Changes in morphology on Sendai Coast and its problems after the 2011 tsunami

Hoang Cong Vo[1], Yuta Mitobe[2] and Hitoshi Tanaka[3]

ABSTRACT

The tsunami in March 2011 caused the significant changes on Sendai Coast. The erosion of sandy beach and the flushing of sand spit at the river mouth can be observed. After the tsunami, the shoreline on the right side of Nanakita River mouth started getting erosion. The erosion was propagating to the south and causing the completed closure of Nanakita River mouth. The changes of morphology and its problems has been identified base on the analyzing of aerial photography. The diffusion coefficient, which is an important parameter in numerical simulation of shoreline change, has been carried out from analytical solution of one-line model and measured data of erosion propagating of shoreline.

1. INTRODUCTION

A massive earthquake occurred in northeastern of Japan on March 11th, 2011. It triggered the powerful tsunami waves which battered Japan Coast and propagated around the Pacific Ocean. The coastal and riverine morphology in the northeast of Japan has been suffered the severe damages. Morphology changes of the coast in Miyagi Prefecture has been pointed out by Tanaka et al. (2012). In which, on Sendai Coast, the sandy beach erosion and breaching and the flushing of sand spit at river mouth can be observed. Soon after the tsunami, morphology of many places were getting on the restoration process, although that can be fast or slow depending on the different hydrologic regimes and available sediment supply (Tanaka et al., 2012). However, the shoreline on the right side of Nanakita River mouth, where the sand spit was flushed by the tsunami, still being eroding. The eroded area was expanding from the river mouth toward over the drainage of Minami Gamo wastewater treatment plant. The changes and its problems of morphology around a river mouth subsequently after the tsunami is important on the morphology recovery process of the entire area. In this study, the changes and evolution of shoreline around a river mouth after the tsunami will be investigated base on the analysis of aerial photography and applying of analytical solution of one-line model.

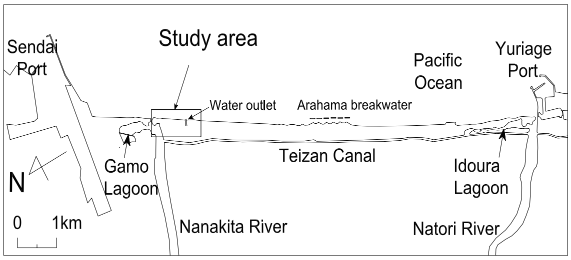


Fig. 1. Study area

2. STUDY AREA AND DATA COLLECTION

Sendai Coast, (Fig. 1), which is located between Sendai Port at North and Yuriage Port at South, is a sandy beach with approximately 12 km in length. This study mainly focuses on the beach of about 1000m on the right side of Nanakita River mouth which located about 2.5km south of Sendai Port. The length of Nanakita River is 45km, the basin area is 229.1 km^2 and the average river discharge is about $10m^3/s$. There is a jetty on the left side of river mouth, while on the right side, about 700m south from the river mouth there is a drainage which belongs to the Minami Gamo wastewater treatment plant of Sendai City. The longshore sediment transport in this area, which is from the south to the north, is completely blocked by the breakwaters located at Sendai Port and Yuriage Port.

Aerial photographs of this area have been taken frequently and immediately after the tsunami. There was a photo taking activity on March 6th, 2011, about one week before the tsunami. While, the first batch of photo taking after the tsunami was on June 8th, 2011. In order to get more detail on the subsequent response of morphology, aerial photographs, which taken on March 12th and May 26th, 2011 by Geospatial Information Authority of Japan (GSI) and aerial photographs taken on March 14th, 24th, 27th; April 6th; May 3rd by Google Earth, have been collected. The raw aerial photographs were rectified to World Geodetic System 1984 (WGS84). Shoreline position $y_s(x,t)$ were extracted by every 5m from Nanakita River mouth to the south on the baseline (x-axis in Fig. 2) oriented 212^0 clockwise from North. All the photographs

[1] Graduate Student,Department of Civil Engineering, Tohoku University, 6-6-06 Aoba, Sendai 980-8579, Japan
[2] Assistant Professor, Department of Civil Engineering, Tohoku University, 6-6-06 Aoba, Sendai 980-8579, Japan
[3] Professor, Department of Civil Engineering, Tohoku University, 6-6-06 Aoba, Sendai 980-8579, Japan

collecting from third parties haven't been corrected to the tidal level due to the lack information of exact time of taking.

3. RESULTS AND DISCUSSION

(1) Changes and recovery of the beach on the right side of Nanakita River mouth

Change of shoreline around Nanakita River mouth before the tsunami was pointed out by Pradjoko et al. (2010). A set of aerial photographs was utilized to show the trends of shoreline change. In long-term period, the shoreline change reflects the condition of longshore sediment transport which influenced by the river mouth. In short-term period, the shoreline subjects to seasonal change, moving advance or retreat in response to wave action. The shoreline on the right side of river mouth changes less dramatically than the left side. Overall, before the tsunami, the shoreline around Nanakita River mouth is reached the dynamic equilibrium stage. Fig. 2 is a series of aerial photographs showing the beach morphology before and after the tsunami as well as the propagation of erosion of on the right side of Nanakita River mouth until September 7th, 2011. Due to the low river discharge and the long-shore sediment transport dominant from right side to left side, before the tsunami, a sand spit intermittently developed on the right side of the river mouth (Fig. 2(a)). This sand spit was flushed by the tsunami wave which was reported about 14m height in this area by Mori et al. (2011). The tsunami also caused serious erosion of the sandy beach on the right side of the river mouth (Fig. 2(b)). After the tsunami, in response to the new condition, the beach started getting erosion. At the beginning, the erosion was only occurring on the beach adjacent to river mouth (Fig. 2(c) and 2(d)). However, about 3 months from the tsunami, the erosion had been propagating along the beach and reaching the drainage of Minami Gamo wastewater treatment plant. At the same time with the erosion of shoreline, a sand spit was also formation and intrusion into the river mouth (Fig. 2(d) and 2(e)). Fig. 2(f) shows the shoreline on July 6th, 2011, the erosion gets more serious and a complex sand spit has been formed. The phenomenon of sand spit intrusion into river mouth and its mechanism have been reported by Tanaka et al. (2013). The sediment source from the erosion of the beach on the right side of Nanakita River mouth has caused the completed closure of river mouth which can be seen on Fig. 2(g).

Figure 3 shows the temporal variation of shoreline on the right side of Nanakita River mouth. Shoreline position is extracted at cross sections within every 50m or 100m along the beach, coordinate system of these cross sections can be seen in Fig. 2(b). The shoreline in vicinity to river mouth (x=50m, x=100m) has larger amplitude of erosion than the shoreline far away from the river mouth. While the shoreline in vicinity to river mouth was moving retreat immediately after the tsunami and started moving advance after 117 days (July 6th) then the shoreline far away from river mouth was just getting serious retreat after 53 days (May 3rd) and still on the retreat after the tsunami 180 days (September 7th).

The studying of erosion of shoreline on the right side of Nanakita River mouth and its propagating to the south has shown this is an interesting phenomenon which indicates the subsequent response of shoreline in order to get the new equilibrium state after the significant changes induced by the tsunami. However, this is just a small area of Sendai Coast. Though, there is a need of further study on the subsequent response of shoreline for entire the Coast where there is the present of detached breakwater, lagoons, etc., which could have significant influence on the response of shoreline.

(2) The interruption of wastewater drainage on the propagation of erosion

The drainage of Minami Gamo wastewater treatment plant is almost perpendicular to the shoreline. The last section of this drainage is an open rectangular concrete channel with about 80m in length. The elevation of the top of drainage is a bit higher than the elevation of beach ground. Fig. 4(a), 4(b) and 4(c) show that, before or in the short time after the tsunami, the drainage has almost no or unclear interruption on the variation of the adjacent shoreline. However, about 3 months after the tsunami, when the erosion reaching the drainage, the interruption getting clearer (Fig. 4(d)). After the serious retreat of shoreline, it is believed that the drainage not only has the interruption on the propagation of erosion, but also on the transport of longshore sediment because it is now semi-submerged in the sea. The most significant interruption of the drainage on the propagation of erosion can be seen in Fig. 4(e) which was taken on July 6th, 2011. There is a big gap between shoreline position on the left side and on the right side. After that about two months, the erosion point has been getting over the drainage and moving to the south (Fig. 4(f)).

(a) March 6th, 2011

(b) March 12th, 2011 (GSI)

(c) March 27th, 2011

(d) May 3rd, 2011

(e) June 8th, 2011

(f) July 6th, 2011

(g) September 7th, 2011

Fig. 2. Morphological changes on the right side of Nanakita River mouth before and after the 2011 tsunami (the black line is shoreline position on March 6th, 2011)

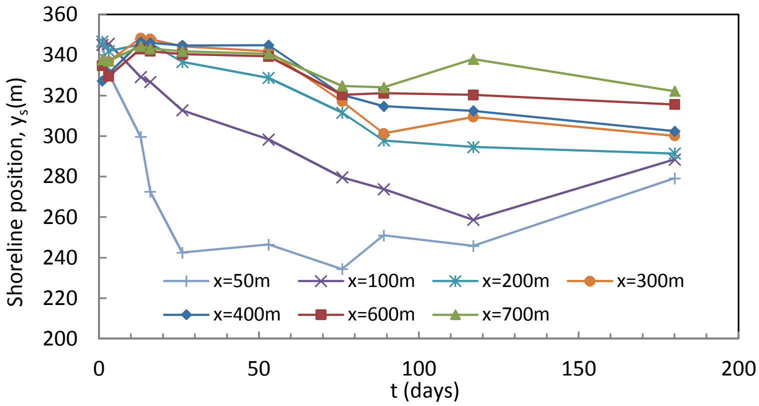
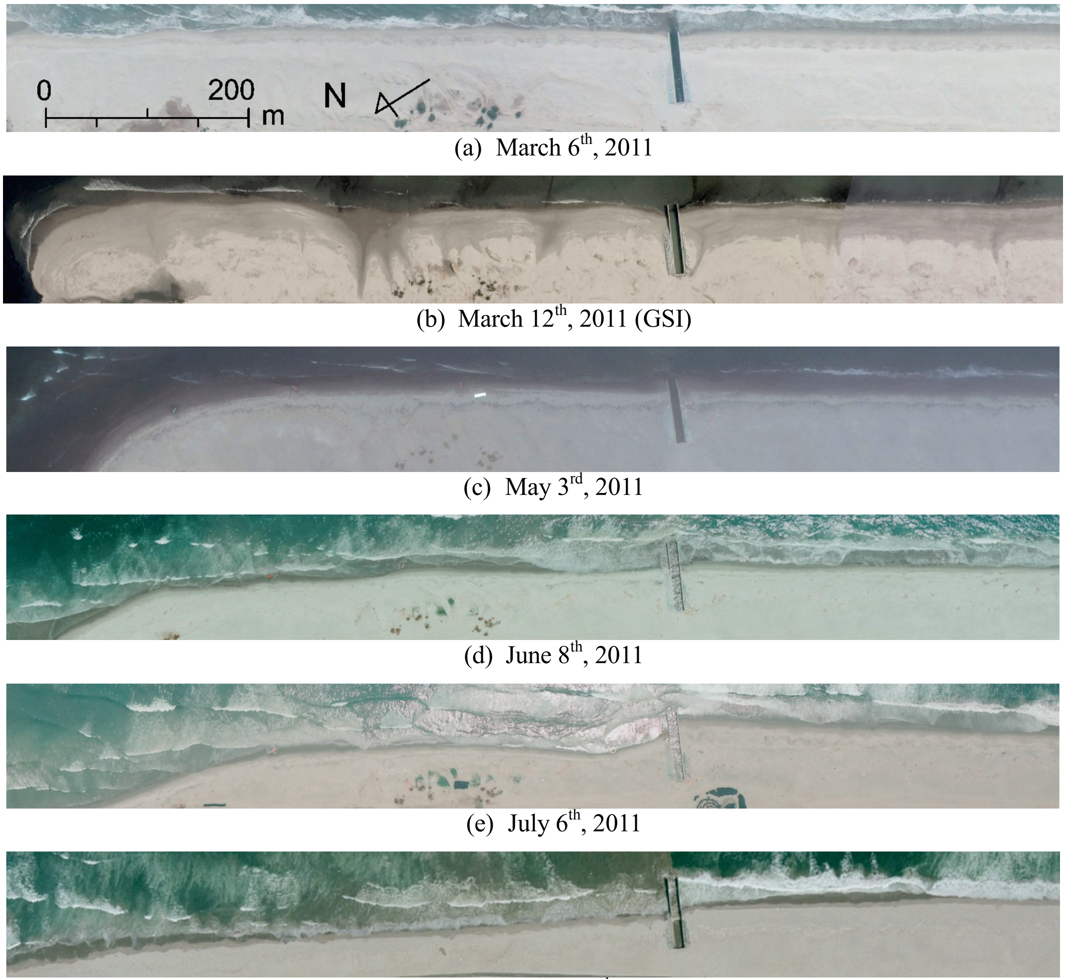


Fig. 3. Temporal variation of shoreline



(a) March 6th, 2011

(b) March 12th, 2011 (GSI)

(c) May 3rd, 2011

(d) June 8th, 2011

(e) July 6th, 2011

(f) September 7th, 2011

Fig.4. Interruption of wastewater drainage on the propagation of erosion

(3) Evaluation of diffusion coefficient, ε

The one-line model, which was introduced in 1956 by Pelnard-Considere, and further developed by many other researchers, has been proven as a useful engineering technique for the simulation of long-term shoreline change. Eq. (1) is the governing equation of shoreline change of one-line model which is derived base on the principle of mass conservation together with the assumption that the amplitude of the longshore sand transport rate and the incident breaking wave angle are constant (independent of *x* and *t*).

$$\frac{\partial y_s}{\partial t} = \varepsilon \frac{\partial^2 y_s}{\partial x^2} \quad (1)$$

In which, y_s is the shoreline position; *x* is the space coordinate along the axis parallel to the shoreline; *t* is the time; and ε is the diffusion coefficient expressing the time scale of shoreline change following wave action and commonly evaluated by following equation.

$$\varepsilon = \frac{2K\left(H^2 c_g\right)_B}{D} \quad (2)$$

In Eq. (2), *H* is the wave height; c_g is the wave group velocity; *B* denotes quantity at the breaking point; *K*, constant parameter, is generally calibrated using measured raw data that include shoreline evolution caused by longshore sediment transport and cross-shore sediment movement. It has been evaluated to be 0.05 by Tanaka et al. (1996) by applying one-line model to shoreline change adjacent to Nanakita River mouth; *D*, depth of closure for a given or characteristic time interval is the most landward depth seaward of which there is no significant change in bottom elevation and no significant net sediment transport between the nearshore and the offshore (Kraus et al., 1998). The value of depth of closure in study area is reported about 8m corresponding to high frequent wave in a year by Uda et al. (1997); Both *K* and *D* are uncertainty, variation from area to area and there hasn't been research to evaluate these parameters in the study area after the tsunami yet. In addition, the wave data is not available after the tsunami due to the destruction of wave gauge. Hence, to evaluate the diffusion coefficient from Eq. (2) now could not be done, a feasible approach else need to be employed. This study proposes a new approach to carry out the diffusion coefficient from the analytical solution of one-line model and measured data of erosion distance on the right side of Nanakita River mouth.

Equation (3) is the analytical solution of one-line model for expressing the shoreline position variation in the case of semi-infinite beach fill (Fig. 5), given by Walton and Chiu (1979).

$$y_s(x,t) = \frac{1}{2}Y_0\left[1 + erf\left(\frac{x}{2\sqrt{\varepsilon t}}\right)\right] \text{ with } \quad y_s(x,0) = \begin{cases} Y_0 & x > 0 \\ 0 & x \le 0 \end{cases} \quad (3)$$

In which, Y_0 is the cross-shore distance of the beach nourishment region from the initial shoreline; *erf* is an error function.

From Eq. (3), the relationship between x_e, the distance along the beach from the point x=0 to the point when shoreline position is asymptotic $0.99Y_0$ and *t*, the corresponding time is derived as following.

$$x_e = 3.30\sqrt{\varepsilon t} \quad (4)$$

Figure 6 shows the erosion distance x_e(m) of shoreline on the right side of Nanakita River mouth which measured from aerial photograph and its corresponding time *t*(days) since the tsunami. Erosion distance is distance along the x axis from x=0 to the point when shoreline, which is on the wet/dry line, to reach the initial shoreline. Initial shoreline (Fig. 6) representing the shoreline right after the tsunami, in this study, the photograph on March 12th is taken for the determination of initial shoreline. Fig. 7 shows the relationship between x_e and *t* in a log-log scale graph. The trend line has the slope about of 0.5 which indicates that the erosion distance is a function of square root of time. The relationship between erosion distance and its corresponding time deriving on the same format with Eq. (4) is as following.

$$x_e = 58.8\sqrt{t} \quad (5)$$

From Eq.(5), the value of ε is obtained, 317m^2/day (or 13.2m^2/h). This value is close to the value carried out by Hirao et al. (2012), 13m^2/h for Akaiko area which is located 7.5km south of Natori River mouth. That value was computed based on the constant wave height and period from wave climate statistics and other parameters from the previous studies (before the tsunami) on that area.

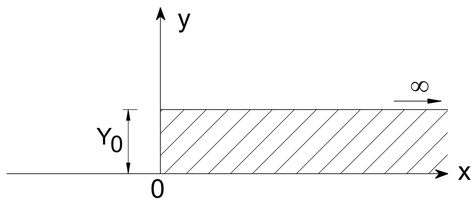


Fig. 5. Semi-infinite beach fill (t=0)

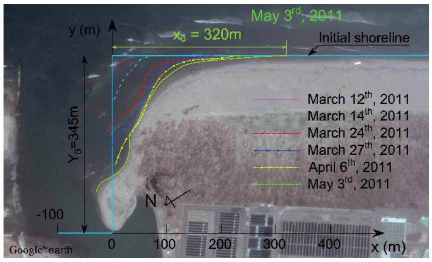


Fig. 6. Measured erosion distance

On the comparing, these two areas have similar condition and characteristics, hence, it can be said that the value of diffusion coefficient carried by this study is reliable.

4. CONCLUTIONS

This study has investigated the changes and evolution of morphology around river mouth on Sendai Coast subsequently after the tsunami. The diffusion coefficient has been carried out from the analytical solution of one-line model and measured erosion distance. And, this value could be used for the numerical simulation of shoreline change in the future. It also pointed out that, there is a need of further study on the response after the tsunami of shoreline entire the Sendai Coast.

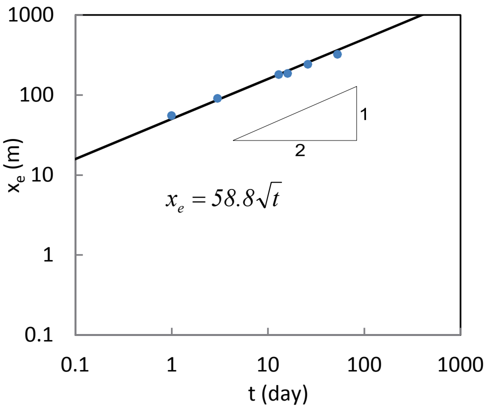


Fig. 7. Measured erosion distance

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