal currents, wind stress, internal friction and bottom friction can reduce or eliminate density stratification of the water column. The zone with high concentration of suspension will change its position within the estuary depending on the tidal cycle and the input of fresh water from river. In this condition the salinity around the area also is important.

The intrusions of salt water to Chikugo and Kase river are presented which

Figure 4.30 Salinity stratification IP1 effected by tide-wind(Kase river)
consider to high water level in spring tide effect. In the Chikugo river estuary, the salinity gradually decreases if salt water flows more to upstream of river. In the intersection point between fresh and salt water, in surface layer low salinity (fresh water) more towards offshore, while in bottom layer higher salinity (saltwater) more towards upstream of river. The intrusion of salt water approximately 4,200 m from the point of river mouth to upstream in Chikugo River, while the maximum suspended sediment concentration occurred at about 5,000 m upstream from the river mouth. In the Kase river same condition occur which the salinity gradually decreases if salt water flows more to upstream of river. The intersection point between salt and fresh water, in surface layer low salinity more towards to offshore while in the bottom layer higher density flow more to upstream. The intrusion of salt water approximately 1,200 m from the point of river mouth to upstream, while the maximum suspended sediment concentration occurred at about 1,200 m upstream from the river mouth.
5.1 Introduction

The understanding of mud sediment transport processes has significant economical and ecological importance. The ability to predict the movement of fine sediments (mud sediments) is necessary for prediction of the area where the transparency of water environment decreases or increases, and the distribution of contaminants from chemical materials in the coastal area. Fresh water supply flows through main river including Chikugo river into north part of Ariake bay, where intertidal mudflats are developed. Using the MIKE3 Mud Transport Model after successful calibrations, the suspended sediment concentration (SSC) in the north part of the Ariake Sea caused by tidal currents and effect if tide and wind take place concurrently, can be predicted.

5.2 The SSC stratifications checking points effected by tide

The random points had been determined through line-points from Chikugo river consists IP1 to IP13, and line-points through Kase river consists IP1 to IP15, can be seen in Fig.5.1 and Fig.5.2. Stratification consists suspended sediment concentration and tidal currents. The tidal currents velocity graph definition is based on the time step of simulation with considering there is a delay between peak of velocity and peak of water level. Sometimes the peak of current precede the peak of water level and otherwise.

The movement of SSC along the spring tide, neap tide and currents flooding, can be
evaluated by comparing with the pattern of tidal currents in the point of checking with assume if current is positive (+) it means that current moves toward land and conversely.

**Figure 5.1** Checking points path through Chikugo river

**Figure 5.2** Checking points path through Kase river
5.2.1 Checking- Points through Chikugo river at spring tide:

The stratification points had been taken are based on Figure 5.1 checking points path through Chikugo river. The calculation is undertaken by using the parameter and boundary condition had been gotten from calibration. Every point of checking has current velocity and SSC stratification with time of occurrence at spring tide.

IP1:

**Figure 5.3** Current and SSC graph of IP1 in spring tide (Chikugo path)

IP2:

**Figure 5.4** Current & SSC graph of IP2 in spring tide (Chikugo path)
IP3:

Figure 5.5 Current & SSC graph of IP3 in spring tide (Chikugo path)

IP4:

Figure 5.6 Current & SSC graph of IP4 in spring tide (Chikugo path)

IP5:

Figure 5.7 Current & SSC graph of IP5 in spring tide (Chikugo path)
IP6:

Figure 5.8 Current & SSC graph of IP6 in spring tide (Chikugo path)

IP7:

Figure 5.9 Current & SSC graph of IP7 in spring tide (Chikugo path)

IP8:

Figure 5.10 Current & SSC graph of IP8 in spring tide (Chikugo path)
IP9:

**Figure 5.11** Current & SSC graph of IP9 in spring tide (Chikugo path)

IP10:

**Figure 5.12** Current & SSC graph of IP10 in spring tide (Chikugo path)

IP11:

**Figure 5.13** Current & SSC graph of IP11 in spring tide (Chikugo path)
IP12:

![Figure 5.14 Current & SSC graph of IP12 in spring tide (Chikugo path)](image)

**Figure 5.14** Current & SSC graph of IP12 in spring tide (Chikugo path)

IP13:

![Figure 5.15 Current & SSC graph of IP13 in spring tide (Chikugo path)](image)

**Figure 5.15** Current & SSC graph of IP13 in spring tide (Chikugo path)

Point IP1 and IP2 as had been denoted in Figure 5.3 and Figure 5.4, indicates that the currents are moving to southward because in this area water flows are influenced by river water flowing. In Figure 5.5 denotes that there is a change in current direction in IP3 which in surface layer the current keeps on moving to south while in the bottom changes to north direction. SSC in IP1 to IP3 are a little higher than IP4 until IP13 as can be seen in Figure 5.6 to Figure 5.15, this means that much sediment from Chikugo river flows from upstream to downstream. The vertical distribution of SSC from surface to bottom is almost same in each point except in point IP3 which in this point the surface current flows to south while the bottom current flows to north.
5.2.2 Checking -Points through Kase river at spring tide:

The stratification points had been taken are based on Figure 5.2 checking points path through Kase river. The calculation is undertaken by using the parameter and boundary condition had been gotten from calibration. Every point of checking has current velocity and SSC stratification with time of occurrence at spring tide.

Point IP1 until point IP3 are shown in Figure 5.16 to Figure 5.18, it reside slightly to upstream of Kase river. In this area fresh water flowing of Kase river dominates in the estuary environment. Effect of tidal currents is a little lower than effect of river water flowing in this area.

**IP1:**

![Figure 5.16 Current & SSC graph of IP1 in spring tide(Kase path)](image)

**IP2:**

![Figure 5.17 Current & SSC graph of IP2 in spring tide(Kase path)](image)
IP3:

Figure 5.18 Current & SSC graph of IP3 in spring tide (Kase path)

IP4:

Figure 5.19 Current & SSC graph of IP4 in spring tide (Kase path)

IP5:

Figure 5.20 Current & SSC graph of IP5 in spring tide (Kase path)
Figure 5.21 Current & SSC graph of IP6 in spring tide (Kase path)

Figure 5.22 Current & SSC graph of IP7 in spring tide (Kase path)

Figure 5.23 Current & SSC graph of IP8 in spring tide (Kase path)
**IP9:**

**Figure 5.24** Current & SSC graph of IP9 in spring tide (Kase path)

**IP10:**

**Figure 5.25** Current & SSC graph of IP10 in spring tide (Kase path)

**IP11:**

**Figure 5.26** Current & SSC graph of IP11 in spring tide (Kase path)
IP12:

Figure 5.27 Current & SSC graph of IP12 in spring tide (Kase path)

IP13:

Figure 5.28 Current & SSC graph of IP13 in spring tide (Kase path)

IP14:

Figure 5.29 Current & SSC graph of IP14 in spring tide (Kase path)
IP15:

**Figure 5.30** Current & SSC graph of IP15 in spring tide (Kase path)

From point IP5 to IP15 as shown in Figure 5.20 to Figure 5.30, the values of SSC are lower than in IP1 to IP4 as shown in Figure 5.16 to Figure 5.19. It indicates that much of suspended sediment flow by river water from upstream to downstream which the current direction of IP1 to IP3 is to offshore. The intersection of current direction is between IP3 to IP4 causes suspended sediment concentration in point IP4 is still higher comparing with IP5 to IP15.

5.2.3 Checking-Points through Chikugo river at neap tide:

The stratification points had been taken are based on Figure 5.1 checking points path through Chikugo river. The calculation is undertaken by using the parameter and boundary condition had been gotten from calibration. Every point of checking has current velocity and SSC stratification with time of occurrence at neap tide.
IP2:

Figure 5.31 Current & SSC graph of IP2 in neap tide (Chikugo path)

IP10:

Figure 5.32 Current & SSC graph of IP10 in neap tide (Chikugo path)

In the neap tide which the direction of current moves to offshore denoted in Figure 5.31 and Figure 5.32, and the quantity of SSC is higher in the near estuary of Chikugo river than southward in IP10. Vertical distribution of SSC in IP10 almost same in surface layer as well as bottom layer, while in IP2 distribution of SSC in bottom layer is a little higher than at surface layer because the area is still influenced by river water from upstream to downstream.

5.2.4 Checking-Points through Chikugo river in current flooding:

The stratification points had been taken are based on Figure 5.1 checking points path through Chikugo river. The calculation is undertaken by using the parameter and
boundary condition had been gotten from calibration. Every point of checking has current velocity and SSC stratification with time of occurrence at flooding time of river.

**IP1:**

![Current & SSC graph of IP1 in flooding time](image1)

**Figure 5.33** Current & SSC graph of IP1 in flooding time (Chikugo path)

**IP2:**

![Current & SSC graph of IP2 in flooding time](image2)

**Figure 5.34** Current & SSC graph of IP2 in flooding time (Chikugo path)

Vertical distribution of SSC in IP2 (Figure 5.31) at neap tide is same pattern with IP2 (Figure 5.34) at flooding time because at neap tide and flooding the current direction is to offshore. The distribution value of SSC in flooding is higher than in neap tide at surface layer as well as bottom layer. It indicates that much of suspended sediment
flows from upstream of river to downstream by flooding.

**IP3:**

![Graph of IP3 in flooding time](image)

Figure 5.35 Current & SSC graph of IP3 in flooding time (Chikugo path)

**IP4:**

![Graph of IP4 in flooding time](image)

Figure 5.36 Current & SSC graph of IP4 in flooding time (Chikugo path)

In flooding time the direction of current is to offshore can be seen in Figure 5.33 to Figure 5.36. From point IP1 in surface layer current direction to southward until in IP4 because effect of seawater is stronger than at upstream. This phenomena indicates that effect of flooding is high until point IP4. The value of SSC gradually decreases. This indicates that much of suspended sediment flow from upstream to downstream by flooding.
5.2.5 Longitudinal distribution of SSC.

Distribution of SSC can be evaluated along checking points line through Chikugo and Kase river with coordinate x, y, z are time step, distance (m) and SSC (kg/m$^3$) of checking points each other in surface layer and bottom layer. In Chikugo path (Figure 5.37) horizontal axis consists of distance (m) from IP1 to IP13 and time step from 1 (time simulation begins at 8/28/2004 0:00) to 947 (the last time simulation at 9/7/2004 23:00). In order the time step axis can be seen clearly in graph therefore the time step number is multiplied by 30. The vertical axis is SSC in kg/m$^3$. In Kase path (Figure 5.39) horizontal axis consists of distance (m) from IP1 to IP15 and time step which is same scenario with Chikugo path. The vertical axis is SSC in kg/m$^3$.

5.2.5.1 Longitudinal distribution of SSC through Chikugo river (effected by tide).

![SSC distribution through Chikugo river in surface layer effected by tide](image)

Figure 5.37 SSC distribution through Chikugo river in surface layer effected by tide

In Figure 5.37 and Figure 5.38 the distribution of SSC in checking points line of surface layer as well as bottom layer through Chikugo river is shown in three
dimension graph, where x axis is the checking points IP1 to IP13, y axis is time step of simulation and z axis is SSC in kg/m3. The distribution of SSC in location around IP1 to IP4 is higher than other points. This location is around the mouth of Chikugo river. Two peaks of graph in this location indicate that suspended sediment concentration is higher with other place.

The current velocity between surface and bottom layer (Figure 5.3 to Figure 5.15 and Figure 5.31 to Figure 5.36) in Chikugo path is not much difference, consequently there is not much difference pattern of SSC between surface and bottom layer (Figure 5.37 and Figure 5.38).

**Figure 5.38** SSC distribution through Chikugo river in bottom layer effected by tide
Table 5.1 Stratification points value of SSC and Current Speed in points-line through Chikugo river effected by tide.

<table>
<thead>
<tr>
<th>IP</th>
<th>current(m/s)</th>
<th>SSC(kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>spring</td>
<td>neap</td>
</tr>
<tr>
<td></td>
<td>surface</td>
<td>direct</td>
</tr>
<tr>
<td>IP1</td>
<td>0.4</td>
<td>south</td>
</tr>
<tr>
<td>IP2</td>
<td>0.23</td>
<td>south</td>
</tr>
<tr>
<td>IP3</td>
<td>0.55</td>
<td>south</td>
</tr>
<tr>
<td>IP4</td>
<td>0.55</td>
<td>north</td>
</tr>
<tr>
<td>IP5</td>
<td>0.45</td>
<td>north</td>
</tr>
<tr>
<td>IP6</td>
<td>0.65</td>
<td>north</td>
</tr>
<tr>
<td>IP7</td>
<td>0.85</td>
<td>north</td>
</tr>
<tr>
<td>IP8</td>
<td>0.83</td>
<td>north</td>
</tr>
<tr>
<td>IP9</td>
<td>0.58</td>
<td>north</td>
</tr>
<tr>
<td>IP10</td>
<td>0.55</td>
<td>north</td>
</tr>
<tr>
<td>IP11</td>
<td>0.45</td>
<td>north</td>
</tr>
<tr>
<td>IP12</td>
<td>0.51</td>
<td>north</td>
</tr>
<tr>
<td>IP13</td>
<td>0.35</td>
<td>north</td>
</tr>
</tbody>
</table>

The values of current speed (m) and SSC (kg/m³) in spring-tide, neap-tide and flooding-tide at surface and bottom layer effected by tide are shown in Table 5.1.

The variation of this result indicates that the highest value of SSC was transported by flow of flooding from Chikugo river to the mouth of river.

The lower value that resides more to offshore transported by tidal currents from south to the north and conversely.

5.2.5.2 Longitudinal distribution of SSC through Kase river (effected by tide).

In Figure 5.39 and Figure 5.40 the distribution of SSC in checking points line of surface layer as well as bottom layer through Kase river is shown in three dimension graph, that x axis is the checking points IP1 to IP15, y axis is time step of simulation.
and z axis is SSC in kg/m$^3$. The distribution of SSC in location around IP1 to IP5 are higher than others point. This location is around the mouth of Kase river. The peaks of graph in this location indicate that suspended sediment concentration is higher with other place.

**Figure 5.39** SSC distribution through Kase river in surface layer

The distribution of SSC in around estuary is dominated by effect of river flow where SSC tend to increase or decrease with Kase river discharge. In offshore the distribution of SSC is dominated by effect of tidal current. Around IP13 and IP14 SSC is little higher which the water depth in this location about 35 m from the surface water.
The values of current speed (m) and SSC (kg/m$^3$) in spring-tide, neap-tide and flooding-tide at surface and bottom layer effected by tide are shown in Table 5.2. The variation of this result indicates that the highest value of SSC was transported by tidal currents from south to the north and flow of flooding from Kase river to the mouth of river. The lower value that resides more to offshore transported by tidal currents from south to the north and conversely.

The current velocity between surface and bottom layer (Figure 5.16 to Figure 5.30) is not much difference, consequently there is not much difference pattern of SSC between surface and bottom layer effected by tide(Figure 5.39 and Figure 5.40).
Table 5.2 Stratification points value of SSC and Current Speed in points-line through Kase river effected by tide

<table>
<thead>
<tr>
<th>IP</th>
<th>current(m/s)</th>
<th>SSC(kg/m³)</th>
<th>spring</th>
<th>neap</th>
<th>flooding</th>
<th>spring</th>
<th>neap</th>
<th>flooding</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>surface</td>
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<td>direct</td>
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<td>direct</td>
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</tr>
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<td>IP1</td>
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<td>north</td>
<td>0.13</td>
<td>north</td>
<td>0.6</td>
<td>south</td>
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</tr>
<tr>
<td>IP2</td>
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<td>IP3</td>
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<td>0.14</td>
<td>north</td>
<td>0.39</td>
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<td>0.1</td>
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<tr>
<td>IP4</td>
<td>0.48</td>
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<td>0.18</td>
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<td>north</td>
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<td>south</td>
<td>0.1</td>
<td>south</td>
</tr>
<tr>
<td>IP6</td>
<td>0.55</td>
<td>north</td>
<td>0.2</td>
<td>north</td>
<td>0.38</td>
<td>south</td>
<td>0.15</td>
<td>south</td>
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<tr>
<td>IP7</td>
<td>0.51</td>
<td>north</td>
<td>0.2</td>
<td>north</td>
<td>0.48</td>
<td>south</td>
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<td>south</td>
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<tr>
<td>IP8</td>
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<td>north</td>
<td>0.5</td>
<td>south</td>
<td>0.2</td>
<td>south</td>
</tr>
<tr>
<td>IP9</td>
<td>0.56</td>
<td>north</td>
<td>0.28</td>
<td>north</td>
<td>0.5</td>
<td>south</td>
<td>0.25</td>
<td>south</td>
</tr>
<tr>
<td>IP10</td>
<td>0.5</td>
<td>north</td>
<td>0.3</td>
<td>north</td>
<td>0.55</td>
<td>south</td>
<td>0.3</td>
<td>south</td>
</tr>
<tr>
<td>IP11</td>
<td>0.75</td>
<td>north</td>
<td>0.45</td>
<td>north</td>
<td>0.76</td>
<td>south</td>
<td>0.48</td>
<td>south</td>
</tr>
<tr>
<td>IP12</td>
<td>0.75</td>
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<td>north</td>
<td>0.6</td>
<td>south</td>
<td>0.4</td>
<td>south</td>
</tr>
</tbody>
</table>

5.3 The Profile of Suspended Sediment Concentration and Salinity in the mouth of Chikugo river

The changes of SSC in the mouth of Chikugo river can be seen through points IP1 to IP2 which are longitudinal section of the mouth of Chikugo river. This conditions is considered at the time of river flooding which the fresh water flows to downstream. In the point of intersection between fresh water and salt water, the fresh water profile in surface layer more towards the offshore while the salt water more towards the upstream of river in bottom layer (Figure 5.42) while SSC in this point is higher in surface layer (Figure 5.41).
The area with SSC (green color) is higher than the other place (Figure 5.41). This is the constriction area as the intersection of current from the inner part of the Ariake Sea and the current from the open sea. The area is relative small if it is compared with the other area, therefore it influences the SSC in the place.

Figure 5.42 SSC vertical profile along IP1 to IP2 effected by tide
**Figure 5.43** Salinity vertical profile along IP1 to IP2 effected by tide

Figure 5.44 to Figure 5.45 denote the effect of tide and wind (wind Saga SONGDA200418) concurrent took place in the Ariake Sea to suspended sediment concentration at point IP1-IP2.

**Figure 5.44** SSC horizontal distribution in the Ariake Sea effected by tide-wind
Figure 5.45 SSC vertical profile along IP1 to IP2 effected by tide-wind

Figure 5.45 shows that SSC more gather in IP1 in surface layer by tide wind effect beside by water river flows effect.

**Salinity and suspended sediment concentration from IP1 to IP4 in Chikugo estuary effected by tide:**

Figure 5.46 Salinity (left) and SSC (right) vertical profile along IP1 to IP4 in Chikugo estuary effected by tide
Figure 5.46 (left) shows that saltwater from offshore propagates to upstream until 4.2 km from IP1 in bottom layer, while SSC becomes higher in this area (Figure 5.46 right). It indicates that in this area where current flows from offshore with higher salinity (saltwater) gathers with current flows from river upstream with lower salinity (freshwater) result the higher concentration of suspended sediment. Figure 5.46 (right) shows the maximum suspended sediment concentration occurred at about 5.0 km upstream from the river mouth in Chikugo river.

**Salinity and suspended sediment concentration from IP1 to IP4 in Chikugo estuary effected by tide-wind:**

To evaluate the change of salinity and suspended sediment concentration from IP1 to IP4 in Chikugo estuary effected by tide-wind therefore it is considered two conditions of Chikugo river discharge and wind of Saga Songda. Condition A is considered that the wind speed and discharge are rising up. Condition B is considered that the discharge and wind speed are lower (Figure 5.47)

![Discharge Chikugo and Wind Saga Songda](image)

**Figure 5.47** Condition A and B in discharge of Chikugo river and wind Saga Songda
Figure 5.48 Salinity (left) and SSC (right) vertical profile along IP1 to IP4 in Chikugo estuary effected by tide-wind in condition A.

Condition A which the wind speed and discharge are rising up it causes circulation of sea water where in the bottom the circulation direction to nearshore and in the surface to offshore (Figure 5.48 left). The mixture between saltwater and freshwater in this area produce the increasing suspended sediment at more upstream and gather with sediment from river upstream (Figure 5.48 right)

Figure 5.49 Salinity (left) and SSC (right) vertical profile along IP1 to IP4 in Chikugo estuary effected by tide-wind in condition B.

Condition B which the wind speed and discharge are lower, effect of tide concurrent with wind cause the propagation of saltwater in bottom layer with higher salinity is more upstream (Figure 5.49 left). Suspended sediment gathers at more upstream of the river by flowing of river water from upstream to downstream (Figure
5.49 right).

Salinity and suspended sediment concentration from IP1 to IP5 in Kase estuary effected by tide:

**Figure 5.50** Salinity (left) and SSC (right) vertical profile along IP1 to IP5 in Kase estuary effected by tide

Figure 5.50 (left) shows that saltwater from offshore propagates to upstream until 1.2 km from IP1 in bottom layer, while SSC becomes higher in this area. It indicates that in this area where current flows from offshore with higher salinity (saltwater) gathers with current flows from river upstream with lower salinity (freshwater) results the higher concentration of suspended sediment. Maximum suspended sediment concentration occurred at about 1.2 km upstream from the river mouth in Kase river (Figure 5.50 right).
Salinity and suspended sediment concentration from IP1 to IP5 in Kase estuary affected by tide-wind:

To evaluate the change of salinity and suspended sediment concentration from IP1 to IP5 in Kase estuary affected by tide-wind therefore it is considered two conditions of Kase river discharge and wind of Saga Songda. Condition A is considered that the wind speed is up and discharge is rising up. Condition B is considered that the discharge and wind speed are lower (Figure 5.1)

**Figure 5.1** Condition A and B in discharge of Kase river and wind Saga Songda

**Figure 5.2** Salinity (left) and SSC (right) vertical profile along IP1 to IP5 in Kase estuary affected by tide-wind in condition A.
Condition A which wind is up and discharge is rising up, the effect to propagation of saltwater is not so far to upstream (Figure 5.52 left). Suspended sediment maximum occurred more to upstream.

**Figure 5.53** Salinity (left) and SSC (right) vertical profile along IP1 to IP5 in Kase estuary effected by tide-wind in condition B.

Condition B which discharge and wind speed are lower, the mixing between saltwater and freshwater gradually occur to the upstream of river (Figure 5.53 left), suspended sediment gathers more upstream of river (Figure 5.53 right).

### 5.4 The SSC stratifications checking points effected by storm surge and tidal currents

Naturally tidal currents and effect of storm surge in the nature occurence took place concurrent within the time event of storm surge. To consider the effect of storm surge concurrent with tidal currents to the sea environment of the north Ariake Sea, therefore the data of wind Saga SONGDA200418 had been taken, which is a typhoon SONGDA space effects to Saga.
5.4.1 Checking- Points through Chikugo river:

**IP1:**

![Current & SSC graph of IP1 in tide-wind effect](image)

**Figure 5.54** Current & SSC graph of IP1 in tide-wind effect (Chikugo path)

**IP2:**

![Current & SSC graph of IP2 in tide-wind effect](image)

**Figure 5.55** Current & SSC graph of IP2 in tide-wind effect (Chikugo path)

**IP3:**

![Current & SSC graph of IP3 in tide-wind effect](image)

**Figure 5.56** Current & SSC graph of IP3 in tide-wind effect (Chikugo path)
IP11:

**Figure 5.57** Current & SSC graph of IP11 in tide-wind effect (Chikugo path)

IP13:

**Figure 5.58** Current & SSC graph of IP13 in tide-wind effect (Chikugo path)

The effect of wind and tide which had been taken place concurrent can be seen in Figure 5.54 to Figure 5.58 in Chikugo checking points line. The average of current speed are higher in the surface layer than bottom layer. The current direction is dominated of direction to south in surface layer and bottom layer. It indicates that the direction of current is much influenced by direction of wind where at that time the direction of wind is to south (Figure 3.13). The time of simulation that had been taken as is shown in Figure 5.54 to Figure 5.58 where at that time the results of SSC are the
largest result.

The SSC results are average larger than the effect of tide alone in surface layer and bottom layer, implying that the effect of tide if concurrent wind can make the higher concentration of suspended sediment.

5.4.2 Checking- Points through Kase river effected by tide-wind concurrent:

IP1:

![Figure 5.59 Current & SSC graph of IP1 in tide-wind effect (Kase path)](image)

IP2:

![Figure 5.60 Current & SSC graph of IP2 in tide-wind effect (Kase path)](image)

IP3:

![Figure 5.61 Current & SSC graph of IP3 in tide-wind effect (Kase path)](image)
The effect of wind and tide which had been taken place concurrent can be seen in Figure 5.59 to Figure 5.63 in Kase checking points line. The average of current speed are higher in the surface layer than bottom layer. The current direction is dominated of direction to south in surface layer and bottom layer. It indicates that the direction of current is much influenced by direction of wind where at that time the direction of wind is to south (Figure 3.13). The time of simulation that had been taken as is shown in Figure 5.59 to Figure 5.63 where at that time the results of SSC are the largest result. The SSC results are average larger than the effect of tide alone in surface layer and bottom layer, implying that the effect of tide if concurrent wind can make the higher
concentration of suspended sediment.

In the case of tide and wind taking place concurrent, suspended sediment concentration (SSC) will be higher at strong wind time and after this time, the value of SSC is decreases and becomes small like SSC effected by tide alone. It can be seen in Figure 5.64 and Figure 5.65 where the scale of SSC and time are made same in order to compare the both of figure, therefore can be seen in time of about 9/7/2004 the trend of SSC is almost same.

Figure 5.64 to Figure 5.67 below show the change of SSC effected by tide-wind compared with SSC effected by tide in surface layer and bottom layer, for instant in point checking IP13 through Kase river checking points-line.

![Figure 5.64](image1.png)

**Figure 5.64** SSC IP13(Kase-path) by tide wind effect in surface layer

![Figure 5.65](image2.png)

**Figure 5.65** SSC IP13(Kase-path) by tide effect in surface layer
Figure 5.65 had the scale of SSC and time which are made same with Figure 5.64 in order to easy for comparing.

![Graph of SSC IP13 by tide-wind at bottom layer](image)

**Figure 5.66** SSC IP13 (Kase-path) by tide-wind effect in bottom layer

![Graph of SSC IP13 by tide at bottom layer](image)

**Figure 5.67** SSC IP13 (Kase path) by tide effect in bottom layer

Figure 5.67 had the scale of SSC and time which are made same with Figure 5.66 in order to easy for comparing. Figure 5.64 to Figure 5.67 imply that tidal current plays an important role in the resuspension sediment in the north Ariake Sea.
5.4.3 Longitudinal distribution of SSC (tide-wind effect)

5.4.3.1 Longitudinal distribution of SSC through Chikugo river (effected by tide-wind).

Distribution of SSC effected by tide-wind in Chikugo path can be evaluated along checking points line through Chikugo with coordinate x, y, z are time step, distance (m) and SSC (kg/m$^3$) of checking points each other in surface layer and bottom layer. In Chikugo path (Figure 5.68) horizontal axis consists of distance (m) from IP1 to IP13 and time step from 1 (time simulation begins at 8/28/2004 0:00) to 947 (the last time simulation at 9/7/2004 23:00). In order the time step axis can be seen clearly in graph therefore the time step number is multiplied by 30. The vertical axis is SSC in kg/m$^3$.

Figure 5.68, the distribution of SSC from IP1 to IP13 through Chikugo checking points-line denotes that in the surface layer the higher value took place along the path, while the highest value of suspended sediment gather most near the mouth of Chikugo river. At the points IP1 to IP13 respectively had the peak of graph, implying that along the line IP1 to IP13 the higher of suspended sediment concentration occurred in surface layer and bottom layer. In Figure 5.68 and Figure 5.69 at location about IP13 there is little higher peak than at IP6 to IP11. It is caused by effect of intersection of current direction to southward in surface layer and to northward in bottom layer at about IP13 (Figure 5.58). In nearshore the peaks are average higher indicates that much of suspended sediment gather in nearshore or the mouth of the Chikugo river.
Figure 5.68 SSC distribution through Chikugo river in surface layer effected by tide-wind concurrent

Figure 5.69 SSC distribution through Chikugo river in bottom layer effected by tide-wind concurrent
Figure 5.69, the distribution of SSC from IP1 to IP13 through Chikugo checking points-line denotes that in the bottom layer the higher value took place along the path, while the highest value of suspended sediment gather most near the mouth of Chikugo river.-

Along the line checking point of Chikugo river in surface as well as bottom layer, the higher concentration of sediment occur. The stirring sediment had been generated by effect of tide-wind concurrent. The concentration of suspended sediment is higher around the mouth of river.

**Table 5.3** Stratification points value of SSC and Current Speed in points-line through Chikugo river effected by tide-wind concurrent

<table>
<thead>
<tr>
<th>IP</th>
<th>Current (m/s)</th>
<th>SSC(kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Surface layer</td>
<td>Direction to</td>
</tr>
<tr>
<td>IP1</td>
<td>4.5806 south</td>
<td>1.19057 south</td>
</tr>
<tr>
<td>IP2</td>
<td>2.01694 south</td>
<td>0.0164493 south</td>
</tr>
<tr>
<td>IP3</td>
<td>0.64163 south</td>
<td>0.0232309 south</td>
</tr>
<tr>
<td>IP4</td>
<td>7.20059 south</td>
<td>2.50821 south</td>
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<tr>
<td>IP5</td>
<td>3.31733 south</td>
<td>0.470587 south</td>
</tr>
<tr>
<td>IP6</td>
<td>11.8314 south</td>
<td>5.16931 south</td>
</tr>
<tr>
<td>IP7</td>
<td>13.741 south</td>
<td>6.55448 south</td>
</tr>
<tr>
<td>IP8</td>
<td>12.9735 south</td>
<td>5.97084 south</td>
</tr>
<tr>
<td>IP9</td>
<td>11.0995 south</td>
<td>4.58816 south</td>
</tr>
<tr>
<td>IP10</td>
<td>11.844 south</td>
<td>5.20564 south</td>
</tr>
<tr>
<td>IP11</td>
<td>8.61634 south</td>
<td>3.34864 south</td>
</tr>
<tr>
<td>IP12</td>
<td>6.64932 south</td>
<td>2.19183 south</td>
</tr>
<tr>
<td>IP13</td>
<td>0.910686 south</td>
<td>0.0254996 north</td>
</tr>
</tbody>
</table>

From Table 5.3 can be seen that the velocity of current are average higher if
Comparing the effect by tide only (Table 5.1), consequently SSC value are higher as well. The higher SSC occurs along the line of IP1 to IP13, indicates that the stirring sediment took place along area.

The highest values of SSC in Chikugo checking points line were transported more towards the south. The SSC value in points IP6 to IP10 between surface and bottom layer is much difference if it is compared with the other points. It is might caused by the water depth between surface and bottom for each time simulation of occurrence in IP6 to IP10 more than the other points at Chikugo path.

5.4.3.2 Longitudinal distribution of SSC through Kase river (effected by tide-wind).

![SSC distribution through Kase river in surface layer effected by tide & wind](image)

**Figure 5.70** SSC distribution through Kase river in surface layer effected by tide-wind concurrent
Figure 5.71 SSC distribution through Kase river in bottom layer (tide-wind)

Table 5.4 Stratification points value of SSC and Current Speed in points-line through Kase river effected by tide-wind concurrent

<table>
<thead>
<tr>
<th>IP</th>
<th>Current (m/s)</th>
<th>SSC(kg/m^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>surface layer direction to</td>
<td>bottom layer direction to</td>
</tr>
<tr>
<td>IP1</td>
<td>6.90E-04 south</td>
<td>3.72E-05 south</td>
</tr>
<tr>
<td>IP2</td>
<td>0.287341 north</td>
<td>0.198499 north</td>
</tr>
<tr>
<td>IP3</td>
<td>0.289765 south</td>
<td>0.106003 south</td>
</tr>
<tr>
<td>IP4</td>
<td>3.81118 south</td>
<td>0.0731672 south</td>
</tr>
<tr>
<td>IP5</td>
<td>2.03747 north</td>
<td>0.052911 north</td>
</tr>
<tr>
<td>IP6</td>
<td>1.3155 north</td>
<td>0.627273 north</td>
</tr>
<tr>
<td>IP7</td>
<td>0.290493 south</td>
<td>0.351541 south</td>
</tr>
<tr>
<td>IP8</td>
<td>0.431975 north</td>
<td>0.140073 north</td>
</tr>
<tr>
<td>IP9</td>
<td>5.33269 south</td>
<td>1.65235 south</td>
</tr>
<tr>
<td>IP10</td>
<td>10.2785 south</td>
<td>4.00938 south</td>
</tr>
<tr>
<td>IP12</td>
<td>3.45737 south</td>
<td>0.620729 south</td>
</tr>
<tr>
<td>IP13</td>
<td>8.87639 south</td>
<td>3.50534 south</td>
</tr>
<tr>
<td>IP14</td>
<td>11.4271 south</td>
<td>5.3764 south</td>
</tr>
<tr>
<td>IP15</td>
<td>10.0192 south</td>
<td>4.45193 south</td>
</tr>
</tbody>
</table>
Table 5.4 shows the current velocity is higher in offshore part from Kase river, SSC value is higher as well in this part. The higher SSC occurs along the line of IP1 to IP15, indicates that the stirring sediment took place along area.

IP14 and IP15 from Table 5.4 in case of tide-wind concurrent there are difference of SSC between surface and bottom layer, it is might caused by water depth between surface and bottom layer at each time simulation of occurrence in IP14 and IP15 more than other points in Kase path.

5.5 The SSC stratifications checking points effected by storm surge

The effect of storm surge in naturally could decreases or increases the current generated by tidal current. The current is increased if the same direction between storm surge and tidal current, conversely the current is decreased if the direction is against each other. To consider the effect of storm surge to the sea environment of the north Ariake Sea, therefore the data of wind Saga SONGDA200418 had been taken, which this wind is a typhoon SONGDA space effects to Saga.

5.5.1 Checking- Points through Chikugo river effected by wind:

**IP1:**

![Figure 5.72 Current & SSC graph of IP1 in wind effect(Chikugo path)](image-url)
IP2:

**Figure 5.73** Current & SSC graph of IP2 in wind effect (Chikugo path)

IP3:

**Figure 5.74** Current & SSC graph of IP3 in wind effect (Chikugo path)

IP11:

**Figure 5.75** Current & SSC graph of IP11 in wind effect (Chikugo path)
Figure 5.76 Current & SSC graph of IP13 in wind effect (Chikugo path)

Comparing of IP1 effected by tide-wind concurrent with effected by wind alone:

Current speed in surface layer as well as bottom layer in IP1 effected by tide-wind concurrent more than IP1 effected by wind alone caused by water flow from river upstream in Chikugo river contribute to the increasing of current speed effected by tide-wind concurrent.

Table 5.5 Stratification points value of SSC and Current Speed in points-line through Chikugo river effected by wind.

<table>
<thead>
<tr>
<th>IP</th>
<th>Current (m/s)</th>
<th>SSC(kg/m3)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>surface layer</td>
<td>direction to</td>
</tr>
<tr>
<td>IP1</td>
<td>2.73393</td>
<td>south</td>
</tr>
<tr>
<td>IP2</td>
<td>3.26221</td>
<td>south</td>
</tr>
<tr>
<td>IP3</td>
<td>8.19333</td>
<td>south</td>
</tr>
<tr>
<td>IP4</td>
<td>4.23013</td>
<td>south</td>
</tr>
<tr>
<td>IP5</td>
<td>1.46736</td>
<td>south</td>
</tr>
<tr>
<td>IP6</td>
<td>12.029</td>
<td>south</td>
</tr>
<tr>
<td>IP7</td>
<td>13.7981</td>
<td>south</td>
</tr>
<tr>
<td>IP8</td>
<td>13.1599</td>
<td>south</td>
</tr>
<tr>
<td>IP9</td>
<td>10.5022</td>
<td>south</td>
</tr>
<tr>
<td>IP11</td>
<td>8.99388</td>
<td>south</td>
</tr>
<tr>
<td>IP12</td>
<td>8.46042</td>
<td>south</td>
</tr>
<tr>
<td>IP13</td>
<td>8.96687</td>
<td>south</td>
</tr>
</tbody>
</table>
5.5.2 Checking Points through Kase river effected by wind:

**IP1:**

![Graph IP1 Current wind 9/4/2004 4:13](image1)

**Figure 5.77** Current & SSC graph of IP1 in wind effect (Kase path)

**IP2:**

![Graph IP2 Current wind 9/3/2004 15:10](image2)

**Figure 5.78** Current & SSC graph of IP2 in wind effect (Kase path)

**IP3:**

![Graph IP3 Current wind 9/4/2004 2:50](image3)

**Figure 5.79** Current & SSC graph of IP3 in wind effect (Kase path)
IP7:

**Figure 5.80** Current & SSC graph of IP7 in wind effect (Kase-path)

IP15:

**Figure 5.81** Current & SSC graph of IP15 in wind effect (Kase-path)

SSC value of IP1, IP2 and IP3 as shown in Table 5.6 denote that value of SSC in IP1, IP2 and IP3 effected by tide-wind concurrent at Kase path (Table 5.4) were higher than the value effected by wind alone. This condition indicate that suspended sediment concentration had been released from tidal flat in the location near IP1, IP2 and IP3 or in the mouth of Kase river by tidal current.
Table 5.6 Stratification points value of SSC and Current Speed in points-line through Kase river effected by wind.

<table>
<thead>
<tr>
<th>IP</th>
<th>Current (m/s)</th>
<th>SSC(kg/m3)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>surface layer</td>
<td>direction to</td>
</tr>
<tr>
<td>IP1</td>
<td>3.76</td>
<td>south</td>
</tr>
<tr>
<td>IP2</td>
<td>3.91722</td>
<td>south</td>
</tr>
<tr>
<td>IP3</td>
<td>0.0758881</td>
<td>south</td>
</tr>
<tr>
<td>IP4</td>
<td>0.70904</td>
<td>north</td>
</tr>
<tr>
<td>IP5</td>
<td>1.08472</td>
<td>north</td>
</tr>
<tr>
<td>IP6</td>
<td>1.19969</td>
<td>north</td>
</tr>
<tr>
<td>IP7</td>
<td>6.43979</td>
<td>south</td>
</tr>
<tr>
<td>IP8</td>
<td>0.0069985</td>
<td>south</td>
</tr>
<tr>
<td>IP9</td>
<td>5.61632</td>
<td>south</td>
</tr>
<tr>
<td>IP10</td>
<td>2.5237</td>
<td>south</td>
</tr>
<tr>
<td>IP11</td>
<td>13.0751</td>
<td>south</td>
</tr>
<tr>
<td>IP12</td>
<td>2.70055</td>
<td>south</td>
</tr>
<tr>
<td>IP13</td>
<td>6.76671</td>
<td>south</td>
</tr>
<tr>
<td>IP14</td>
<td>11.5561</td>
<td>south</td>
</tr>
<tr>
<td>IP15</td>
<td>10.1522</td>
<td>south</td>
</tr>
</tbody>
</table>

Water depth between surface and bottom layer at each time simulation of occurrence is small consequently the SSC between surface and bottom is not too difference. The water depth of IP15 at Kase path in Figure 5.81 between surface and bottom at time occurrence is large, therefore SSC in surface and bottom is difference as shown in Table 5.6.

Resume:
Comparison the results of suspended sediment concentration effected by tide at spring,
neap tide and flooding, tide-wind concurrent and wind alone in the stratification point of Chikugo path and Kase path, can be seen in the table.

**Table 5.7 Stratification point value through Chikugo path**

<table>
<thead>
<tr>
<th>IP</th>
<th>Effected by tide</th>
<th>Effected by tide-wind</th>
<th>Effected by wind</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>spring SSC(kg/m³)</td>
<td>neap SSC(kg/m³)</td>
<td>flooding SSC(kg/m³)</td>
</tr>
<tr>
<td>IP1</td>
<td>0.4730 0.4727 0.4424 0.4425</td>
<td>0.6440 0.6630</td>
<td>17.6918 17.8191</td>
</tr>
<tr>
<td>IP2</td>
<td>0.4502 0.4498 0.4485 0.4580</td>
<td>0.7180 0.7360</td>
<td>18.0085 18.0079</td>
</tr>
<tr>
<td>IP3</td>
<td>0.2750 0.1000 0.5930 0.6100</td>
<td>0.8800 0.8950</td>
<td>14.9774 14.9788</td>
</tr>
<tr>
<td>IP4</td>
<td>0.0334 0.0337 0.4700 0.3400</td>
<td>0.3800 0.1800</td>
<td>20.0403 20.1504</td>
</tr>
<tr>
<td>IP5</td>
<td>0.0219 0.0220 0.0450 0.0320</td>
<td>0.0700 0.0600</td>
<td>43.0167 43.0467</td>
</tr>
<tr>
<td>IP6</td>
<td>0.0231 0.0228 0.0275 0.0276</td>
<td>31.5343 50.0002</td>
<td>25.7215 48.7978</td>
</tr>
<tr>
<td>IP7</td>
<td>0.0300 0.0420 0.0351 0.0361</td>
<td>11.0011 25.9928</td>
<td>9.48913 28.8332</td>
</tr>
<tr>
<td>IP8</td>
<td>0.0400 0.0600 0.0500 0.0700</td>
<td>25.7753 50.0001</td>
<td>22.1615 50.0001</td>
</tr>
<tr>
<td>IP9</td>
<td>0.0338 0.0347 0.0406 0.0407</td>
<td>15.1350 24.0178</td>
<td>40.051 44.907</td>
</tr>
<tr>
<td>IP10</td>
<td>0.0220 0.0226 0.0205 0.0195</td>
<td>13.0088 24.7093</td>
<td>21.0189 21.0766</td>
</tr>
<tr>
<td>IP11</td>
<td>0.0097 0.0099 0.0081 0.0079</td>
<td>16.5639 17.1423</td>
<td>47.9183 50.0008</td>
</tr>
<tr>
<td>IP12</td>
<td>0.0062 0.0062 0.0065 0.0064</td>
<td>45.8642 46.1602</td>
<td>45.0268 46.7355</td>
</tr>
<tr>
<td>IP13</td>
<td>0.0054 0.0054 0.0092 0.0092</td>
<td>32.0487 32.0499</td>
<td>19.3218 19.2616</td>
</tr>
</tbody>
</table>

Table 5.7, in the spring and neap tide suspended sediment gather most to near the mouth of Chikugo river. The flooding average results in the higher suspended sediment quantity. The effect of tide in spring and neap tide results relative smaller of suspended sediment in offshore than at nearshore. The results effected by tide-wind and wind alone average are higher than effected by tide. The value of suspended sediment effected by tide-wind more than effected by wind or conversely are caused by tide which can increase or decrease the value of suspended sediment. Effect of wind alone seems to be higher than tide and wind if it compares at Table 5.7 in points IP1, IP3, IP4, IP7, IP9,
Table 5.8 Stratification point value through Kase path

<table>
<thead>
<tr>
<th>IP</th>
<th>Effected by tide</th>
<th>Effected by tide-wind</th>
<th>Effected by wind</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SSC (kg/m³)</td>
<td>The highest SSC (kg/m³)</td>
<td>The highest SSC (kg/m³)</td>
</tr>
<tr>
<td></td>
<td>spring</td>
<td>neap</td>
<td>flooding</td>
</tr>
<tr>
<td>IP1</td>
<td>0.1980</td>
<td>0.2125</td>
<td>7.4272</td>
</tr>
<tr>
<td>IP2</td>
<td>0.1225</td>
<td>0.1330</td>
<td>8.45309</td>
</tr>
<tr>
<td>IP3</td>
<td>0.1225</td>
<td>0.1310</td>
<td>10.2727</td>
</tr>
<tr>
<td>IP4</td>
<td>0.1699</td>
<td>0.1702</td>
<td>0.0613</td>
</tr>
<tr>
<td>IP5</td>
<td>0.0178</td>
<td>0.0178</td>
<td>0.0530</td>
</tr>
<tr>
<td>IP6</td>
<td>0.0115</td>
<td>0.0116</td>
<td>0.0228</td>
</tr>
<tr>
<td>IP7</td>
<td>0.0106</td>
<td>0.0106</td>
<td>0.0249</td>
</tr>
<tr>
<td>IP8</td>
<td>0.0109</td>
<td>0.0109</td>
<td>0.0127</td>
</tr>
<tr>
<td>IP9</td>
<td>0.0102</td>
<td>0.0102</td>
<td>0.0103</td>
</tr>
<tr>
<td>IP10</td>
<td>0.0101</td>
<td>0.0101</td>
<td>0.0101</td>
</tr>
<tr>
<td>IP11</td>
<td>0.0102</td>
<td>0.0102</td>
<td>0.0107</td>
</tr>
<tr>
<td>IP12</td>
<td>0.0124</td>
<td>0.0120</td>
<td>0.0143</td>
</tr>
<tr>
<td>IP13</td>
<td>0.0185</td>
<td>0.0205</td>
<td>0.0265</td>
</tr>
<tr>
<td>IP14</td>
<td>0.0140</td>
<td>0.0155</td>
<td>0.0700</td>
</tr>
<tr>
<td>IP15</td>
<td>0.0023</td>
<td>0.0043</td>
<td>0.0042</td>
</tr>
</tbody>
</table>

Table 5.8, in the spring and neap tide suspended sediment gather most to near the mouth of Kase river. The flooding average results the higher suspended sediment quantity. The effect of tide in spring and neap tide results relative smaller of suspended sediment in offshore than at nearshore. The results effected by tide-wind and wind alone average are higher than effected by tide. The value of suspended sediment effected by tide-wind more than effected by wind or conversely are caused by tide which can increase or decrease the value of suspended sediment.
5.6 The bed thickness change

5.6.1 The bed thickness change effected by tide

The change processes of suspended sediment concentration and salinity coincide with the change of bed thickness in spite there are erosion or deposition. The assessment of this in the north Ariake Sea can be determined by checking the spread points in the area. The graph below depicts the bed thickness change within the initial bed thickness is elevation 0.0 of the profile.

![Figure 5.82](image1)

**Figure 5.82** The existence of bed thickness after the changes of sediment and salinity in the north Ariake Sea effected by tide

![Figure 5.83](image2)

**Figure 5.83** Bed thickness decrease trend in south part of the north Ariake Sea
Figure 5.84 Bed thickness increase trend in north part of the north Ariake Sea

Figure 5.83 shows the graph trend of bed thickness tend to decrease (graph lines below 0.0m) at south part of the north Ariake Sea. The maximum decrease of bed thickness is about 0.1 m below of the bed initial surface, indicates that erosion average took place in this part. Various color at the line of graph means the various spread checking points of bed thickness in south part of the north Ariake Sea.

Figure 5.84 shows the tendency of the bed thickness increase (graph lines above 0.0m) in north part. Even though the value of bed thickness is very small, it keep denoting the tendency that indicates that deposition average took place in this part. Various color at the line of graph means the various spread checking points of bed thickness in north part of the north Ariake Sea.

The predicted of bed changes can be more underlined by the plan view of bed thickness change at the horizontal distribution of bed thickness change in Figure 5.85 to Figure 5.86 at the time 3 Sept. 2004 and 7 Sept.2004, imply that in south part of north Ariake Sea bed thickness average tend to decrease, conversely in north part bed thickness average tend to increase.
Figure 5.85 Horizontal view of bed thickness change at 3 Sept. 2004 4:53:20
Figure 5.86 Horizontal view of bed thickness change at 7 Sept.2004 20:50:00

5.6.2 The bed thickness change effected by tide-wind concurrent

Figure 5.87 shows the graph trend of bed thickness effected by tide-wind concurrent, which wind had been taken of Typhoon SONGDA200418 space as wind Saga SONGDA.
The graph shows that the tendency of the bed thickness decrease effected by tide-wind concurrent (graph lines below 0.0m) at north part as well as south part of the north Ariake Sea. Various color at the line of graph means the various spread checking points of bed thickness in the north Ariake Sea.

The effect of wind by Songda to Saga denotes that erosion took place at almost of the all spread points in the basin, indicates that storm surge generated by typhoon stirs up large quantity of sediment resulting the tidal flat’s erosion.

5.7 Mass Balance

The sediment balance is the balance of sediment volume entering and exiting a particular section of the coast or an estuary. These consists of the evaluation of sediment fluxes, sources and sinks from different processes that give rise to additions and subtractions within a control section of the coast in order to gain a better understanding of the coast system. The areas as a control volume are placed in north part and south
part of the North Ariake Sea (Fig. 5.88). Cross section AA, BB and cross section CC, DD are needed as the area that the flow through the control volume at spring tide and neap tide. The suspended sediment concentration entering and exiting within transport process at 30 August 2004 21:10:00 and 31 August 2004 15:46:40 of rectangular AABB and rectangular CCDD at spring and neap tide can be seen in Table 5.9 and Table 5.10.

**Figure 5.88** The area AABB and CCDD as the control volume

Cross-section at spring tide:

**Figure 5.89** Cross section A-A at spring tide
Figure 5.90 Cross section B-B at spring tide

In Figure 5.89 and Figure 5.90 the concentration of sediment gather in right side which these area near to the mouth of Chikugo river. The area of cross section A-A approximately 137,500 m² while the area of cross section B-B approximately 226,705 m². The deepest of bed level in cross section AA about -9.0 m while in cross section BB about -13.0 m.

Figure 5.91 Cross section C-C at spring tide
In Figure 5.91 and Figure 5.92 the concentration of sediment gather in left side which the side shape of area is a curvature. The area of cross section C-C approximately 313,625 m$^2$ while the area of cross section D-D approximately 343,238 m$^2$. The deepest of bed level about -37 m is almost same from the both of cross section.

Cross-section at neap tide:

Figure 5.93 Cross section A-A at neap tide
Figure 5.94 Cross section B-B at neap tide

Figure 5.93 and Figure 5.94 show the concentration of sediment gather in right side. These condition is more influenced by location near the river. The area of cross section A-A approximately 60,240 m$^2$ while the area of cross section B-B approximately 90,450 m$^2$.

Figure 5.95 Cross section C-C at neap tide
Figure 5.96 Cross section D-D at neap tide

In the neap tide which the direction of current to south concurrent with receding of surface water, the sediment concentration more gather in right side with the shape of side is curvature (Fig.5.95, Figure 5.96). Figure 5.96 shows the concentration of sediment gather in left side. The area of cross section C-C approximately 242,438 m² while the area of cross section D-D approximately 269,500 m².

Table 5.9 SSC flux-in and SSC flux-out of rectangular AABB and CCDD at spring tide 30 August 2004 21:10:00

<table>
<thead>
<tr>
<th>Cross section</th>
<th>Area (m²)</th>
<th>SSC average</th>
<th>Settling velocity average</th>
<th>Flux</th>
<th>Flux. area</th>
<th>FluxA-FluxB</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>kg/m³</td>
<td>m/s</td>
<td>kg/m²s⁻¹</td>
<td>kg/s</td>
<td>kg/hr</td>
</tr>
<tr>
<td>A-A</td>
<td>137500</td>
<td>0.0221</td>
<td>9.15722E-09</td>
<td>2E-10</td>
<td>2.7779E-05</td>
<td></td>
</tr>
<tr>
<td></td>
<td>AB</td>
<td>0.05108</td>
<td></td>
<td></td>
<td></td>
<td>0.05108</td>
</tr>
<tr>
<td>B-B</td>
<td>226705</td>
<td>0.0211</td>
<td>8.76581E-09</td>
<td>1.9E-10</td>
<td>4.1968E-05</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C-C</td>
<td>313625</td>
<td>0.0385</td>
<td>1.59656E-08</td>
<td>6.1E-10</td>
<td>0.00019259</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CD</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.387728</td>
</tr>
<tr>
<td>D-D</td>
<td>343238</td>
<td>0.0244</td>
<td>1.01322E-08</td>
<td>2.5E-10</td>
<td>8.4892E-05</td>
<td></td>
</tr>
</tbody>
</table>
Table 5.10 SSC flux in and SSC flux out of rectangular AABB and CCDD at neap tide 31 August 2004 15:46:40

<table>
<thead>
<tr>
<th>Cross section</th>
<th>Area (m²)</th>
<th>SSC average (kg/m³)</th>
<th>Settling velocity average (m/s)</th>
<th>Flux (kg/m²·s⁻¹)</th>
<th>Flux area (kg/s)</th>
<th>FluxA-FluxB (kg/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-A</td>
<td>137500</td>
<td>0.02206</td>
<td>9.15722E-09</td>
<td>2E-10</td>
<td>2.7779E-05</td>
<td></td>
</tr>
<tr>
<td>AB</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5.509396</td>
</tr>
<tr>
<td>B-B</td>
<td>226705</td>
<td>0.12883</td>
<td>5.33496E-08</td>
<td>6.9E-09</td>
<td>0.00155817</td>
<td></td>
</tr>
<tr>
<td>C-C</td>
<td>313625</td>
<td>0.05222</td>
<td>2.16729E-08</td>
<td>1.1E-09</td>
<td>0.00035496</td>
<td></td>
</tr>
<tr>
<td>CD</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.043732</td>
</tr>
<tr>
<td>D-D</td>
<td>343238</td>
<td>0.05076</td>
<td>2.10703E-08</td>
<td>1.1E-09</td>
<td>0.00036711</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.9 shows mass flux-in and mass flux-out at time 30 August 2004 21:10:00 effected by tide. At the spring tide time where the direction of current from south to north in rectangular AABB, SSC flux-in is from cross section BB and flux-out from cross section AA. Same with rectangular CCDD where SSC flux-in is from cross section DD and flux-out from cross section CC. In column flux multiplied by area shows the values in cross section AA and BB.

Table 5.10 shows mass flux-in and mass flux-out at time 31 August 2004 15:46:40. At the neap tide time where the direction of current from north to south in rectangular AABB, SSC flux-in is from cross section AA and flux-out from cross section BB. Same with rectangular CCDD where SSC flux-in from cross section CC and flux-out from cross section DD. In column flux multiplied by area shows the values in cross section AA and BB.

Mass balance in rectangular AABB and CCDD can be achieved if accumulated mass rate in each rectangular is equal with mass flux-in minus mass flux-out plus...
production. The production needs a longer time duration. The calculation results with longer time duration can be seen in Figure 5.97 to Figure 5.100 effected by tide and Figure 5.101 to Figure 5.104 effected by tide-wind. The figures show the trend of sediment transport and cumulated sediment during the time of simulation.

The trend of transport suspended sediment concentration in rectangular AABB and rectangular CCDD effected by tide is calculated with the time of simulation within the tidal cycle from 28 August 2004 00:00 to 30 September 2004 23:00.

![Transport SSC at rectangular AABB (tide)](image)

**Figure 5.97** The trend of transport sediment at rectangular AABB from 28 August 2004 00:00 to 30 September 2004 23:00 effected by tide

Figure 5.97 shows that the trend of transport sediment in rectangular AABB effected by tide it tends to catch little more sediment or deposition occurs. Figure 5.98 shows the cumulated suspended sediment concentration at rectangular AABB. During one month period (28August to 30 September 2004) a total of about 2,000 tons of deposited sediment was mobilized to rectangular AABB.
Figure 5.98 Cumulated sediment transport through rectangular AABB at 28 August 2004 00:00 to 30 September 2004 23:00 effected by tide

Figure 5.99 The trend of transport sediment at rectangular CCDD from 28 August 2004 00:00 to 30 September 2004 23:00 effected by tide

Figure 5.99 shows that the trend of transport sediment in rectangular CCDD effected by tide it tends to export more sediment or erosion occurs. Figure 5.100 shows the cumulated suspended sediment concentration at rectangular CCDD. During one month period (28August to 30 September 2004) a total of about 35,000 tons of
sediment was exported from rectangular CCDD.

**Figure 5.100** Cumulated sediment transport through rectangular CCDD at 28 August 2004 00:00 to 30 September 2004 23:00 effected by tide

The transport of suspended sediment concentration in rectangular AABB and rectangular CCDD effected by tide-wind is calculated with the time of simulation within the tidal cycle from 28 August 2004 00:00 to 30 September 2004 23:00.

**Figure 5.101** The trend of transport sediment at rectangular AABB from 28 August 2004 00:00 to 30 September 2004 23:00 effected by tide-wind

Figure 5.101 shows that the trend of transport sediment in rectangular AABB effected by tide-wind it tends to export sediment or erosion occurs. Figure 5.102 shows the cumulated suspended sediment concentration at rectangular AABB effected by tide-wind. During one month period (28 August to 30 September 2004) a total of about
20,000 tons of sediment was exported from rectangular AABB.

**Figure 5.102** Cumulated sediment transport through rectangular AABB at 28 August 2004 00:00 to 30 September 2004 23:00 effected by tide-wind

**Figure 5.103** The trend of transport sediment at rectangular CCDD from 28 August 2004 00:00 to 30 September 2004 23:00 effected by tide-wind

Figure 5.103 shows that the trend of transport sediment in rectangular CCDD effected by tide-wind it tends to export sediment or erosion occurs. Figure 5.104 shows the cumulated suspended sediment concentration at rectangular CCDD effected by tide-wind. During one month period (28 August to 30 September 2004) a total of about 40,000 tons of sediment was exported from rectangular AABB.
Figure 5.104 Cumulated sediment transport through rectangular CCDD at 28 August 2004 00:00 to 30 September 2004 23:00 effected by tide-wind

5.8 Conclusion

The changes of suspended sediment concentration in north Ariake sea effected by tide as well as wind, can be predicted by using MIKE3 FM Mud Transport Model. By comparing the pattern of tidal currents in checking points through Chikugo path and Kase path at spring, neap and flooding tide, and the mass balance analysis, the movement of suspended sediment can be evaluated.

At spring tide:

Through Chikugo path, largely quantity of SSC (0.1-0.5 kg/m3) concentrate around the mouth of Chikugo river at surface layer and bottom layer which currents (0.1-0.6 m/s) flow to the south and north.

Through Kase path, largely quantity of SSC about 0.13-0.48 kg/m3 concentrate around the mouth of Kase river at surface layer and bottom layer with currents speed about 0.1-0.5 m/s to north.

At neap tide:
Through Chikugo path, largely quantity of SSC (0.3- 0.6 kg/m³) concentrate around the mouth of Chikugo river at surface layer and bottom layer with currents (0.1-0.8 m/s) flow to the south.

Through Kase path, SSC about 0.1-0.17 kg/m³ concentrate around the mouth of Kase river at surface and bottom layer with currents 0. 1-0.7 m/s to south.

**At flooding tide:**

Through Chikugo path, SSC about 0.2-0.9 kg/m³ concentrate around the mouth of Chikugo river in surface and bottom layer, which currents velocity about 0.1-1.6m/s.

Through Kase path, SSC about 0.1-0.2 kg/m³ in surface and bottom layer, which currents about 0.3-2.6 m/s to south. Stratification checking points through Chikugo as well as Kase river effected by tide indicate that largely quantity of SSC gather in around the mouth of river, while few quantity of SSC are distributed in the offshore part. much of suspended sediment flows from upstream of river to downstream by flooding.

The distribution value of SSC in flooding is higher than in neap tide at surface layer as well as bottom layer. It indicates that much of suspended sediment flows from upstream of river to downstream by flooding.

Effect of tide to bed thickness denotes that in the south part of north Ariake sea the bed thickness tend to decrease and conversely in the north part of north Ariake sea the bed thickness tend to increase, which this is consistent with the nature occurrence in the nearshore of north part that tidal flats are developed.

**Tide and wind take place concurrent:**

Through Chikugo path and Kase path denote that largely quantity of SSC mostly gather near the estuary of river. In checking point IP6 Chikugo path which is influenced by Yabe river sediment environment as well, the quantity about 25-50.00 kg/m³ of SSC
in surface and bottom layer and the currents speed about 6-12 m/s to the south. In checking point IP10 Kase path the quantity of SSC about 48-49 kg/m$^3$ in surface and bottom layer, and the currents speed about 4-10 m/s to the south.

The quantity of SSC effected by tide-wind concurrent more than effected by tide caused by effect of typhoon force where SSC is higher in the time of strong wind, but after this time SSC would be same like effected by tide alone.

Effect of tide-wind take place concurrent to bed thickness, denotes that bed thickness tend to decrease in all checking points through the north Ariake Sea. This indicates that tide wind concurrent generate the stirring sediment in the north Ariake Sea.

**Mass balance calculation:**

The trend of transport sediment in rectangular AABB effected by tide it tends to catch little more sediment or deposition occurs. During one month period (28 August to 30 September 2004) a total of about 2,000 tons of deposited sediment was mobilized to rectangular AABB. The trend of transport sediment in rectangular CCDD effected by tide it tends to export more sediment or erosion occurs. During one month period (28 August to 30 September 2004) a total of about 35,000 tons of sediment was exported from rectangular CCDD.

The trend of transport sediment in rectangular AABB effected by tide-wind it tends to export sediment or erosion occurs. During one month period (28 August to 30 September 2004) a total of about 20,000 tons of sediment was exported from rectangular AABB. The trend of transport sediment in rectangular CCDD effected by tide-wind it tends to export sediment or erosion occurs. During one month period (28 August to 30 September 2004) a total of about 40,000 tons of sediment was exported from rectangular AABB.
6.1 Conclusion

The overarching aim of this dissertation is to investigate and prediction the condition of sediment and its transport in response to tidal currents and storm surge in the north Ariake Sea. This objective has been achieved according to the results presented in the previous chapter.

The results below are obtained from this research:

The development and application of computational models are necessary for prediction the mud sediment transport for evaluation the water environment in the north Ariake Sea. From the environmental view point within the study area, the sea products of the Ariake Sea tend to decrease in recent year and might be caused by environmental changes in this area, environmental deterioration, changing in tidal currents or increase in transparency. The interaction between rivers flow which to pick up more quantity of sediment, against tidal currents or tidal currents concurrent with storm surge, more enhance the tidal flats development in nearshore of the north Ariake Sea. The application by using the computational models in this research had been shown this situation.

The MIKE3 Hydrodynamic and Mud Transport Model which took time simulation between 28 August to 7 September 2004 indicates that suspended sediment concentration circulation effected by tidal currents more gather to the mouth of Chikugo and Kase river. The salt water intrusion from estuary of the both rivers that had been shown in simulation, takes part in support to tidal flats development. Suspended sediment concentration average becomes largely quantity effected by tidal currents
concurrent with storm surge, but the largely quantity occur at the time of strong wind, after this time the quantity becomes smaller like effect by tide alone.

In this study, the results of research based on the simulation of computational model of suspended sediment concentration and salinity changes in the north Ariake Sea can be concluded as follows:

- The model has been calibrated against water level, salinity and sediment concentration data as the good agreement.
- The effect of tidal currents to deposition took place more to the north and almost along nearshore and river mouth, while erosion occurred more in the south.
- The effect of tidal current by mass balance analysis shows that in offshore of the north Ariake Sea the pattern of sediment transport is dominated by erosion pattern, while in nearshore of the north Ariake Sea is dominated by deposition pattern.
- The highest suspended sediment concentration took place near the river mouth caused by flooding towards the offshore.
- Wind combined with tide affects the erosion taking place at almost all the points in basin of the north Ariake Sea.
- Salinity intrusion process takes place in the estuary of Chikugo and Kase Rivers to the upstream, approximately 4.2 km in Chikugo River and 1.2 km in Kase River. Maximum suspended sediment concentration occurred at about 5.0 km upstream from the river mouth in Chikugo River, while about 1.20 km upstream from the river mouth in Kase River.
- The tidal current is an important effect that should be counted to sediment resuspension, while storm surge influenced the most to suspended sediment at
strong wind period.

- The results of the research show the phenomena in the north Ariake Sea that tidal flats keep existence and the concentration of sediment is higher around Chikugo and Kase River estuaries and nearshore, and the resuspension of sediment keep occurring at offshore of the north Ariake Sea.

All predicted suspended sediment concentration as qualitatively agree with the major morphological features in the north Ariake Sea that is average in nearshore part and around the estuary of rivers, tidal flats are exist. The results simulation of intrusion salt water in the mouth of Chikugo and Kase river imply its condition. Predicted of suspended sediment concentration change, qualitatively agree with the previous research of Cao Don et al. (2007) implying that the tidal currents play an important role in the sediment resuspension in the tidal flat area and the majority of released sediment during both the ebb and flood tides will deposit on the tidal flats.

This research will propose for sedimentation information to the Ariake Sea especially in the north Ariake Sea, even though this paper still in preliminary study, which the results were not satisfying due to the lack of observation data. Therefore this model provides as a technical support and reference for sedimentation in the Ariake Sea and expected will be useful method.

6.2 Suggestions

Further observation of bed level change of bathymetry and the longer time of simulation in order to evaluate the such steady results condition of salinity and SSC are recommended.
REFERENCES


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