ANALYSIS OF SHORELINE BEHAVIOR ON SENDAI COAST BEFORE AND AFTER THE 2011 TSUNAMI

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

The earthquake and tsunami in 2011 caused serious damages on Sendai Coast, Miyagi Prefecture, Japan. Shoreline change characteristics for periods both before and after the tsunami are extracted from processing of aerial photographs together with conducting of Empirical Orthogonal Function (EOF) analysis. The evolution of shoreline at the Nanakita River mouth and the Natori River mouth areas both before and after the tsunami has been discussed. Shoreline change rates at both the river mouths reveal the recovery of morphology but in different aspect, the fast recovery at the Nanakita River mouth while very slow recovery at the Natori River mouth. The results of EOF analysis show that the dominant components of shoreline changes before and after the tsunami are different each other. The dominant component after the tsunami at the two river mouths is also different. The total contribution of the first and the second component is very high in the total contribution of all the components. The contribution of the first component after the tsunami is larger than the first component before the tsunami. The results also show the significant effect of the river mouth on the recovery of the morphology around.

Keywords: tsunami; shoreline change; EOF analysis; recovery;

INTRODUCTION

Background

A 9.0-magnitude earthquake hit off the east coast of Japan on March 11th, 2011. It triggered the powerful tsunami waves which battered Japanese Coast and propagated around the Pacific Ocean. In the coastal area along northeast part of Japan, this double disaster caused the widespread and severe damages to the infrastructure and significant changes on the coastal morphology. Before this occasion, the tsunami, which caused the close scale of damage, is the 2004 Indian Ocean tsunami. The significant changes and recovery process of the coastal and estuarine morphology of affected areas in Indonesia, Thailand and Sri Lanka were the topics of studies such as Liew et al. (2010) and Choowong et al. (2009). These studies investigate the damages and the recovery of coastal area after the tsunami based on the average resolution satellite images which were taken in every one year or longer. After the 2011 tsunami, there have been studies on the damages and recovery process of morphology in Sendai Bay area such as Tanaka et al. (2012), Tappin et al. (2012) and Udo et al. (2012). According to these studies, the severe damages and subsequent recovery of morphology on Sendai Coast have been reported. On Sendai Coast, various kinds of damages were reported by Tanaka et al. (2012). The typical damages on this coast are the erosion of sandy beach, the disappearance of sand barriers in front the Nanakita River mouth and the Natori River mouth and the flushing of sand spits in front of these river mouths. Moreover, that study also investigated the subsequent recovery of morphology of the two river mouths mentioned above. After the tsunami, the recovery process of morphology at these river mouths took place in different ways; the quick recovery at the Nanakita River mouth and the slow recovery at the Natori River mouth can be observed. The evolution of morphology is also much different between before and after the tsunami.

The recovery of morphology on Sendai Coast, especially at the two river mouth areas is very important for the coastal management. As mentioned above, only the subsequent recovery has been investigated hence it is needed to be study further in longer time period. Moreover, the understanding of the recovery process will be very useful for the preparation for similar disasters in future.

This study investigates the recovery of morphology and its behavior at the Nanakita River mouth and the Natori River mouth from frequent aerial photography together with conducting Empirical Orthogonal Function (EOF) analysis. The evolution of morphology before the tsunami at these two areas is also investigated to reveal the aspects of morphology recovery before and after the tsunami.

Study Area

This study focuses on the Nanakita River mouth (Area 1A on the left side, Area 1B on the right side in Figure 1) and the Natori River mouth (Area 2) on Sendai Coast which is located in the eastern part of Sendai City, Miyagi Prefecture, Japan (Figure 1). Sendai Coast is approximately 12km in length stretching from Sendai Port at north to Yuriage Port at south. There is a canal named Teizan Canal connecting the Nanakita River mouth and the Natori River mouth. The direction of longshore sediment transport on this coast is from south to north.

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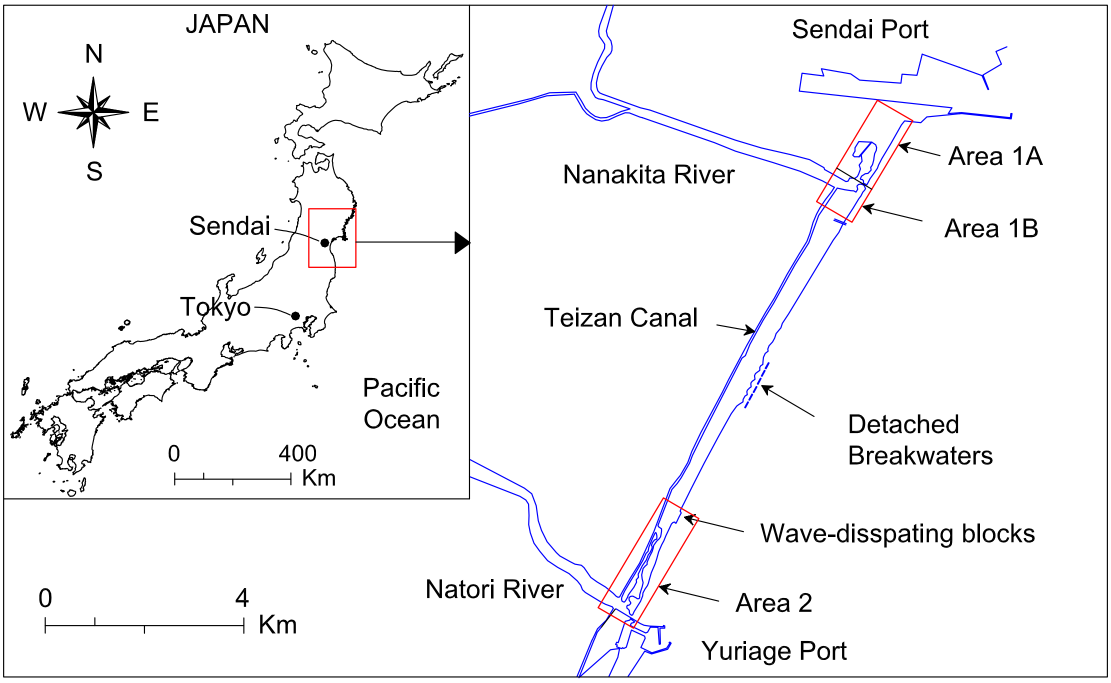


Figure 1. Location map of study area

The Nanakita River mouth is located about 1.8km south of Sendai Port. The length of this river is 45km, the basin area is 229.1 km^2 and the average river discharge is about $10m^3/s$. Total sediment supply from this river is about $2000m^3$/year. There is a jetty on the left side of the river mouth. Gamo Lagoon is also located adjacently on this side.

Natori River mouth is located next to the Yuriage Port. The length of this river is about 55km and catchment area is about $939km^2$. Total sediment supply from this river is about $10000m^3$/year. There are two jetties at the river mouth area and Idoura Lagoon adjacent on the left side.

Data Collection and Analysis

Aerial photographs of the study area have been taken by airplane regularly in every one or two month since 1990 until now. This study utilizes the aerial photographs taken from March, 2009 until March, 2011 for the period before the tsunami and from June, 2011 until February 2014 for the period after the tsunami. In order to show more details on the damage of morphology induced by the tsunami, aerial photographs, which were taken by Geospatial Information Authority of Japan (GSI) on March 12^{th}, 2011 (1 day after the tsunami), have been utilized.

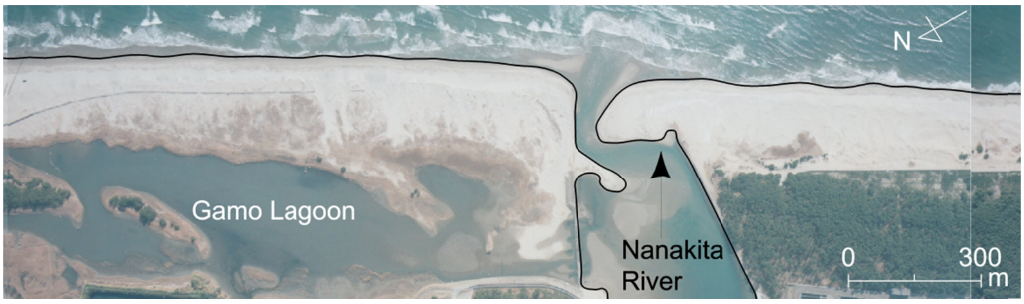
All of raw aerial photographs are geo-referenced to the World Geodetic System (WGS-84). The line, which is 210^0 clockwise from the north, was taken as the baseline for shoreline position measurement. Shoreline positions are extracted in every 20m in longshore direction from aerial photographs. In order to eliminate the effect of tide, detected shoreline positions have been corrected with astronomical tide level in Sendai Port which was calculated by Japan Meteorological Agency and average beach slope of 0.11.

The technic of shoreline position detection and digitization and uncertainty of assessment have been discussed by Pradjoko and Tanaka (2012).

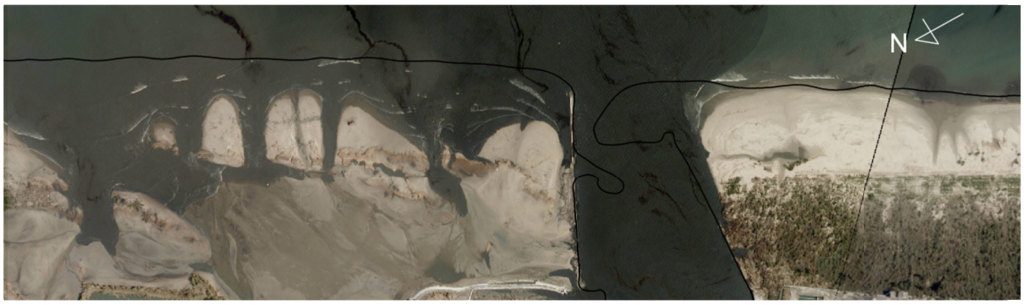
RESULTS AND DISCUSSION

Morphological change at the Nanakita River mouth

According to Pradjoko and Tanaka (2012), before the tsunami shoreline around the Nanakita River mouth area was in the dynamic equilibrium. The left side had more fluctuation than the right side. The morphological changes and subsequent recovery after the tsunami in this area were reported by Tanaka et al. (2012). In that study, the recovery of morphology in longer time period is introduced. However, in order to make it more clear, then some key points of the significant changes and subsequent recovery process are also reintroduced. Figure 2 shows the morphological changes around the Nanakita River mouth for the both periods before and after the tsunami. As can be recognized from Figure 2(a) and Figure 2(b), the tsunami caused the severe erosion of the sandy beach, the flushing of sand spit located



(a) March 6th, 2011



(b) March 12th, 2011 (GSI)

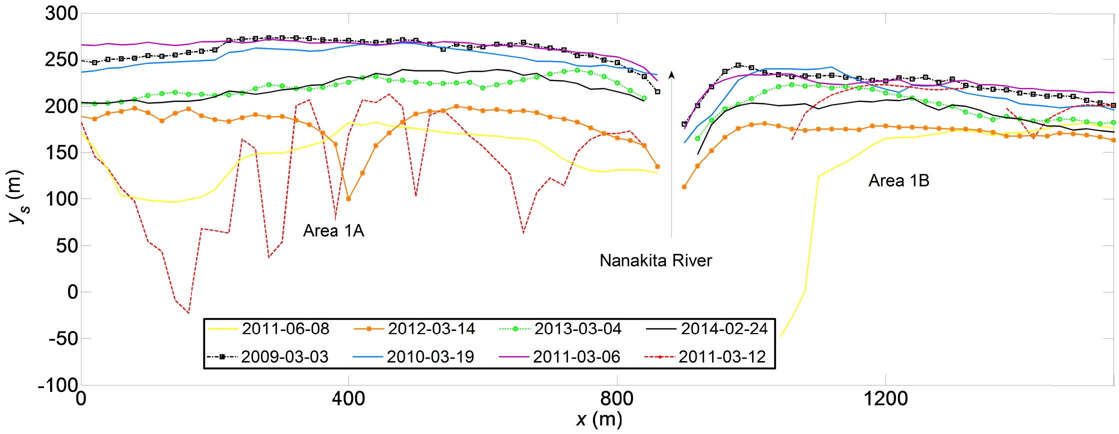
(c) June 8th, 2011

(d) September 7th, 2011

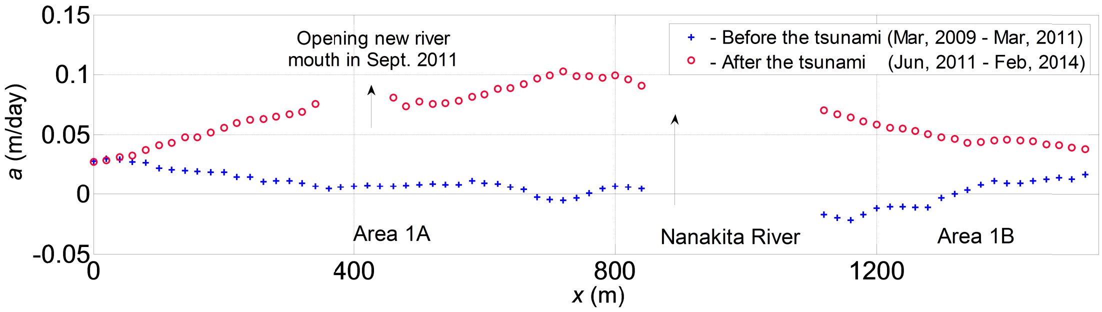
(e) March 14th, 2012

Figure 2. Morphological changes at the Nanakita River mouth (to be continued in the next page) (Black solid line is the shoreline position on March 6th, 2011)

(f) February 24th, 2014



(g) Detected shoreline positions around the Nanakita River mouth



(h) Shoreline change rate around the Nanakita River mouth

Figure 2. Morphological changes around the Nanakita River mouth (continued)

in front of the river mouth and the disappearance of the sand bar in front of the Gamo Lagoon. Due to these damages, the Nanakita River mouth has concave landform after the tsunami. This landform plays the role as the sink of sediment and causes the erosion of the adjacent areas. The severe erosion occurred subsequently and on both sides of the river mouth (Figure 2(b), Figure 2(c)). Adityawan et al. (2013) has discussed clearly the erosion mechanism of the shoreline on the left side. The recovery process caused the sediment movement from the north to the south filling into the concave shape. This direction of sediment movement is contrary with the normal direction of longshore sediment transport in this area, which is from the south to the north. The erosion propagation of the beach on the right side was investigated by Hoang et al. (2014). During the subsequent recovery process, sand spit intrusion into the river mouth can be observed (Figure 2(c)). The depth of river mouth is deeper than the depth of closure induced by the tsunami and return flow is the reason of this intrusion (Tanaka et al., 2013). Figure 2(d) shows the completed closure of the Nanakita River entrance in September, 2011. The mechanism of this closure has been discussed by Tanaka et al. (2012). The photography taken in February, 2014 [Figure 2(f)] shows that shoreline has not reached the position before the tsunami. Detected shoreline positions extracted from some selected photographs are presented in Figure 2(g). The tsunami caused the large amount of retreat of shoreline. The subsequent recovery took place. The recovery process at this area is quite fast. However, until February, 2014, shoreline still remains 50m to 80m to reach the position before the tsunami.

The average change rate of shoreline position on every transections are obtained by using the simple linear approximation from the relationship $y_s=at+b$ (*t* is time; *a* and *b* are coefficients). For the period before the tsunami, the average shoreline change rate *a*(m/day) is estimated based on the set of shoreline data from March, 2009 to March 6th, 2011, while the set of shoreline data from June, 2011 to February, 2014 is used for the period after the tsunami. The shoreline change rates of the shoreline on both sides of the Nanakita River mouth before and after the tsunami are shown in Figure 2(h). Before the tsunami, change rate in Area 1A is positive except a small portion is negative with very small value of change rate. Shoreline change rate in Aera 1B is negative on the part adjacent to the river mouth while the remaining part is positive. The average value of shoreline change rates in Area 1A and Area 1B are 0.1 (m/year) and 1.3(m/year), respectively. Shoreline change rates after the tsunami on both sides of the Nanakita River mouth are positive. The value of shoreline change rate on both sides after the tsunami is much bigger than the one before the tsunami. The average value of shoreline change rates in Area 1A and Area 1B are 28.6m/year and 16.7m/year, respectively.

Morphological Change at the Natori River Mouth

Figure 3 shows the morphological changes at the Natori River mouth. It is similar to the case of the Nanakita River mouth, tsunami also caused severe damages at this river mouth. Sandy beach erosion, flushing of sand spit and disappearance of sand barrier also can be observed (Figure 3(a), Figure 3(b)). However, the recovery of the morphology in this area is in different aspect compared to the recovery at the Nanakita River mouth. Due to the interruption on longshore sediment transport from the south of the breakwater at Yuriage Port and the retained sand of wave-dissipating blocks on the left, then the recovery is very slow (Hoang et al. 2014) (Figure 3(c), Figure 3(d)). During the recovery process, the sand spit intrusion into the river mouth area also can be observed (Figure 3(e)). Figure 3(f) shows the morphology of this river mouth in February, 2014. Shoreline has not reached the position before the tsunami; a big gap still remains. The evolution of shoreline at this river mouth area is revealed more details from detected shoreline positions extracted from aerial photographs and presented in Figure 3(g). It clearly shows that, a large retreat still remains behind the position of shoreline before the tsunami. The value of shoreline change rate for both periods before and after the tsunami is also computed for this area. Before the tsunami, change rate of shoreline far away the river mouth is almost stable. While the part, which is adjacent to the river mouth, has very large value of shoreline change rate. This can be related to the effect of river mouth and the developing of the sand spit in front of this river mouth. The average value of shoreline change rate of this area before the tsunami is 2.8m/year. The value of shoreline change rate is different in the period after the tsunami, the part of shoreline which is far away from the river mouth, has large positive value of change rate, while the part, which is adjacent to the river mouth, has negative value of change rate. This could be related to the sand spit intrusion into the river mouth. The average value of shoreline change rate of this area after the tsunami is 10m/year. This value is much lower than the average change rate at the Nanakita River mouth.

(a) March 6th, 2011

Figure 3. Morphological changes at the Natori River mouth (to be continued in the next page)

(b) March 12th, 2011 (GSI)

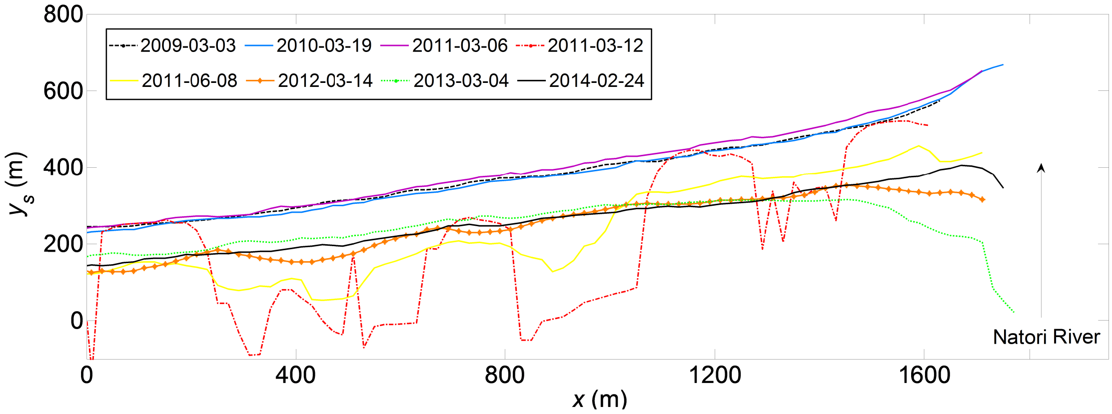
(c) June 8th, 2011

(d) March 14th, 2012

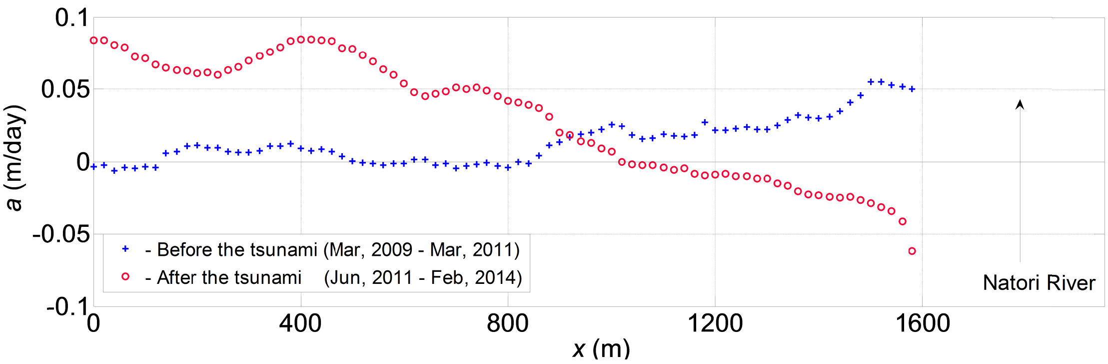
(e) March 4th, 2013

Figure 3. Morphological changes at the Natori River mouth (to be continued in the next page) (Black solid line is the shoreline position on March 6th, 2011)

(f) February 24th, 2014



(g) Detected shoreline positions around the Natori River mouth



(h) Shoreline change rate around the Natori River mouth

Figure 3. Morphological changes around the Natori River mouth (continued)

Empirical Orthogonal Function (EOF) Analysis

Empirical Orthogonal Function (EOF) analysis is the method used to extract the dominant patterns from data sets. In coastal morphology, it can extract the significant components of shoreline variability from data sets. It has been applied widely in coastal morphology to study either cross-shore or longshore variability of shoreline (Miller and Dean, 2007b; Miller and Dean, 2007a; Kang and Tanaka, 2006; Winant et al., 1975). In the study area, this technique has been applied by Pradjoko and Tanaka (2012). That studied the behavior of shoreline around the Nanakita River mouth based on data sets of aerial photographs taken from 1990 to 2010.

In EOF analysis, the separation of variables approach is used to isolate the temporal and spatial dependence of shoreline data. Hence, it can be represented by a series of linear combination of corresponding function of time and space, respectively.

$$y(x,t) = \sum_{n=1}^{\infty} e_n(x) c_n(t) \qquad (1)$$

where $y(x,t) = y_s(x,t) - \bar{y}(x)$, $y_s(x,t)$ is the distance from baseline to shoreline, $\bar{y}(x)$ is the mean shoreline position, $c_n(t)$ and $e_n(x)$ are the temporal and spatial eigenfunctions, respectively. Due to the severe erosion, just after the tsunami, shoreline at many places on Sendai Coast was discontinuous (Figure 2(b) and Figure 3(b)). Hence, the shoreline on June 8th, 2011, which almost recovered to the continuous status, was taken as the first shoreline data input for EOF analysis. Moreover, in order to obtain the characteristics of the overall recovery process of shoreline on entire of the coast, about 200m of shoreline on the right side of the Nanakita River mouth and about 200m of shoreline on the left side of the Natori River mouth, which involved into the strong fluctuation regarding to the recovery at breaching points or sand spit intrusion into the river mouth, etc., were not included in the EOF analysis.

EOF analysis of the Nanakita River mouth

Before the tsunami (Area 1)

Figure 4 shows the spatial eigenfunctions of the first two components at the Nanakita River mouth (Area 1A and Area 1B) both the periods before and after the tsunami. The spatial eigenfunctions of the first component on both areas before the tsunami are almost constant in the longshore direction (Figure 4). The temporal eigenfunctions of the first component on both areas, which are shown in Figure 5, fluctuate up and down around 0. Moreover, the combination of the first temporal and the spatial eigenfunctions, which is presented in Figure 6(a), has same trend of variation on both sides. From the above reasons, it can be said that, the first component of shoreline variability on both areas around the Nanakita River mouth is related to the cross-shore movement. The contribution of this component in Area 1A and Area 1B are 68% and 53%, respectively.

The value of spatial eigenfunctions of the second component on both areas have the opposite sign (+,-) on the close and far side of the river mouth (Figure 4). The value of temporal eigenfunction of these areas is close in the period from 740days to 430days before the tsunami. After that, temporal eigenfunction in Area 1A fluctuates stronger than in Area 1B. The combination of the temporal

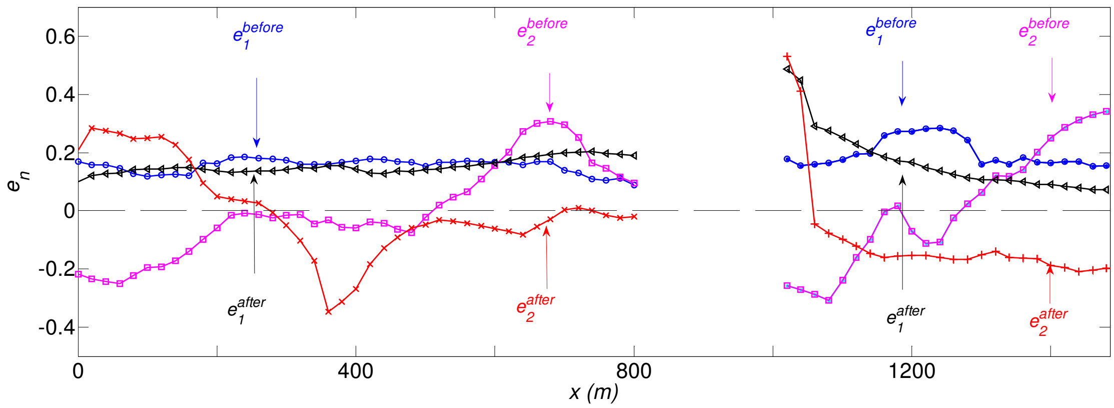


Figure 4. Spatial eigenfunctions of the first two components at the Nanakita River mouth both before and after the tsunami

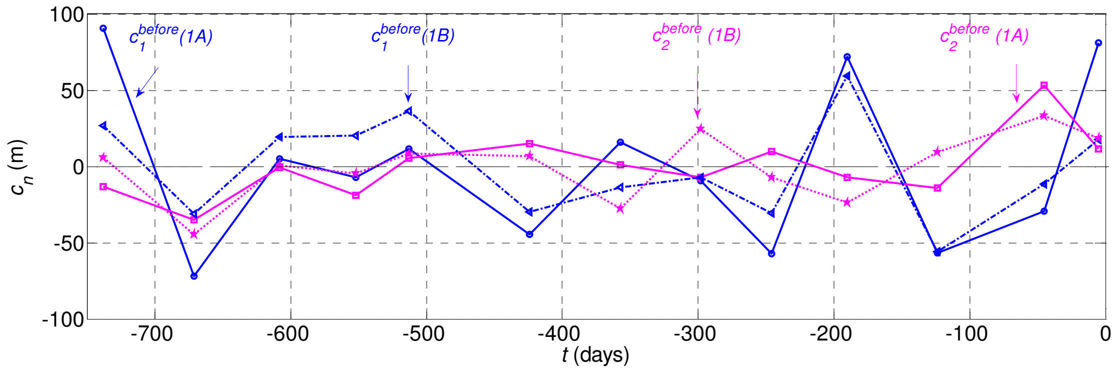
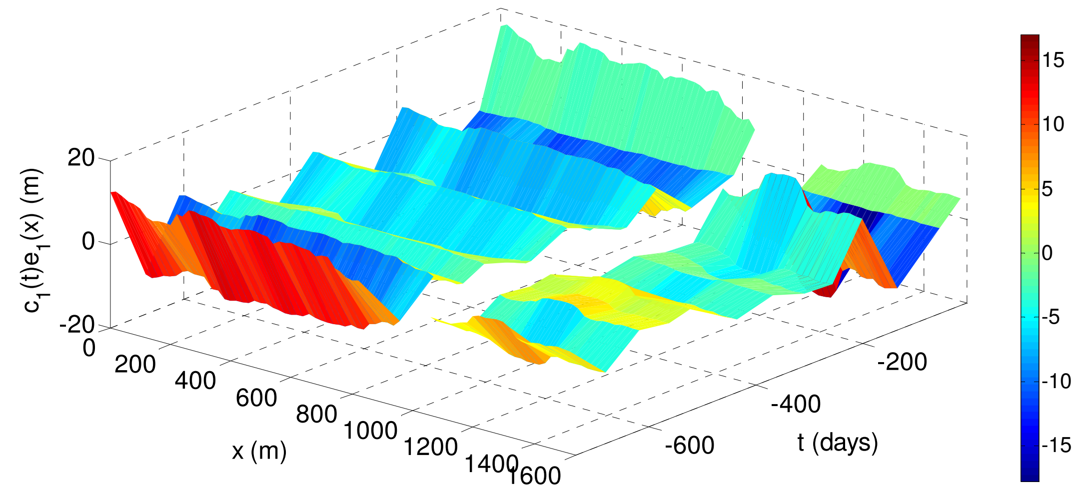
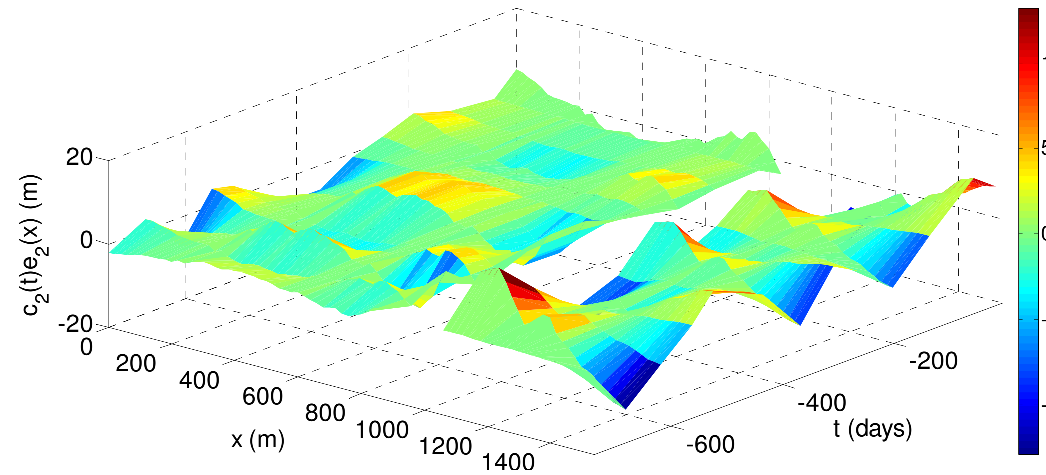


Figure 5. Temporal eigenfunctions of the first two components at the Nanakita River mouth before the tsunami



(a) First component variability



(b) Second component variability

Figure 6. Combination of temporal eigenfunction and spatial eigenfunction of the Nanakita River mouth before the tsunami

eigenfunction and spatial eigenfunction show that shoreline has small amplitude of variation. Hence, the second component can be related to the longshore sediment transport and reflects the effect of river mouth. The contribution of this component in Area 1A and Area 1B are 15% and 30%, respectively. The total contribution of the first and the second component on each side is higher than 80%, so this study analyzes the dominant component up to the second component only.

After the tsunami (Area 1)

The spatial eigenfunction of the first component of Area 1A after the tsunami is almost constant (Figure 4). On the other hand, the first component of Area 1B has higher value near the river mouth and is gradually decreasing to right side. Value of temporal eigenfunctions of the first component on both areas are increasing after the tsunami up to the time of about 670days after the tsunami. After that, they are almost constant (Figure 7). The tendency of the temporal eigenfunctions of the first component of two areas is similar. The value of the combination of the temporal eigenfunction and spatial eigenfunction is increasing gradually on both sides. Hence, the first component of on Area 1A related to the cross-shoreline movement or in other word is the recovery process of shoreline where severely damaged by the tsunami. While in Area 1B, it relates to longshore sediment transport and recovery process is strongly affected by the river mouth. The contribution of the first component of Area 1A and Area 1B are 86% and 83%, respectively. These contribution values are much higher than the contribution values of the first component before the tsunami.

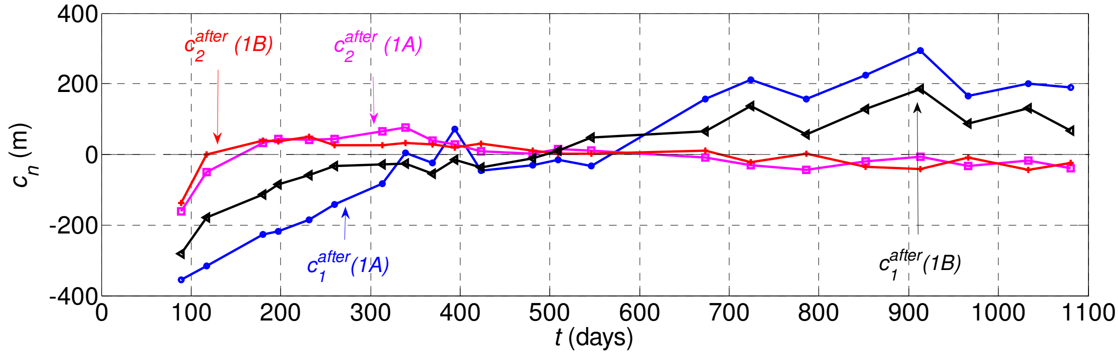
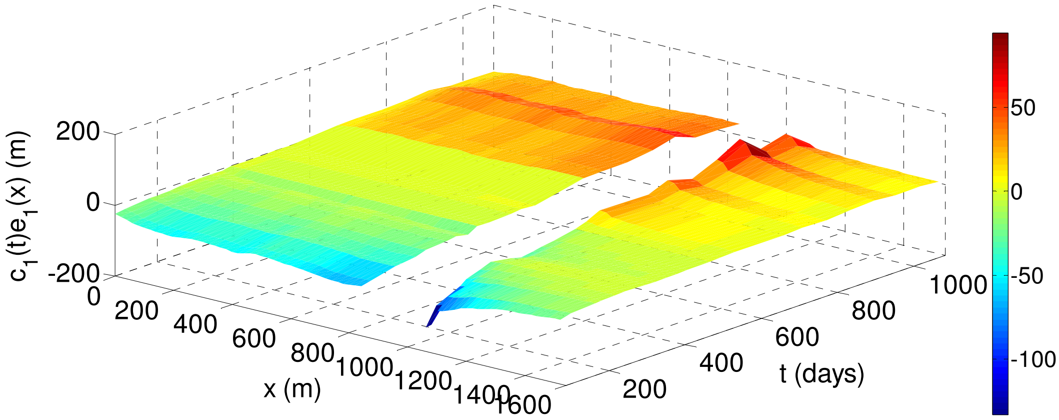
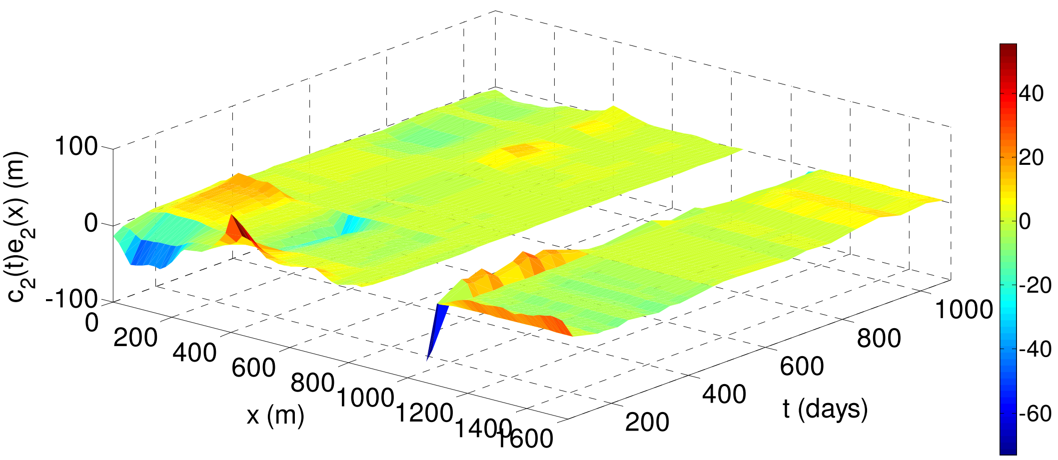


Figure 7. Temporal eigenfunctions of the first two components at the Nanakita River mouth after the tsunami



(a) First component variability



(b) Second component variability

Figure 8. Combination of temporal eigenfunction and spatial eigenfunction of the Nanakita River mouth after the tsunami

The value of spatial eigenfunction of the second component in Area 1A is very high value at the left end of the area; after that it decreases up to the point x of about 350m (Figure 4); after that, it increases and get stable around 0. The area on most left and the area in the middle are corresponding to the place of severe erosion and the place of opening new river mouth after the completed closure of the Nanakita River entrance in September, 2011, respectively. In Area 1B, the spatial eigenfunction of the second component has high value at the area adjacent to the river mouth, and decreasing after that (Figure 4). The temporal eigenfunctions of the second component on both areas are increasing the early stage, after that keep constant around the 0 (Figure 7). In Area 1A, the value of combination of temporal eigenfunction and spatial eigenfunction is low on the most left area and is high at the place of new river mouth opening and near the river mouth. In Area 1B, this value is high in the area adjacent to the river mouth where the shoreline was strongly evolved regarding to the sand spit intrusion into the river mouth and the erosion propagation to the south. In addition, these values are high in the early stage of the recovery process. Hence, it can be said that, the second component after the tsunami is related to the recovery of morphology in the early state at places where the morphology was severely damaged induced by the tsunami. The contribution of the second component in Area 1A and Area 1B are 13% and 7.3%.

EOF analysis of the Natori River mouth

Before the tsunami (Area 2)

The value of spatial eigenfunction of the first component at Area 2 before the tsunami is almost constant in the longshore direction (Figure 9). While the temporal eigenfunction fluctuates up and down around 0. The combination of the temporal eigenfunction and spatial eigenfunction also shows the fluctuation up and down of the shoreline. Hence, the first component at Area 2 is similar to the first component at Area 1. It relates to the cross-shore movement. The contribution of this component is 66%. The first dominant component in this area is same with the one in Area 1A and Area 1B. The contribution of the first component is almost same between Area 1A, Area 1B and Area 2.

The value of spatial eigenfunction of the second component is almost constant in the area far from the river mouth (Figure 9). It increases from the middle area to the river mouth. The value of temporal eigenfunction fluctuates up and down and also almost opposite with the first component. The combination of temporal eigenfunction and spatial eigenfunction show the shoreline far away from the river mouth fluctuates up and down. However at the area close to the river mouth, the evolution of shoreline is different. In this case, the second component can be related to the cross-shore movement with strongly effect of the river mouth, jetty or breakwater. Its contribution is about 18%.

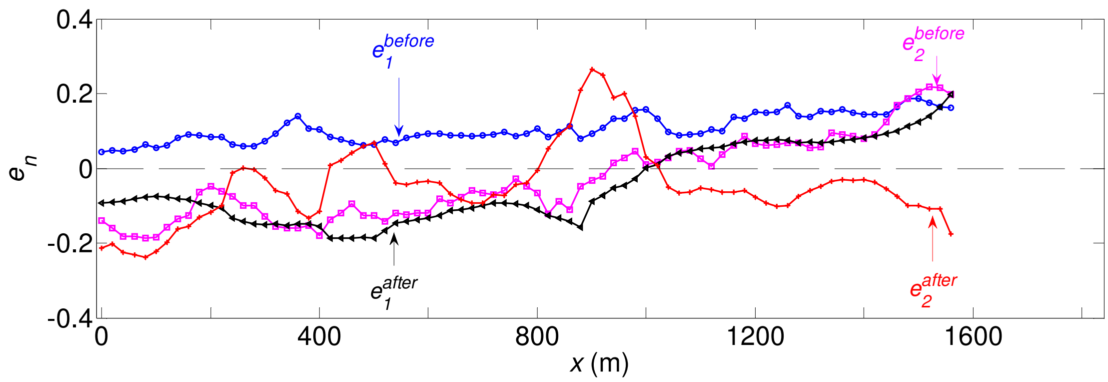


Figure 9. Spatial eigenfunctions of the first two components at the Natori River mouth both before and after the tsunami

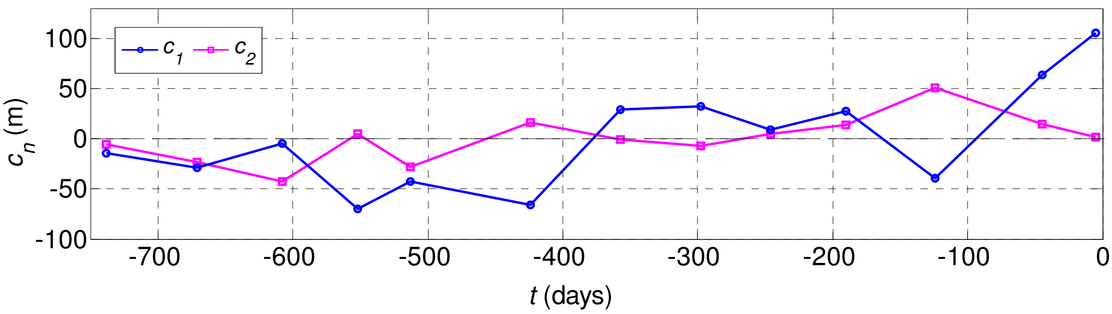
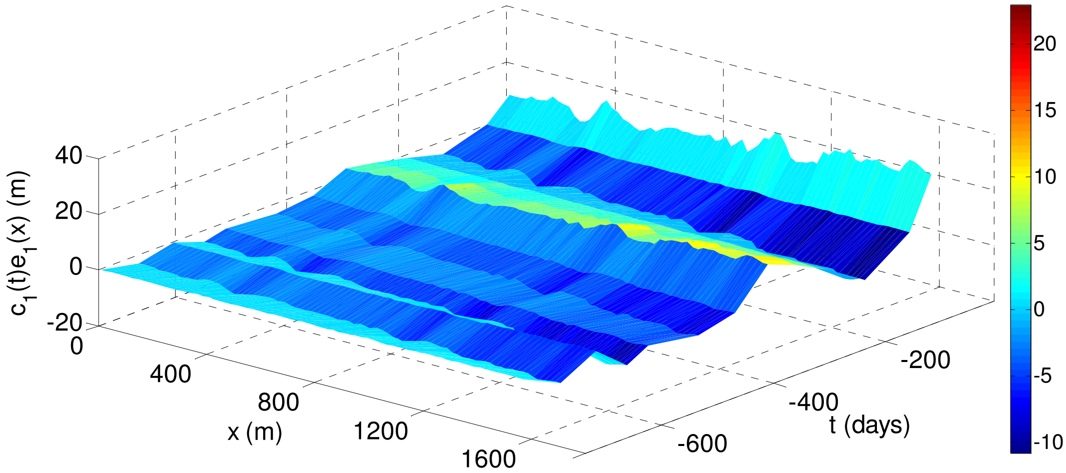
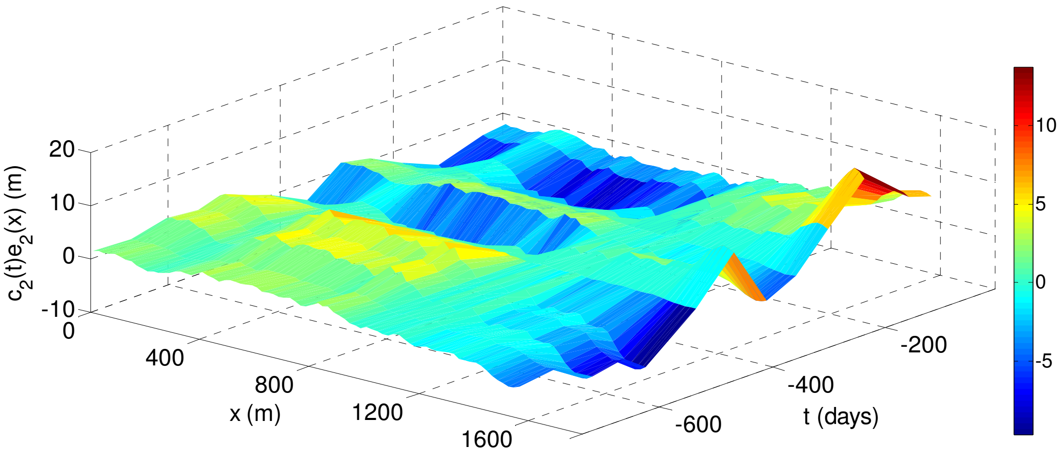


Figure 10. Temporal eigenfunctions of the first two components at the Natori River mouth before the tsunami



(a) First component variability



(b) Second component variability

Figure 11. Combination of temporal eigenfunction and spatial eigenfunction of the first two components at the Natori River mouth before the tsunami

After the tsunami (Area 2)

The value of spatial eigenfunction of the first component after the tsunami is completely different with the first component before the tsunami. However, its tendency is similar to the second component before the tsunami (Figure 9). The value of temporal eigenfunction decreases from just after the tsunami up to the time of about 400days. After that, it is almost constant (Figure 12). The combination of temporal eigenfunction and spatial eigenfunction is increasing but only at the area far away from the river mouth. On the other hand, at the area adjacent to the river mouth, that value is decreasing (Figure 13). Hence, the first component can be related to the cross-shore movement, the slow recovery of the area far from the river mouth and the retreat at the area adjacent to the river mouth due to the sand spit intrusion into river mouth. The contribution of this component is 77%.

The fluctuation of spatial eigenfunction of the second component is corresponding to shoreline positions in June 2011 (3 months after the tsunami). Its temporal eigenfunction is almost constant and fluctuation around 0, only a small changing in the early stage after the tsunami (Figure 12). The changing of the temporal eigenfunction and the spatial eigenfunction shows the strong evolution of shoreline is along the area and in the early stage of the after the tsunami (Figure 13). Hence, the second component can be related to the beach smoothing process and the recovery process in the early stage. This is same with the second component at area 1A. The contribution of this component is 7.3%.

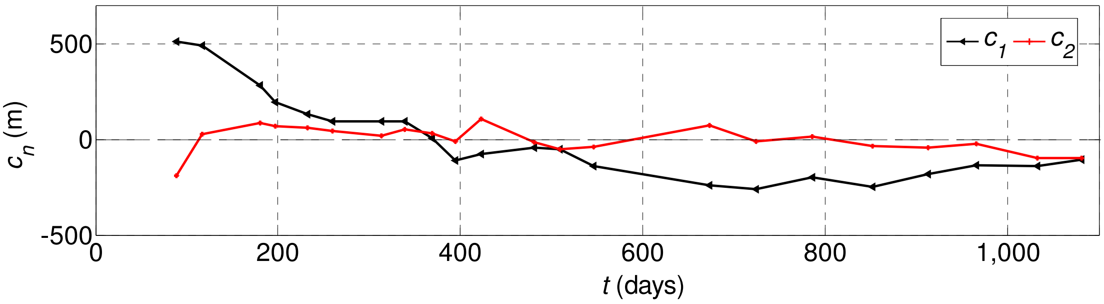
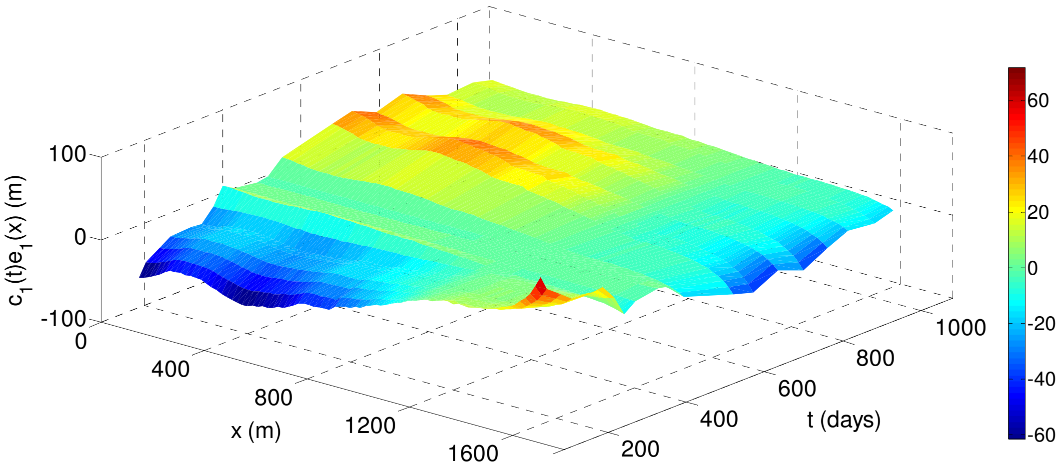
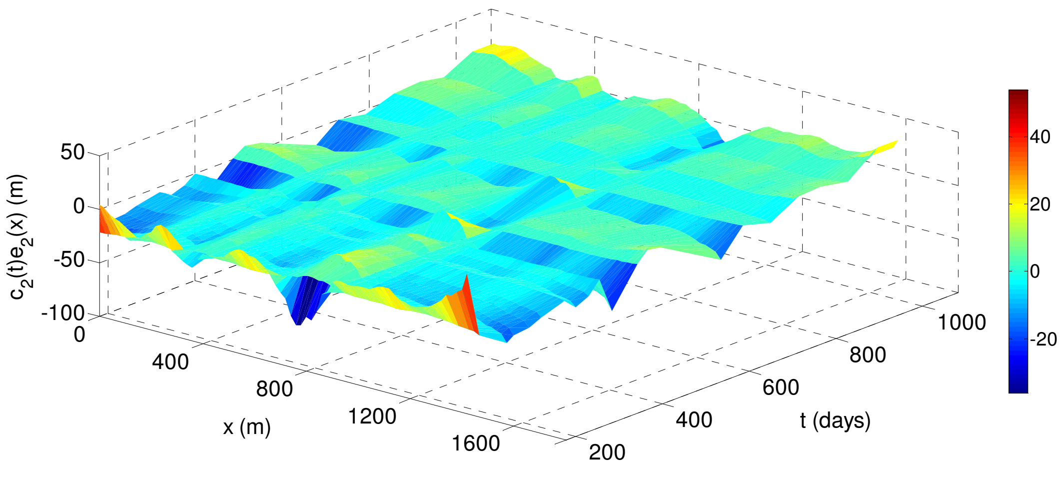


Figure 12. Temporal eigenfunctions of the first two components at the Natori River mouth after the tsunami



(a) First component variability



(b) Second component variability

Figure 13. Combination of temporal eigenfunction and spatial eigenfunction of the first two components at the Natori River mouth after the tsunami

CONCLUSIONS

This study has investigated the behavior of morphology at the Nanakita River mouth and the Natori River mouth on Sendai Coast both periods before and after the 2011 tsunami through aerial photograph and Empirical Orthogonal Function (EOF) analysis. The following conclusions have been made.

- The morphology of Nanakita River mouth and Natori River mouth on Sendai Coast was severely damaged by the 2011 tsunami. The recovery took place after the tsunami. Shoreline around the Nanakita River mouth has been moving advance with high rate. It has also been moving advance at the Natori River mouth but lower rate. Shoreline at both river mouth areas has not yet reached the position before the tsunami.

- The serious erosion caused by the tsunami has made the difference of dominant components of shoreline change between before and after the tsunami. The total contribution of the first and second components is about 85% up to 95% of the total contribution of all components. The contribution of the first component after the tsunami is larger than the contribution before the tsunami. They are related to the recovery process of the areas which were severely damaged.
- Two river mouths have strongly effect on the recovery process of the morphology in the around areas.

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