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Study on Formation and Deformation of River Delta Coastlines

（河口デルタ海岸線の形成と変形に関する研究）

by

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Abstract

Study on formation and deformation of river delta coastlines

Dinh Van Duy

In this study, the analytical solutions of one-line model for shoreline changes is employed to investigate the formation and deformation of three wave-dominated river delta coastlines. Prior to the application of one-line model, characteristic quantities of each study area are estimated by means of image analysis, shoreline rate-of-change statistics, and sediment budget analysis.

The wave-dominated river deltas as indicated in the three cornerstones of delta morphological classification (Galloway, 1975) is the subject of this study. This type of river delta satisfies the application of one-line model due to its regular shoreline shapes and the dominant of longshore sediment transport along the delta lopes (Seybold et al., 2007). Three wave-dominated river deltas with different scales including Thu Bon River delta in Vietnam, Ombrone River delta in Italy, and Funatsu River delta in Lake Inawashiro, Japan will be investigated to give a comprehensive perspective on the formation and deformation of wave-dominated river delta coastlines.

From the results of image analysis, it is found that erosion of the delta apex can be caused by the asymmetric distribution of sediment input from the river as evidenced in the case of Thu Bon River delta. Specifically, due to the southward shifting of the Thu Bon River mouth, 85% of sediment input from the river is going to the southern shoreline which results in deficit of sediment supply to the northern shoreline and causes severe erosion of a beach located immediate north of the Thu Bon River mouth (Cua Dai Beach). Longshore sediment transport rates along two coastlines of Thu Bon River delta and sediment input from Thu Bon River are obtained based on the shoreline rate-of-change statistics and sediment budget analysis. An asymmetric sediment distribution has characterized the Thu Bon River delta apex since 2002: about 70,000 m³/y and 390,000 m³/y of sediment are moving to the north and south, respectively, from the river mouth. The southward (rightward) shifting of the sand terrace in front of Thu Bon River mouth in
the recent years has confirmed the asymmetric shoreline shapes at the river mouth. It is also found that the shoreline orientation at the river mouth can be used to discuss the temporal variation of sediment input from the river qualitatively and quantitatively.

In the application of analytical solution of one-line model, it is first found that the diffusion coefficient which represents the alongshore dispersion of sediment caused by breaking waves can be simply estimated based on the delta shoreline shapes. The application of analytical solution provided by Larson et al. (1987) can be used to well describe the formation of Thu Bon River delta. In the deformation process, although the analytical solution still shows the general trend of the shoreline, differences between the calculated results and the measured data can be observed. The complex coastal process at the river mouth such as welding of a sand spit or human intervention like sand mining can contribute to the differences between the calculated results and the measured data.

Since the analytical solution of Larson et al. (1987) can be applied only to the river delta with infinite shorelines, a new analytical solution was developed to consider effects of lateral boundaries to the evolution of the delta coastlines. It was figured out that two demarcations represented by the dimensionless times $t^*$ can be used to judge whether the lateral boundaries have affected the coastline evolution or not.

After a successful application of the new analytical solution to the experimental results of Refaat (1990), the new analytical solution was applied to predict the formation and deformation of the Ombrone River delta and the Funatsu River delta shorelines. Results obtained from the analysis showed that the new analytical solution can be used to well describe the formation and deformation of finite river delta shorelines.

Based on the two demarcations at represented by the dimensionless time $t^*$, the Thu Bon River delta shorelines are classified as infinite shorelines while the shorelines of Ombrone River and Funatsu River deltas are classified as finite shorelines.

In this study, the sediment supply from the river is assumed to be a constant value. However, this quantity is highly seasonal variation in reality. Therefore, this seasonal variation of sediment supply from the river and its effect on the morphological changes of the delta shorelines with finite extents should be considered in the future.

Finally, Mobilization of sediment in the river basin is extremely important for the control of the downstream coastal zone. A model to study the mobilization of sediment in the river basin should be developed for an integrated management from upstream to
downstream. This aspect is very important to many river catchments around the world with inadequate monitoring of the rivers.
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CHAPTER 1

INTRODUCTION

1.1 Background

Since the beginning of human civilization, people have settled along rivers and fertile deltas created by them. The sand rich in nutrient of the river delta is favorable for crops and livestock. At the present time, human development of the coastal zone in river delta is happening in a rapid manner (Masria et al., 2012). In which, the coasts of river deltas have been developed to support trade and commerce, agriculture, tourism, urbanization, and so forth. In addition to human exploitation, the coastal zones along the river delta shorelines are also home for many species and can act as a barrier to reduce the impact of natural disasters such as hurricanes and typhoons.

The human intervention in the coastal area and the river basin often results in the coastal erosion of the river delta shorelines, especially near the river mouth. For example, damming rivers for hydropower has been reported as one of the most common problems resulting in severe erosion of the downstream beaches. Recent coastal erosion of river delta shoreline has been reported in the global scale including those of the Nile (Refaat, 1990; Stanley, 1995), Mississippi (Blum and Roberts, 2009), Yangtze (Yang et al., 2011), Tenryu (Uda, 2010; Huang, 2011), and Thu Bon (Tanaka et al., 2016) Rivers.

As coastal erosion is happening in a global scale and threatening the hundreds of millions of people living in deltas today (Anthony, 2015), it is necessary to take into consideration the morphological changes of river delta coastlines. Unfortunately, inadequate monitoring of many rivers around the world has limited the ability to identify the impacts of coastal erosion at the river mouth (Yang et al., 2011). It is, therefore, necessary to employ a method which can be used as a starting point for any coastal project to give a comprehensive discussion about the fundamental beach behavior under simplified initial and boundary conditions. For that reason, the analytical approach is preferable since it requires less measured data for the calculation. Specifically, the analytical solution of one-line model provided by Larson et al. (1987) will be utilized in
In addition, a new analytical solution is developed to study the formation and deformation of river deltas with finite shorelines. Prior to the application of the one-line model, image analysis is used to monitor the delta shoreline erosion/accretion trends as well as to determine the required parameters as the input for the analytical model.

1.2 Objectives of the study

The objective of this study is to understand the formation and deformation processes of river delta coastlines with and without effects of the lateral boundaries. In order to achieve this objective, the following questions should be answered.

(1) Which river deltas are suitable for the application of the analytical solutions of one-line model for river delta shoreline changes?

(2) How to calibrate the analytical model?

(3) How to estimate the required parameters as the input for the application of analytical solutions of one-line model for river delta shoreline changes?

(4) The most recent analytical solution for river delta shorelines proposed by Larson et al. (1987) is for infinite shorelines. What is the behavior of a shoreline having a finite extent between the river mouth and a coastal structure or a headland located at a distance from the river mouth?

(5) Among river deltas in the world, which can be considered as infinite delta shorelines and which can be considered as finite delta shorelines?

In order to answer these questions, the following tasks will be done:

(1) Reviewing the classification of river deltas in the world to figure out the suitable river delta type for the application of the analytical solutions. Among the river deltas in the world, three river deltas with different scales including Thu Bon River delta in Vietnam, Ombrone River delta in Italy and Funatsu River delta in Japan are selected as the subject of this study to give a comprehensive perspective about the formation and deformation of river delta shorelines. The reasons for selecting these three river deltas are (i) they are wave-dominated river deltas which are suitable for the application of analytical model, (ii) availability of data for the analysis, and (iii) they show different spatial scales of the shoreline length which is a very important parameter in this study.

(2) Investigating the morphological changes of three river deltas which are the subject of this study using image analysis, shoreline rate-of-change statistic, and sediment

2
budget analysis. The analysis in this step provides characteristic parameters associated with each river delta and can be used to calibrate the analytical model.

(3) Applying the analytical solution of Larson et al. (1987) to the case of Thu Bon River delta.

(4) Developing a new analytical solution which is useful to study the morphological change of a river delta shoreline with finite length. The new analytical solution is applied to the Ombrone River and Funatsu River deltas.

(5) Classifying the river delta shorelines into two categories which are the finite and infinite shorelines based on their temporal and spatial scales.

1.3 Outline of the dissertation

The outline of this dissertation is presented in Figure 1.1 and can be summarized as follows:

Chapter 1. Introduction

This chapter introduces the background, the necessity and the objectives of the study.

Chapter 2. Literature review:

This chapter reviews the literature related to the research topic and existing methods used to study the morphological change of river delta coastlines such as aerial photograph analysis, Even and Odd analysis, sediment budget analysis, analytical solutions of one-line model for river delta shoreline evolution.

One of the important parts of this chapter is the reviewing of classification of river deltas in the world. Based on the classification, the subject of this study is identified which is the wave-dominated river delta.

Chapter 3. Study area, data collection, and methodology:

This chapter aims to give a general view about three river deltas selected as the subject of this study. In addition, the methodology of aerial photograph analysis, as well as the analytical solution of the one-line model to study the morphological changes of river delta shorelines, are provided.

Chapter 4. Morphological change of Thu Bon River delta

This chapter investigates the short-term and long-term morphological change of the Thu Bon River delta shorelines which are 80 km long in total based on the
images analysis and points out the factors resulting in the coastal erosion of Cua Dai Beach which is located immediate left of the Thu Bon River mouth. Longshore sediment transport rates (LSTR), which is crucial for any discussion of beach morphological change, will be calculated along the Thu Bon River delta shorelines. Sediment supply from the Thu Bon River is also calculated. Finally, this chapter analyzes the evolution of a sand terrace in front of the Thu Bon River mouth to discuss the interrelationship between the morphological change of this sand terrace and the morphological evolution of the adjacent sandy coasts on both sides of the Thu Bon River mouth.

Chapter 5. Morphological change of Ombrone River delta

In Chapter 4, morphological changes of large river delta coastlines have been investigated. This chapter investigates the short-term and long-term morphological changes of the Ombrone River delta which has a smaller spatial scale as compared to the Thu Bon River delta. The analysis is performed based on Google earth and Landsat images. In the short-term morphological change, the LSTRs along the coastlines of the Ombrone River delta are estimated as well as the sediment supply from the Ombrone River. The long-term analysis focuses on an area around the Ombrone River mouth. In which, the evolution of shoreline orientations on both sides of the river mouth are analyzed to observe the variation of sediment supply from the Ombrone River.

Chapter 6. Morphological change of Funatsu River delta in Lake Inawashiro, Japan

In Chapters 4 and 5, morphological changes of two open-coast river delta shorelines have been investigated. In this chapter, morphological change of a lakeshore located on the left of the Funatsu River mouth in Lake Inawashiro, Japan is investigated. Due to the small scale of the lakeshore, only high resolution images including Google earth and aerial photos are utilized in the analysis. The shoreline changes on the left of the Funatsu River mouth is analyzed and the LSTR along this lakeshore is calculated. Based on the analysis of shoreline evolution adjacent to the river mouth, the ratios of sediment input from the Funatsu River to both sides are figured out and the sediment input from the Funatsu River is obtained.
Chapter 7. Analytical solutions for formation and deformation of river deltas

This chapter first investigates the formation and deformation of the Thu Bon River delta shorelines using the analytical solution provided by Larson et al. (1987).

In the analytical solution proposed by Larson et al. (1987), the coastlines are infinite. However, in reality, coastlines are always finite due to the existence of coastal structures or headlands located at distances to the river mouth. Therefore, this chapter introduces a new analytical solution which would be useful to study the delta shoreline evolution with effects of rigid boundaries located at distances to the river mouth. The new analytical solution is verified using recorded shoreline data in two field cases: Ombrone River and Funatsu River deltas. In addition, experimental results from Refaat (1990) are also utilized for the verification of the new analytical solution.

A comprehensive discussion is made at the end of this chapter by combining the field and experimental data. In which, river deltas are classified into finite and infinite shorelines based on their temporal and spatial scales.

Chapter 8. Conclusions and recommendations

This chapter draws a general conclusion about this study and gives suggestions for engineering application as well as future research.
Figure 1.1 Framework of the dissertation
CHAPTER 2

LITERATURE REVIEW

2.1 River delta
2.1.1 Definition of the river deltas

River deltas are classified as lowland area formed by the prolonged accumulation of river-borne-sediment. This low topography area may provide a wide range of ecosystem services such as coastal defense, drinking water supply, and tourism, plus industry and transport which lead to major urbanization activities (Anthony, 2015). Due to their potentially rich economic and ecological functions, river deltas are of considerable interest to many researchers as evidenced by a tremendous amount of publications around the world in the last few decades (Write and Coleman, 1972; Komar, 1973; Coleman, 1981; Pranzini, 1989; Liu et al., 2009; Milliman and Farnsworth, 2011; Thao et al., 2014; Anthony, 2015, Besset, 2017).

In the early works of Wright and Coleman (1972), comprehensive discussion about the roles of wave climate and river discharge to the coastal landform of the river delta has been made. In which, wave climate accounts for a considerable degree in shaping the deltaic configuration. River flow and tidal current dominated types result only when discharged sediment from the river is large enough to form a flat offshore profile (sand terrace) which in turn will reduce nearshore wave power.

Komar (1973) utilized the numerical approach to simulate the formation process of river deltas owing to sediment supply from the river and longshore sediment transport caused by the waves. The equilibrium shape of the cuspate river delta was examined with different wave conditions.

Notable recent works concerning the interaction between waves and the fluvial loads to control the plan shape of river deltas are presented in Anthony (2015) and Besset et al. (2017). In the study of Besset et al. (2017), a baseline which can be used to separate the protruding part of the cuspate delta to the non-protruding deltaic shoreline was introduced to analyze the deltaic protruding area (Figure 2.1). From the analytical point of view, this straight initial shoreline also reasonably allows the application of analytical solution for deltaic shoreline change.
2.1.2 Classification of river deltas and subject of this study

According to Galloway (1975), river deltas in the world can be divided into three categories as (Figure 2.2):

(1) River-dominated type: River-dominated deltas have irregular shorelines that extend significantly away from the general shoreline into the basin. In some cases, distributaries will prograde as finger-like extensions. Conditions that favor river-dominated deltas includes high fluvial discharge and sediment load, low wave and tide activities, and a shallow basin. Example of this delta morphology is the Mississippi Delta.

(2) Wave-dominated type: Wave-dominated deltas have relatively straight shorelines that extend slightly to moderately away from the general shoreline into the basin. Distributaries are mostly restricted to the major delta plain, and the delta front is dominated by beach ridge progradation. Conditions that favor wave-dominated deltas include low fluvial discharge and sediment load, high wave and low tide activity, and a deep basin. This delta morphology can be found in the Nile Delta.

(3) Tidal-dominated type: Tide-dominated deltas form highly irregular shorelines that extend slightly to moderately away from the general shoreline into the basin. Distributaries tend to be numerous, wide, irregular in shape, and cover most of the delta plain. The delta front is dominated by tidal bars oriented perpendicular to the shoreline. Conditions that favor tide-dominated deltas include low fluvial discharge and sediment load, high wave activity, and a shallow basin. Example of this delta morphology is the Ombrone River Delta.

![Figure 2.1 Schematic of delta protrusion area (Besset et al., 2017)](image-url)
discharge and sediment load, high tide, low to moderate wave activity, an embayed coast, and a shallow basin. The Mahakam River delta is a typical example of this deltaic morphology.

According to Seybold et al. (2007), the wave-dominated delta shorelines have regular shapes where the breaking waves redistribute the sediment loads along the coastlines. This indicates that longshore sediment transport is predominant in the wave-dominated deltas. Since this study utilizes the analytical solutions of the one-line model to discuss the formation and deformation of river delta coastlines, the subject of this study is limited in the wave-dominated deltas. For the cases of river-dominated and tide-dominated deltas, the analytical solutions of one-line model are no longer applicable due to the highly irregular delta shorelines and cross-shore sediment transport processes.
2.2 Mapping shoreline change using image analysis

2.2.1 Shoreline and shoreline indicator

Shoreline, the physical interface between land and water, changes continuously through time due to the dynamic nature of water levels at the coastal boundary (Boak and Turner, 2005). Numerous studies concerning the importance of getting information from the shoreline position have been reported in the literature. For example, an analysis of shoreline position is required for estimating beach width and volume (Smith and Jackson, 1992), to calibrate and verify numerical model (Hanson et al., 1988).

Due to the dynamic nature of the shoreline, shoreline indicators are often used for the practical purpose. According to Boak and Turner (2005), a shoreline indicator is a proxy that is used to represent the true shoreline position where the shoreline is considered in both temporal and spatial sense. Three categories of shoreline indicators have been developed. From a process point of view, the first group is classified based on the indicator feature that is physically visual to the human eye while the second group is classified based on a specific tidal datum. For example, Stafford and Langfelder (1971) used the erosion scarp as the shoreline indicator from aerial photograph source. Fisher and Overton (1994) and Parker (2001) used the mean high water as the shoreline indicator which is classified in the second group. With the development of computer science, the third group of shoreline indicator was developed and these shoreline indicators are not necessarily visible to the human eye. A notable example of this shoreline indicator can be found in Aarninkhop (2003). In the study of Aarninkhop (2003), the shoreline intensity maxima were used as the shoreline indicator which was later generally called as shorebreak maximum intensity.

Boak and Turner (2005) summarized 45 examples of shoreline indicators from the literature. Of these, the “high-water line” (HWL) which is defined as the changing tone (the marked contrast between the wet and dry sand) left by the maximum runup from the last high tide is the most common shoreline indicator. The HWL is considered as the best shoreline indicator due to its easy field-located and photo-interpreted (Crowell et al., 1991). However, numerous definitions were provided for this shoreline indicator in different studies by their respective authors and hence leads to a source of error when applying this for shoreline mapping. For example, Leatherman (1983) used the term wet/dry line to indicate the HWL while other authors consider the wet/dry line to be the
maximum runup limit on a flooding tide and the landward extent of the “wetted” beach during tidal ebb (Dolan et al., 1978; Overton et al., 1999).

### 2.2.2 Data sources

For shoreline analysis, available data sources such as historical land-based photographs, coastal maps, aerial photography, and GPS shorelines are of central importance. However, a majority of coastal sites lack historical data and a combination of available data must be used as a result. In the following sections, several data sources which give a quantitative to the shoreline mapping using image analysis will be reviewed.

### 2.2.3 Aerial photography

Aerial photos are any photos taken from an aircraft or other flying objects such as helicopters, unarmed aerial vehicles (UAVs or drones) and so forth. Although aerial photography dates back to the 1920s, it is still considered as one of the most valuable sources in monitoring coastal change. This type of data provides a more frequent temporal scale than the historical map and therefore can be used to monitor the evolution of complex beach stretches (Anders and Byrnes, 1991). Using air photo for monitoring of coastal landforms started in the 1920s with the vertical black and white images. The technique of using air photo as a source for mapping shoreline change started in the late 1960s as reported in Moffitt (1969), Langfelder et al. (1970), and Stafford and Langfelder (1971). Due to the routine obtaining of air photos in the developed countries like U.S. and Japan, this type of data source is available and can be ordered at a reasonable cost for a majority of coastal zones in the abovementioned countries.

According to U.S. Army Corps of Engineers (2006), an aerial photograph can be classified to a vertical or the oblique type depending on the altitude of the camera with respect to the earth’s surface at the time of exposure (Figure 2.3).
A vertical photograph is taken with the camera pointed as straight down as possible and has the following characteristics:

- The lens axis is perpendicular to the surface of the earth.
- It covers a relatively small area.
- The shape of the ground area covered on a single vertical photo closely approximates a square or rectangle.
- Being a view from above, it gives an unfamiliar view of the ground.
- Distance and directions may approach the accuracy of maps if taken over flat terrain.
- Relief is not readily apparent.

In the second category which is the oblique photograph, it is useful to divide this type into low oblique and high oblique photographs. Of these, a low oblique photograph taken with the camera inclined about 30 degrees from the vertical and has the following characteristics:

- It covers a relatively small area.
- The ground area covered is a trapezoid, although the photo is square or rectangular.
- The objects have a more familiar view, comparable to viewing from the top of a high hill or tall building.
No scale is applicable to the entire photograph, and distance cannot be measured. Parallel lines on the ground are not parallel on this photograph; therefore, direction (azimuth) cannot be measured.

Relief is discernible but distorted.

It does not show the horizon.

As compared to the low oblique air photo, the high oblique air photo taken with the camera inclined at an angle about 60 degrees from the vertical and has the following characteristics:

- It covers a very large area (not all usable).
- The ground area covered is a trapezoid, but the photograph is square or rectangular.
- The view varies from the very familiar to unfamiliar, depending on the height at which the photograph is taken.
- Distances and directions are not measured on this photograph for the same reasons that they are not measured on the low oblique.
- Relief may be quite discernible but distorted as in an oblique view. The relief is not apparent in a high altitude, high oblique.
- The horizon is always visible.

2.2.4 Satellite image

Satellite imagery is the acquisition of images of Earth or other planets from space using space-borne satellites. With approximately 1,459 satellites orbiting the Earth, there is an abundance of data for the users to obtain regardless where they live.

In remote sensing, satellite images are classified as they are collected using active or passive sensors. Of these, the active sensor sends its own source of light to the object and capture the reflected light. As opposed to the active sensor, the passive sensor capture the reflected sunlight produced by the sun. The schematic of active and passive remote sensing are presented in Figure 2.4.
From the viewpoint of application, remote sensing has been widely applied in the field of coastal engineering such as monitoring of sea surface temperature (Njoku, 1990), estimating suspended sediment concentration (Pavelsky and Smith, 2009), wave characteristics (Strizhkin, 2013) and so on.

Among the available sources for downloading satellite images, Landsat archive is one of the most important ones considering its longest time data acquisition. Although the Landsat program offers a long-term and continuous source of satellite images, the number of spectral bands and relative spatial resolutions usually pose challenges for the analysis (Young et al., 2017) especially for time series analyses (Holden and Woodcock, 2016). In order to provide a guide for the user of the Landsat imagery, Chander et al. (2009) classified the Landsat satellites into three groups based on their sensors. From the classification, the spatial resolution can be easily associated with the satellites as in the following table.

Table 2.1 Landsat satellites and the relative spatial resolution of the images

<table>
<thead>
<tr>
<th>Group</th>
<th>Satellites</th>
<th>Spatial resolutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Landsat 1, 2 and 3</td>
<td>60 m</td>
</tr>
<tr>
<td>2</td>
<td>Landsat 4 and 5</td>
<td>30 m and 120 m</td>
</tr>
<tr>
<td>3</td>
<td>Landsat 7 and 8</td>
<td>15 m to 100 m</td>
</tr>
</tbody>
</table>

2.2.5 Video-based image

The video-based image is the image extracted from the video monitoring system which provides information for coastal processes on spatiotemporal scales of meters to
kilometers and days to months (Smit et al., 2007). This type of remote sensing provides an efficient, economical means to capture the coast's evolution which can be used to quantify any discernable nearshore phenomena (Holland et al., 1997). Therefore, it has been widely applied in coastal engineering and management in the developed countries. For example, Aarninkhof (2003) utilized the video-based monitoring techniques to quantify the intertidal beach and subtidal beach bathymetries. In addition, his analysis also provided evidence that video monitoring can be used in support of coastal zone management. Holman and Stanley (2007) enabled the remote monitoring of coastal processes by reviewing the development of Argus Stations. Nurfaida and Sato (2015), using a series of images from a field camera system at Tenryu River mouth to observe the morphology of the sand spit backside. Besides the applications in developed countries, this nearshore monitoring method has a high potential in the developing countries due to its cost-effective characteristics as evidenced in Thanh et al. (2015), Tanaka et al. (2017).

### 2.3 Even and Odd analysis

According to Rosati and Kraus (1997), even-odd analysis has been proven to be a powerful tool to separate the symmetric shoreline (even) from those that are asymmetric (odd). The application of this method is so direct and easy that it has been popularized by many researchers such as Work and Dean (1990), Rosati and Kraus (1997), Walton (2002). In addition, this method was applied to discuss the relationship between the erosion phenomenon on the right bank of the Da Rang River estuary in Vietnam and the movement of the river mouth (Hiep et al., 2016).

Regarding the shoreline positions at time $t_n$ and time $t_m$, the difference between them is taken and a function $f$ for shoreline change is defined as:

$$f(x) = y(x,t_n) - y(x,t_m)$$

(2.1)

where $x$ is the alongshore distance and $y$ is the offshore distance.

The shoreline change, denoted as $f(x)$, is the sum of even function $f_E(x)$ and odd function $f_O(x)$.

$$f(x) = f_E(x) + f_O(x)$$

(2.2)

In which, the even and odd functions can be obtained from the following equations:
2.4 Sediment budget analysis

A sediment budget is a tallying of sediment gains and losses within a specified control volume (cell), over a given time (Rosati and Kraus, 1999). In this respect, sediment budget can be thought of as a sandbank, when the material added to is larger than the material removed from this sandbank, there is a surplus of sediment and the sandy shoreline will move seaward. On the other hand, when the material removed from is more than the material added to the system, there is a sand-starved beach and the shoreline will move landward. Sediment budget is one of the three factors that control the beach morphology (sediment budget, sea level, and wave energy). This concept is widely applied to estimate the balance between volume of sediment entering and exiting a particular section of the coast or estuary.

Sediment source and sink are two important aspects that should be considered in the sediment budget analysis. As indicated by their names, sediment source refers to the delivery of sediment to the coast and sediment sink refers to the place where beach material is temporarily or permanently lost from a coastal system. For example, longshore sand transport, sea cliff erosion, eroded sediment from beach erosion, beach fill and sediment input from rivers can be considered as sediment sources while longshore sediment transport, dredging and mining, relative sea level rise, and offshore lost are considered as sediment sinks. Theoretically, all the sources and sinks must be identified for the calculation of sediment budget. However, this is a very challenging task in practical and lead to many uncertainties in the sediment budget analysis.

Rosati and Kraus (1999), provided an equation for sediment budget based on the idea of mass conservation as:

\[
\sum Q_{source} - \sum Q_{sink} - \Delta V + P - R = Residual
\] (2.5)
where $Q_{\text{source/sink}}$ is the sources and sinks to the control volume; $\Delta V$ is the net change in the control volume within the cell; $P$ and $R$ are the amounts of material placed and removed from the cell; Residual is the degree to which the cell is balanced.

Figure 2.5 Schematics of a littoral sediment budget analysis (Rosati and Kraus, 1999)

### 2.5 One-line model of shoreline change

The one-line concept was first introduced by Pelnard-Considere (1956) in his mathematical theory for shoreline change due to wave action. In his model, the beach profile was assumed to move uniformly. In other words, there are no changes in the shape of the beach during its landward or seaward movements in response to the erosion and accretion, respectively (Figure 2.6).

An important geometrical aspect in the one-line theory is the profile height which has a landward limit at the top of the beach berm ($D_B$) and seaward limit where there is no significant change of the depth which often referred to as the so-called depth of closure ($D_C$).

Based on the aforementioned ideas, any point on the beach profile can be used to represent this profile and as a result, one contour line can be used to sufficiently represent the beach plan shape for the computation of shoreline change or beach volume change. This provides a simple relationship between the shoreline change ($\Delta y$) and the change in cross-sectional area $\Delta A$ as:
\[ \Delta A = \Delta y D \]  

(2.6)

Figure 2.6 Sketch of uniform beach profile (Roelvink and Reniers, 2012)

where

- \( \Delta A \) is the change in cross-sectional area of the beach (m\(^2\))
- \( \Delta y \) is the change in shoreline position (m)
- \( D \) is the height of the beach profile, \( D = D_B + D_C \);

By considering a shoreline segment \( \Delta x \), the change volume in this segment is (Figure 2.7):

\[ \Delta V = \Delta x \Delta y D \]  

(2.7)

This change in volume is determined by the net rate of sand entering and leaving the beach segment over a given time as:

\[ \Delta V = \Delta Q \Delta t \]  

(2.8)

Rearranging Eqs. (2.7) and (2.8) yields the principle of mass conservation for sediment volume as:
\[
\frac{\Delta y}{\Delta t} = \frac{1}{D_B + D_C} \frac{\Delta Q}{\Delta x}
\]  

(2.9)

If there is source or sink of sediment along the beach segment, Eq. (2.9) becomes:

\[
\frac{\Delta y}{\Delta t} = \frac{1}{D_B + D_C} \left( \frac{\Delta Q}{\Delta x} \pm q \right)
\]  

(2.10)

where \( q \) is the source (e.g., rivers, coastal cliffs) or sink (e.g., sand mining, sand dredging) of sediment along the segment.

Based on the one-line theory, numerous models have been developed with an attempt to simulate the long-term shoreline change in coastal engineering projects. Of these, three have become popular in the engineering applications since the 1980s as:

- GENESIS (GENEralized model for SImulating Shoreline change).
- UNIBEST (UNIform BEach Sediment Transport).
- LITPACK (integrated model for LIIToral Processes And Coastline Kinetics).

Thomas and Frey (2013) gave a detailed discussion and comparison among those models with respect to the availability of model documentation, model technical description, model grid and domain, longshore sediment transport calculation, wave conditions, lateral boundary conditions, and so forth. Concerning the model documentation, various documentation for GENESIS can be found online such as Hanson (1987); Hanson and Kraus (1989); Gravens et al. (1991); Hanson and Kraus (2004). The developers of LITPACK and UNIBEST generally provide documentation freely for these models through requests of the users.

It should be noted that the development of GENESIS has been frozen by its developer (USACE). However, a recent model with the so-called GENCADE has been developed as a mean to extend the capability of GENESIS (Frey et al., 2012).
Since the shoreline change models are developed based on the theory of one-line model and bulk transport models, it is necessary to estimate the rate of longshore sand transport. The importance of longshore sediment transport and method to quantitatively and quantitatively evaluate this value will be reviewed in the next section.

2.6 Longshore sediment transport (LST)

The movement of beach material along the coast as a result of waves breaking obliquely to the coast and the longshore currents they generate is referred to as longshore sediment transport. This transport is essential in studying beach morphological change since it can be used to determine whether the beaches erode, accrete or remain stable (Rosati et al., 2002).

2.6.1 Quantitative indicators of longshore sediment transport and direction

Many indicators have been reported in the literature as potential evidence to recognize the net motion of sediment along the beach. According to Rosati et al. (2002), these indicators of longshore sediment transport path can be classified into geomorphic and sedimentological groups. As examples for the first group, deposition of sediment on the updrift side and erosion on the downdrift side of shore-normal structures (e.g., groins, jetties) is one of the clearest signals for the long-term net transport direction (FitzGerald, 1993). Grain size distribution of sediment along the beach was also considered as another
geomorphic indicator for net longshore sediment transport path. Concerning the analysis of unique material within the beach material as an indicator to deduce longshore sediment transport paths, Trask (1952, 1955), used the heavy material augite as a tracer to observe longshore sediment directions at Santa Barbara, California. Also along the California Coast, Bowen and Inman (1966), by examining the dilution of beach sand augite, gave a discussion about the directions and magnitudes of the net transport. Other notable examples regarding the used of beach sediment to quantitatively evaluate the directions of longshore sediment transport can be found in Meisburger (1989) and Johnson (1992).

### 2.6.2 Prediction of longshore sediment transport

Among many methods which have been proposed since the 1930s for the estimation of the longshore sediment transport magnitude, the energy flux method has been proven to be the most common tool as evidenced by its application worldwide.

The energy flux method was developed based on a fact which has been long recognized that when waves break at an angle to the shoreline, they produce the so-called longshore currents which will, in turn, cause the transport of sand along the beach (Komar and Inman, 1970). Before Komar and Inman, several works were done using both laboratory experiments and field measurements to indicate the relation between the work induced by waves and the longshore transport of sand (Caldwell, 1956; Ingle, 1966). Based on the aforementioned works, two concepts for calculating longshore sediment transport were proposed.

The first concept relates the potential longshore sand transport rate to the so-called longshore component of wave energy flux as:

\[
P_l = \left( E C_g \right)_b \sin \alpha_b \cos \alpha_b
\]

where \( P_l \) is the potential longshore sand transport rate having the unit of N/sec, \( E \) is the wave energy, \( C_g \) is the wave group velocity, and \( \alpha \) is the wave angle. The subscript \( b \) denotes the wave breaker position.

The wave energy evaluated at the breaker line as:

\[
E_b = \frac{\rho g H_b^2}{8}
\]
and the wave group speed at the breaker line is determined as:

$$C_{gb} = \sqrt{gd_b} = \left( g \frac{H_b}{\kappa} \right)^{\frac{1}{2}}$$

(2.13)

where \( \kappa \) is the breaker index, \( \kappa = H_b/d_b \) and the term \((EC_g)_b\) is the wave energy flux.

The second concept was initially developed by Caldwell (1956) as the immersed weight transport rate. Inman and Bagnold (1963) related the immersed weight transport rate to the potential longshore sand transport rate by:

$$I_l = KP_l = K\left(EC_g\right)_b \sin \alpha_b \cos \alpha_b$$

(2.14)

where \( I_l \) is the immersed weight transport and has the same unit to \( P_l \), hence, \( K \) is a dimensionless coefficient.

Eq. (2.14) is commonly known as the CERC equation after being adopted by the U.S. Army Corps of Engineers (1966).

In Engineering application, the longshore sediment transport rate is often expressed in the form of volume transport rate having the unit of cubic meters per year as:

$$Q_l = \frac{I_l}{(\rho_s - \rho)g(1-n)}$$

(2.15)

where \( \rho_s \) is the mass density of the sediment grain usually taken as 2,650 kg/m\(^3\) for quartz-density sand; \( \rho = 1,025 \) kg/m\(^3\) is the mass density of salt water; \( g=9.81 \) m/s\(^2\) is the gravitational acceleration; \( n \) is the sediment porosity (\( n \approx 0.4 \)).

From Eq. (2.15), the volume transport rate is the total volume which includes about 40% of void space between the grains and 60% solid grains.
CHAPTER 3

STUDY AREA, DATA COLLECTION, AND METHODOLOGY

3.1 Study area

In this section, three study areas will be introduced including Thu Bon River delta in Vietnam, Ombrone River delta in Italy and Funatsu River delta in Lake Inawashiro, Japan. Of these, Thu Bon River and Ombrone River deltas are two open coast river deltas with different spatial scales while the Funatsu River delta is formed in a lake. Therefore, investigation of these three river deltas can sufficiently give a general picture about the formation and deformation of wave-dominated river deltas in the world.

From the viewpoint of spatial scale, the Thu Bon River delta which is the largest one among the three deltas will be presented first in the next.

3.1.1 Thu Bon River delta

Figure 3.1 shows the map Thu Bon River delta. As can be seen in Figure 1, Thu Bon River delta is located in the central region of Vietnam. Thu Bon River rises from the mountainous region in the west of Quang Nam Province and flows over a distance of 234 km before discharging to the ocean at Thu Bon River mouth or Cua Dai River mouth. It should be noted that a part of the water from Vu Gia River is carried to the Thu Bon River by Quang Hue River located about 30 km upstream from the Thu Bon River mouth. Therefore, the Thu Bon River basin is well-known as Vu Gia – Thu Bon basin with the total area of 10,350 km². For years, the annual average water discharge has been estimated as 400 m³/s. Water discharge in the Vu Gia – Thu Bon basin is highly seasonal variation with about 40-50 m³/s in the dry season and can be up to 27,000 m³/s in the flood season (Hoi et al., 2016).

As can be seen in Figure 3.1, Thu Bon River delta has a long coastline from Son Tra Peninsula to An Hoa Cape. This nearly 100 km long coastline plays a significant role in the economic growth of the Quan Nam Province. The marine tourism in Quang Nam Province based on its wide sandy beaches has left a positive impression, both nationally and internationally and has become a model for future development of other cities in Central Vietnam (Hoi et al., 2016).
3.1.2 Ombrone River delta

Figure 3.2 shows the map of Ombrone River basin located in Central Italy. The Ombrone River has a steep basin with the average relief of approximately 250 m and a small catchment area of about 3,500 km². The annual precipitation in this basin is 800 mm. In its steep basin, the Ombrone River flows over a distance of 130 km before discharging to the Tyrrhenian Sea. From the study of Bartolini and Pranzini (1985), the total sediment input from the Ombrone River is $1.35 \times 10^6$ m³/y. In which, only 30% of this total volume contribute to the morphological changes of the delta’s lopes where beaches contained mostly of gravel and sand.
The Ombrone River delta is one of the major Tyrrhenian deltas and the most natural area in the Tuscany region which has not been much disturbed by the humans concerning both the delta’s coastal area and river basin (Tortora et al., 2001; Bellotti et al., 2004).

The Ombrone River delta a coastline of about 30 km running from Castiglione Della Pescaia in the north to Cala di Forno in the south. It is clear that the Ombrone River delta coastline has a smaller scale than the Thu Bon River delta coastline.

Figure 3.2 Ombrone River delta
As can be seen in Figure 3.3, Funatsu River delta is formed by the sediment discharged from Funatsu River to Lake Inawashiro. Lake Inawashiro is located in...
Fukushima Prefecture. According to Matsumoto (1999), the catchment area of Funatsu River is 61.5 km².

As this delta is formed in a lake, its spatial scale is very small with the shoreline on the left of the Funatsu River is approximate to 500 m.

3.2 Data collection

The main data source for the analysis in this study consists mainly of Google earth and Landsat images. Of these, the Google earth with high resolution will be used for the short-term analysis of morphological change at three study areas. Following the analysis of Google earth images, the longer-term evolution of the river deltas will be investigated using Landsat images. In some cases, additional data such as old maps and aerial photographs are utilized to improve the reliability of the analysis. In the case of Funatsu River delta, due to its small spatial scale, the Landsat images cannot be used and only short-term morphological change of this river delta is investigated based on Google earth images and aerial photograph.

Detailed data collection will be presented in Chapters 4, 5, and 6 where the morphological changes of the Thu Bon River, Ombrone River, and Funatsu River deltas are investigated.

3.3 Methodology

3.3.1 Image rectification

Image rectification is a process of transforming information from one image into a common mapping system using a geometric transformation. This process is done by matching corresponding points from the mapping system with the same points on the image to be processed. The corresponding points are usually known as the ground control points (GCPs). GCPs should be chosen as the permanent objects or stationary features such as road intersections, building corners, and sea walls. Choosing natural features for GCPs should be avoided since these features often change with the lapse of time. The GCPs should also be distributed evenly throughout the image since the accuracy of will decrease as we move away from the GCPs. In this study, all the images will be rectified to the World Geodetic System 84 (WGS-84).

(a) Shoreline extraction

The shoreline is defined as the interface between the sand and water body. Although it seems to be simple, precisely estimate this interface has proven to be a difficult task in
reality due to the dynamic characteristic of the water. Therefore, a set of shoreline indicators have been introduced in the literature with an attempt to accurately capture the shoreline position. In this study, the wet/dry line is chosen as the shoreline proxy as exemplified in Figure 3.4 (the blue line).

![Figure 3.4 The wet/dry line is chosen as the shoreline proxy](image)

(b) The uncertainty of image analysis

According to Moore (2000), there are many potential errors associated with the shoreline mapping. In which, errors are divided into two categories: 1) error introduced by data sources and 2) errors introduced by measurement methods.

In this study, the mapping method presented in Pradjoko and Tanaka (2010) was utilized. This mapping method was reported to have a maximum error up to 6 m in the rectification.

3.3.2 Methodology for shoreline change rate analysis

In order to calculate the rate of shoreline change utilizing all the available shoreline samples, the linear regression method (Dolan et al., 1991) was used. Based on the available shoreline positions, a best fit line will be calculated using the method least squares through all the shoreline samples and the slope of the best fit line is the shoreline change rate. The best fit line can be expressed as:

\[ y = at + b \]  \hspace{1cm} (3.1)

According to Dolan et al. (1991), one of the main problems related to the linear regression method is that the influence of old data to the regression. For example, the data source usually includes a cluster of recent data and one or two old data from the old maps
which have less accuracy in the measurement. This old data can significantly change the slope of the regression line.

### 3.3.3 Methodology for deriving analytical solutions of the one-line model

Larson et al. (1987) simplified the governing equation of one-line model to a linear differential equation which can be solved to obtain many solutions for the shoreline evolution under different boundaries and initial conditions. In the following discussion, the simplified procedure of Larson et al. (1987) will be presented.

Peldnard Considere (1956) introduced the theory of one-line model based on the conservation of sand as:

\[
\frac{\partial v}{\partial t} + \frac{1}{D} \frac{\partial Q}{\partial x} = 0
\]  

(3.2)

where \(x\) and \(y\) are the alongshore and offshore distances, \(t\) is the time, \(D = D_B + D_C\) (\(D_B\): berm height, \(D_C\): depth of closure), and \(Q\) is the longshore sediment transport rate.

In order to solve Eq. (3.2), an expression for the longshore sediment transport rate is specified as:

\[
Q = Q_0 \sin 2\alpha_b
\]  

(3.3)

where \(Q_0\) is the amplitude of longshore sediment transport rate and \(\alpha_b\) is the angle between breaking wave crests and shoreline.

The angle of the breaking wave crests with respect to the shoreline can be expressed as (Figure 3.5):

\[
\alpha_b = \alpha_0 - \arctan \left( \frac{\partial v}{\partial x} \right)
\]  

(3.4)

\(\alpha_0\) is the angle of breaking wave crests relative to the \(x\)-axis and \(\partial v/\partial x\) is the local shoreline orientation.
Figure 3.5 Definition sketch for geometric properties at a specific location as related to shoreline change (Larson et al., 1987)

Substituting Eq. (3.4) to Eq. (3.3), it yields:

$$Q = Q_0 \sin \left\{ 2 \left[ \alpha_0 - \arctan \left( \frac{\partial y}{\partial x} \right) \right] \right\}$$

(3.5)

For beaches with mild slopes, it can be assumed that the breaking wave angle relative to the shoreline and the shoreline orientation are small. Therefore:

$$Q = Q_0 \left( 2\alpha_0 - 2 \frac{\partial y}{\partial x} \right)$$

(3.6)

If the amplitude of the longshore sand transport rate and the incident breaking wave angle are constant, the following equation can be obtained:

$$\frac{\partial y}{\partial t} = \varepsilon \frac{\partial^2 y}{\partial x^2}$$

(3.7)
where $\varepsilon$ is the diffusion coefficient expressed as:

$$
\varepsilon = \frac{K \left(H^2 C_g \right)}{8} \left( \frac{\rho}{\rho_s - \rho} \right) \left( \frac{1}{1-n} \right) \left( \frac{1}{D_B + D_C} \right)
$$

(3.8)

where $n$ is the sediment porosity.

According to Eq. (3.8), the diffusion coefficient is highly depended on the breaking wave height, $H_b$, and the dimensionless empirical coefficient for longshore sediment transport, $K$.

According to Larson et al. (1987), Eq. (3.7) is identical to the one-dimensional equation of heat conduction or diffusion equation. Therefore, by applying the proper analogies between initial and boundary conditions for shoreline evolution and the processes of heat conduction, many analytical solutions for shoreline change can be obtained.

Based on the above comment of Larson et al. (1987), a new analytical solution for the formation and deformation of river delta shorelines will be derived and introduced in this study. Since the judgment of any solution is its ability to be applied to real case studies, Thus, a series of river deltas in the world will be investigated in this study. These river deltas will be first investigated concerning their morphological changes to estimate the characteristic quantities associated with each study area. Then, these characteristic quantities will be utilized in the application of analytical solution of one-line model to predict the evolution of these river deltas.

Concerning the spatial scales of the river deltas in this study, the morphological change of Thu Bon River delta which is the largest one, will be investigated in the next chapter.
CHAPTER 4

MORPHOLOGICAL CHANGE OF THU BON RIVER DELTA

4.1 Introduction

In the recent years, coastal erosion in Cua Dai Beach which is a part of the shoreline located immediate left of Thu Bon River mouth has become severe (Figure 4.1). Thu Bon River rises from the mountainous region in the west of Quang Nam Province and flows over a distance approximate to 240 km before discharging to the ocean at Thu Bon River mouth or Cua Dai River mouth. The total area of Vu Gia-Thu Bon River basin is approximate to 10,350 km² with the annual flow discharge of 327 m³/s measured at Giao Thuy Station located 30 km upstream of the river mouth. Tidal range in the study area is 0.82 m (Lam, 2009). It should be noted that Cua Dai Beach is the name of the 5 km long sandy coast on the left side of Thu Bon River mouth and the other parts of the coastlines in this region have different names. Since marine tourist is one of the most important services in Quang Nam Province, the local authority has called for investigations from many domestic and international scientists about the severe coastal erosion in the Cua Dai Beach. Although several studies have been conducted, these studies just focused on a small area around the Thu Bon River mouth and during a short period of time. In addition, no idea about erosion mechanism at the Cua Dai Beach has been stated from the past studies. Therefore, based on a series of satellite images including Google™ earth and Landsat images, longer and larger temporal and spatial scales, respectively, of shoreline evolution in Thu Bon River delta will be analyzed and the erosion mechanism in Cua Dai Beach will be figured out.

In the first part of this chapter, short-term but high resolution Google earth images will be utilized to discuss the recent shoreline change in the Cua Dai Beach. Additional results of the recent field trips to the Cua Dai Beach and several video images are also introduced to present the significant erosion at this beach in the recent years. Since longshore sediment transport rate (LSTR) is crucial for any discussion about beach morphological change, this quantity will be integrated into a whole littoral cell of Thu Bon River delta to give a comprehensive discussion about coastal erosion in the Cua Dai Beach. The LSTR will be calculated based on the shoreline change rate.
Figure 4.1 Thu Bon River delta and Cua Dai Beach where severe erosion is happening. Cua Dai Beach is a 5 km shoreline located immediate left of the Thu Bon River mouth.

In the second part of this chapter, long-term but low-resolution Landsat images will be used to discuss the relationship between sediment supply from the Thu Bon River and coastal morphological changes around the Thu Bon River mouth.

Since the sand terrace in front of the river mouth has been thought as the sand source for beaches adjacent to the river mouth, morphological evolution of the sand terrace in front of the Thu Bon River mouth will be discussed based on the combination of the Google earth, Landsat images and an old map in 1965.
4.2 Short-term evolution of the Cua Dai Beach and its surrounding coastlines

A coordinate system used for all analysis in this chapter is presented in Figure 4.2. All collected images will be re-rectified to this coordinate system with the origin located at 15°50.976' N and 108°21.624' E in the World Geodetic System 1984 (WGS-84). A baseline is set at 144.94 degrees clockwise to the north.

4.2.1 Recent coastal erosion in the Cua Dai Beach

As can be seen in Figure 4.2, shorelines in Thu Bon River delta were formed by the prolonged accumulation of sediment supply from the Thu Bon River. Therefore, coastal erosion in the Cua Dai Beach is inevitable when there is a drop of sediment input from the Thu Bon River (Komar, 1973; Uda, 2010; San-nami, 2012). Viet et al. (2015) reported that severe erosion has happened in the Cua Dai Beach in the recent years and the erosion area is expanding northwestward from the Thu Bon River mouth. In order to observe the development of the erosion zone, three endpoints of the eroded area determined on Google™ earth images from Feb 8, 2011 to Mar 1, 2014 are used. Furthermore, several field trips have been made from Dec 24, 2014 to Oct 19, 2016. For each observation, the location of the latest erosion point was recorded using a GPS device. These points are plotted in the same diagram to clearly represent the expansion of the erosion zone from Feb 8, 2011 to Oct 19, 2016. In the following discussion of the erosion zone in the Cua Dai Beach, the term end-point of the erosion zone will be used consistently to discuss the propagation of the erosion zone along the Cua Dai Beach.
Figure 4.2 The coordinate system used in the analysis. Due to the severe erosion in the Cua Dai Beach, a camera system (red dot) was set up at 5 km from the Thu Bon River mouth to continuously monitor the beach morphology.
Figure 4.3 The end-point of the erosion zone determined from the Google™ earth images.

Figure 4.3 shows the locations of the end point of the erosion zones on Feb 08, 2011; Apr 10, 2012; and Mar 01, 2014. In these photos, the end-points of the erosion zone are determined as the contact point between the shoreline and the sea walls. As can be seen from the figure, the erosion zone propagated about 700 m from Feb 08, 2011 to Mar 01, 2014.
(a) Dec 24, 2014, corresponding to point (4) in Figure 4.6

(b) Dec 15, 2015, corresponding to point (5) in Figure 4.6
Figure 4.4 The end-points of the erosion zone determined from the field trips
Figure 4.4 shows the end-points of the erosion zone determined from the field trip from 2014 to 2016. Since there is no sea wall in this shoreline segment, the end point of the erosion zone is determined based on the beach scarp since the beach scarp is one of the indications for beach erosion. In these photos, the end point of the erosion zone is determined at the end of the beach scarp.

Figure 4.5 shows a general view of the locations of the erosion end-points from 2011 to 2016. In this figure, the blue arrows denote the end-points of the erosion zone from Feb 08, 2011 to Mar 01, 2014 determined from the Google earth images while the red arrows denote the end-points of the erosion zone from Dec 24, 2014 to Oct 19, 2016 determined from the field trips.

In order to estimate the propagation speed of the erosion zone along the Cua Dai Beach, the alongshore coordinates of these end-points \( (x_e) \) are plotted in Figure 4.6. From Figure 4.6, one can determine that the erosion zone in the Cua Dai Beach is moving at a remarkable speed of 350 m/y to the northwest. It should be noted in Figure 4.6 that, from point (7) to point (8), the erosion zone moved rapidly about 400 m in a short period of time from Sep 14, 2016 to Oct 19, 2016. This can be caused by the Typhoon No. 4 occurred in September 2016.
Due to the significant landward movement of the shoreline in Cua Dai Beach in the recent years, a video camera system was implemented in Oct 2015 to continuously monitor the beach deformation in this area. From Figure 4.2, it can be seen that the camera system was installed at \( x = -5,000 \) m. From the camera system, three types of images are generated: a snapshot image, a 15-min average image, and a time-stacks (Thuan et al., 2016). In this study, the instant (snapshot) video images from Nov 14, 2015 to Dec 09, 2015 will be used to confirm the propagation direction of the erosion zone. These images are shown in Figure 4.7.

Figure 4.7 shows video images captured by the camera system with the aim of showing the recent beach topography change. In Figure 4.7(a), no erosion is observed because there is still a wide beach for putting umbrellas for the tourists. However, at the top right corner of the image, erosion can be recognized with countermeasure as sandbags are being carried out by using heavy machines. Wave arriving at an oblique angle to the shoreline in Figure 4.7(b) is remarkable and it can be presumed that the sediment is moving to the north due to the longshore currents created by this oblique angle waves.
Beach scarp was beginning to form and it can be seen in Figure 4.7(c) that a bather can sit on top of the scarp. From Nov 25, 2015 (Figure 4.7(d)) to Nov 26, 2015 (Figure 4.7(e)), beach erosion advanced so that there was no more space for putting the umbrellas. In the erosion area, seawall with sandbags and bamboo are placed in the direction from the back towards the front side of the image. The curved shoreline towards the seawall in Figure 4.7(e) indicates the retreat of the shoreline by the discontinuous littoral drift. As a countermeasure against the retreat of the shoreline, local material such as bamboo is used to construct a fence for wave energy dissipation which can be seen in Figure 4.7(f).
Figure 4.3(b) (Dec 15, 2015) which was captured 6 days after the capturing time of the image in Figure 4.7(f) tells us that the erosion zone is propagating to the north.

4.2.2 Temporal variation of shoreline positions in the Thu Bon River delta

High resolution images are always required as the fundamental data to precisely obtain the shoreline positions. However, this data source is not always available and in many cases must be ordered with expensive prices. Fortunately, open source images from Google™ earth imagery can be utilized as an alternation which provides a clear view of the interface between land and water. Therefore, in this study, 210 tiles of Google™ earth images covering the whole coastlines in Thu Bon River delta will be utilized to discuss the shoreline evolution from 2002 to 2015. The coverage areas of Google™ earth images used in this study are presented in Figure 4.8.
Figure 4.8 Capturing time and capturing areas of Google™ earth images in this study.
Shoreline positions at some beach sections along the coastlines of Thu Bon River delta are plotted in Figure 4.9. In which, Figure 4.9(a) shows the shoreline positions on the left and Figure 4.9(b) shows the shoreline positions on the right, respectively, of the Thu Bon River mouth. From Figure 4.9(a), significant shoreline retreats immediate left of the Thu Bon River mouth can be observed while there is shoreline advance near the end of the left coastline. This indicates that the eroded sediment near the river mouth is being transported and deposited at a located on the same coastline but far from the river mouth. In other words, longshore sediment transport is predominant in this area. On the other hand, beside the fluctuation of the cuspsate shoreline immediate right of the Thu Bon River mouth, the shoreline positions in two beach sections of the right coastline seem to be stable as presented in Figure 4.9(b).

(a) The northwestern coastline

(b) The southeastern coastline

Figure 4.9 Shoreline positions at some locations along the Thu Bon River delta coastlines

Shoreline change ($\Delta y$) along the coastlines of Thu Bon River delta is presented in Figure 4.10 at the interval of 1,000 m. In this plot, the raw shoreline positions will be
handled using the moving average to reduce the effect of the beach undulation to the temporal variation of the shoreline. In addition, tidal correction (Hoang et al., 2017) will also be made to obtain more precise shoreline positions. According to Figure 4.8, there are no images covering the whole study area. Therefore, shorelines on Nov 10, 2004 and Feb 08, 2011 will be respectively used as the reference years to calculate the shoreline changes on the left and the right sides of the Thu Bon River mouth.

![Figure 4.10 Shoreline changes along the Thu Bon River delta coastlines.](image)

According to Figure 4.10, the erosion zone is limited in the area at \(-5,000 \leq x \leq 0\) m near the river mouth. The shoreline retreated significantly over the period of ten years with the maximum magnitude approximate to 170m. After 2014, the retreat of the shoreline is no longer observed at some locations due to the constructions of sea walls. Apart from the retreat of shoreline adjacent to the river mouth, the shoreline advanced gradually at \(x \leq -5,000\) m and reached 20m from 2004 to 2015. Based on that, dominant direction of longshore sediment transport on the left coastline is northwestward. On the other hand, the advance of shoreline on the right bank can be recognized in the area immediate right of the Thu Bon River mouth and at the very end of the littoral system (\(x=50,000\) m) while no shoreline change occurs at the other locations of the coastline. From the shoreline changes at the Thu Bon River mouth, it can be said that there is an asymmetric shoreline change at this river mouth.
In order to easily observe the temporal variation of the shoreline positions, shoreline change rates along the Thu Bon River delta shorelines are calculated using Eq. (3.1):

\[ y = at + b \]  

(3.1)

where \( a \) (m/y) is the shoreline change rate, \( t \) is the time and \( b \) is a constant.

The temporal variations of shoreline positions at some locations along the Thu Bon River delta shorelines are presented in Figure 4.11. In which, remarkable moving landward of the shoreline immediate left of the Thu Bon River mouth (the Cua Dai Beach) can be observed at the rate of 14.7 m/y (Figure 4.11(a)). In contrast to severe erosion in the Cua Dai Beach, shoreline advance at a location of 15,000m northwestward from the river mouth can be observed. This development rate of the shoreline is 2 m/y. On the right coastline, there is shoreline advance at \( x=3,000 \) m near the river mouth with the rate of 4.6 m/y. At \( x=30,000 \) m, the shoreline fluctuated between 2001 and 2014 but there is no clear trend in the shoreline evolution which is indicated by a small value of the coefficient of determination (\( R^2=0.003 \)).

(a) at \( x=-2,000 \) m and \( x=-15,000 \) m on the left shoreline

(b) at \( x=3,000 \) m and \( x=30,000 \) m on the right shoreline

Figure 4.11 Temporal variations of shoreline positions at some locations along the Thu Bon River delta shorelines
All the shoreline change rate values calculated at an interval 1,000 m along the Thu Bon River delta shorelines are presented in Figure 4.12.

It should be noted that the shoreline change rates at $6,000 m \leq x \leq 25,000 m$ are presented by both a thin broken line (least square method) and a straight dashed line (linear interpolation). Since there are only two shoreline positions at $6,000 m \leq x \leq 25,000 m$ (Figure 4.8), which are not sufficient for the least square method, a straight dashed-dot line determined by the linear interpolation is used as the shoreline change rates in this section. On the right shoreline, a significant increase of the shoreline change rates can be observed near the right end of the shoreline between $x = 49,000 m$ to $x = 51,000 m$. This remarkable increase of the shoreline change rate can be explained by the existence of the Cua Lo River mouth in this location (Figure 4.2). In which, a sand-spit on the left of the Cua Lo River mouth is elongated by a large amount of longshore sediment transport along this sand-spit and sediment bypass the Cua Lo River mouth is deposited at the end of the beach which is a rocky boundary called An Hoa Cape (Duy et al., 2018). This causes the shoreline in this region to advance rapidly. Using the shoreline change rate diagram, discussion on sand balance can be made by calculating the longshore sediment transport rates.
4.2.3 Longshore sediment transport rates along the Thu Bon River delta shorelines

LSTRs immediately left and right of Cua Dai River mouth denoted by $Q_L$ and $Q_R$, respectively, are estimated based on a schematic diagram shown in Figure 4.13.

Using conservation equation, it yields:

$$\frac{\partial y}{\partial t} + \frac{1}{D} \frac{\partial Q}{\partial x} = 0 \quad (3.2)$$

where $D=D_B+D_C$ ($D_B$: berm height, $D_C$: depth of closure), and $Q$ is the longshore sediment transport rates on both sides of the river mouth.

From Eq. (3.2) and Figure 4.13, the longshore sediment transport rate along the coastlines can be determined as in the following equations.

For the left coastline:

$$Q(x) = -D \int_{x_1}^{x} \frac{\partial y}{\partial t} \cdot dx \quad (4.1)$$

For the right coastline:

$$Q(x) = D \int_{x}^{x_2} \frac{\partial y}{\partial t} \cdot dx \quad (4.2)$$
in which \(x_1\) and \(x_2\) indicate the \(x\)-coordinates of two boundaries for the littoral cell where \(Q(x)=0\) is satisfied. In the study area shown in Figure 4.8, Son Tra Peninsula and An Hoa Cape can be considered as two boundaries at which \(Q(x)=0\). Therefore, \(x_1=-30,000\text{m}\) and \(x_2=51,000\text{m}\) are chosen as the boundaries for the integration of LSTR.

Figure 4.14 LSTRs calculated based on shoreline change rate values

From the definition of shoreline change rate, \(\partial y/\partial t\) in the Eqs. (4.1) and (4.2) can be determined using the values of shoreline change rate in Figure 4.12. From Figure 4.13 and Figure 4.14, it is easy to determine the magnitudes of longshore sediment transport rates to both sides at the river mouth are \(Q_L=70,000\text{m}^3/\text{y}\) and \(Q_R=390,000\text{m}^3/\text{y}\), respectively. Sediment input of Thu Bon River can be determined based on values of \(Q_L\) and \(Q_R\) as follows:

\[
q_0 = Q_L + Q_R
\]  

(4.3)

where \(q_0\) is sediment input from Thu Bon River, \(q_0=460,000\text{m}^3/\text{y}\). This value shows good correspondence to the sediment supplies from the Thu Bon River estimated by Fila et al. (2016). According to Fila et al. (2016), three different methods to estimate sediment input from Thu Bon River were proposed with the values of 390,000\text{m}^3/\text{y}, 440,000\text{m}^3/\text{y}, and 600,000\text{m}^3/\text{y}.
In addition, Mau (2006) performed the calculations for longshore sediment transport rates around the Thu Bon River mouth with the average transport rates between 1999 and 2000 are 150,000 m³/y towards the north (on the left coastline) and 230,000 m³/y towards the south (on the right coastline). These estimations are in the same order of magnitude with the values of LSTRs on the left and the right coastlines in Figure 4.14.

Let α is the ratio of sediment transported from the river mouth to the right coastline, α can be determined from the following equation:

\[ \alpha = \frac{Q_R}{Q_L + Q_R} \]  

(4.4)

One important conclusion can be drawn from Figure 4.14 and Eq. (4.4) is that about 85% of sediment supply from Thu Bon River is being transported to the right. This causes insufficient sediment supply to the left coast and results in significant erosion at Cua Dai Beach which is adjacent to the left of the Thu Bon River mouth.

4.3 Long-term evolution of the Thu Bon River mouth and its adjacent shorelines

Shoreline changes in a whole transport system of sediment in the Thu Bon River delta have been investigated. However, this investigation is just for the period from 2002 to 2015. Therefore, based on a long-term data of Landsat images, a longer-term evolution of the Thu Bon River mouth will be investigated in this section to make a more comprehensive discussion about the morphological change in the Thu Bon River delta. Concerning the spatial scale, the investigation in this step will focus on a small area around the Thu Bon River mouth since the low ground resolution of the Landsat image makes this type of data source applicable only to the study areas with substantial changes in the morphology such as the river mouth (Pardo-Pascual et al., 2012; Hoang et al., 2015).

4.3.1 Long-term morphological evolution of the Thu Bon River mouth

Several Landsat images of the Thu Bon River mouth from 1973 to 2015 are shown in Figure 4.15. As can be seen in this figure. The Thu Bon River mouth’s morphology in the last 40 years can be divided into 3 periods. In which, the first period from 1972 to 1979 shown the asymmetric shape of the shorelines on both sides of the river mouth.
In the second period from 1989 to 1997, symmetric shorelines on both sides of the river mouth can be observed. The notable morphological change between the first and the second period is the formation of a sandbar in front of the river mouth in 1989. This sandbar might be created by a big flood of the year before. The sandbar attached to the shoreline on the left of the river mouth in 1993 to form a sand spit. Since then, under the action of the waves, the sand spit was pushed inland and a welding process between the sand spit and the left shoreline can be seen from 1995 to 2000.

In 2000, the asymmetric shape of the delta apex was formed again and this asymmetric shape has remained until present. In addition, rightward shifting of the river mouth from 2000 are also notable. This rightward shifting phenomenon can be explained by the landward moving of the sand spit which diverted the river flow from the axis of the

Figure 4.15 Morphological evolution of the Thu Bon River mouth from 1973 to 2015. Images are from Landsat USGS
river to the right. The construction site the Cua Dai Bridge (Figure 4.16) also contributes to the rightward shifting of the Thu Bon River mouth since it caused the constriction of the river flow and diverted this flow to the right.

![Image of the Cua Dai Bridge construction site on the left bank indicated by the red rectangle.](image)

Figure 4.16 The construction site of the Cua Dai Bridge on the left bank indicated by the red rectangle is also a reason for the rightward shifting of the Thu Bon River mouth. Image from Google earth.

### 4.3.2 Changes of the shoreline angles at the river mouth

From the previous comments on the long-term morphology of the Thu Bon River mouth, asymmetric and symmetric shapes of the delta apex in each period of the river mouth’s evolution were figured out. In this sub-section, more quantitative discussion about this asymmetric and symmetric shapes of the delta’s protrusion portion is performed based on the shoreline angles at the river mouth. In addition, since the shoreline angles at the river mouth is directly related to the amount of sediment input from the river (Komar, 1973), the evolution of the shoreline angles at the river mouth can be used to discuss the temporal variation of sediment supply from the river. The shoreline angles at the Thu Bon River mouth are determined as the angle between the baseline (the x-axis in Figure 4.15) and the best fit line calculated from the shoreline position of a beach segment adjacent to the Thu Bon River mouth. The beach segment for the right shoreline is defined as $1,500 \text{ m} \leq x \leq 2,500 \text{ m}$ and the beach segments for the left shoreline
are defined as \(-2,500 \text{ m} \leq x \leq -2,000 \text{ m}\) (from 1973 to 1979) and \(-1,500 \text{ m} \leq x \leq -1,000 \text{ m}\) (from 1989). This is due to the rightward shifting of the Thu Bon River mouth as stated above. The shoreline positions used for calculating the best fit line are collected at the interval of 30 m.

Figure 4.17 Temporal variations of the shoreline orientations at the Thu Bon River mouth.

Figure 4.17 represents the temporal variations of the shoreline orientations on both sides of the Thu Bon River mouth from 1973 to 2015. The shoreline orientations are indicated by \(\beta_R\) and \(\beta_L\) where the subscript “R” and “L” denotes the right and left sides, respectively, of the river mouth. As can be seen in Figure 4.17, there are three periods in the evolution of the Thu Bon River mouth. In which, the asymmetric shoreline shape as evidenced by the differences between \(\beta_R\) and \(\beta_L\) can be found in the first and the third periods. In the second period from 1989 to 1995, the protrusion part of the Thu Bon River delta can be classified as symmetric with respect to the river mouth due to the equality between \(\beta_R\) and \(\beta_L\).

Tanaka et al. (2015) mathematically expressed the boundary condition at the river mouth as the relationship between the sediment input from the river and the shoreline orientations at the river mouth as:
\[
\frac{\partial y}{\partial x} = -\frac{q_0}{2\varepsilon D}
\]

(4.5)

where \(\partial y/\partial x\) denotes the shoreline orientations on both sides at the river mouth, \(q_0\) is the sediment input from the river, number 2 indicates the symmetric distribution of sediment to both sides of the river mouth, \(\varepsilon\) is the diffusion coefficient and \(D\) is the total of berm height and depth of closure.

In the case of asymmetric sediment supply from the river, \(\alpha\) can be used as the ratio for sediment transported from the river mouth to the right side, the boundary conditions at the river mouth for the right coastline can be rewritten as:

\[
\beta_R = \alpha \frac{q_0}{D\varepsilon}
\]

(4.6)

and for the left coastline:

\[
\beta_L = (1 - \alpha) \frac{q_0}{D\varepsilon}
\]

(4.7)

From Eqs. (4.8) and (4.9), the following equation can be obtained:

\[
\alpha = \frac{\beta_R}{\beta_R + \beta_L}
\]

(4.8)

It can be interpreted from the definition of \(\alpha\) that when \(\alpha\) equals 0.5, sediment input from the Thu Bon River will distribute equally to both sides of the river mouth. On the contrary, asymmetric distribution of sediment to both sides of the river mouth will happen with the values of \(\alpha\) different from 0.5.

Figure 4.18 shows the temporal variation of \(\alpha\) during the survey period from 1973 to 2015. As can be seen from the figure, a substantial amount of sediment input from the Thu Bon River is being distributed to the right coastline in the recent years. This causes a deficiency of sediment supply to the left coastline where Cua Dai Beach is located. This reason for coastal erosion in the Cua Dai Beach well agrees with the findings in the
previous analysis of Google earth images. In the previous analysis of Google earth images, it is found that about 85% of sediment input from the Thu Bon River is being transported to the right coastline in the recent years while in the analysis of Landsat images, as can be seen in Figure 4.18, the ratio of sediment supply to the right coastline is around 80% from 2005.

Figure 4.18 Temporal variations of the ratio of sediment supply to the right coast at the Thu Bon River mouth.

4.3.3 Asymmetric shoreline change at the Thu Bon River mouth

Since the erosion of Cua Dai Beach is caused by asymmetric shoreline change at the Thu Bon River mouth, this phenomena will be investigated more detailed using the even and odd analysis which is a powerful tool to separate the symmetric shoreline (even) from those that are asymmetric (odd) (Rosati and Kraus, 1997). The application of this method is so direct and easy that it has been popularized by many researchers such as Work and Dean (1990), Rosati and Kraus (1997), Walton (2002). In addition, this method was applied to discuss the relationship between the erosion phenomenon on the right bank of the Da Rang River estuary in Vietnam and the movement of the river mouth (Hiep et al., 2016).

Regarding the shoreline positions at time $t_n$ and time $t_m$, the difference between them is taken and a function $f$ for shoreline change is defined as:

\[(4.11)\]
\[ f(x') = y(x', t_n) - y(x', t_m) \]  
(4.9)

Due to the shifting rightward of the river mouth, a new alongshore coordinate \( x' \) is defined by Eq. (4.12) based on the old alongshore coordinate \( x \) and the coordinate of the center point \( x_c \) at the narrowest section of the river mouth.

\[ x' = x - x_c \]  
(4.10)

The shoreline change, denoted as \( f(x') \), is the sum of even function \( f_E(x') \) and odd function \( f_O(x') \).

\[ f(x') = f_E(x') + f_O(x') \]  
(4.11)

In which, the even and odd functions can be obtained from the following equations:

\[ f_E(x') = \frac{f(x') + f(-x')}{2} \]  
(4.12)

\[ f_O(x') = \frac{f(x') - f(-x')}{2} \]  
(4.13)

In Figure 4.19, the even-odd analysis is performed based on the difference between the shoreline position of June 1995 and that of May 2005. The shoreline positions are extracted from Landsat images at the interval of 10 m, extending from -5 km to +5 km across the Thu Bon River mouth. Moving average is also applied to overcome the problem related to the low ground resolution of the Landsat image. Figure 4.19 shows the analysis results with the shoreline change (measured, black lines), even function (even, red lines), and odd function (odd, blue lines). As can be seen from the figure, the application of even-odd analysis results in a negligible even function, which indicates that the asymmetric shoreline change had been dominant over the symmetric shoreline change for 10 years since 1995. This asymmetric shoreline change well agrees with the third
period in Figure 4.17 with the asymmetric in the shoreline orientations started to occur in 1995.

\[ f(x') \times 10^3 \text{ m} \]

Figure 4.19 Results obtained from the even-odd analysis show the dominance of asymmetric shoreline change.

### 4.3.4 Evolution of the sand terrace in front of the Thu Bon River mouth

Uda and Matsuda (1995) made an investigation of the Omono River mouth and discussed the interrelationship between sand terrace evolution and morphological change of beaches adjacent to the river mouth. According to them, the sand terrace off the river mouth has a certain influence on the temporal variation of the adjacent beaches. Therefore, it needs to be studied to gain a better understanding of the shoreline evolution around the river mouth.

In order to observe and discuss the morphological change of beaches adjacent to a river mouth, it is common to use bathymetry maps. This method is an efficient way to study the beach morphology at a river mouth or jetty and was introduced by many researchers (FitzGerald et al., 1976; Komar and Terich, 1976; Uda, 2010).

Generally, in developing countries, field measurement data such as bathymetry data is very limited, and it is very difficult to conduct a detailed study on the beach deformation.
As a matter of fact, there is a shortage of field survey data in the Thu Bon River mouth. Particularly, the shallow surveys were only conducted in 1965 and 2014. With the availability of satellite images, it is, therefore, necessary to employ a method which can utilize the satellite images. Although the number of studies about the sand terrace off the river mouth using aerial photograph is very limited, there is a comparative study of Sawamoto and Shuto (1988). In their study, they discussed the disappearance of the estuary terrace from the information of the wave breaking line in front of the Abukuma River mouth using aerial photographs. In order to overcome the problem of lacking survey data, the method of Sawamoto and Shuto (1988) is employed in the present study. According to Sawamoto and Shuto (1988), sediment discharge from the river mouth will form a sand terrace in front of the river mouth. The shape of the wave breaking line off the river mouth can be used as an indicator of the outer edge of the sand terrace.

In order to confirm the accuracy of this method, the contour line (-3 m) in the shallow survey data was used to validate the wave breaking line obtained from Google Earth images (Figure 4.20). In the figure, the shallow survey was conducted in June 2014 while the Google Earth image was captured in March 2014. Therefore, the results from the shallow survey and the Google Earth image are assumed to be acquired at the same time period and can be used for the comparison. The result of the comparison is shown in Figure 4.20. From the figure, it can be said that the outer edge of the sand terrace can be satisfactorily obtained from the wave breaking line in the satellite image.

Figure 4.21 shows the terraced shape obtained using wave breaking line from satellite images and from the shallow survey data (-3 m contour). It is clear that the position of the estuary terrace in recent years has shifted significantly to the south compared to the one in 1965. In addition, the degeneration of the sand terrace with the lapse of time can be observed and it is presumed that the sand mining at the river mouth has a big influence on the degeneration of this estuary terrace.

In order to quantitatively investigate the characteristics of the sand terrace, Figure 4.22 was plotted to show the center of gravity \((x_c, y_c)\) and the area \(A\) of the terrace. In which, the center of gravity and the area of the sand terrace were calculated based on the plane shapes above the broken line in Figure 4.21. It can be seen in Figure 4.22 that from 2013 onwards, although there is no marked change in \(x_c\), the decrease of \(y_c\) is visible as evidenced by the shrinkage of the sand terrace.
Figure 4.20 Comparison of terrace shape (-3 m contour surveyed in June 2014) and wave breaking line (Google Earth image captured in March 2014).

Figure 4.21 Rightward moving and degenerating of the estuary terrace.
Figure 4.22 Quantitative evaluation of estuary terrace’s characteristics.

It has been long understood that wave breaking at the edge of the estuary terrace generates drift currents which transport sand along the edge of the terrace toward the shorelines, thereby causes sand to move onshore (Uda and Matsuda, 1995; Takahashi and Takewaka, 2014). From the deviation of the estuary terrace as shown in Figure 4.21, it can be said that there is a biased movement of the sand from the terrace towards the right coastline. In other words, the right shoreline is being nourished by the sand returning from the terrace. The severe coastal erosion at Cua Dai Beach on the left coastline is presumed to be caused by the asymmetry of such onshore movement of sediment. Therefore, in order to save Cua Dai Beach, the sand supply to this beach must be increased. This can be done by constructing a training wall to divert the flow of Thu Bon River to the left.

4.4 Conclusions of this chapter

Satellite images including Google earth and Landsat images have been used to investigate the morphological change of the Thu Bon River delta shorelines. Main conclusions of this chapter are as follows:

- Severe erosion is happening in Cua Dai Beach which is a 5 km shoreline located immediately left of the Thu Bon River mouth where the shoreline is moving landward at a maximum rate approximate to 15 m/y.
The severe erosion in Cua Dai Beach is caused by asymmetric shoreline change due to the unequal distribution of sediment input from the Thu Bon River. In which, about 85% of sediment input from the Thu Bon River is being distributed to the right coastline.

Longshore sediment transport is predominant along the Thu Bon River delta lopes and the eroded sediment from the Cua Dai Beach is being moved to the north.

By integrating the volume change rate of the beaches along the Thu Bon River delta shorelines, the sediment input from the Thu Bon River is about $460,000 \text{ m}^3/\text{y}$. This estimation is in good agreement with the previous studies in this area.

Analysis of the longer-term Landsat images shows that there are three periods in the evolution of the Thu Bon River mouth from 1973 to 2015. In which, the first (1973-1979) and the third (1996-2015) periods show asymmetric shoreline shapes while the second period (1989-1990) shows the symmetric shape of the shorelines.

Results from the Landsat image analysis also indicate that the asymmetric shoreline change at the Thu Bon River mouth is caused by the unequal distribution of sediment input from the Thu Bon River and this unequal ratio is about 80% and 20% for the right and the left shorelines, respectively. This result well agrees with the Google earth image analysis.

Studying on the evolution of the sand terrace confirms the asymmetric distribution of sediment from the Thu Bon River which results in the severe erosion in Cua Dai Beach. In order to save Cua Dai Beach, a training wall should be built to divert the flow from Thu Bon River to the left where Cua Dai Beach is situated.

In this chapter, the morphological change of a river delta has been studied. However, it is suggested by Galloway (1975) that, due to the variability of the modern deltas, studying on a single delta is not sufficient. Instead, a series of investigation is required. Therefore, in the next chapter, morphological change of a smaller scale wave dominate delta will be investigated.
CHAPTER 5

MORPHOLOGICAL CHANGE OF OMBRONE RIVER DELTA

5.1 Introduction

In Chapter 4, morphological change of the Thu Bon River delta in Central Vietnam has been investigated. However, due to the variability of river deltas with respect to the scales of external forces and geomorphological changes, it would be useful to make a series investigation of different river deltas to gain a better understanding about the physical processes within the deltas around the world. For this reason, Ombrone River delta located in the Tuscany region, Central Italy will be chosen as another case study. An outline of the Ombrone River delta is presented in Figure 5.1.

The Ombrone River delta (Figure 5.1) is one of the major Tyrrhenian deltas and the most natural area in the Tuscany region which has not been much disturbed by the humans concerning both the delta’s coastal area and river basin (Tortora et al., 2001; Bellotti et al., 2004). Therefore, a wild Mediterranean environment characterized by agricultural crops, deciduous woods, and long sandy beaches with no tourist structures can be found in this area especially along the southern slope of the delta (Cipriani, 2013).

The Ombrone River has a steep basin with the average relief of approximately 250 m and a small catchment area of about 3,500 km². The annual precipitation in this basin is 800 mm. In its steep basin, the Ombrone River flows over a distance of 130 km before discharging to the Tyrrhenian Sea.

According to Pranzini (1989), the apex of the Ombrone River delta is formed and maintained by the large quantities of sediment supply from the river. However, this protruding portion of the Ombrone River delta is suffering from coastal erosion due to the reduction of sediment input since the second half of the Nineteenth century. In another study, Pranzini (1994) also showed that there is a drop of sediment for nourishing the beaches adjacent to the Ombrone River mouth. This reduction rate is of three fourths from mid Nineteenth century to present.
Figure 5.1 The Ombrone River delta in Central Italy
Due to the importance of river sediment input for the control of river delta lopes, numerous studies for evaluating the sediment input from the Ombrone River have been conducted. Unfortunately, a majority of these works were published in Italian. From the study of Bartolini and Pranzini (1985), the total sediment input from the Ombrone River is $1.35 \times 10^6$ m$^3$/y. In which, only 30% of this total volume contribute to the morphological changes of the delta’s lopes where beaches contained mostly of gravel and sand. The composition of beaches at the Ombrone River mouth was clarified by a useful study of Tortora (1999). In which, 108 sedimentary samples were collected and analyzed. From the analysis results, a comprehensive map of sediment distribution on the Ombrone River delta seafloor was published.

Although the mean tidal range at the mouth of the Ombrone River is quite small at about 0.2 m - 0.3 m (Marques et al., 2003), the tidal effect on shoreline positions must be considered in this region due to a very mild slope of the beach at about 1% (Cipriani et al., 2013).

As the longshore sediment transport rate (LSTR) is very important to the geomorphic changes of open-coast beaches where waves generate the longshore drift, the LSTR along the two delta lopes of the Ombrone River delta will be estimated based on the analysis of Google earth images from 2001 to 2017.

In the second part of this chapter, longer-term Landsat images will be utilized to discuss the morphological change of the delta’s protrusion area by means of the angle of the delta’s lopes at the river mouth (Duy et al., 2016). This approach is extremely useful since it does not require direct measurement of wave data in the study area (Besset et al., 2017).

5.2 Short-term morphological change of the Ombrone River delta

Google earth images from 2001 to 2017 are collected and georeferenced to a same coordinate system in the World Geodetic System 1984 (WGS-84) with the origin located at 42° 40.845’N and 11° 3.190’E. A line which is 317.41 degree clockwise to the North is set as the baseline for image processing. Since the coastlines of the Ombrone River delta stretch for 22 km from Castiglione Odella Pescaia in the north to Cala di Forno in the south (Figure 5.2), the study area is divided into 10 zones for the collection of Google earth images to ensure the quality of the images.
Figure 5.2 Schematic diagram of the Ombrone River delta coastlines from Castiglione Odella Pescaia in the north to Cala di Forno in the south.
Each tile of the Google earth image covers a beach segment from 2.5 km to 3.0 km. In the area of lacking ground control points, the image tilt will be enlarged to include sufficient ground control points for the rectification. The availability of Google earth images is also shown in Figure 5.2.

5.2.1 Shoreline changes along the Ombrone River delta coastlines

As can be seen in Figure 5.2, the oldest available image which covers the whole range of the Ombrone River delta lopes was captured on 2004-09-03. Therefore, in order to show a continuous shoreline change along the delta’s lopes, the shoreline change with reference to this date will be calculated as:

$$\Delta y = y(x, t) - y(x, 2004 - 09 - 03)$$ (5.1)

In which, $\Delta y$ is the shoreline change, $x$ is the alongshore distance, $y(x, t)$ is the shoreline positions at time $t$, and $y(x, 2004-09-03)$ is the shoreline position on 2004-09-03.

Changes of the Ombrone River delta shorelines are presented in Figure 5.3. As can be seen in Figure 5.3, significant shoreline retreat occurs at the river mouth while shoreline advance happens on both wings of the delta. This phenomena well agree with the delta retreat due to the reduction of sediment supply from the river. In which, severe erosion will happen first at the river mouth where the longshore sand transport induced by waves is more significant due to the apex shape of the delta. Eroded sediment will then be transported along the shore to a distance from the river mouth and causes beach accretion (Komar, 1973; Pranzini, 1989; Nienhuis et al., 2016; Basset et al., 2017). This beach accretions can be observed at 4,000 m to the south and 2,000 m to the north from the Ombrone River mouth. It should be noticed that the shoreline positions are smoothened using the moving average method with the aim of removing the effect of the shoreline undulations.

5.2.2 Shoreline change rates along the Ombrone River delta coastlines

The shoreline change rates at the interval of 100 m along the Ombrone delta’s coastlines are calculated based on the shoreline positions using the least squares method (Dolan et al., 1991). Figure 5.4 presents the temporal variation of shoreline positions at several beach cross-sections. As can be seen in Figure 5.4, for each beach cross-section,
the best fit line is determined through the entire samples of shoreline positions, the slope of this line is the shoreline change rate at this beach section.

Figure 5.3 Shoreline changes of the Ombrone River delta coastlines from 2001 to 2017

After calculating all the shoreline rate of change along the entire coastlines, these data are plotted in the same figure at an interval of 100 m to show the shoreline change rates along the Ombrone delta’s coastlines (Figure 5.5). From Figure 5.5, it is clear that erosion is happening at the river mouth and beaches along two flanks of the delta are moving seaward due to the eroded sediment from the beaches adjacent to the river mouth. From the movement of sediment, it can be concluded that longshore sediment transport is predominant in this area.
Figure 5.4 Temporal variations of shoreline positions at several beach sections along the south and the northern coastlines of the Ombrone River delta.
5.2.3 Longshore sediment transport rates along the Ombrone River delta coastlines

Based on the values of shoreline change rates along the Ombrone River delta coastlines, the area change rate of each beach segment can be calculated. This can be done by simply calculate the trapezoidal area bounded by the two adjacent shoreline change rate values and the beach interval which is 100 m. After obtaining the area change rates, the volume change rates are calculated as the product of the area change rate and the critical depth for longshore sediment transport. According to (De Filippi et al., 2008), the value for critical depth of longshore sediment transport in this area is 9 m. The volume change rates of the beach can be integrated to estimate the longshore sediment transport rate using the same method as presented in 4.2.3. The integrate must start from a location where the longshore sediment transport rate can be considered as zero. For the case of Ombrone River delta coastlines, the Cala di Forno headland in the south end and a breakwater located in Castiglione Odella Pescaia in the north (Figure 5.2) are chosen as the boundary for the calculation.

The longshore sediment transport rates along the Ombrone River delta coastlines are presented in Figure 5.6. As can be seen in this figure, northward longshore sediment transport is predominant in this area as evidenced by 120,000 m$^3$/y of sediment moving northward on the northern coastline while this value is only 20,000 m$^3$/y on the southern coastline. This can be explained by the current wave climate offshore the Ombrone River.
delta (Nienhuis et al., 2016). In the study of Nienhuis et al. (2016), oblique wave approaching the Ombrone River delta from the south is adding an additional longshore current and causes net longshore sediment transport to the north. In the calculation of Aminti and Pranzini (1990), current wave data were used to estimate the longshore sediment transport rates along the two coastlines of the Ombrone River delta. They came to the conclusion that asymmetric distribution of fluvial sediment from the Ombrone River is happening at the present as evidenced by 150,000 m$^3$/y of sediment moving northward on the northern coastline and only 65,000 m$^3$/y of sediment moving southward on the southern coastline. Estimated longshore sediment transport rates in Figure 5.6 show quite good agreement with the previous study of Aminti and Pranzini (1990).

![Figure 5.6 Longshore sediment transport rates along the Ombrone River delta coastlines](image)

5.3 Long-term morphological change of the Ombrone River delta

In this section, low ground resolution but longer-term Landsat images are used to investigate the long-term evolution of the Ombrone River mouth with the aim of evaluating the sediment input from the river as well as sediment transport around the complex coastal system of this river mouth.

Landsat images from 1972 to 2018 are collected for the analysis. In order to make a comparison with the results obtained from the analysis of the Google earth images, image rectification is processed using the same coordinate system as in the Google earth image analysis.
5.3.1 Long-term morphological change of the Ombrone River mouth

Landsat images from 1972 to 2018 are presented in Figure 5.7 to observe the morphological change of the river mouth in the last 4 decades. From the series of the Landsat images, a remarkable change in the morphology of the northern lope can be seen during the survey period, especially near the river mouth. It indicates that longshore sediment transport is more significant along the northern lope than the southern one in the Ombrone River delta.

Specifically, from 1972 to 1984, changes of the delta lopes were very small and difficult to recognized by the Landsat images. Since 1990, marked changes of the beaches on the northern part of the river mouth can be observed with the erosion of the beach immediately north of the river mouth and progradation of the adjacent beach. In addition, sand spit development between 1993 and 1994 signaled the northward direction of longshore sediment transport induced by oblique angle wave from the south (Figure 5.8). A significant flood in 1992 reported by Caporali et al. (2005) which occurred in the Arno River basin adjacent to the Ombrone River basin can be the reason for the formation of the sand spit in front of the Ombrone River mouth. The authors also indicated that there was a flood hit the Ombrone River watershed in October 1991.

From 2000 to 2018, the beach on the right of the river mouth had been cut to approximately 1 km while the progradation of the delta wing at the right end was very weak. This can be due to the marked reduction of sediment supply from the Ombrone River in the recent years at about three fourths (Pranzini, 1994). This should be noticed that this calculation did not account for river bed excavation along the Ombrone River.
Figure 5.7 Ombrone River delta from 1972 to 2018. Images from USGS Landsat.
Figure 5.8 Elongation of sand spit from the south to the north indicates the northward direction of longshore sediment transport in the study area. Background images from USGS Landsat

In order to quantitatively assess the morphological change of the Ombrone River delta, shoreline positions in several years during the survey period are plotted in Figure 5.9. It can be said that erosion of the delta apex and progradation of the delta wings is the general trend in the morphological evolution of the Ombrone River delta in the last 40 years. Erosion of the northern delta lope is more severe than the southern one. Due to the existence of a rip-rap built around 1984 (Cipriani et al., 2013) in the immediate south of the river mouth (Figure 5.10), the shoreline positions between 2008 and 2018 in this beach segment remained stable. On the other hand, significant shoreline retreat is still happening on the beach immediately north of the river mouth.

Sand bypass as evidenced by the development of the sand spit can also be observed. From 1994 to 1996, a sand spit was formed by the flood in 1992 (Caporali et al., 2005) and pushed southward by the oblique waves. After that, breaching occurred and an amount of sand was left on the northern side of the river mouth. The sand spit area is calculated as 50,500 m², together with the 9 m active depth of longshore sediment transport in this region, the volume of sand bypass can be estimated as 454,500 m³.
Figure 5.9 Significant shoreline retreat at the protrusion part of the delta and sand bypass as due to northward development of the sand spit (yellow and orange lines). Background images from USGS Landsat

Figure 5.10 Rip-rap immediate south of the Ombrone River mouth (Cipriani et al., 2013)

5.3.2 Temporal variation of sediment input from the Ombrone River to beaches on both sides of the river mouth

In wave-dominated river delta like the Ombrone River delta (Wright and Coleman, 1973; Besset et al., 2017), angle dependence longshore sediment transport is very important to the orientation of the delta lopes. Therefore, the idea for calculating sediment
supply from the river using the delta angle at the river mouth has been proposed in the literature (Tanaka et al., 2015; Duy et al., 2016; Besset et al., 2017).

Figure 5.11 shows the sketch of how the shoreline orientations are determined with respect to the x-axis. In order to determine the angles of the delta shorelines, a regression line is calculated based on the shoreline positions extracted at a constant interval in a beach segment close to the river mouth. In this case, beach segments from 0 to -1,500 m on the south and from 500 m to 2,000 m on the north, respectively, of the Ombrone River mouth, will be collected at an interval of 30 m for calculating the delta shoreline angles.

Figure 5.11 Example of regression lines (red lines) determined from the shoreline positions at the interval of 30 m (green circles). Shoreline positions are plotted at the interval of 60 m for the legible purpose.

Temporal variations of the shoreline orientations on both sides of the river mouth are plotted in Figure 5.13. In which, $\beta_R$ and $\beta_L$ are the shoreline orientations on the right and the left, respectively, of the river mouth. As can be seen from Figure 5.12, there is a decreasing trend in the shoreline angles on both sides of the river mouth. The decreasing trend of shoreline angle on the right side (northern side) is more significant than the left one. Dominant longshore sediment transport to the north and reduction of river sediment input might result in this phenomena. In which, reduction of sediment causes the amount of sand delivered to the river mouth less than the potential longshore sediment transport and the shoreline orientation will be re-orientated to reduce the maximum potential of alongshore sediment transport by the breaking waves.
In addition, the total of shoreline orientations on both sides is plotted. Since the apex shape of the delta related to the sediment input from the river (Komar, 1973; Besset, 2017), the total value of shoreline orientations on both sides can be used to qualitatively discuss the sediment input from the river. From Figure 5.12, the delta angle of the Ombrone River delta has decreased sharply since 1997, this indicated that there has been a decreasing trend of sediment supply from the Ombrone River.

Figure 5.12 Temporal variation of the shoreline orientations on both sides of the river mouth. The decreasing trend of the delta angle indicates a reduction of sediment input from the river.

Tanka et al. (2015), mathematically expressed the relation between the shoreline angle at the river mouth and the sediment supply from the river with the assumption that sediment is distributed symmetrically to both sides of the river mouth as:

$$\frac{\partial \nu}{\partial x} = -\frac{q_0}{2\varepsilon D}$$  \hspace{1cm} (5.2)$$

where \(q_0\) is the sediment input from the river, \(\varepsilon\) is the diffusion coefficient induced by breaking waves, \(D\) is the total of berm height and depth of closure. From Eq. (5.2), if the
diffusion coefficient is determined, quantitative estimation of sediment input from the river can be performed.

The ratio of sediment transport from the Ombrone River to the right side denoted by $\alpha$ is presented in Figure 5.13. From Figure 5.13, asymmetric distribution of sediment transport from the river to both sides has occurred since 2007. Before that, sediment input from the Ombrone River was distributed equally to the right and left sides as evidenced by the variation of $\alpha$ around 0.5 from 1972 to 2006. According to the value of longshore sediment transport rate evaluated in Figure 5.6, there is currently no sediment distribution on the left coastline, however, the results in Figure 5.13 indicate that about 40% of sediment from the Ombrone River are still going to the left. This difference can be caused by two reasons (i) the rip-rap on the left of the Ombrone River definitely affects the results in Figure 5.13 since this rip-rap has stabilized the angle of the shoreline and (ii) the oblique waves from the south, in reality, cause the difference in longshore sediment transport regime.

![Figure 5.13 The ratio of sediment supply from the river to the right side](image)

**5.4 Conclusions of this chapter**

Morphological change of the Ombrone River delta has been discussed using short-term and long-term satellite images. The main conclusion from the above analysis are as follows:

- Severe erosion is happening around the Ombrone River mouth and beaches are prograding at two flanks of this delta.
- Northern longshore sediment transport is predominant in the Ombrone River delta.
- Results from the Google earth image analysis indicates that a substantial amount of sediment input from the Ombrone River is being transported to the northern coastline in the recent years.
- Results from the Landsat image analysis indicates that about 40% of sediment input from the Ombrone River is being transported to the southern coastline in the recent years.
- The different results in the Google earth and Landsat image analysis can be caused by the protected rip-rap immediate left of the Ombrone River mouth and the oblique waves in the Ombrone River delta.
- Sediment supply from the Ombrone River shows a decreasing trend in the recent years.

In chapters 4 and 5, discussion on the morphological change of river delta has been made for open coast deltas. However, river deltas are also found in lakes where different scales in the external forces affecting the morphology of the delta are introduced. Until now in this study, no investigation has been made for river delta formed in the lakes. Therefore, the next chapter will contribute to the morphological change of river delta formed by sediment discharged from rivers to lakes.
6.1 Introduction

In Chapter 4 and Chapter 5, morphological changes of the Thu Bon and Ombrone deltas’ coastlines with different scales have been investigated to cover the variability of modern river deltas in the world. It should be noted that the Thu Bon and Ombrone deltas’ coastlines are formed by sediment discharged from the river to the ocean. However, it can be found in the literature that there are many river deltas were formed by the sediment input from the river to the lake especially in Japan (Refaat, 1990; Tanaka et al., 2003). For this reason, Funatsu River delta located in Lake Inawashiro, Fukushima Prefecture, Japan will be chosen as another case study. An outline of Lake Inawashiro is presented in Figure 6.1.

As can be seen in Figure 6.1, Funatsu river is located in the southern part of Lake Inawashiro. Lake Inawashiro is one of the four largest lakes in Japan located in Fukushima Prefecture. Due to the acidic characteristic with the pH varies from 2 to 5 (Kurosawa et al., 1997), the water lake has a high degree of transparency and therefore the lake is also known as the “Heavenly Mirror Lake”.

According to Matsumoto (1999), the catchment area of Funatsu River is 61.5 km$^2$. Another notable river in this lake is Nagase River. Although there has not been much study about the Funatsu River mouth, there have been numerous studies about the morphological change as well as longshore sediment transport in Nagase River delta (Tanaka et al., 2004; Fujita and Tanaka, 2002). From those studies, the depth of closure and the average longshore sediment transport rate along the southern shoreline of Nagase River are reported as 1.36 m and 1,700 m$^3$/year, respectively. Recently, Uda et al. (2017) related the high-wave-angle instability to the significant development of the sand spit on the lakeshore south of Nagase River mouth. This study provides useful information on wave data in the study area which is one of the most important factors for any study about shoreline morphological change. It should be noted that the wave data was computed from an empirical method using wind data. In addition, longshore sediment transport
along the southern shoreline of Nagase River mouth was also calculated in the study of Uda et al. (2017). This value of longshore sediment transport rate is $1,180 \, \text{m}^3/\text{y}$.

Figure 6.1 Outline of lake Inawashiro with the Funatsu River located in the southern part (top) and an air photo showing a shoreline on the left of Funatsu River mouth (bottom)
Since the shorelines of Funatsu River delta are considered as lakeshores, study on the formation processes of these shorelines are extremely useful in understanding the similarity law for sediment transport because the scales of topographic changes and external forces in the lake can be considered as the intermediate between coastal zones and laboratory experiments (Tanaka et al., 2003).

Because the Funatsu River delta was formed in a lake. This delta lakeshores are not affected by tidal level as for the case of delta coastlines. However, due to the utilization of lake water for power generation, irrigation and domestic use, the lake levels fluctuate with the maximum range approximately 0.6 m (Figure 6.2). It should be noted that data in Figure 6.2 includes only several months from 2006 to 2015.

According to the measured data presented by Tanaka et al. (2004), the average beach slope in the southern shoreline of Nagase River mouth (Figure 6.1) is about 0.13. Together with the difference in water level presented in Figure 6.2, the maximum difference in shoreline positions caused by fluctuation of the water level can be easily obtained as 4.6 m. This indicates that shoreline positions should be corrected to the average water level. This process can be done by employing the method introduced by Hoang et al. (2017). In the method of Hoang et al. (2017), exposure times of the images are required due to the fluctuation of the hourly water level. Fortunately, the water level in Lake Inawashiro is almost constant within one day as indicated in Figure 6.3. Therefore, the correction of shoreline positions to the mean lake level will be done using daily water levels instead of hourly water levels.

![Figure 6.2 Monthly water level in several months from 2006 to 2015. Data is provided by Fukushima Prefecture Government.](image)
Figure 6.3 Water levels in Lake Inawashiro corresponding to the captured dates of images used in the analysis
6.2 Morphological change of Funatsu River delta shorelines

6.2.1 Morphological change from image analysis

Figure 6.4 Evolution of the Funatsu River delta from 1982 to 2015
A time series of air photos and satellite images are utilized to analyze the long-term morphological change of the Funatsu River mouth. These photos and images were rectified to a same coordinate system as can be seen in Figure 6.4. In which, the origin of this coordinate system located at 37° 24.987'N and 140° 7.362'E in the WGS-84, and the baseline is set at 53.68 degrees clockwise from the north.

Figure 6.4 shows the long-term morphological change of the Funatsu River mouth from 1982 to 2015. As can be seen in this figure, there was no delta shape in 1982. In 2006, an apex delta shape can be observed clearly at the Funatsu River mouth. Despite a small retreat of the shorelines in 2002, the shorelines on both sides of the Funatsu River mouth generally show an advancing trend during the survey period.

The extracted shoreline positions from the rectified photos in Figure 6.4 are also shown in Figure 6.5. In this figure, shoreline advances can be seen along the left shoreline of the Funatsu River mouth where the shoreline at the river mouth moved offshore approximately to 30 m and the shoreline near the beach end move offshore approximately to 15 m.

Figure 6.5 Shoreline positions along the left side of the Funatsu River mouth from 2006 to 2015

**6.2.2 Shoreline change along the left shoreline in the recent years**

The shoreline changes with reference to the shoreline position in 2006 are also plotted in Figure 6.6. It can be seen in Figure 6.6 that shorelines in all the years after 2006
advanced apart from the one in 2012. As compared to the shoreline position in 2006, the shoreline in 2012 retreats in the beach segment of about 100 m immediate left of the Funatsu River mouth.

Figure 6.6 Shoreline change along the left side of the Funatsu River mouth with respect to the shoreline position in 2006

6.2.3 Shoreline change rate

Shoreline change rate at a specific beach cross section is calculated as the slope of the best fit line going through all the shoreline samples at this beach cross section from 2006 to 2015 (Figure 6.7). These shoreline change rates are calculated at a constant interval of 10 m along the left shoreline. Figure 6.8 shows the shoreline change rates along the left shoreline of the Funatsu River mouth.
Figure 6.7 Temporal variation of shoreline positions at some locations along the left shoreline of the Funatsu River mouth
6.2.4 Longshore sediment transport rate along the left shoreline of the Funatsu River mouth

The longshore sediment transport rate is calculated based on the sketch shown in Figure 4.13

![Diagram for estimations of LSTRs](image)

where $x_1$ and $x_2$ indicate the $x$-coordinates of two boundaries for the littoral cell where $Q(x)=0$ is satisfied. In the case of Funatsu River delta, only the left shoreline has the lateral boundary condition where $Q(x)$ can be considered as 0 (Figure 6.1). Therefore, LSTR is estimated only along the left shoreline.

Using conservation equation, it yields:

$$
\frac{\partial y}{\partial t} + \frac{1}{D} \frac{\partial Q}{\partial x} = 0
$$

(3.2)

where $D=D_B+D_C$ ($D_B$: berm height, $D_C$: depth of closure), and $Q$ is the longshore sediment transport rates on both sides of the river mouth. In the case of the lakeshore, there is no berm in the beach profile which results in $D_B=0$. 

Figure 6.8 Shoreline change rate along the left shoreline of the Funatsu River mouth
From Eq. (3.2) and Figure 4.13, the longshore sediment transport rate along the left shoreline can be determined as:

$$Q(x) = -D \frac{\partial y}{\partial t} \cdot dx$$  \hspace{1cm} (4.1)

As can be seen in Figure 6.1, $x_1 = -490$ m can be used as the boundary for the integration of LSTR on the left shoreline.

Figure 6.9 shows the LSTR along the left shoreline of Funatsu River mouth. As can be seen in this figure, the LSTR immediately left of the Funatsu River mouth is $Q_L = 670$ m$^3$/y. This indicates that Funatsu River is supplying about 670 m$^3$ sand annually to the left shoreline. From the value of $Q_L$, the sediment input from the Funatsu River can be obtained if the ratio of sediment supply from this river to the adjacent shorelines is known.

In order to estimate the ratio of sediment supply to both sides of the river mouth, the evolution of the Funatsu River mouth will be examined in the next section.

6.2.5 Evolution of the Funatsu River mouth

The so-called shoreline orientation is used to examine the morphology of the Funatsu River mouth from 2006 to 2015. Using the same method as in Section 4.3.2, the shoreline orientations at the Funatsu River mouth are calculated based on the shoreline positions in the beach segments $-100 \leq x \leq 0$ m on the left and $100 \leq x \leq -200$ m on the right,
respectively (Figure 6.10). Figure 6.11 shows the temporal variation of shoreline orientations on the left ($\beta_L$) and the right ($\beta_R$) at the Funatsu River mouth. It can be said that there is an asymmetric shoreline shape between the left and the right sides at the Funatsu River mouth as evidenced by the differences between $\beta_L$ and $\beta_R$ (Figure 6.11).

Using Eq. (4.8), the ratio of sediment supply from the Funatsu River to the right shoreline ($\alpha$) can be determined as:

$$\alpha = \frac{\beta_R}{\beta_R + \beta_L}$$  \hspace{1cm} (4.8)

![Figure 6.10 Shoreline positions at the interval of 10 m are used for calculating the shoreline angles with respect to the x-axis](image)

![Figure 6.11 Temporal variation of shoreline positions at some locations along the left shoreline of the Funatsu River mouth](image)
Figure 6.12 shows the ratios of sediment supply from the Funatsu River to the right shoreline from 2006 to 2015. The variation of $\alpha$ around 0.6 indicates that more sediment was distributed to the right shoreline from 2006 to 2015.

6.2.6 Sediment supply from the Funatsu River

Based on the value of sediment supply to the left shoreline ($Q_L$) in Figure 6.9 and the average value of $\alpha$ in Figure 6.12, the amount of sediment supply from the Funatsu River can be estimated as:

$$q_0 = \frac{Q_r}{1-\bar{\alpha}}$$  \hspace{1cm} (6.1)

where $q_0$ is the average rate of sediment supply from the Funatsu River; the bar indicates the average value of $\alpha$ in Figure 6.12, $\bar{\alpha} = 0.6$.

From Eq. (6.1), $q_0$ is approximate to 1,700 m$^3$/y. This value is an important boundary condition which will be utilized for the application of the one-line model in the next chapter.
6.3 Conclusions of this chapter

Morphological change of the Funatsu River delta in Lake Inawashiro has been investigated. Main conclusions of this chapter are as follows:

- The shoreline on the left of the Funatsu River mouth advanced about 30 m from 2006 to 2015.
- There is no erosion along the left shoreline of the Funatsu River delta.
- About 670 m$^3$ of sediment from the Funatsu River is going to the left shoreline every year.
- There are asymmetric shoreline shape and sediment supply to both sides at the Funatsu River mouth where 60% of the sediment input from the river is going to the right shoreline.
- Sediment supply from the Funatsu River is estimated as 1,700 m$^3$/year.

Until now, morphological investigations of the three river deltas are based only on the image analysis and empirical equations. In order to quantitative understand the fundamental responses of river delta shorelines to the governing processes, the one-line model will be utilized in the next chapter.
CHAPTER 7

ANALYTICAL SOLUTION FOR FORMATION AND DEFORMATION OF RIVER DELTAS

7.1 Introduction

From Chapter 4 to Chapter 6, morphological changes of three river deltas with different scales have been investigated to cover the variability of modern deltas in the world. However, these investigations based only on the image analysis and empirical equations which allow for monitoring shoreline change in a specific period of time when the data is available. In order to forecast the long-term evolution of river delta shoreline, a mathematical model is required. According to Larson et al. (1987), analytical solutions originating from mathematical models have proven to be a useful engineering technique for understanding and predicting the evolution of the plan shape of sandy beaches to a satisfactory level of accuracy. Therefore, the analytical approach will be used in this chapter to economically and quickly predict the fundamental changes in the formation and deformation processes of the three river deltas which were introduced in Chapter 4 (Thu Bon River delta), Chapter 5 (Ombrone River delta), and Chapter 6 (Funatsu River delta).

The results of morphological changes obtained from Chapter 4 to Chapter 6 will play an important role in the calibration and validation of the analytical models used in this chapter.

7.2 Formation and deformation processes of the Thu Bon River delta

7.2.1 Formation process of the Thu Bon River delta

As can be seen in Figure 4.1, the Thu Bon River delta can be classified as a wave-dominated delta where the delta is sourced in sediments by the river catchment and this sediment is redistributed alongshore by waves.

Larson et al. (1987) proposed an analytical solution which can be used to represent the shoreline evolution in the vicinity of a river discharging sand and acting as a point source. In the case of Thu Bon River, the sand discharging from the river can be considered as a point source because the width of the river mouth (about 500 m) is much smaller than the area where sand is discharging into (approximately to 80 km coastlines).
Another condition should be satisfied in the application of the simplified one-line model (Larson et al., 1987) is that breaking wave angle relative to the shoreline is small.

Figure 7.1 Schematic diagram for delta shoreline formation owing to sediment supply from the river as a point source

Binh (2014) measured 4 beach profiles along the northern coastline of Thu Bon River mouth and reported that the beach slopes change from 0.05 in the non-monsoon season to 0.13 in the monsoon season. From the study of Binh (2014), beaches along the coastline of Thu Bon River delta are quite mild and it is reasonable to assume that the breaking wave angle relative to the shoreline is small.

From the above explanation, the formation process of the Thu Bon River delta can be represented as:

\[
y = \frac{q_0}{D} \sqrt{\frac{t}{\pi \varepsilon}} e^{-x^2/(4\varepsilon t)} - \frac{q_0}{D} \frac{|x|}{2\varepsilon} \text{erfc}\left(\frac{|x|}{2\sqrt{\varepsilon t}}\right)
\]

where \(y\) is the shoreline positions; \(x\) is the longshore coordinate with the origin at the river mouth; \(t\) is the time; \(q_0\) is the sediment supply rate from the river; \(D = D_B + D_C\) (\(D_B\): berm height, \(D_C\): depth of closure); \(\varepsilon\) is the diffusion coefficient related to the longshore sediment transport; \(\text{erfc}\) is complementary error function.

From Eq. (7.1), the maximum shoreline position can be expressed as:

\[
y_0 = \frac{q_0}{D} \sqrt{\frac{t}{\pi \varepsilon}}
\]

where \(y_0\) is the maximum shoreline position.

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Eq. (7.1) can be expressed in the dimensionless form as:

\[ y^* = \exp\left(-x^* \right) - \sqrt{\pi} x^* \text{erfc}(x^*) \]  

(7.3)

where \( y^* = y/y_0 \) and

\[ x^* = \frac{|x|}{2\sqrt{\varepsilon t}} \]  

(7.4)

Using Taylor series expansion, the polynomials of degree 1 and 2 are expressed as:

\[ y^* = 1 - \sqrt{\pi} x^* \]  

(7.5)

\[ y^* = 1 - \sqrt{\pi} x^* + x^{*2} \]  

(7.6)

Figure 7.1 shows the formation process of a river delta owing to the sediment supply from the river. In which, the initial delta shoreline is a straight line and delta formation is generally related to periods of high sediment input and relatively stable sea level when the river was able to transport vast quantities of sediments eroded in the basin to the sea (Pranzini, 1989). In order to calculate the formation process of a river delta using Eq. (7.1), it is necessary to determine this straight initial shoreline. As the estimation of the initial shoreline is an extremely hard task especially in a region with no well documented geological study like Thu Bon River delta, the initial shoreline is therefore chosen as a straight line which separates the protrusion part of the delta from the non-protruding delta shoreline. The rationale for choosing this initial shoreline is that the longshore sand transport rate is proportional to the angle of incidence of breaking wave crests to the shoreline (Komar, 1973; Larson et al., 1987).

As can be seen in Eq. (7.1) and Figure 7.1, values of \( q_0, \varepsilon, t, \) and \( D=D_b+D_c \) are required for the application of Eq. (7.1) to the formation of Thu Bon River delta.

According to Fila et al. (2016), the sediment supply from Thu Bon River varies from 390,000 m\(^3\)/y to 600,000 m\(^3\)/y.
The formation time \((t)\) of the Thu Bon River delta was based on the report of Kubo (2000). According to Kubo (2000), there was a trading port in Hoi An City around the 17\textsuperscript{th} Century. However, this trading port lost its function due to a substantial amount of sediment supply from the Thu Bon River. Hence, it can be assumed that the deltaic portion of the Thu Bon River delta was formed from 400 to 500 years ago.

Concerning the depth of closure \((D_C)\) and the berm height \((D_B)\), these values were reported to be 6 m and 2 m, respectively, in the studies of Mau (2006) and Anh et al. (2018).

In order to estimate the diffusion coefficient \(\varepsilon\), the fitting method will be used. In which, the calculated shoreline and the measured shoreline will be compared. This will be done iteratively and the Root Mean Square Error (RMSE) will be calculated for each comparison. The fitting process will stop when the minimum RMSE is obtained.

In the fitting method, the maximum shoreline position is chosen as the measured shoreline to calibrate the model. From the series of Landsat images presented in Figure 7.2, it can be seen that the maximum shoreline position occurred in 1990. Therefore, this shoreline positions will be used as the measured shoreline for the comparison with the calculated shoreline.

Figure 7.3 shows the best fit between the calculated shoreline and the measured shoreline in 1990 as evidenced by the smallest RMSE of 0.03. It should be noted that the dimensionless forms of the shorelines are plotted in this diagram. The calibrated values of \(q_0\), \(\varepsilon\), and \(t\) are also presented in Table 7.1.

\begin{table}[h]
\centering
\begin{tabular}{|l|l|}
\hline
Sediment supply from the river – \(q_0\) & 570,000 m\(^3\)/y \\
\hline
Formation time – \(t\) & 500 years \\
\hline
Diffusion coefficinet – \(\varepsilon\) & 125 m\(^2\)/day \\
\hline
Depth of closure – \(D_C\) & 6 m \\
\hline
Berm height – \(D_B\) & 2 m \\
\hline
\end{tabular}
\caption{Calibrated values of parameters required for the application of Eq. (7.1)}
\end{table}
Figure 7.2 Several Landsat images from 1975 to 2014 of the Thu Bon River mouth. It can be seen that the maximum shoreline position occurred in 1990. The coordinate system used in this analysis is exactly the same with the coordinate system used in the morphological investigation of the Thu Bon River delta in Chapter 4.
Figure 7.3 Comparison between calculated shoreline and measured shoreline in 1990. The dimensionless forms are used in this plot.

7.2.2 Deformation process of the Thu Bon River delta

It can be seen in Figure 7.2 that, after reaching its maximum progradation state in 1990, the apex portion of the Thu Bon River delta has suffered from erosion as evidenced by the remarkable retreat of the shoreline on the left of the river mouth. Therefore, it would be useful to calculate the deformation process of the Thu Bon River delta to validate the parameters obtained in Table 7.1.

As Thu Bon River is the only source of sediment which controls the shape of the delta lopes, the erosion is obviously related to the reduction of sediment input from the river. From the findings in 4.2.3, it is concluded that only 15% of sediment input from Thu Bon River is going to the left coastline instead of 50% as in the past. Therefore, it is believed that erosion of beaches on the left of Thu Bon River mouth is caused by a reduction of sediment input from the Thu Bon River and this reduction rate can be calculated as:

\[ R = \frac{0.5 - 0.15}{0.5} = 0.7 \]  

(7.7)

By adding this reduction rate to Eq. (7.1), the deformation of the Thu Bon River delta can be expressed as:

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\[
y = \frac{q_0}{D} \sqrt{\frac{t}{\pi \varepsilon}} e^{-\frac{x^2}{(4\varepsilon)}} - \frac{q_0}{D} \frac{|x|}{2\varepsilon} \text{erfc} \left( \frac{|x|}{2\sqrt{\varepsilon}} \right) \\
- \left[ \frac{R \cdot q_0}{D} \sqrt{\frac{t-t_1}{\pi \varepsilon}} e^{-\frac{(t-t_1)x^2}{(4\varepsilon)}} - \frac{R \cdot q_0}{D} \frac{|x|}{2\varepsilon} \text{erfc} \left( \frac{|x|}{2\sqrt{\varepsilon(t-t_1)}} \right) \right]
\]  

(7.8)

In which, \( R \) is the reduction rate of sediment supply to the left coastline, \( t_1 \) is the time when erosion started.

Eq. (7.8) is the analytical solution describing the shoreline evolution corresponding to the deformation of river delta due to the reduction of sediment supply. This equation is the combination of the formation and the reduction term representing the reduction of sediment. Since Eq. (7.1) is the solution of a linear equation, Eq. (3.7), Eq. (7.8) is also a solution. It should be noted that this superposition characteristic can also be applied to discuss the recovery of river delta shoreline owing to the increase of sediment supply. This aspect is very useful in practical application to restore the beach.

Figure 7.4 shows the shoreline evolution on the left of the Thu Bon River mouth. In which, shoreline positions in Figure (a) are calculated using data in Table 7.2 and shoreline positions in Figure (b) are measured from Landsat images.

### Table 7.2 Calculation conditions for the deformation of Thu Bon River delta

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Diffusion coefficient</strong></td>
<td>( \varepsilon = 125 \text{ m}^2/\text{day} )</td>
</tr>
<tr>
<td><strong>Sediment supply from the river</strong></td>
<td>570,000 \text{ m}^3/\text{y}</td>
</tr>
<tr>
<td><strong>Formation time</strong></td>
<td>( t_0 = 500 \text{ years} )</td>
</tr>
<tr>
<td><strong>Deformation period (from 1990 to 2016)</strong></td>
<td>26 years</td>
</tr>
<tr>
<td><strong>Depth of closure</strong></td>
<td>( D_C = 6 \text{ m} )</td>
</tr>
<tr>
<td><strong>Berm height</strong></td>
<td>( D_B = 2 \text{ m} )</td>
</tr>
<tr>
<td><strong>Reduction rate of sediment supply from Thu Bon River</strong></td>
<td>( R = 0.7 )</td>
</tr>
</tbody>
</table>

In general, the analytical solution shows similar shoreline evolution to the measured shorelines. However, the shoreline retreat is more significant in reality. This is due to the welding process of the sandspit to the shoreline between 1995 and 2000 as indicated in Figure 4.15. Because this welding process cannot be included in the analytical solution, there is a difference between the calculated results and the measured data.
Another reason which might contribute to the difference between the calculated results and the measured data is the sand mining in front of the Thu Bon River mouth.

Figure 7.4 The deformation of the left shoreline in Thu Bon River delta by calculated shorelines and measured shorelines

Figure 7.5 Excavated sand in front of Thu Bon River mouth was used to fill the reclamation area as bounded by the red line
An example of sand mining offshore the Thu Bon River mouth is shown in Figure 7.5. As can be seen in the photo captured on Feb 08, 2011, sand was used to fill the reclamation area for coastal development. This area used to be the shrimp ponds of local people as evidenced in the photo taken on Nov 10, 2004. In 2012, severe erosion can be observed in the beach adjacent to the Thu Bon River mouth, this indicates that sand was extracted in the area offshore of this beach.

The time series of Landsat images in Figure 4.15 confirms that the sand filling was implemented between 2010 and 2011.

7.3 **New analytical solution for river delta with finite shorelines**

The analytical solution provided by Larson et al. (1987) has been used to investigate the formation and deformation of the Thu Bon River delta. It should be noted that the analytical solution of Larson et al. (1987) is applicable for shorelines of infinite lengths. However, in reality, the shorelines are always finite due to the existence of headlands or coastal structures located at distances from the river mouth as exemplified by the southern shoreline of the Ombrone River delta (Figure 5.1) or the shoreline on the left the Funatsu River mouth (Figure 6.1).

Therefore, it would be useful to derived another analytical solution which can be used to study the evolution of river delta with finite shorelines as schematized in Figure 7.6 where \( L \) is the length of the shoreline and \( y_c \) is the shoreline position at the river mouth.

![Figure 7.6 Schematic diagram of river delta with finite shorelines](image)

Although there has not been any analytical solution for the development of a river delta coastline with a finite length, there is a comparative study about the heat conduction in a medium between two insulated boundaries (Myers, 1971). It is interesting that restricted sediment input boundaries in the shoreline change model can be considered as a proper analogy to the heat flux and the insulated wall in the heat conduction process.
Therefore, the new equation for shoreline evolution under the effect of no-transport boundaries can be obtained as:

\[
y^* = \frac{x^*}{2} - \left| x^* \right| + \frac{1}{3} + t^* - \frac{2}{\pi^2} \sum_{n=1}^{\infty} \frac{e^{-n^2 x^* t^*}}{n^2} \cos(n \pi x^*)
\]  

(7.9)

where

\[
y^* = \frac{2 \varepsilon D}{q_0 L}
\]  

(7.10)

\[
x^* = \frac{x}{L}
\]  

(7.11)

\[
t^* = \frac{\varepsilon t}{L^2}
\]  

(7.12)

where \( y \) is the shoreline positions; \( x \) is the longshore coordinate with the origin at the river mouth; \( t \) is the time; \( q_0 \) is the sediment supply rate from the river; \( D=D_B+D_C \) (\( D_B \): berm height, \( D_C \): depth of closure); \( \varepsilon \) is the diffusion coefficient related to the longshore sediment transport, \( L \) is the shoreline length.

In order to observe the differences between the new analytical solution and the analytical solution provided by Larson et al. (1987), the analytical solution of Larson et al. (1987) is transformed into the dimensionless form using Eqs. (7.10), (7.11), and (7.12) as:

\[
y^* = 2 \sqrt{\frac{t^*}{\pi}} e^{-\left(x^*/2t^* \right)^2} - \left| x^* \right| \text{erfc} \left( \frac{x^*}{\sqrt{2t^*}} \right)
\]  

(7.13)

Figure 7.7 shows the comparison between the new analytical solution and the solution provided by Larson et al. (1987). The diagram is plotted only for \( x^* \geq 0 \) since the solutions are symmetric with respect to the \( y^* \)-axis. As can be seen in Figure 7.7, when \( t^* \) is smaller than 0.1, Eqs. (7.9) and (7.13) are in perfect agreement. From around \( t^* = 0.2 \), a difference starts to appear at the right end boundary. However, there is no difference at the river
mouth. Thereafter, the difference between the two solutions has expanded, and the influence of the lateral boundary is clear. After \( t^* = 0.4 \), the shoreline of parabolic shape is moving forward in the offshore direction.

The behaviors of the two solutions in Figure 7.7 can be explained by examining the dimensionless time \( t^* \). When \( t^* \) is small, sediment from the river has not reached the lateral boundary and there is no effect of the boundary. Therefore, the behavior of the shoreline must follow Eq. (7.13). However, at large value of \( t^* \), the exponential term in Eq. (7.9) vanished and the shoreline with a parabolic shape will move seaward at a constant speed as:

\[
y^* = \frac{x^*}{2} - |x^*| + \frac{1}{3} + t^*
\]

(7.14)

Figure 7.7 Comparison of shoreline positions calculated by two solutions

Figure 7.8 shows the shoreline evolution at the river mouth where the shoreline position can be expressed as \( x^* = 0 \):

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\[ y_0^* = t^* + \frac{1}{3} - \frac{2}{\pi^2} \sum_{n=1}^{\infty} \frac{e^{-n^2\pi^2 t^*}}{n^2} \]  
\hspace{2cm} (7.15)

Figure 7.8 Shoreline evolution at the river mouth

As can be seen in this figure, when \( t^* \) is small, the new analytical solution and the one provided by Larson et al. (1987) are in perfect agreement which indicates that there is no influence of the lateral boundary to the shoreline evolution at the river mouth. Hence, shoreline evolution at the river mouth when \( t^* \) approaches 0 can be represented as:

\[ y_0^* = 2 \sqrt{\frac{t^*}{\pi}} \]  
\hspace{2cm} (7.16)

When \( t^* \) is large, the difference between the new analytical solution and the solution of Larson et al. (1987) can be observed. This indicates the influence of the lateral boundary to the shoreline evolution at the river mouth after a sufficient time. At this stage, the shoreline evolution at the river mouth can be expressed as \( (t^* \to \infty) \):

\[ y_0^* = t^* + \frac{1}{3} \]  
\hspace{2cm} (7.17)

In Figure 7.8, it should be noted that the transit time between Eqs. (7.16) and (7.17) exists around \( t^* = 0.3 \).
Figure 7.9 shows the shoreline evolution at the boundary which can be expressed as 
\( x^* = 1 \):

\[
y_1^* = t^* - \frac{1}{6} - \frac{2}{\pi^2} \sum_{n=1}^{\infty} (-1)^n \frac{e^{-n^2 \pi^2 t^*}}{n^2}
\]  
(7.18)

By taking the two limits as \( t^* \to 0 \) and \( t^* \to \infty \), the shoreline evolutions at the lateral boundary for small \( t^* \) and large \( t^* \) are obtained as:

\[
y_1^* = 2 \sqrt{\frac{t^*}{\pi}} \left( \frac{y}{4t^*} \right) - \text{erfc} \left( \frac{y}{2 \sqrt{t^*}} \right)
\]  
(7.19)

\[
y_1^* = t^* - \frac{1}{6}
\]  
(7.20)

As can be seen in Figure 7.9, the transit time between Eqs. (7.18) and (7.19) exists near \( t^* = 0.1 \).
In order to validate the new analytical solution, experimental results from Refaat (1990) are utilized. This experiment was conducted to study the formation process of a river delta in a wave basin which is 8 m wide. Two waveguide walls are located at about 3.5 m on both sides of the wave basin. A sediment feeder machine was used to automatically discharge sand as a point source to the wave basin. In the first series of the experiment, sand was discharged constantly at a rate of 7.06 cm$^3$/s in 80 minutes. Waves were set to approach normally to the shoreline. The wave height and period are 2.0 cm and 0.8 sec., respectively. Water depth was set constantly at 30 cm. The shoreline positions were recorded at every 10 minutes and 50 cm interval.

From Eqs. (7.9), (7.10), (7.11), and (7.12), the dimensional form of Eq. (7.9) can be expressed as:

\[
y = \frac{q_0}{2\epsilon DL} \left[ \frac{x^2}{2} + L^2 \frac{L^2}{3} + \epsilon t - \frac{2L^2}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} e^{-n^2 \pi^2 \frac{\epsilon t}{L^2}} \cos \left( \frac{n \pi x}{L} \right) \right]
\]  

(7.21)

In order to make a comparison, the shoreline evolution was calculated using Eqs. (7.1) and (7.21) as well as the value of $\epsilon=15$ cm$^2$/s. The diffusion coefficient $\epsilon$ is determined based on the shoreline positions recorded from the experiment. The recorded beach profiles in the experiment were also used to obtain the value of $D_C=3.9$ cm. As can be seen in Figure 7.10, the new solution achieves better agreement with the experimental results, especially near the boundary, which is the side wall of the wave basin ($x=300$ cm).

![Figure 7.10 Comparison with experimental results](image)

Figure 7.10 Comparison with experimental results
7.4 Formation and deformation processes of the Ombrone River delta

In the previous section, a new analytical solution for studying the evolution of river delta with finite shorelines has been derived and validated using experimental results. However, the validation is only for the delta formation and the delta deformation has not been studied. Therefore, the new analytical solution will be applied to the Ombrone River delta in this section to:
- study both the formation and deformation of a river delta and
- confirm the applicability of the new analytical solution through a real case study.

7.4.1 Formation of the Ombrone River delta

The formation process of the Ombrone River delta is calculated using the same procedure as in the Thu Bon River delta. However, Eq. (7.21) is used instead of Eq. (7.3). The parameters required for the application of Eq. (7.21) are summarized in Table 7.3.

<table>
<thead>
<tr>
<th>Calculation conditions for the formation of the Ombrone River delta</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diffusion coefficient</td>
</tr>
<tr>
<td>Sediment supply from the river</td>
</tr>
<tr>
<td>Formation time</td>
</tr>
<tr>
<td>Depth of closure</td>
</tr>
<tr>
<td>Berm height</td>
</tr>
<tr>
<td>Length of the shoreline</td>
</tr>
</tbody>
</table>

As can be seen in Table 7.3, there is only one unknown which is the diffusion coefficient. This value will be determined using the fitting method as in 7.2.1. In which, the measured shoreline in 1883 is chosen as the final one in the formation of the Ombrone River delta (Pranzini, 1989; Silva et al., 2013; Cripiani et al, 2013).

Table 7.4 shows the calibrated values for the Ombrone River delta.

The calculated and the measured shorelines in 1883 are shown in Figure 7.11. For each calculation, the calculated shoreline in 1883 is compared with the measured shoreline in 1883. The RMSE is calculated and the calculation will stop when the minimum RMSE is obtained. Figure 7.12 shows the best fit between the calculated...
shoreline using Eq. (7.21) and the measured shoreline in 1883 corresponding to the minimum RMSE=130 m. It should be noted that the comparison is only for the left shoreline. The calibrated values determined from the fitting process are presented in Table 7.4.

Table 7.4 Calibrated parameters for the Ombrone River delta

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diffusion coefficient</td>
<td>$\varepsilon=45$ m$^2$/day</td>
</tr>
<tr>
<td>Sediment supply from the river</td>
<td>$q_0=345,000$ m$^3$/y</td>
</tr>
<tr>
<td>Formation time</td>
<td>$t_0=900$ years</td>
</tr>
<tr>
<td>Depth of closure</td>
<td>$D_c=8$ m (De Filippi et al., 2008)</td>
</tr>
<tr>
<td>Berm height</td>
<td>$D_B=1$ m (De Filippi et al., 2008)</td>
</tr>
<tr>
<td>Length of the shoreline</td>
<td>6,000 m</td>
</tr>
</tbody>
</table>

Figure 7.11 Calculated shoreline using Eq. (7.21) and the measured shoreline in 1883

Figure 7.12 Fitting between the calculated shoreline using Eq. (7.21) and the measured shoreline in 1883
7.4.2 Deformation of the Ombrone River delta

The parameters determined in Table 7.4 are validated by applying to the deformation of the Ombrone River delta. In order to calculate the deformation of the Ombrone River delta, superposition is applied to form an analytical solution which can be used to express the deformation of the river delta shoreline as:

\[
\begin{align*}
  y &= \frac{q_0}{2\varepsilon DL} \left[ \frac{x^2}{2} - L|x| + \frac{L^2}{3} + \epsilon \left( t - t_1 \right) - \frac{2L^2}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} e^{-n^2 \pi^2 \frac{\epsilon}{L^2}} \cos \left( \frac{n\pi x}{L} \right) \right] \\
  &\quad - \frac{R \cdot q_0}{2\varepsilon DL} \left[ \frac{x^2}{2} - L|x| + \frac{L^2}{3} + \epsilon \left( t - t_1 \right) - \frac{2L^2}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} e^{-n^2 \pi^2 \frac{\epsilon \left( t - t_1 \right)}{L^2}} \cos \left( \frac{n\pi x}{L} \right) \right] 
\end{align*}
\]  

(7.22)

where \( R \) is the reduction of sediment supply from the river and \( t_1 \) is the time when erosion started in the delta.

As mention previously, the maximum shoreline position in the progradation of the Ombrone River delta was obtained in 1883. Therefore, the year 1883 considered as the time when erosion started to happen. Concerning the reduction rate of sediment input from the Ombrone River, this rate is about 0.75 (Pranzini, 1994). The calculation conditions for the deformation of the Ombrone River delta are presented in Table 7.5.

<table>
<thead>
<tr>
<th>Calculation conditions for the deformation of the Ombrone River delta</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Diffusion coefficient</strong></td>
</tr>
<tr>
<td><strong>Sediment supply from the river</strong></td>
</tr>
<tr>
<td><strong>Formation time</strong></td>
</tr>
<tr>
<td><strong>Depth of closure</strong></td>
</tr>
<tr>
<td><strong>Berm height</strong></td>
</tr>
<tr>
<td><strong>Length of the shoreline</strong></td>
</tr>
<tr>
<td><strong>Reduction rate</strong></td>
</tr>
<tr>
<td><strong>Time when erosion happened</strong></td>
</tr>
</tbody>
</table>
The calculated shoreline and the measured shoreline in 2017 are presented in Figure 7.13. These shorelines are plotted in Figure 7.14 for the comparison. As can be seen in Figure 7.14, there is a good agreement between the calculated shoreline and the measured shoreline as evidenced by the RMSE=46.8 m. This indicates that the calibrated parameters can be used to predict the shoreline evolution in the Ombrone River delta.

Figure 7.14 Comparison of the calculated shoreline using Eq. (7.22) and the measured shoreline in 2017.

Figure 7.15 shows the deformation of the shoreline at the Ombrone River mouth. In which, the red line represents the calculated shoreline evolution with the effect of the boundary, Eq. (7.22), and the blue line shows the shoreline evolution without the effect of the boundary, Eq. (7.8). It can be seen that the calculated result using Eq. (7.22) shows better agreement with the measured data than the result of Eq. (7.8).
Figure 7.16 shows the deformation of the shoreline at the boundary which is the Cala di Forno headland. In which, the red line represents the calculated shoreline evolution with the effect of the boundary, Eq. (7.22), and the blue line shows the shoreline evolution without the effect of the boundary, Eq. (7.8). It can be seen that the calculated result using Eq. (7.22) shows better agreement with the measured data than the result of Eq. (7.8).

The results shown in Figure 7.15 and Figure 7.16 indicate that the new analytical solution is more suitable than the solution provided by Larson et al. (1987) to study the formation and deformation of the Ombrone River delta.
7.5 Formation process of the Funatsu River delta

As can be seen in Eq. (7.12), the dimensionless time \( t^* \) which determine the effect of the boundary is the function of the shoreline length, \( L \), and the diffusion coefficient, \( \varepsilon \). Therefore, it would be useful to examine the formation of a river delta lakeshore which has smaller scales in both the external forces and the geometry.

In Figure 6.1, the left shoreline of Funatsu River delta can be considered as a finite extent between the river mouth and the pier located at 490 m from the river mouth. From Figure 6.8, it can be said that erosion has not happened along the left shoreline of the Funatsu River delta. Therefore, the formation of this shoreline will be examined using the new analytical solution for the formation of finite delta shorelines, Eq. (7.21).

Using the same procedure as in 7.4.1, the parameters required for the studying of Funatsu River delta can be obtained as in Table 7.6 and Figure 7.17. The sediment supply from the Funatsu River in Table 7.6 \( (q_0=1,100 \text{ m}^3/\text{y}) \) is quite comparable to the one estimated in 6.2.6 which equals to 1,700 m\(^3\)/y.

Table 7.6 Calibrated parameters for the Funatsu River delta

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Diffusion coefficient</td>
<td>( \varepsilon=4.5 \text{ m}^2/\text{day} )</td>
</tr>
<tr>
<td>Sediment supply from the river</td>
<td>( q_0=1,100 \text{ m}^3/\text{y} )</td>
</tr>
<tr>
<td>Formation time</td>
<td>( t_0=33 \text{ years} )</td>
</tr>
<tr>
<td>Depth of closure</td>
<td>( D_c=1.36 \text{ m} ) (Fujita and Tanaka, 2002)</td>
</tr>
<tr>
<td>Length of the shoreline</td>
<td>( L=490 \text{ m} )</td>
</tr>
</tbody>
</table>

Figure 7.17 Fitting between the calculated shoreline and the measured shoreline in 2015
Figure 7.18 shows the formation of the shoreline at the boundary which is the pier located at 490 m from the Funatsu River mouth. In which, the red line represents the calculated shoreline evolution with the effect of the boundary, Eq. (7.22), and the blue line shows the shoreline evolution without the effect of the boundary, Eq. (7.8). It can be seen that the calculated result using Eq. (7.22) shows better agreement with the measured data than the result of Eq. (7.8). This indicates that the boundary has already affected the evolution of the left shoreline in the Funatsu River delta.

### 7.6 Classification of river delta based on the spatial and temporal scales

Among the three river deltas investigated in this study, the evolution of Thu Bon River delta shorelines can be studied using the analytical solution for infinite shorelines while the analytical solution for river delta of finite lengths is more suitable for the cases of the Ombrone River and the Funatsu River deltas. It is, therefore, would be useful to classify the river delta based on a demarcation from which suggestions for using an appropriate analytical solution can be given.

In 7.3, two demarcations for the boundary to take effect were figured out as \( t^* = 0.1 \) at the boundary and \( t^* = 0.3 \) at the river mouth. In the next, discussion on the effect of the boundary will be based on the two demarcations.

The dependence of \( t^* \) on the temporal \( (t) \) and spatial \( (L) \) scales of the delta can be seen in Eq. (7.12) as:

\[
    t^* = \frac{at}{L^2} \tag{7.12}
\]
Rewriting Eq. (7.12), the relation between the temporal and spatial scales of a river delta can be express as:

\[ t = t^* \frac{L^2}{\varepsilon} \]  \hfill (7.23)

From two demarcations of \( t^*=0.1 \) at the boundary and \( t^*=0.3 \) at the river mouth, two lines can be drawn with the slopes of 0.1 and 0.3. For a delta with given parameters of \( t, L, \) and \( \varepsilon \), the values of \( t \) and \( L/\varepsilon^2 \) can be plotted on the same diagram with the two lines representing the demarcations when the boundary affects the shoreline evolution. Based on the location of the plotting point with respect to the demarcation lines, it can be concluded that whether boundary effect occurs in this delta or not.

Table 7.7 shows the spatial and temporal scales of several river delta in the world and in two experiment series. Figure 7.20 shows the log-log plot of the data in Table 7.7 and two demarcations at \( t^*=0.1 \) and \( t^*=0.3 \).

Table 7.7 Spatial and temporal scales of several river deltas in the world and in two experiment series

| Thu Bon River delta | | | |
|---------------------|------------------|--|
| \( L \) (m)         | \( \varepsilon \) (m\(^2\)/day) | \( t \) (years) |
| 50,000              | 125               | 500 |
| 28,000              | 125               | 500 |

| Tenryu River delta  | | |
|---------------------|------------------|
| \( L \) = 20,000 (Duy et al., 2016) | \( t = 500 \) (Hori et al., 2017) |
| \( L \) = 10,000 (Duy et al., 2016) | \( t = 500 \) (Hori et al., 2017) |

<table>
<thead>
<tr>
<th>Ombrone River delta</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>( L ) = 6,000</td>
<td>( \varepsilon ) = 45</td>
<td>900</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Funatsu River delta</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>( L ) = 490</td>
<td>( \varepsilon ) = 4.5</td>
<td>33</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Experiment Series A (Refaat, 1990)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>( L ) (cm)</td>
<td>( \varepsilon ) (cm(^2)/s)</td>
<td>( t ) (s)</td>
</tr>
<tr>
<td>400</td>
<td>15</td>
<td>600</td>
</tr>
<tr>
<td>400</td>
<td>15</td>
<td>1,200</td>
</tr>
<tr>
<td>400</td>
<td>15</td>
<td>1,800</td>
</tr>
<tr>
<td>400</td>
<td>15</td>
<td>2,400</td>
</tr>
<tr>
<td>400</td>
<td>15</td>
<td>3,000</td>
</tr>
<tr>
<td>400</td>
<td>15</td>
<td>3,600</td>
</tr>
<tr>
<td>400</td>
<td>15</td>
<td>4,200</td>
</tr>
<tr>
<td>400</td>
<td>15</td>
<td>4,800</td>
</tr>
</tbody>
</table>
Figure 7.19 shows a fundamental diagram for the classification of river delta shorelines. In which, the demarcation (red lines) are plotted to divide the abscissa into three regions. The left region is for infinite delta shorelines and the middle and right ones are for finite delta shorelines. In which, the demarcation at $t^*=0.1$ indicates that sediment has reached the boundary while at $t^*=0.3$, the shoreline profile at the river mouth are affected by the boundary. As can be seen in the figure, time evolution of Thu Bon River delta has not reach the demarcation (red line for $t^*=0.1$). Therefore, the shoreline profile of Thu Bon River delta still can be treated as infinite. In the case of the experiment (Refaat, 1990), the Funatsu River delta and Ombrone River delta, they are finite delta shorelines since the time evolution of these river deltas has passed the demarcation.

In order to combine the data in different study areas into one diagram, the log-log plot is used in Figure 7.20. The log-log plot is useful in this case due to the extreme difference in the time scales of different studies.
Figure 7.20 Classification of river delta shorelines with demarcations at $t^*=0.1$

It is clear in Figure 7.20 that there is no influence of the boundary on the shoreline evolution in the Thu Bon River delta. Therefore, the shoreline in Thu Bon River delta can be considered as infinite shorelines. On the other hands, the shorelines in Ombrone River, and Funatsu River deltas can be considered as finite shorelines since all the dimensionless times in these deltas stand above the demarcation line of $t^*=0.1$. Similarly, the shorelines for the delta formed in the experiments are also considered as finite shorelines.

In order to make the classification more comprehensive, another diagram is plotted using the term “diffusion length” which is denoted by $\lambda$ as in Eq. (7.1) and Figure 7.21.

$$\lambda = 3.2\sqrt{\alpha t}$$  \hspace{1cm} (7.24)

The diffusion length is defined as a distance from the river mouth to a location where the shoreline advance is one percent of the shoreline position at the river mouth.
In Figure 7.21, the diffusion length is plotted versus the shoreline length with the implication that if the diffusion length is larger than the shoreline length, the shoreline will be finite and vice versa. From the plot of the diffusion length with respect to the elapsed time, it can be seen that in the early stages of the formation process, the sediment has not been transported to the boundary and the diffusion length is smaller than the shoreline length. After a sufficient time, the sediment has reached the boundary and the shorelines becomes finite as in the cases of Experiment (Refaat, 1900), Funatsu River, and Ombrone River deltas. In the case of Thu Bon River delta, after 500 years or at present, the sediment from the river has not reached the boundary which is located about 30 km from the river mouth. Therefore, the shorelines of Thu Bon River delta are infinite.

![Figure 7.21 Classification of river delta shorelines based on the diffusion length $\lambda$.](image)
7.7 Conclusions of this chapter

Formation and deformation of Thu Bon River, Ombrone River, and Funatsu River deltas have been studied using analytical solutions. The main conclusions of this chapter are as follows:

- The analytical solution provided by Larson et al. (1987) has been used to study the formation and deformation of the Thu Bon River delta shorelines. The analytical solution for infinite shorelines of river delta well represents the formation of the Thu Bon River delta. In the deformation process, although this analytical solution can predict the general trend of the shorelines, there are still differences between the calculated results and the measured data. The differences are caused by the complex coastal process at the river mouth such as welding of the sand spit and human intervention such as sand mining.

- By applying the analytical solution, a new method for estimating the diffusion coefficient has been introduced. This method is very useful since it does not require the direct calculation of wave conditions.

- A new method to estimate sediment supply from the river based on the shoreline orientations at the river mouth has been proposed.

- By applying the superposition characteristic, not only the deformation but also the recovery of river delta shorelines can be studied.

- A new analytical solution has been derived to study the formation and deformation of river delta with finite shorelines. Two demarcations were figured out to indicate whether the boundaries have an effect on the shoreline evolution or not.

- The new analytical solution has been applied to the Ombrone River and the Funatsu River deltas. Comparison with measured data shows that the new analytical solution is a useful tool for studying river delta with finite shorelines.

- Based on the demarcations represented by the dimensionless time $t^*$, the Thu Bon River delta shorelines are classified as infinite shorelines while the shorelines in the Ombrone River and the Funatsu River deltas are finite shorelines.

- Although the term diffusion length has been utilized for the classification of river delta shorelines, the criteria used to determine this term is highly affected by many factors such as sediment supply from the river, evolution time of the shoreline, etc. This problem should be considered in the future study.
CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

The formation and deformation of wave-dominated river delta coastlines have been investigated in this study based on image analysis and analytical approach through a series of river deltas with different scales in external forces and geometries. In which, the image analysis was used first to estimate characteristic quantities associated with each river delta. In the second step, the analytical solutions were used to calculate the formation and deformation of each river delta. The overall conclusions of this study are as follows:

- In the wave-dominated river deltas, erosion of the delta apex is not always caused by the reduction of sediment supply from the river. Asymmetric distribution of sediment supply from the river is also a reason for the erosion of beaches adjacent to the river mouth as evidenced by the asymmetric shoreline changes in the Thu Bon River delta.

- By applying the analytical solution, a new method for estimating the diffusion coefficient has been introduced. This method is very useful since it does not require the direct calculation of wave conditions.

- A new method to estimate sediment supply from the river based on the shoreline orientations at the river mouth has been proposed.

- A new analytical solution to study the formation and deformation of river delta coastlines with finite extents has been introduced. Two demarcations were figured out to indicate whether the boundaries have an effect on the shoreline evolution or not. These two demarcations are $t^*=0.1$ at the boundary and $t^*=0.3$ at the river mouth.

- Application of the new analytical solution to the formation of river deltas in the experiment of Refaat (1990) and in two real case studies of the Ombrone River delta and the Funatsu River delta has been made. The good agreement between the calculated results and the measured data proved that the new analytical solution can be used to study the formation and deformation of river delta with finite shorelines.
By superimposing the quantities of sand released from the river at different points of time, the deformation of river delta shorelines due to the reduction of sediment supply can be investigated. In addition, the recovery of river delta shorelines can also be studied if there is an increase of sediment supply. This approach is very useful in engineering application.

Classification of river delta based on their temporal and spatial scales has been made. Based on this classification, shorelines of the Thu Bon River delta are infinite while shorelines of the Ombrone River delta and the Funatsu River delta are finite.

8.2 Recommendations

Based on the results obtained in this study, some suggestions for the application of the results of this study as well as the necessary improvements in the upcoming study are as follows:

- The results obtained in this study are for wave-dominated river deltas as classified by Galloway (1975).

- The method for estimating sediment supply from rivers based on the shoreline orientations at the river mouth is very useful and can be applied easily to other study areas. It should be noted that this estimation accounts only for the sediment load deposited along the coastlines which control the morphologies of the coastlines.

- Superposition is very useful in studying different processes of river delta shorelines including deformation and recovery of the shorelines.

- Based on the demarcations where the boundary will take effect on the shoreline evolution and the classification of the delta shorelines, coastal structures can be built at a distance to the river mouth to change the infinite shorelines to the finite shorelines and the beach within this finite shoreline can be controlled. This can be done in engineering application to restore the beach from erosion.

- The term diffusion length has been utilized for the classification of river delta shorelines. However, the criteria used to determine this term is highly affected by many factors such as sediment supply from the river, evolution time of the shoreline, etc. This problem should be considered in the future study.

- Sediment supply from the river is assumed to be a constant value. However, this quantity is highly seasonal variation in reality. Therefore, this seasonal variation
of sediment supply from the river and its effect on the morphological changes of the delta shorelines with finite extents should be considered in the future.

- In this study, formation and deformation of the river deltas have been investigated in the light of modern remote sensing techniques and analytical solutions due to lack of field measurement data, especially the sediment yield from the river basins. Because sediment yield in the river catchment is one of the most important factors naturally affect the coastal morphology at the river mouth, the mobilization of sedimentation in the river basin should be studied for an integrated management between river basin and coastal areas. This idea is an important aspect not only in Vietnam but also in many river catchments around the world with inadequate monitoring of the rivers.
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