# CHAPTER 312

# EROSIVE WAVES IN SHORELINE CHANGE DUE TO THE REDUCTION OF A RIVER DELTA

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ABSTRACT: Using observations of long-term data of shoreline change during the reduction process of a river-mouth delta, space-time shoreline changes and their variations are clarified by the moving-average method. There clearly exist two modes of shoreline changes due to distinct types of erosive wave. The first mode is defined to be an erosive wave propagating down-coast as a diffusion phenomenon. The second was estimated from the variation from the erosive wave and defined to be an erosive wave propagating down-coast as a wave phenomenon. We suggest new terminology for these two kinds of erosive wave. The erosive waves of the first mode are subject to change as positive and negative erosive waves due to the initial and boundary conditions at the river mouth in relation to the sediment input from the river and local change in the submerged river delta. The erosive wave of the second mode propagates down coast faster than the first mode erosive wave. We therefore conclude that shoreline change due to beach erosion can be described as space-time change propagating down-coast as a diffusion phenomenon, upon which shoreline variation propagates as a wave phenomenon faster than the shoreline change. Additionally, a theory for the diffusion-wave phenomenon of shoreline change is attempted using a set of equations of longshore sediment transport rate and continuity of shoreline change to find the dispersion relation of erosive waves.

## INTRODUCTION

In the past, it has been considered that shoreline change is a diffusion process, governed by a diffusion-type equation in a one-line theory. It has been observed that, in the reduction process of a river delta, severe shoreline change takes place in the vicinity of the cause of erosion, sometimes with beach collapse, and that shoreline change propagates down-coast like a wave phenomenon. In 1987, Inman defined the propagation velocity of an accretion or erosion wave in terms of the longshore sediment transport rate. By use of this method, Uda and Yamamoto (1994) recently estimated the velocity of a sandy body on the Mihono-matsubara sand spit. In understanding

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the shoreline change and establishing methodologies for its control, it is of course very important to recognize whether the shoreline change can be described as a diffusion or a wave phenomenon, or as a diffusion-wave phenomenon.

Recently, Tsuchiya (1995, 1996) studied erosive waves in shoreline change by analyzing long-term shoreline change data from the Shizuoka and Shimoniikawa coasts, using the method of moving average.

In this paper, we analyze data of long-term shoreline change along the Shizuoka Coast facing Suruga Bay by the method of moving average, to find the space-time change of the shoreline and its propagation speed. The narrow, sandy beach was formed on the collision coast due to there being a lot of sediment input from the Abe river. Due to a rapid decrease in sediment input, severe beach erosion and collapse began to take place near the river mouth in 1965. This extends in the direction of longshore sediment transport. The beach erosion can therefore be considered as a reduction process of the river delta. There clearly exist two modes of shoreline change. The first mode is space-time shoreline changes such as positive and negative erosive waves as diffusion phenomena. The second mode is an erosive wave propagating faster than the first mode shoreline change. We demonstrate that shoreline change due to beach erosion must therefore be considered as a diffusion-wave phenomenon.

Additionally, a theory of shoreline change is proposed from a set of equations for longshore sediment transport and continuity of shoreline change. We conclude that the shoreline change can be described by a diffusion-wave phenomenon. The dispersion relation is obtained, and the resulting propagation speed is discussed.

## THE DATA

**The Shizuoka Coast and Its General Features**: Although depth sounding was first performed in 1969, regular surveys of shoreline change and soundings on the

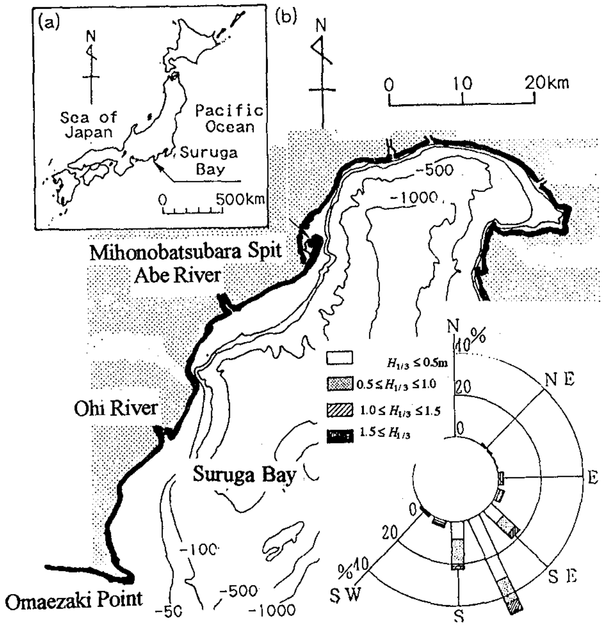



Figure 1. Location of Shizuoka coast and wave rose (Modified from Uda, 1994)

Shizuoka coast have been carried out annually since 1974 by the Shizuoka Prefectural Government.

In this paper, the measured data were used. The Shizuoka coast is one of the Pacific Ocean coasts of the Japanese islands, facing Suruga bay as shown in Figure 1. This coast is a typical collision and mountainous coast according to the coastal classification of Inman and Nordstorm (1971). The width of the coast is very narrow. The beach profiles are very steep and connect with the steep offshore slopes in Suruga bay. Because of the high rate of sediment input from the Abe river, a narrow sandy beach has been formed on the coast by typhoon waves from the south to southeast directions. At the northeast end of the coast, a sand spit called Mihono-batsubara sand spit is beautifully formed by the longshore sediment transport in the northeast direction. Near the sand spit, a sea canyon is located into which part of the longshore sediment is deposited.

Coastal Disasters and the Main Causes of Beach Erosion: Coastal disasters occurred due to the Isewan typhoon in 1959 and Typhoon 6626 in 1966, resulting in

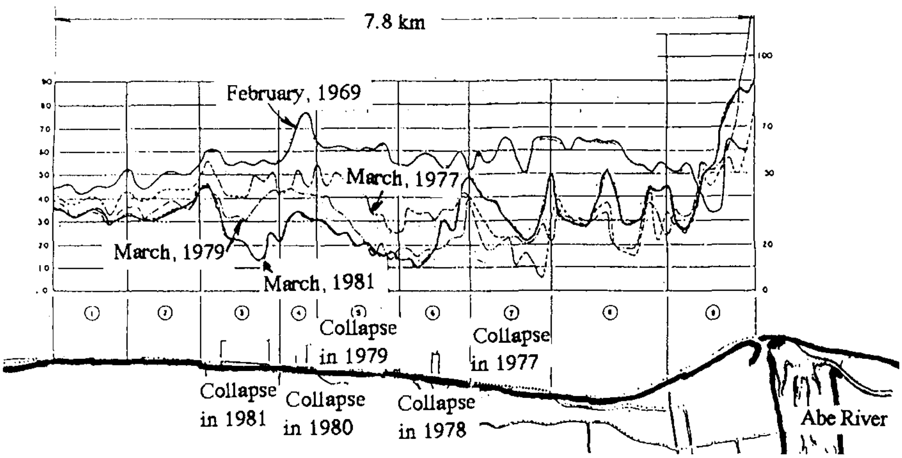



Figure 2. Shoreline changes due to beach erosion and collapse in the initial stages of beach erosion (Toyoshima,Takahashi & Suzuki,1981).

beach collapse in some locations on the beach north of the river mouth, as shown in Figure 2. Since then sea dikes have been constructed along the coast. Because there was remarkable beach erosion at that time, soundings and shoreline surveys have been carried out along the coast since 1969. The sea dikes were sometimes destroyed and the eroded area extended further along the north-east coast. Therefore offshore breakwaters were begun to be

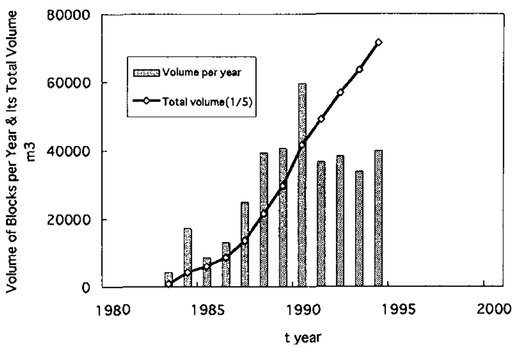



Figure 3. Annual change of total volume of concrete units used for offshore breakwaters.

constructed, and these are now completed along the whole coast. Figure 3 shows the total volume of concrete units used for the offshore breakwaters. In the Abe River sediment mining had been done widely and severely before 1968 for construction works, resulting in severe beach erosion. We therefore conclude that the main cause for beach erosion is due to the decrease in sediment input from the Abe River, and that the beach erosion can be explained as a reduction process of the river delta.

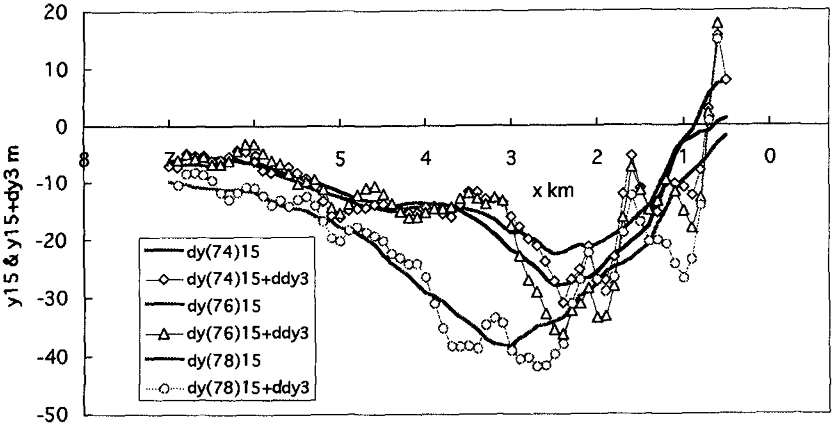
## THE METHOD OF DATA ANALYSIS

Purpose of Data Analysis: Shoreline changes are usually measured at intervals of 100m or 200m. As shown in Figure 2, beach collapse takes place locally over several hundred meters, and extends down-coast as it propagates. The spatial magnitude of shoreline change due to beach erosion is wider and reaches sometimes a few kilometers. Therefore, we have to consider shoreline changes extending from several hundred meters up to several kilometers. The shoreline change data include local shoreline changes and some errors in the measurements. In order to clarify the shoreline changes more naturally than we have understood them, it may be effective to analyze the data using spatial smoothing methods.

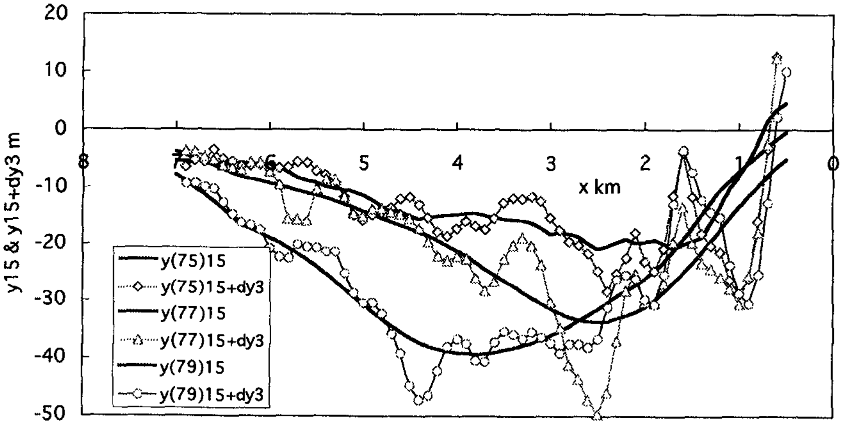
Methods of Data Analysis: We have two traditional methods for smoothing fluctuating data; 1) the triangle-weighting or uniform-weighting method, and 2) the Fourier transform method. Shoreline changes take place not only due to beach erosion, but also by beach collapse under the action of wave concentration, and extend widely along the coast. In this paper, the uniform-weighting method was used. The number of points for weighting was determined by considering whether the phenomena in question can be clearly observed in the smoothed data. 11, 13 and 15 points were used for large-scale shoreline change as a diffusion phenomenon, and 3 points were used for variations from the large-scale shoreline change as a wave phenomenon. The applicability of the smoothing method was established by comparing the results from using different numbers of smoothing points. We conclude that, in the data measured at intervals of 100 m, 13 and 15 smoothing points are suitable for large-scale shoreline change, but 3 points for variations from the shoreline change.

## THE CLASSIFICATION OF EROSIVE WAVES

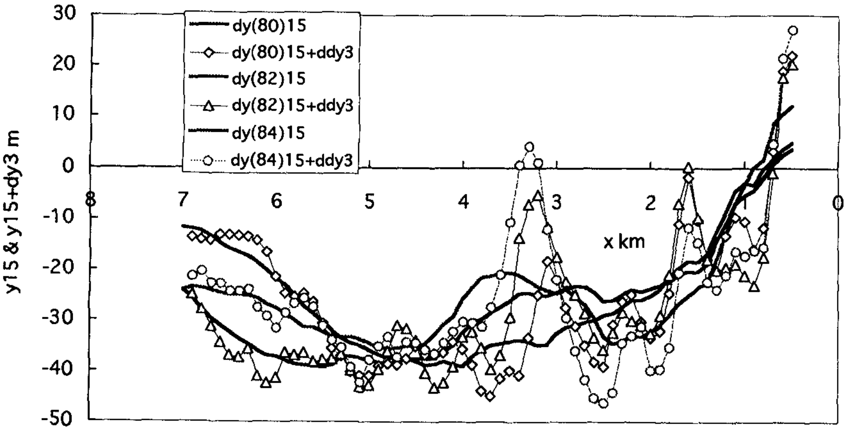
Spatial and Temporal Shoreline Changes: Using the 15-point smoothing method, smoothed shoreline changes and their variations are shown in Figure 4 at intervals of two every years. In the figure there clearly exist two modes of shoreline change. The first mode, indicated by the thick solid curves, is the large-scale shoreline change. The second mode, indicated by the thin curves with marks, is the variation from the first-mode shoreline change. The large-scale shoreline changes show clearly the annual change of shoreline in spatial form from the river mouth of the Abe river. The shoreline change expands widely down-coast in the north-east direction. This shoreline change clearly demonstrates the total shoreline change under the condition of beach erosion, which we understand as a diffusion phenomenon. This shoreline change propagation may correspond to the accretion or erosion wave proposed by Inman (1987). Referring to the cause of beach erosion, which is a decrease in sediment input from the Abe river, this total shoreline change can be understood to be a reduction process of the river delta. However, the boundary condition for the shoreline change at the river



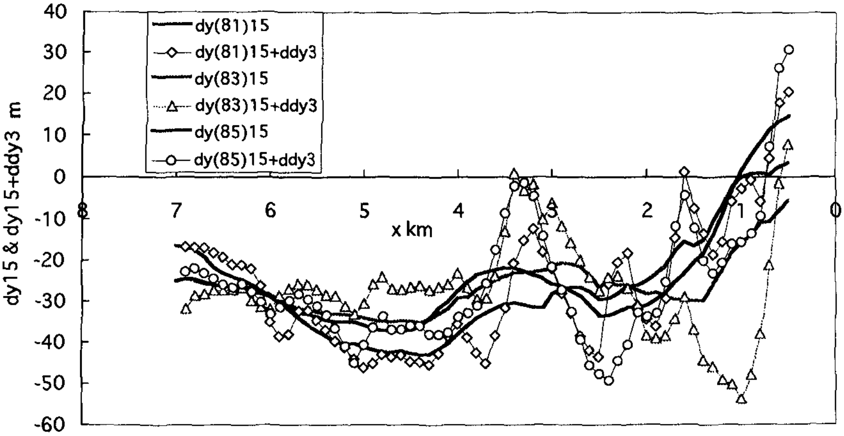

(a) 1974 to 1978.




(b) 1975 to 1979.




(c) 1980 to 1984.

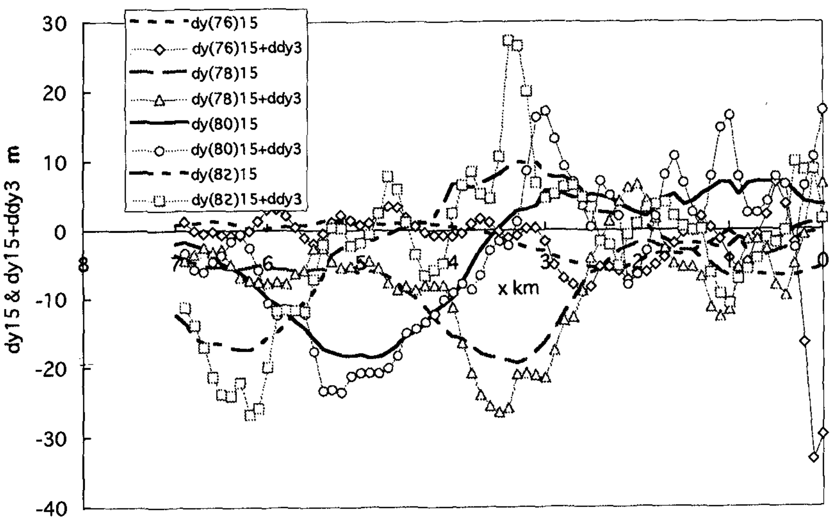



(d) 1981 to 1985.

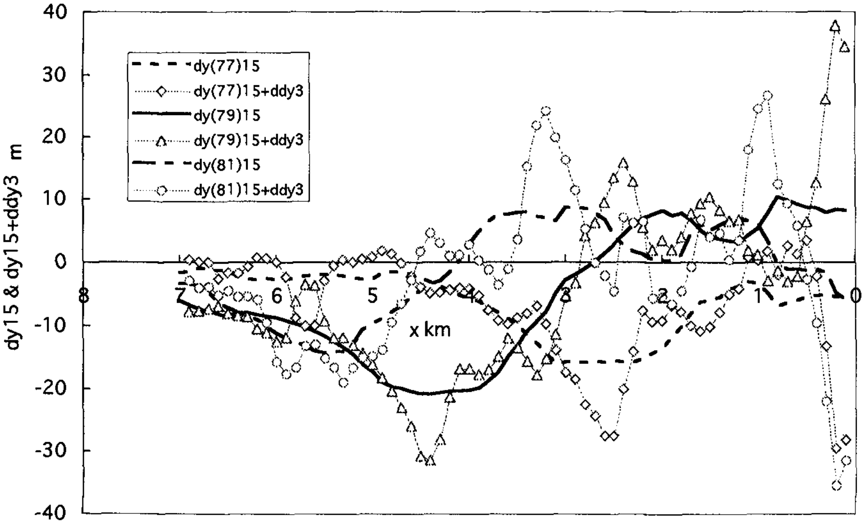
Figure 4. Total shoreline changes with erosive waves (W) down-coast from the river mouth.

mouth will be discussed in relation to the generation of erosive waves, as well as the decrease in sediment input from the river.

Erosive Waves: The thick curves shown in Figure 5 illustrate annual changes in total shoreline change, for which I define an *erosive wave as a diffusion phenomenon.* The erosive wave propagates down-coast, reducing in amplitude gradually. In this case, it has a wave crest defined by a minimum in the spatial shoreline change, and a trough defined by a maximum. Note the fact that the erosive wave is composed of two elementary waves such as positive and negative erosive waves. The positive erosive wave propagates accompanying the negative erosive wave. Further, note that these two waves were generated by different events at the river mouth, probably rapid decrease and increase in sediment input from the river, or their resulting local changes




(a) 1976 to 1982.




(b) 1977 to 1981.

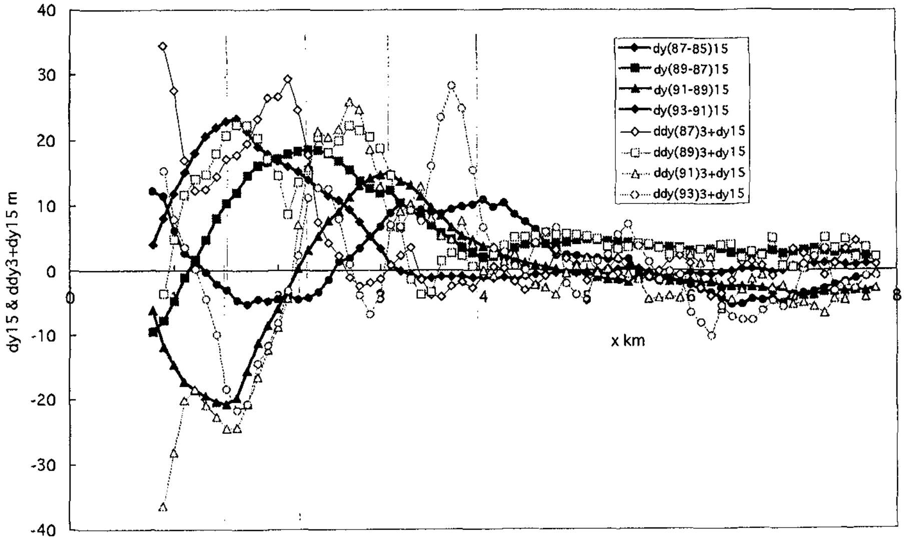
Figure 5. Spatial profiles and propagation of erosive waves (DP) and (DN) with erosive wave (W) before the construction of offshore breakwaters.

in the submerged river delta. Therefore, I define the erosive wave propagating as a diffusion phenomenon as *erosive wave (D)*, and the positive and negative erosive waves as *erosive wave (DP)* and *erosive wave (DN)*, respectively.

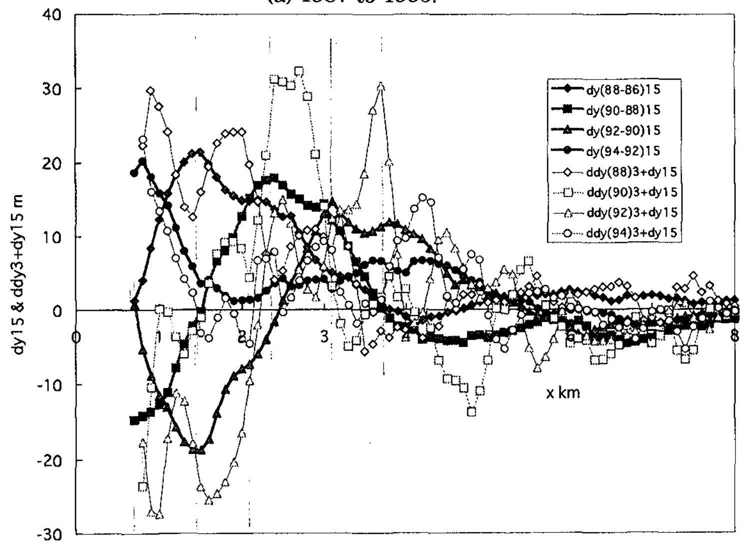
When the erosive waves are specified at the river mouth as the initial and boundary conditions for shoreline change, we may predict the total shoreline change using a common shoreline change model. Actually, beach profiles change in relation to shoreline changes around the river delta, so that the application of the model may need further consideration. The thin curves shown in Figure 6 indicate the variations from the erosive wave (D), for which I define *an erosive wave as a wave phenomenon.* This erosive wave propagates down-coast on the erosive wave (D). Thus, I define it as *erosive wave (W).* The crest and trough of the erosive wave (W) are denoted as erosive wave (Wc) and (Wt), respectively.

## THE EROSIVE WAVE(D) AND ITS PROPAGATION AS A DIFFUSION PHENOMENON

Spatial Profiles and Propagation of the Erosive Waves (D): As previously seen in Figure 5, this erosive wave (D) propagates down-coast accompanying erosive waves (DP) and (DN). Note that the spatial profiles of erosive waves (D) have nearly the same form, but reduce their amplitude gradually as a diffusion phenomenon, until the construction of offshore breakwaters. The erosive waves generated during and after the construction are shown in Figure 6, the thick curves with solid marks indicate the erosive wave (D), and the thin curves with open marks the erosive wave (W) propagating on the erosive wave (D). Note that during this period erosive waves (DN) were generated, and then erosive waves (DP) were then generated. Both the erosive waves propagate slowly down-coast in the same form, but their amplitudes clearly tend to decay down-coast. This fact may be due to the offshore breakwater effect of trapping of longshore sediment.




(a) 1987 to 1993.




(b) 1988 to 1994.

Figure 6. Spatial profiles and propagation of erosive waves (DP) and (DN) with erosive wave (W) during and after the construction of offshore breakwaters.

Propagation Speeds of Erosive Waves (DP) and (DN): The amount of data for the erosive waves is limited. Therefore, by use of the successive spatial profiles corresponding to the crests of erosive waves (DP) and (DN), the positions of the crests can be determined. Figure 7 shows the time-change of the crest positions where the straight line with solid diamond and square marks indicate respectively erosive waves (DP) generated before and during/after the construction of offshore breakwaters. The propagation speeds of erosive waves are obtained from the gradient of the straight lines.

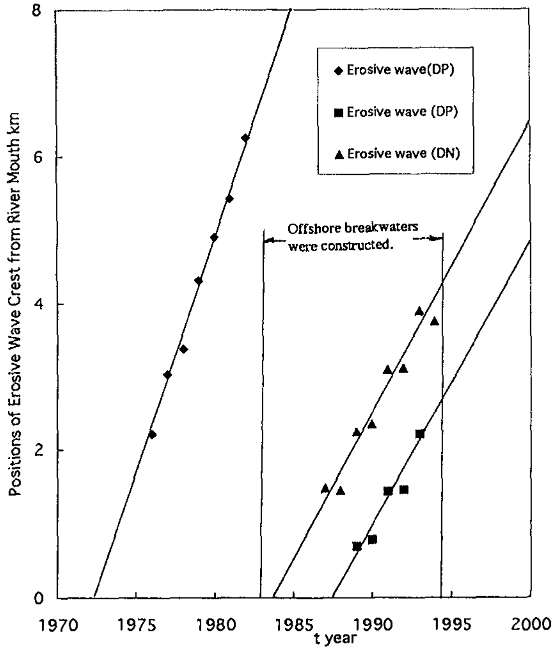


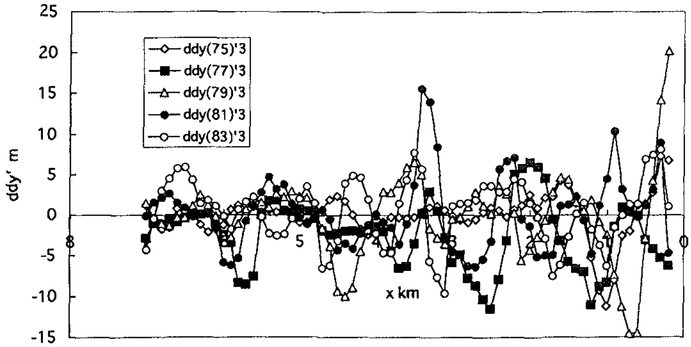

Figure 7. Propagation speed of erosive waves (DP) and (DN) before and during/after the construction of offshore breakwaters.

Note that the propagation speed of erosive waves generated during and after is less than that before the construction. Further, note that the propagation speed of erosive waves (DP) and (DN) are the same. This may explain the fact that the spatial profiles shown in Figure 6 are decaying gradually down-coast, but maintain almost the same form. If the straight line of erosive wave (DP) is extended, the time when the erosive wave was generated is found to be around the year 1972. Alternatively, the times when erosive waves (DP) and (DN) were generated during and after the construction are found to be around the years 1983 and 1987, respectively.

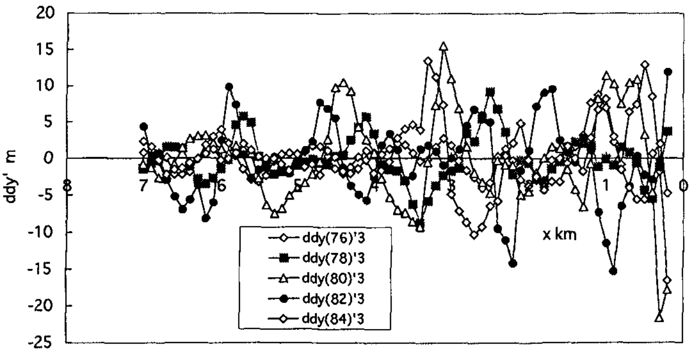
Possible reasons for generation of erosive waves (DP) and (DN): As previously discussed the main cause of beach erosion is due to the decrease in sediment input from the Abe river. Uda, Misawa and Matsui (1996) recently qualified this fact considering river bed changes due to mining of sand and gravel in the river. They conclude that the river bed had been lowered within the alluvial reach near the river mouth during mining until 1968, but changed to deposition of sediment during the period between 1970 and 1973. It therefore seems that within the period, there was no sediment input into the beach, resulting in either the direct generation of the erosive wave(DP) shown in Figure 7, or changing the submerged river delta which may have generated erosive waves. They also described that after the generation of the erosive wave no remarkable floods have been experienced, but a huge flood occurred in 1982, of which the maximum discharge was 3,860 $m^3$/sec. It also seems that the flood generated the erosive wave(DN), and that variations in the submerged river-mouth delta in relation to floods might generate erosive waves .

## THE EROSIVE WAVE(W) AND ITS PROPAGATION AS A WAVE PHENOMENON

**Erosive Wave (W) and Its Propagation:** Figures 8 and 9 show erosive waves (W) generated before and during/after the construction of offshore breakwaters respectively. A careful inspection shows that the erosive waves (W) propagate down-coast, with some exceptions. Note that the wave amplitudes show their maximum values near the river mouth, and reach over 30 m. Further, note that they decay in their propagation down-coast. It seems that this tendency is the same both before and during/after the construction of offshore breakwaters.



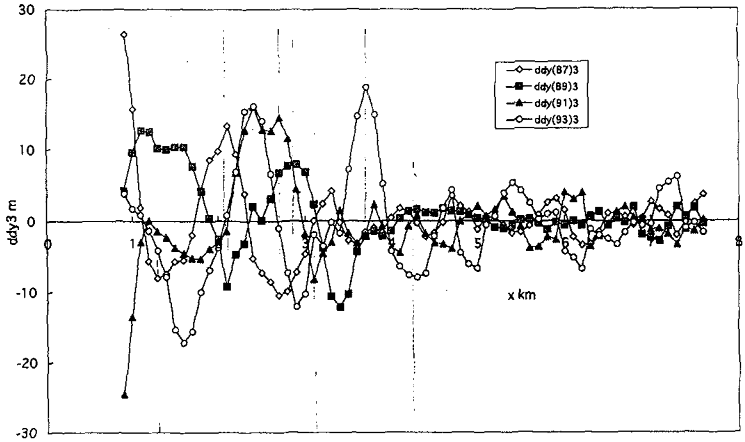

(a) 1975 to 1983.



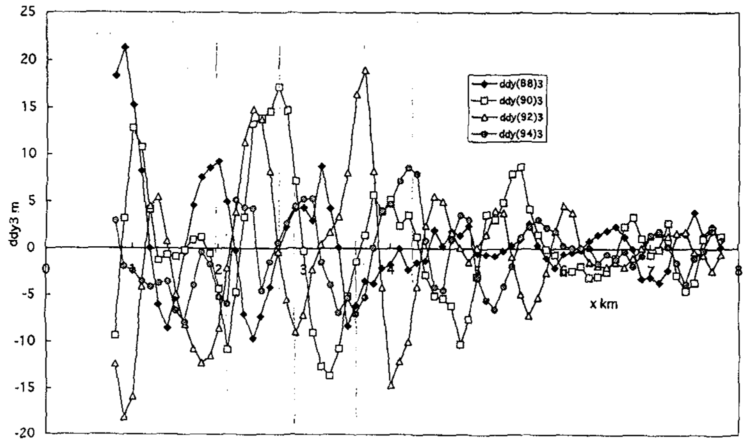

(b) 1976 to 1984.

Figure 8. Erosive waves (W) and their propagation, with wave amplitudes damping down-coast, before the construction of offshore breakwaters.

**Wavenumber Spectrum of Erosive Waves (W):** The amount of data is not sufficient for calculating wave number spectra of erosive waves (W) accurately. There is also a decay of their wave amplitudes. These may prevent the spectrum from being calculated accurately. However, we tried to estimate them using Mathematica to examine whether a peak wavenumber exists. Figure 10 shows some examples of the spectra. The spectra are not well formed, but there exists a peak wavenumber. The wavelength corresponding to the peak wave number was calculated. Figure 11 shows change in the wave length. It is nearly constant, being about 500 m until 1985, and thereafter varies and increases. This may be due to the trapping effect of longshore




(a) 1987 to 1993.

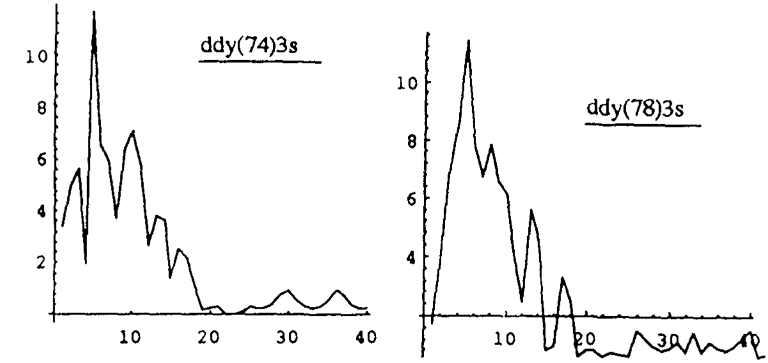



(b) 1988 to 1994.

Figure 9. Erosive waves (W) and their propagation, with wave amplitudes damping down-coast, during and after the construction of offshore breakwaters.

sediment transport by offshore breakwaters.

Propagation Speed of Erosive Waves (W): From successive crests of erosive waves (W) which were selected from the spatial profiles shown in Figures 8 and 9, the positions of the crests were determined. Figure 12 illustrates time changes of the crest positions of erosive waves (W) where the straight line with solid circles indicates the crest position of erosive wave (DP) and those with open squares and triangles mark the crest and trough positions of erosive waves (Wc) and (Wt), respectively. The propagation speeds of the crest and trough of erosive wave (W) are nearly same, and faster than that of erosive wave (DP). We therefore conclude that the erosive wave (W) propagates faster than the erosive wave (DP). This fact may explain why beach collapse or severe erosion takes place locally at some locations down-coast with the sandy beach being eroded.



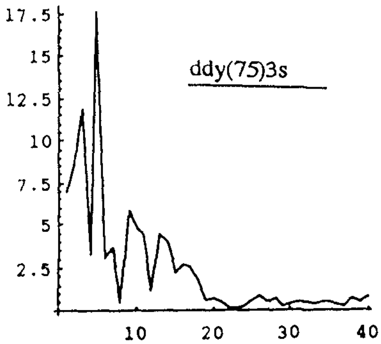




Figure 10. Some examples of wave-number spectra of erosive waves (W).

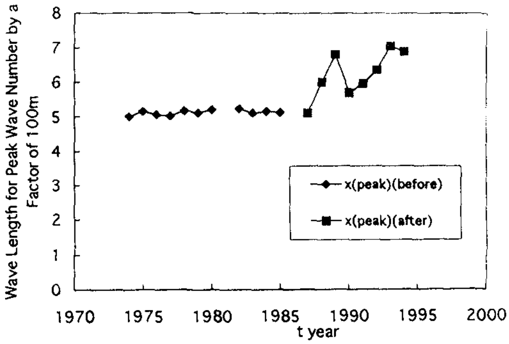



Figure 11. Changes in wavelength corresponding to the peak wavenumber.

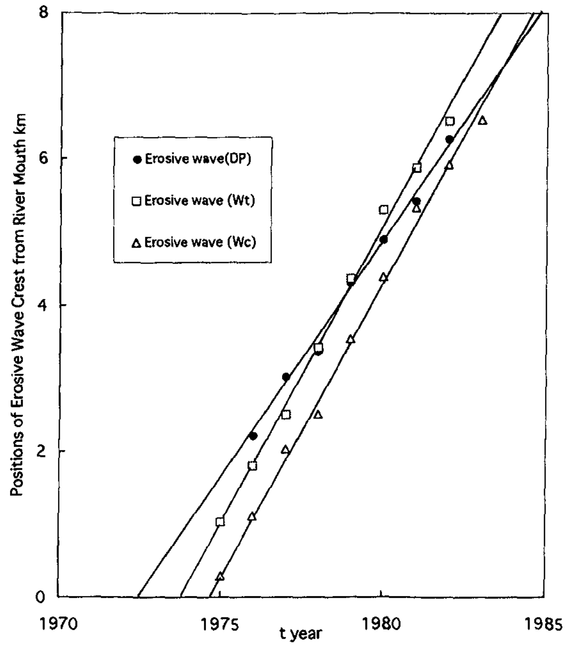



Figure 12. Propagation speed of erosive wave (W) compared with those of erosive waves (DP) and (DN).

Possible Reasons for Generation of Erosive Waves (W): Where there exists a wave phenomenon, there must be a generation force to produce the wave. Such generation forces do exist, such as incoming waves with some frequency of occurrence, but what the restoring forces are should be clarified. As will tentatively be explained later, the local change of shoreline may result in changing the total rate of longshore sediment transport. This may generally result in restoring the shoreline change. Therefore, once a local shoreline change has taken place, the shoreline change propagates down-coast, probably decaying in amplitude.

## THE EROSIVE WAVES AS A DIFFUSION-WAVE PHENOMENON AND THEIR PROPAGATION

So far a set of governing equations for shoreline change, composed of the equation of continuity for shoreline change, the total rate of longshore sediment transport and the geometrical relation of shoreline change has been used to derive a diffusion equation for shoreline change. In order to study a natural phenomenon dynamically, a set of both the equations of motion and continuity must be established. The equations of longshore sediment transport rate and continuity of shoreline change are approximately given by (Refaat and Tsuchiya, 1991)

$$\frac{\partial Q}{\partial t}+a\frac{\partial}{\partial x}\left(\frac{Q}{h_b}\right)^2=bgh_b^2\left(\sin 2\alpha_{b0}-2\frac{\partial y_0}{\partial x}\right)-e\sqrt{\frac{g}{h_b}}Q \tag{1}$$

$$\frac{\partial y_0}{\partial t}+\frac{1}{(1-\lambda)h_k}\frac{\partial Q}{\partial x}=0 \tag{2}$$

where $y_0$ is the shoreline position from the datum line, $h_b$ the breaker depth, $h_k$ the threshold depth of sediment movement, $g$ the acceleration of gravity, $\lambda$ the porosity of the bottom sediment, and $a$, $b$ and $e$ are practically constants. The second term in the first term on the right side of (1) demonstrates the restoring force of shoreline change in the wave phenomenon. The linearization of (1) and (2) results in

$$\frac{1}{e}\sqrt{\frac{h_b}{g}}\frac{\partial^2 y_0}{\partial t^2}+\frac{\partial y_0}{\partial t}-\frac{\sqrt{2}b}{e(1-\lambda)}\frac{h_b^2\sqrt{gh_b}}{h_k}\frac{\partial^2 y_0}{\partial x^2}=0 \tag{3}$$

which is the linearized wave-diffusion equation for shoreline change. Neglecting the first term the second and third terms reduces to the usual diffusion equation of shoreline change. The dispersion relation of (3) is given by

$$\frac{(\sigma/k)^2}{gh_b}=2b\left\{\frac{h_b}{(1-\lambda)h_k}\right\}\frac{1}{1-e\sqrt{g/\sigma^2 h_b}} \tag{4}$$

The term $g/\sigma^2 h_b$ in (4) describes the diffusion term effect on the dispersion. When the term vanishes (4) demonstrates the wave celerity in the wave equation which can be obtained by neglecting the second term. The wave celerity shows that the wave celerity of erosive waves is proportional to the long-wave velocity evaluated from the breaker depth and the square root of the ratio of breaker depth to threshold depth of sediment movement.

## CONCLUSION

By the use of data on long-term shoreline change in the reduction process of the river delta on the Shizuoka coast, we found that there exist two modes of shoreline change, namely shoreline change as a diffusion phenomenon and variation from shoreline change as a wave phenomenon. We name these erosive waves, which are defined respectively as erosive wave (D) and erosive wave (W) for the two modes of shoreline change. We conclude that the erosive wave (D), the first mode of shoreline change, expands down-coast as a diffusion phenomenon; but the erosive wave (W), the second mode of shoreline change, propagates down-coast as a wave phenomenon faster than the erosive wave (D). The shoreline change in the river delta coast can then be described as a diffusion-wave phenomenon.

The generation of the erosive waves was considered in terms of the sediment input from the river and local change in the submerged river-mouth delta. Finally, a theory for the diffusion-wave phenomenon of shoreline change was attempted using a set of equations of longshore sediment transport rate and continuity of shoreline change. From these the dispersion relation of the phenomenon was found. Further theoretical investigations are now being made to establish a predictive method for shoreline change.

## Acknowledgments

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