EFFECT OF GROUND SUBSIDENCE DUE TO CRUSTAL MOVEMENT ON BEACH CHANGES ON OMAEZAKI COAST, JAPAN

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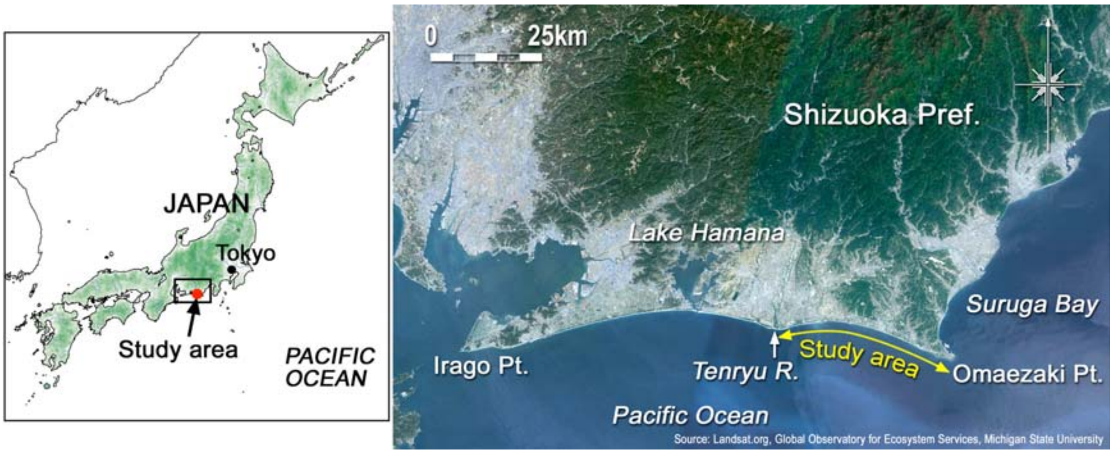
Shoreline changes along the coasts between the Tenryu River mouth and Omaezaki Point facing the Pacific Ocean were investigated using aerial photographs. Beach has been eroded on the coast located near the east end of the coastline far from the river mouth. Although beach erosion on the nearby coasts to the Tenryu River mouth was triggered by the decrease in fluvial sand supply and the obstruction of longshore sand transport by a port breakwater, beach erosion on a coast far from the river mouth was due to the effect of ground subsidence associated with crustal movement, and partly due to the effect of windblown sand.

Keywords: Ground subsidence; crustal movement; beach erosion; longshore sand transport

INTRODUCTION

The coastline west and east of the Tenryu River has been formed as a fluvial fan of the Tenryu River (Fig. 1). Because the coast is part of a river delta, beach changes due to the decrease in sand supply from the river have occurred mainly around the river mouth in recent years, and various measures have been taken, including sand bypassing from dams in upstream basins (Miyahara et al., 2010). However, severe beach erosion has been occurring on the Omaezaki coast located 40 km east of the Tenryu River mouth and near the east end of an arc-shaped shoreline, even though the eastern shoreline closer to the river mouth has been stable. Difficulties have arisen in considering suitable countermeasures in this area because the exact causes of beach erosion have not been identified. In this study, therefore, beach changes between the Tenryu River mouth and Omaezaki Point were investigated using aerial photographs. It was found that ground subsidence due to crustal movement was a key factor causing the beach changes in this area, along with the predominance of eastward longshore sand transport.



Source: Landsat.org, Global Observatory for Ecosystem Services, Michigan State University

Figure 1. Location of study area facing the Pacific Ocean.

SHORELINE CHANGES BETWEEN TENRYU RIVER MOUTH AND OMAEZAKI POINT

Overall Shoreline Changes in Study Area

Figure 2 shows an aerial photograph taken in 1997 of the study area between the Tenryu River mouth and Omaezaki Point facing the Pacific Ocean. A gradually curved embayment shoreline extends from the Tenryu River mouth to Omaezaki Point with four small rivers, namely, Benzaiten, Kikugawa, Niino and Osagawa Rivers, in between. Also the Fukude fishing port was constructed 10 km east of the Tenryu River mouth and the Hamaoka Nuclear Power Station (NPS) is located 8.6 km west of

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Omaezaki Point. Figures 3(a) and 3(b) show the shoreline changes in the study area between 1946 and 1966 before the construction of the Fukude fishing port breakwater, and those between 1977 and 2008 after the construction of the breakwater using aerial photographs.

Although the shoreline recession had already occurred at the Tenryu River mouth and its nearby area, systematic erosion and accretion had not taken place between 1946 and 1966 east of the Ota River, except for the local variations in shoreline position. Then, the shoreline markedly advanced west of the fishing port breakwater, whereas the shoreline retreated east of the fishing port between 1977 and 2008, because the Fukude fishing port breakwater was extended, and eastward longshore sand transport was blocked by the breakwater. Although the shoreline between the Benzaiten and Niino Rivers east of the Fukude fishing port was stable with an irregular, local variation in shoreline configuration, the shoreline markedly receded east of the Osagawa River.

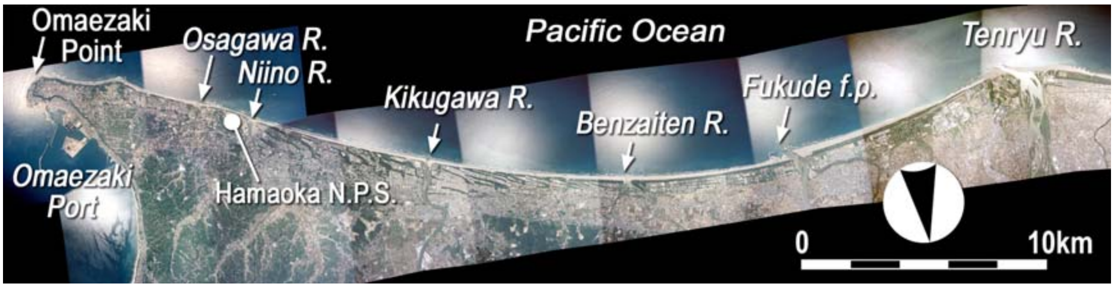
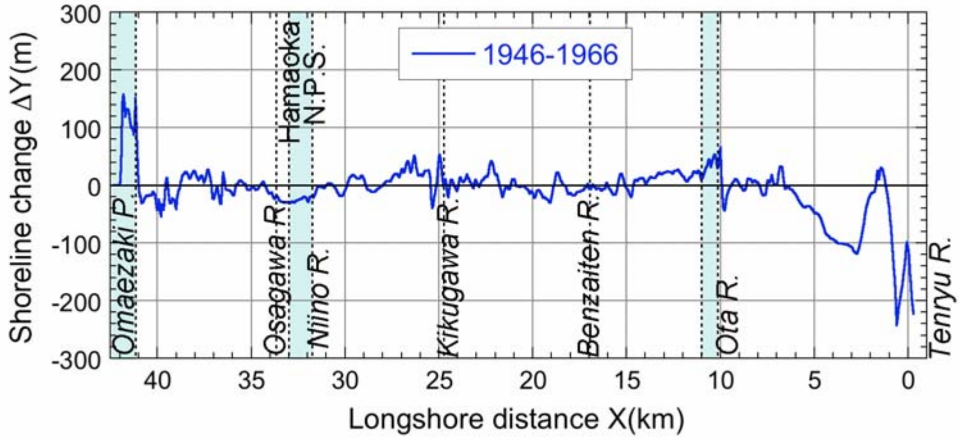


Figure 2. Aerial photograph in 1997 between Tenryu River mouth and Omaezaki Point.

(a) Shoreline changes between 1946 and 1966



(b) Shoreline changes between 1977 and 2008

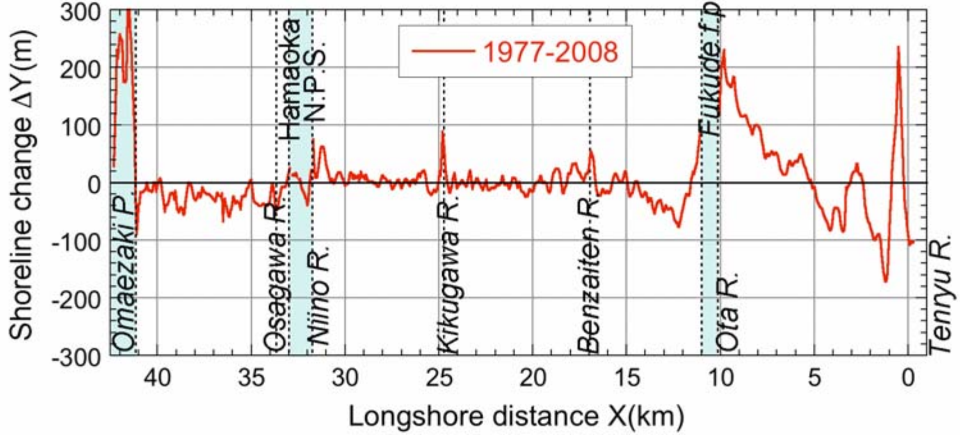


Figure 3. Shoreline changes between 1946 and 1966, and between 1977 and 2008.

Detailed shoreline changes in selected areas

By selecting the segments where marked shoreline changes were observed, as shown in Fig. 3, detailed shoreline changes were investigated. First, the detailed shoreline changes between the Tenryu River mouth and the Fukude fishing port are shown in Fig. 4. The most marked change observed in this segment is the shoreline advance west of the fishing port associated with the extension of the fishing port breakwater with a maximum shoreline advance of up to 290 m at the Ota River mouth adjacent to the fishing port. The shoreline advance decreases with the westward distance, and a nodal point with no shoreline advance or recession is located at approximately X = 6 km, where it is located 4 km west of the Fukude fishing port. The shoreline west of this nodal point significantly receded up to the location of the detached breakwaters but on the Ryuyo coast with a 150 m recession at the east end of the

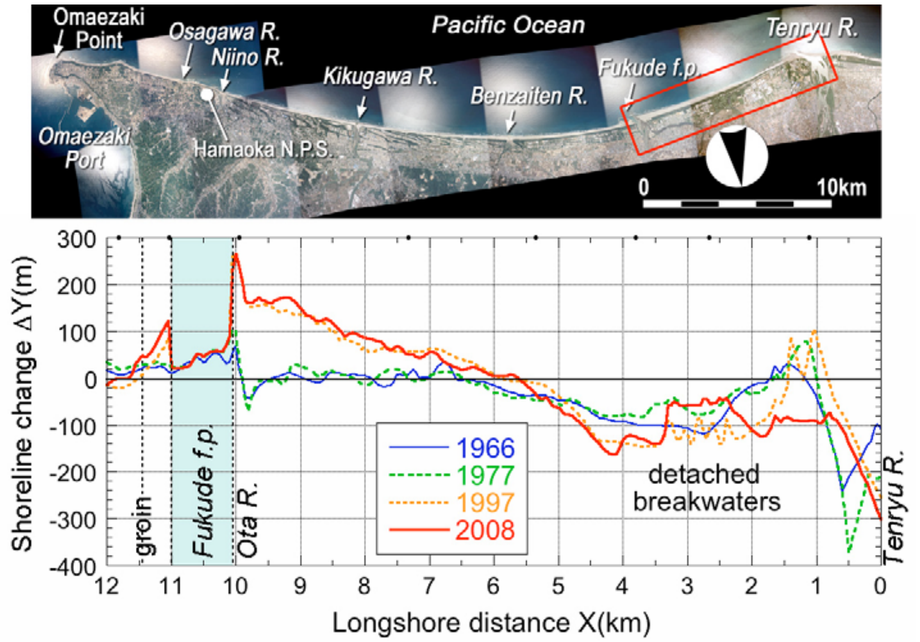


Figure 4. Detailed shoreline changes between Tenryu River mouth and Fukude fishing port with reference to shoreline in 1946.

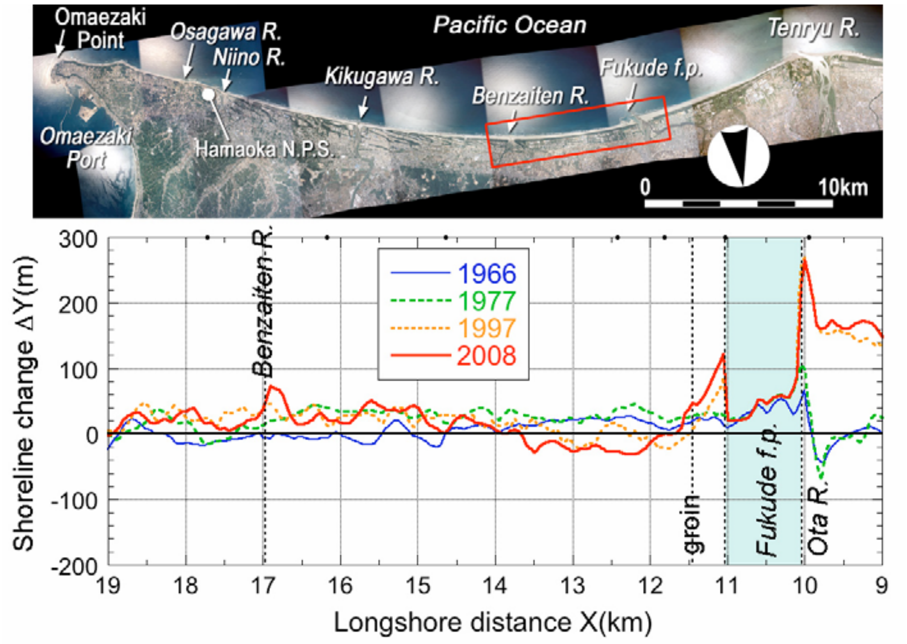


Figure 5. Detailed shoreline changes between Fukude fishing port and Benzaiten River with reference to shoreline in 1946.

detached breakwaters. Furthermore, comparison of the shoreline configuration taken between 1997 and 2008 from the nodal point at X = 6 km to the Fukude fishing port showed that the accretion area did not increase while maintaining the same shoreline configuration, implying that eastward longshore sand transport, originally supplied from the Tenryu River mouth, discharged eastward from the Fukude fishing port, turning around the tip of the fishing port.

Figure 5 shows the shoreline changes of the Asaba coast located east of the Fukude fishing port with reference to that in 1946. Although the shoreline had advanced up to 290 m by 2008 upcoast of the Fukude fishing port at maximum with the shoreline advance by 110 m in the wave-shelter zone of the fishing port breakwater immediately east of the fishing port, the net shoreline recession was only 30

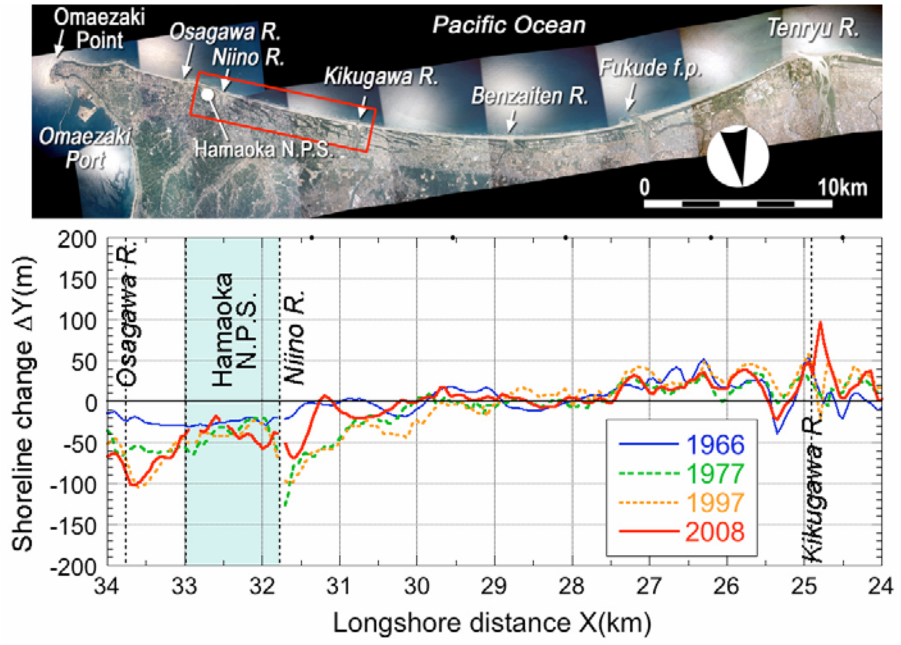


Figure 6. Detailed shoreline changes between Kikugawa and Osagawa Rivers via Hamaoka NPS with reference to shoreline in 1946.

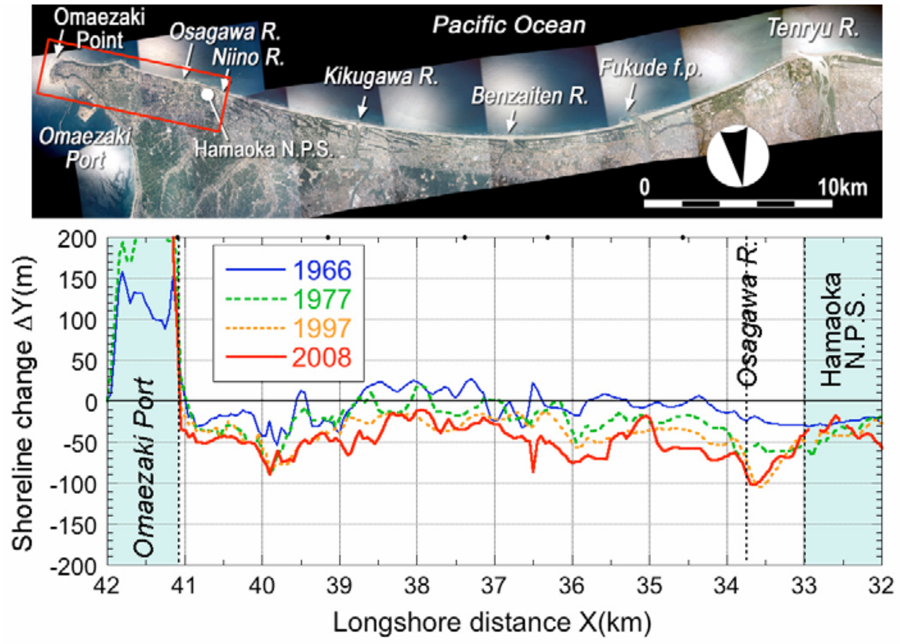


Figure 7. Detailed shoreline changes between Hamaoka NPS and Omaezaki Port with reference to shoreline in 1946.

m, which is much smaller than the shoreline advance near the fishing port, at approximately 1.5 km east of the fishing port, and the shoreline only had a large variation east of the most eroded location.

Similarly, Fig. 6 shows the shoreline change between the Kikugawa and Niino Rivers with reference to that in 1946. In this area, different shoreline changes can be observed west and east of a location of X = 28 km; the entire area west of this point is accreted, whereas the shoreline recession gradually increases east of this location, except for the vicinity of the Hamaoka NPS where the shoreline that receded until 1977 advanced again. Figure 7 shows the shoreline changes on the Hamaoka and the Omaezaki coasts located at the east end of the study area. The shoreline in this segment had almost retreated in parallel with time in the entire area between the vicinity of the Osagawa River and Omaezaki Port with a smaller shoreline recession near the Omaezaki Port. Note that the shoreline only receded without any accretion zone in this area, which is a typical pattern observed on a coast where predominant longshore sand transport was blocked: sand deposition on upcoast and erosion on downcoast.

ESTIMATION OF WINDBLOWN SAND OVER GEOMORPHOLOGICAL TIME SCALE

Sand dunes have well developed along the coastline between the Tenryu River mouth and Omaezaki Point. Figure 8 shows the distribution of the sand dune area (red color in Fig. 8) drawn on the basis of the landform classification map with a ratio of 1/50000 (Economic Planning Agency, 1965), using the map produced from the 10-m-mesh Digital Elevation Model (DEM) data of the Geographical Survey Institute. Although the sand dune width is narrow between the Tenryu and Benzaiten Rivers, it extends inland and becomes wider east of the Benzaiten River with an approximately 3 km width west of the Niino River. Simultaneously, the elevation of the sand dunes increases inland east of the Kikugawa River, as shown in Fig. 8, with a location where the elevation reaches over 20 m high in front of the hills. These sand dunes were assumed to be formed by the deposition of windblown sand transported inland from the shoreline, and deposited on the coastal lowland with the shoreline advance since the Jomon Transgression of Sea approximately 6000 years ago. Therefore, the total volume of deposited sand is equivalent to the volume of sand transported by wind from the shoreline since the Jomon Transgression of Sea, and this volume of sand was estimated using the sand dune distribution, as shown in Fig. 8, and the DEM data.

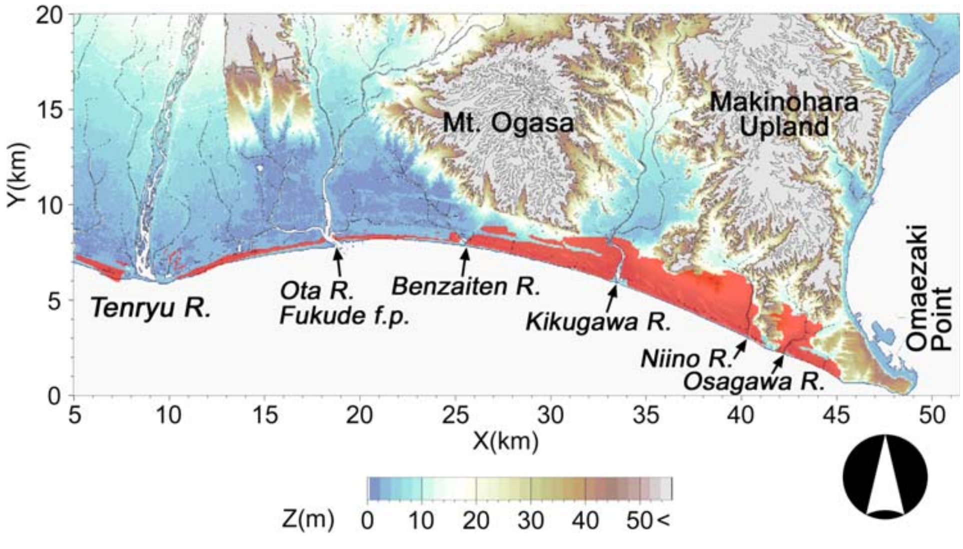


Figure 8. Distribution of sand dune along coastline.

First, the elevation of the coastal lowland behind the coastline before the development of the sand dunes can be assumed to be 3 m on average, because the elevation of the rows of the beach ridge formed inland ranges from 3 to 4 m, and the elevation of the lowland between them is approximately 2 m, which comprise the coastal lowland between the Ota and Benzaiten Rivers. This elevation was assumed to be the height of the basement for the sand dunes. Figure 9 shows the distribution of the thickness of the sand layer of the sand dunes, assuming that the elevation of the basement of the sand dunes is 3 m. The thickness of the sand layer increases inland, and a thick sand layer was observed along the marginal line covering the southern end of the Makinohara Upland. The entire volume of sand deposited in the sand dune area, as shown in Fig. 9, was 2.0×10^8 m^3.

On the other hand, Kashima et al. (1985) showed that the closure of the Kikugawa River mouth, which was enclosed in a bay during the Jomon Transgression of Sea, occurred 3000-3500 years ago on the basis of the geological study. Therefore, a sandy beach, from which windblown sand can be supplied, is considered to have developed while forming a continuous shoreline since this period, and then, the beginning of the development of the sand dunes could be 3500 years ago. Dividing the entire volume (2.0×10^8 m^3) of sand deposited by 3500 years shows that the rate of windblown sand is 5.7×10^4 m^3/yr.

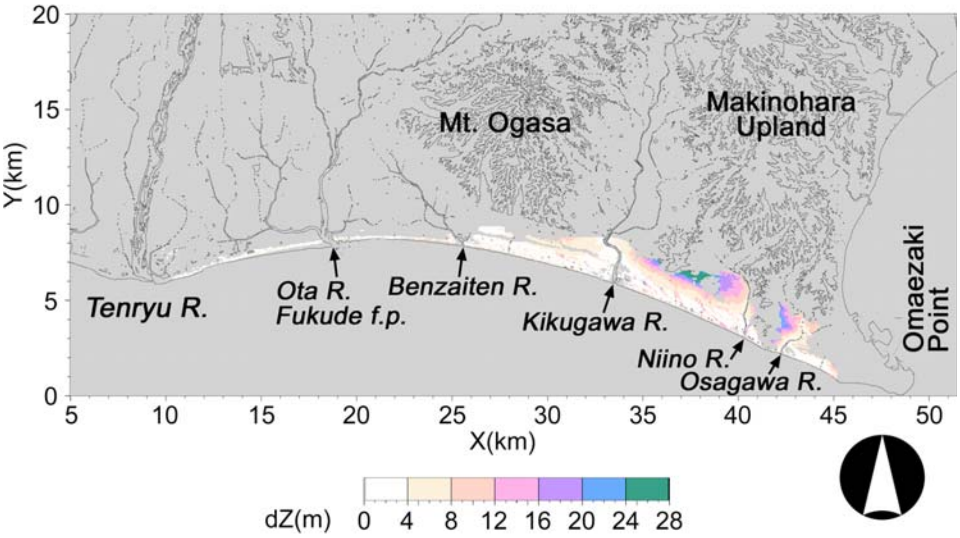


Figure 9. Thickness of sand layer composed of sand dune.

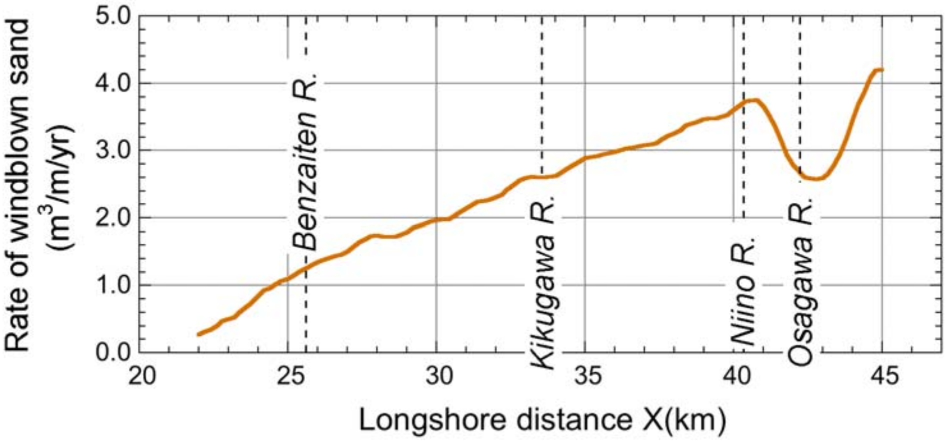


Figure 10. Longshore distribution of windblown sand calculated on the basis of directions of shoreline and predominant wind of west.

Next, the longshore distribution of windblown sand was calculated on the basis of the rate of windblown sand and the shoreline direction. The windblown sand being transported landward per unit length of the shoreline at a location of the coastline is proportional to $\cos\alpha$, where α is the angle between the predominant wind direction and the direction normal to the coastline. Owing to the distribution of the sand dunes shown in Fig. 8, the development of the sand dunes is not clear west of the Benzaiten River, whereas it develops deep inland east of this river with a further development of the sand dunes near the Niino and Osagawa Rivers. Although the shoreline near the Benzaiten River almost runs in the east-west direction, the shoreline in the eastern area rotates clockwise, causing the greater landward component of the predominant wind direction of west, and thus, resulting in the increase in the amount of windblown sand. Therefore, the distribution of cosα was calculated on the basis of the predominant wave direction of west and the direction of the coastline between the Benzaiten River and the Hamaoka NPS. Since the rate of windblown sand under the natural condition is given by 5.7×10^4 m^3/yr, windblown sand was distributed alongshore using the distribution of cosα, so that the total windblown sand is equal to 5.7×10^4 m^3/yr. The results are shown in Fig. 10. The amount of windblown sand per unit shoreline length increases from the Benzaiten River to the Hamaoka NPS at 2.6 and 3.7 m^3/m/yr at the Kikugawa and Niino Rivers, respectively. In the vicinity of the Osagawa River, it decreases with the projection of the shoreline, but it is maximum at 4.2 m^3/m/yr east of the Osagawa River. The estimated rate of windblown sand is comparable to that of windblown sand of 5 m^3/m/yr per unit shoreline length on the Tsujido coast in Kanagawa Prefecture, where sand dunes develop well (Ishikawa et al., 2009). Thus, the order of magnitude of the rate of the windblown sand was the same in both areas, suggesting the appropriateness of the estimation.

EFFECT OF GROUND SUBSIDENCE

Ground subsidence associated with the northwestward subduction of the Philippine Sea Plate has occurred over the past several decades in a widespread area including Suruga Bay and the Enshu-nada Sea, as shown in Fig. 11. Figure 12 shows the rate of vertical crustal movement between 1996 and 2000 in central Japan measured as the change in the ground elevation at the GPS-based control station of the Geospatial Information Authority of Japan (Sagiya and Inoue, 2003). The ground subsidence occurred between the Tenryu River mouth and Suruga Bay, and the rate of subsidence increases from the Tenryu River mouth to Omaezaki Point with a maximum of 5-8 mm/yr around Omaezaki Point.

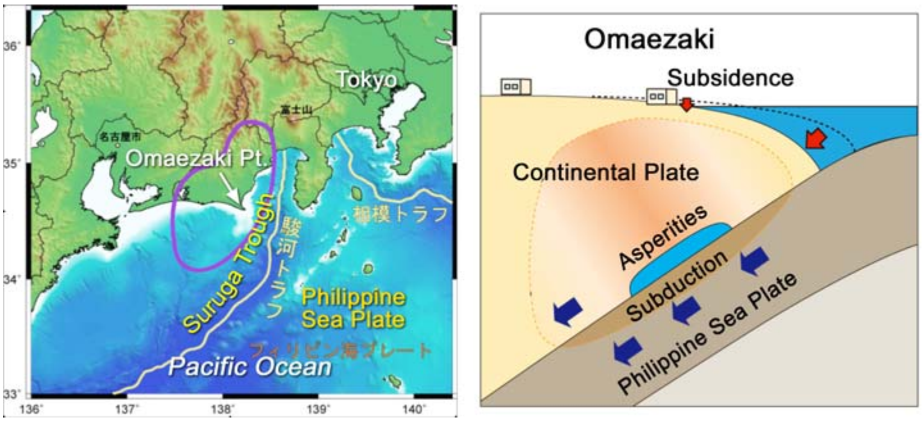


Figure 11. Schematic diagram of subsidence of Omaezaki associated with subduction of Philippine Sea Plate (Meteorological Agency)

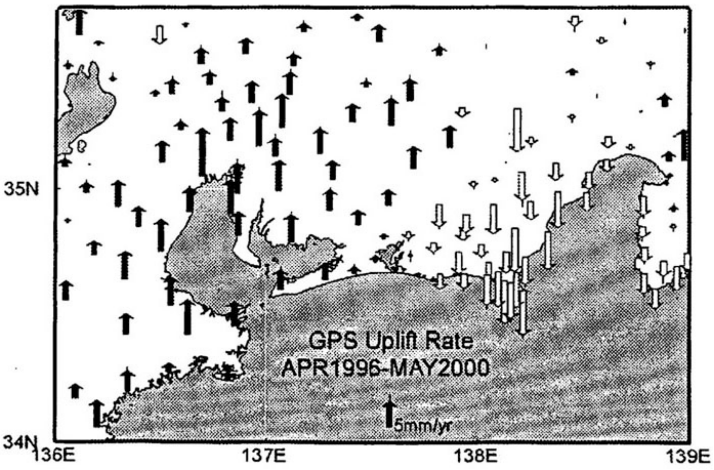


Figure 12. Rate of vertical crustal movement between 1996 and 2000 in central Japan (Sagiya and Inoue, 2003).

Figure 13 shows the average annual vertical movement calculated from the statistical analysis of the leveling data of the Geospatial Information Authority of Japan from 1983 to 2002 along the coastal zone area facing the Pacific Ocean and Suruga Bay including Omaezaki Point (Meteorological Research Institute, 2005). The variation in ground elevation is measured with reference to that in Kakegawa (Reference point of No. 140-1). The rate of ground subsidence increases from the Tenryu River mouth to Omaezaki Point, at a maximum of 6-8 mm/yr near Omaezaki Point, and the rate of ground subsidence is also as large as 4 mm/yr along the coastline in Suruga Bay.

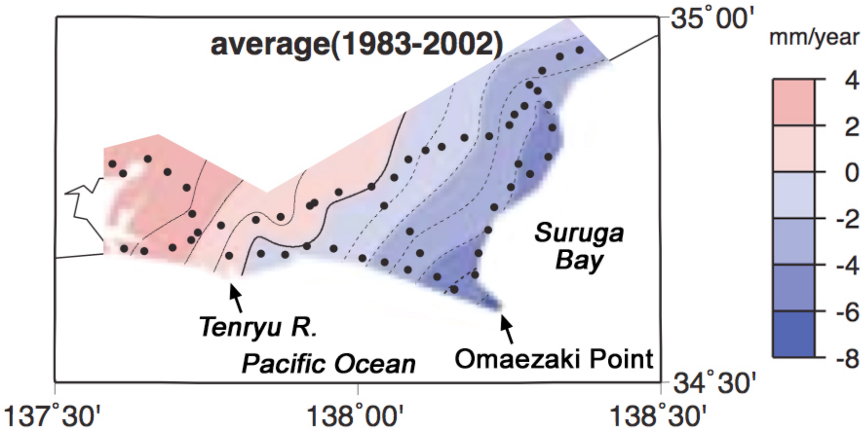


Figure 13. Average annual vertical movement from 1983 to 2002 in study area (Meteorological Research Institute, 2005).

Figure 14 shows the vertical change in ground elevation at the tide gauge station with reference to the mean sea level on the basis of the observation data of tide level over the past 50 years, excluding the variation in the tide level originating from oceanographic and meteorological disturbances (Geospatial Information Authority of Japan, 2013). In contrast to the uplift at Maisaka located at the mouth of Lake Hamana, the ground level at Omaezaki Point has continued to subside since the 1960s to the present with a cumulative subsidence of 40 cm and a rate of subsidence of approximately 8 mm/yr. This rate of subsidence and that measured from the leveling and the GPS measurement are in good agreement.

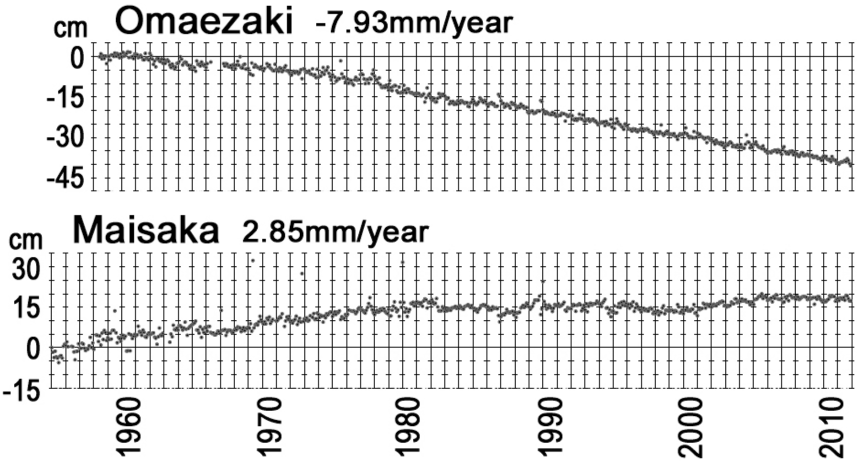


Figure 14. Vertical change in ground elevation at tide gauge stations with reference to mean sea level (Geospatial Information Authority of Japan, 2013).

It is concluded that the ground subsidence has continuously occurred over at least 50 years east of the Tenryu River mouth, and the subsidence velocity could be negligible in the vicinity of the Tenryu River mouth, but it increases eastward toward Omaezaki Point at a maximum of 8 mm/yr. This subsidence of the ground is synonymous with the fact that an amount of sand equivalent to the decrease in sand volume of the beach due to ground subsidence is removed from the beach, resulting in the net decrease in sand volume.

Setting the ground subsidence in a year at a particular location as Δh_s, the mean beach slope between the shoreline and the depth of closure h_c as $\tan\beta$, and the characteristic height of beach changes as D_s, which can be determined as a regression coefficient between the change in the cross-sectional area and the shoreline changes, the annual decrease in the cross-sectional area of the beach ΔS between the berm height h_R and the depth of closure h_c is obtained as $\Delta S = \Delta h_s / \tan\beta \times D_s$, as schematically shown in Fig. 15. Here, assuming that $\tan\beta$ is 1/70 and D_s = 12 m as mentioned in the next section, the annual decrease in the cross-sectional area of the beach at Omaezaki Point became 6.7 m^2/yr. Δh_s takes values of 0 at the Tenryu River mouth and 8 mm/yr at Omaezaki Point, and a linear distribution is assumed for Δh_s between the Tenryu River mouth and Omaezaki Point. Thus, the rate of decrease in the sand volume is 1.34×10^5 m^3/yr, taking the coastline length of 40 km into account. This is not negligible compared with the longshore sand transport of approximately 3.0×10^5 m^3/yr measured along the Enshu-nada coast (Miyahara et al., 2010).

Furthermore, the fact that the ground subsidence increases toward Omaezaki Point although the effect of ground subsidence could be neglected at the Tenryu River mouth is important, because it might be the cause of the beach erosion concentrated around Omaezaki Point.

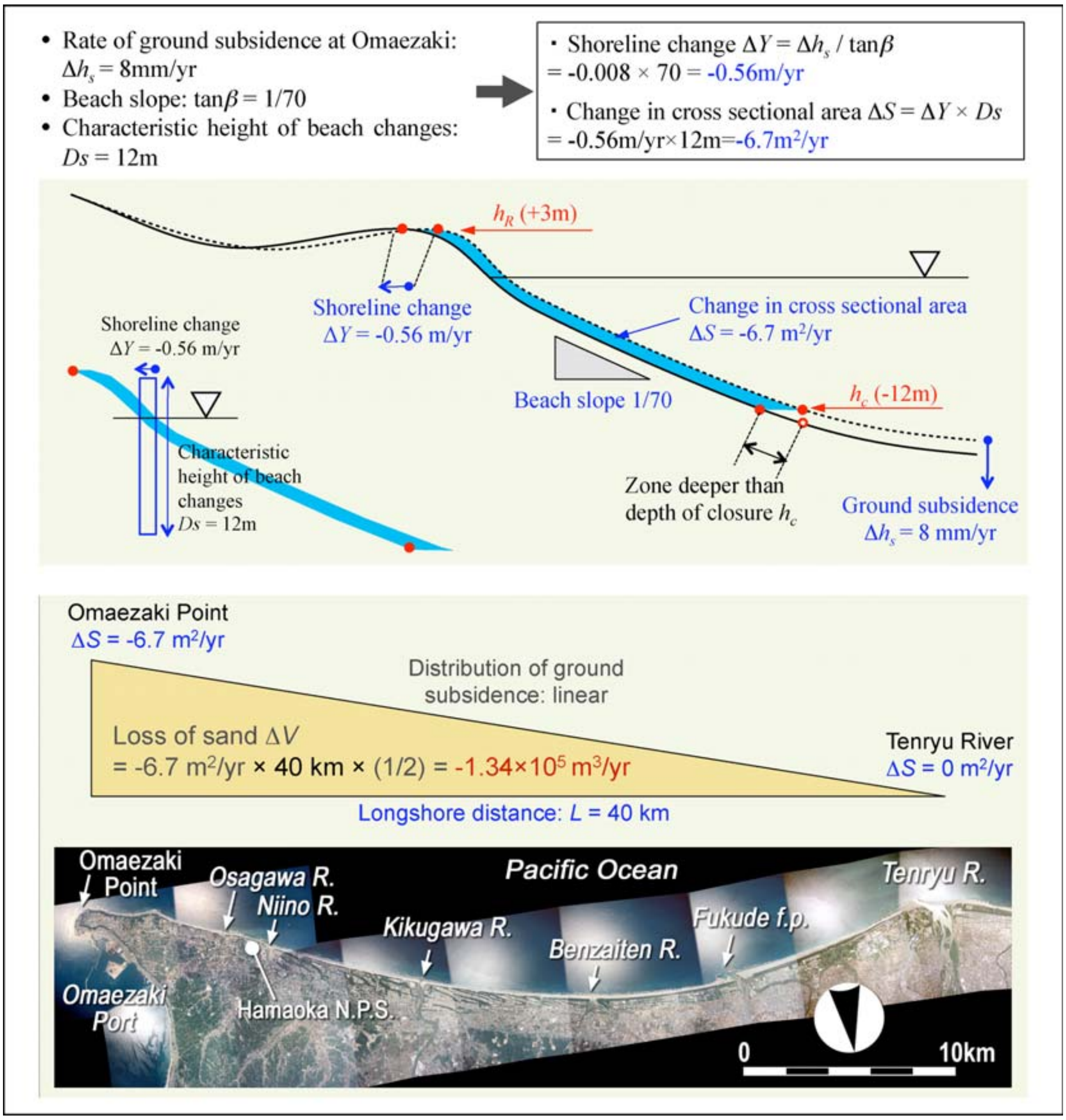


Figure 15. Schematic view of loss of sand associated with ground subsidence.

On the other hand, regarding the crustal movement near Omaezaki Point over a geomorphological time scale, it is clear that the ground level has been uplifted in the late Quaternary, taking the development of four marine terraces of the Holocene around the Omaezaki Upland (Azuma et al., 2005) into account, as shown in Fig. 16. The major earthquakes caused along the boundary of the plates, which occur near the Suruga Trough, have occurred every 150-300 years near Omaezaki Point, and the ground uplift at Omaezaki during the Ansei-Tokai Earthquake that occurred in 1854 was 0.9-1.2 m (Ishibashi, 1984). Thus, the gradual subsidence is considered to cause beach erosion around Omaezaki Point over an engineering time scale; however the ground subsidence has been canceled out by the uplift during the major earthquakes over a geomorphological time scale. The geomorphology around Omaezaki Point has been formed by the combined effects of these phenomena over a geomorphological time scale and those caused by the spatial imbalance in longshore sand transport.

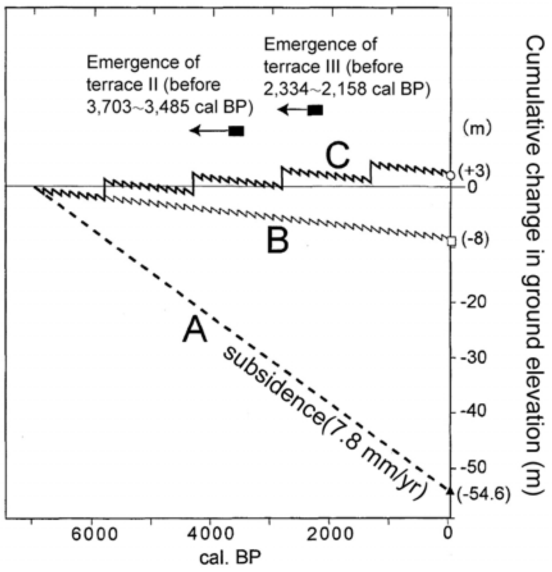


Figure 16. Development of four marine terraces of Holocene around Omaezaki Upland and cumulative crustal movement (Azuma et al., 2005).

ESTIMATION OF DISTRIBUTION OF LONGSHORE SAND TRANSPORT CONSIDERING GROUND SUBSIDENCE AND WINDBLOWN SAND

The distribution of longshore sand transport between the Tenryu River mouth and Omaezaki Point was calculated, as shown in Fig. 17, by integrating the change in foreshore area and multiplying it by the characteristic height of beach changes, assuming that Q is 0 at Omaezaki Point. Furthermore, the results were divided by the elapsed time to calculate the longshore distribution of longshore sand transport. The contributions in change in sand volume owing to ground subsidence and windblown sand were removed for the correction of the distribution of longshore sand transport.

Table 1. Depth of closure.

Study area and period for calculation	Beach condition	Characteristic height of beach changes (m)
Ryuyo and Fukude coasts, No. 200-185 Between 1984 and 2012	Eroded beach downcoast of detached breakwaters	12
Asaba coast, No. 156-139 Between 1984 and 2012	Eroded beach downcoast of Fukude fishing port	12
Osuga and Ohama coasts, No. 120-95 Between 1994 and 2012	Stable	12
Hamaoka coast, No. 80-55 Between 1994 and 2012	Stable – slightly eroded	12
Omaezaki coast	Eroded area	3

Regarding the characteristic height of beach changes D_s, which is necessary for the calculation of the sand volume, the relationship between the change in shoreline position Δy and the change in cross-sectional area ΔA was investigated in five areas, as shown in Table 1, using the annual bathymetric survey data along the Enshu-nada coast, and then D_s was determined by regression analyses of the variables Δy and ΔA. In the area where a linear relationship between the variables did not stand, D_s was estimated from the relationship of D_s = (1-1.3) h_c, using the depth of closure h_c given by Uda (1997). Table 1 shows the characteristic height of beach changes.

Longshore sand transport was separately estimated in two periods, namely, between 1946 and 1966, and between 1977 and 2008, because it has been markedly affected by anthropogenic factors: the construction of the Omaezaki Port since 1950, extensive riverbed mining, the construction of large dams in upstream basins since 1955, and the extension of the Fukude fishing port in 1978. The results are shown in Figs. 17 and 18.

According to the longshore sand transport before correction between 1946 and 1966 (black line in Fig. 17), the maximum longshore sand transport was as small as 6×10^4 m^3/yr between the Tenryu River mouth and Omaezaki Point, resulting in reverse sand transport toward the river mouth of 2.0×10^5 m^3/yr. This is contradictory to the features of the river mouth, which has long supplied sand to the neighboring coasts. Therefore, the distribution of longshore sand transport was corrected by taking the effect of the distribution of ground subsidence and windblown sand into account. Here, the rate of ground subsidence has a linear distribution between 0 mm/yr at the Tenryu River mouth and 8 mm/yr at Omaezaki Point. Since the seabed slope is 1/70 and the characteristic height of beach changes is equal to 12 m, the distribution of the correction component owing to the ground subsidence is given by the dotted line in Fig. 17. Furthermore, the loss of sand due to wind can be calculated as shown by the broken line, using the results shown in Fig. 10, because a large amount of sand could be transported away from the shoreline in the area east of the Benzaiten River. The corrected distribution of longshore sand transport is also shown in Fig. 17, together with the correction of the loss of sand due to wind from the shoreline. The blue line in Fig. 17 shows the new distribution of longshore sand transport after these corrections.

In the past, longshore sand transport at the Tenryu River mouth was small because of the decrease in fluvial sand supply but it increased eastward with a maximum of 2.5×10^5 m^3/yr immediately west of the Fukude fishing port, before decreasing toward Omaezaki Point. This distribution of longshore sand transport is considered to be appropriate for the time that fluvial sand supply from the Tenryu River began to decrease owing to the construction of large dams and extensive riverbed mining to obtain aggregates. This reversely explains that beach erosion of the Omaezaki coast was triggered by the ground subsidence.

Figure 18 shows the distribution of longshore sand transport between 1977 and 2008 after the construction of the Fukude fishing port, taking the effect of ground subsidence and windblown sand into account. This distribution shows that longshore sand transport recovered near the Tenryu River

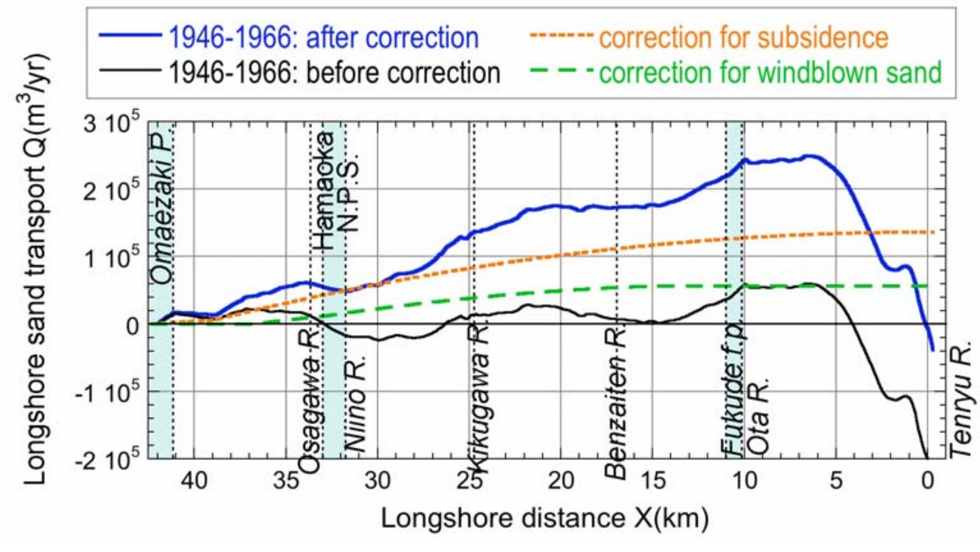


Figure 17. Distribution of longshore sand transport between 1946 and 1966, and corrections by ground subsidence and windblown sand.

mouth, whereas it decreased east of the Fukude fishing port as a whole. Longshore sand transport passing through the Fukude fishing port is approximately 1.3×10^5 m^3/yr, which includes sand bypassing at a rate of 8×10^5 m^3/yr.

When extrapolating the distribution of longshore sand transport after the correction of the effect of ground subsidence and windblown sand between 1946 and 1966 toward the Tenryu River mouth, as shown in Fig. 18, the eastward longshore sand transport at the river mouth became 3×10^5 m^3/yr, which is in good agreement with the longshore sand transport of 3.0×10^5 m^3/yr obtained in a previous study (Miyahara et al., 2010).

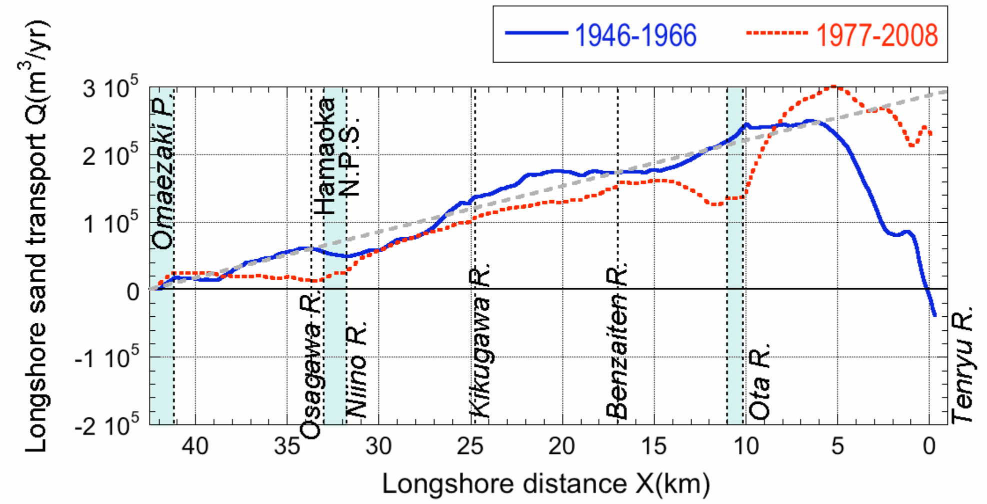


Figure 18. Corrected distribution of longshore sand transport.

CONCLUSIONS

The results of this study clearly show that over an engineering time scale of several decades, ground subsidence had a major impact on beach erosion in the study area, whereas over a geomorphological time scale, the ground subsidence was canceled out by abrupt ground uplift during major earthquakes. Thus, the phenomena associated with crustal movement are superimposed on beach changes owing to the imbalance in longshore sand transport in the study area, including the decrease in sand supply from the river and the construction of the fishing port breakwater. For effective shore protection in this area, the consideration of these phenomena with different time scales is very important.

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