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REPORT OF THE PORT AND
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Medium-Term Variations of Bar Properties and Their Linkages with Environmental Factors at HORS

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Synopsis

Beach profile data obtained every weekday for 15 years from 1987 to 2001 along a 427-meter-long pier were analysed by Complex Empirical Orthogonal Function analysis. The seaward bar migration was represented by the first mode, and the migration frequency and the temporal variation of the bar amplitude were estimated with the complex time coefficient of the first mode. Although the seaward bar migration frequency, which is the reciprocal of the duration time of the bar migration cycle, was relatively constant before 1993 and ranged between 1.3 to 0.8 cycle/year (0.7 to 1.25 year/cycle), it gradually decreased after 1994 and reached 0.1 cycle/year (10 year/cycle) at the end of 1996. Subsequently, it gradually recovered to the frequency before 1993. The bar amplitude had a similar long period fluctuation. It was large before 1993, but small from 1995 to 1997, and then returned to the pre-1993 value. The bar migration frequency was weakly correlated with the offshore wave energy flux and the bar amplitude. The bar amplitude change frequency also had weak correlations with the parameters. The negative correlation between the bar amplitude and its change frequency indicates that there is a negative feedback system in the bar amplitude.

Key Words: longshore bar, beach profile response, Complex Empirical Orthogonal Function analysis, morphodynamics

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波崎海洋研究施設で観測された沿岸砂州の中・長期変動特性 およびその影響要因

栗山　善昭*・柳嶋　慎一**

要　旨

茨城県の波崎海洋研究施設において 15 年間（1987 年～2001 年）にわたりほぼ毎日取得された断面データを経験的複素固有関数法（CEOF 解析）を用いて解析した．バーの沖向き移動速度に比例するバーの位相の変動周波数は, 1994 年以前は 0.8～1.3 cycle/year（周期 0.7～1.25 年）であったものの，1994 年以降，次第に小さくなり，1996 年末には 0.1 cycle/year（周期 10 年）にまで低下した．バーの振幅も，長期的にはバーの移動速度と同様の時間変動を示しており，その値は，観測期間前半（1994 年以前）よりも後半（1995 年以降）の方が小さかった．このようなバーの長期変動には，外的要因である沖波エネルギーフラックスが影響していただけでなく，バーの振幅に関する負のフィードバック機構も関与していた．

キーワード：沿岸砂州，断面変化，経験的複素固有関数法

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1. Introduction

Longshore bars are frequently observed on sandy beaches and significantly influence currents, morphological variations and ecological systems in the nearshore zone. Bars migrate seaward and shoreward with development and decay of the amplitudes in response to variations of several environmental factors. Seaward bar migrations in short terms, one or two weeks, have been observed when the wave heights are relatively large (*Lippman and Holman*, 1990; *Plant et al.*, 1999). A high wave height-water depth ratio also induces seaward bar migration (*Plant et al.*, 1999). *Larson et al.* (2000) demonstrated a strong correlation between the beach profile and the ratio of wave breaking, with the bar migrating seaward as the offshore wave height increases and the ratio of wave breaking offshore increases. In contrast, *Sallenger and Howd* (1989) reported that the influence of wave breaking on the bar migration is small. *Kuriyama and Yamada* (2002) found that long period waves have less influence in inducing seaward bar migration.

Short-term shoreward bar migrations have been found to be caused by shoreward velocity skewness (*Greenwood and Osborne*, 1991; *Miller et al.*, 1999), a low undertow velocity (*Miller et al.*, 1999) and a low wave height-water depth ratio (*Plant et al.*, 1999). On the basis of two-month field measurement and numerical simulation of wave transformation, *Elgar et al.* (2001) suggested that shoreward bar migration is influenced by the acceleration skewness.

Short-term seaward and shoreward bar migrations were conceptually modelled. *Wright and Short* (1984), *Wright et al.* (1985) and *Sunamura* (1988) proposed parameters for the beach stage represented by the cross-shore bar position, while *Larson and Kraus* (1994) and *Sunamura and Takeda* (1993) proposed parameters to predict the direction of bar movement. *Thornton et al.* (1996) and *Gallagher et al.* (1998) numerically predicted bathymetry changes of a barred beach using an energetic-type sediment transport model (*Bailard*, 1981) and current velocities measured in the field, and showed that the numerical model is good for predicting the seaward bar migrations in storms, but not the shoreward migrations under mild wave conditions. *Hoefel and Elgar* (2003) succeeded in predicting the shoreward bar migration by adding a velocity acceleration term to the energetic-type sediment transport model. *Plant et al.* (1999) developed a numerical model to predict the bar crest position as a function of the offshore wave height, which showed good agreement between the bar crest positions measured and predicted for 16 years.

Although bars migrate seaward and shoreward in the short term, medium-term bar migrations are frequently in the seaward direction. Bathymetric data and video images have revealed medium-term seaward bar migrations with duration times of 1 year at Hasaki in Japan (*Kuriyama*, 2002), 4 years at Duck on the United States east coast (*Birkemeier*, 1984; *Lippmann et al.*, 1993), 2 to 5 years in New Zealand (*Shand and Bailey*, 1999), 12 years or more in Poland (*Rozynski*, 2003), and 6 to 20 years in the Netherlands (*Ruessink and Kroon*, 1994; *Wijnberg and Terwindt*, 1995). On the basis of field data obtained at these sites, *Shand et al.* (1999) and *Ruessink et al.* (2003) investigated the relationships between temporal and spatial bar properties such as duration time, cycle return period and bar amplitude, and environmental factors representing waves, currents, winds and beach slopes.

While a number of investigations have been conducted for short-term bar migrations and time-averaged bar properties, except for *Plant et al.* (1999), there have been few investigations on temporal variations of bar properties on a medium-term scale of several months to several years. Thus, medium-term variations of bar properties are poorly understood. In the present study, we investigated medium-term variations of bar properties and their linkages with environmental factors based on Complex Empirical Orthogonal Function (CEOF) analysis of beach profile data obtained almost every day for 15 years along a 427-meter-long pier on the Hasaki coast of eastern Japan.

2. Data description

Beach profile data were obtained for 15 years from January 1987 to December 2001 at Hazaki Oceanographical Research Station (HORS), located on the Hasaki coast of Japan facing the Pacific Ocean (**Figure 1**). HORS has a 427-m-long pier, with the deck of 3.3 m in width and 6.9 m above the low water level being supported by single pilings. The beach profiles along the pier were measured at 5 m intervals every day, except for weekends and holidays, with a 5 kg lead from the pier, and with a level and a staff shoreward of the pier. The median sediment diameter along the profile is 0.18 mm and remains almost uniform along the profile. However, it occasionally increased to 1.0 mm in troughs after severe

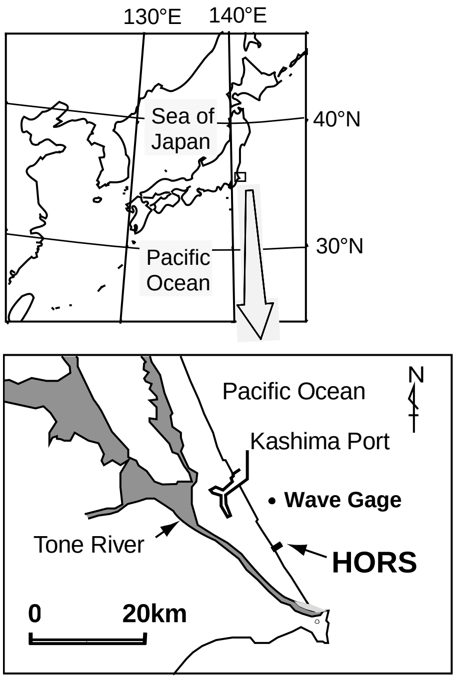

Figure 1 Locations of the study site and the offshore wave gage.

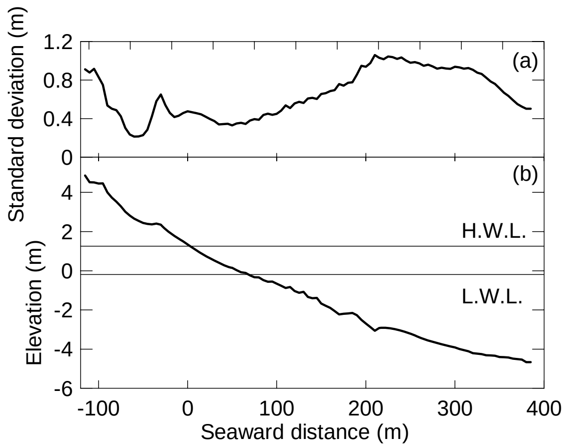

Figure 2 Standard deviation in elevation (a) and mean beach profile (b) based on 15 years of data from 1987 to 2001 of beach profiles along the HORS pier. The elevation is based on the Hasaki datum level.

storms (*Katoh and Yanagishima*, 1995). Based on the datum level at Hasaki (Tokyo Peil -0.687 m), the high, mean and low water levels are 1.252 m, 0.651 m, and -0.196 m, respectively, and the tidal range is 1.448 m. Deepwater waves were measured at a water depth of about 24 m with an ultrasonic wave gage for 20 minutes every 2 hours throughout the investigation period (see location on **Figure 1**). Missing wave data from the period February 7 to March 3 in 1993 were estimated using the method of *Hashimoto et al.* (2000).

Figure 2 shows the averaged beach profile. Each position along the pier is referred to as the seaward distance relative to the reference point, located close to the entrance of the pier and designated as "P." For example, P230m denotes a position 230 m seaward from the reference point. The mean beach slope decreases gradually offshore. Gradients are about 1/40 near the shoreline at the low water level, about 1/80 at P250m and about 1/110 near the tip of the pier. The standard deviation in elevation increases seaward from around P50m, with a peak of about 1 m around at P210m, and then gradually decreases to 0.5 m at P380m.

Alongshore uniformity of bathymetry near HORS has been investigated by *Kuriyama* (2002). Besides the daily surveying at HORS, the bathymetry near HORS has been surveyed once or twice a year in an area 600 m wide in the alongshore direction and about 700 m long in the cross-shore direction. *Kuriyama* (2002) applied Empirical Orthogonal Eigenfunction (EOF) analysis to 17 bathymetric maps around HORS obtained from 1986 to 1998, and showed that the beach profiles adjacent to the pier were almost uniform alongshore, and the influence of the pilings on the bathymetry appears to be minimal.

3. Medium-term bar behavior

Figure 3 shows the spatial and temporal variations of the deviation in elevation from the mean beach profile, and **Figure 4** shows the temporal variation of the bar crest position. The bar crest and the trough were defined as points of local maximum and minimum elevations, respectively, as in *Kuriyama* (2002). A bar of height less than 50 cm, defined as the difference in elevation between a bar crest and the shoreward trough, was eliminated from the analysis.

The Hasaki coast had a single outer bar and sometimes an inner bar after a storm. The outer bar was generated at around P180m, migrated seaward and reached the tip of HORS. Almost at the same time when the bar crest reached the tip of HORS, a new bar crest was generated at around P180m and began to migrate seaward. Because no bars were observed seaward of P450m according to the 17 bathymetric maps around HORS (*Kuriyama*, 2000), bar crests are expected to disappear shortly after reaching the tip of HORS. The mean and standard deviation of the crest elevations of the outer

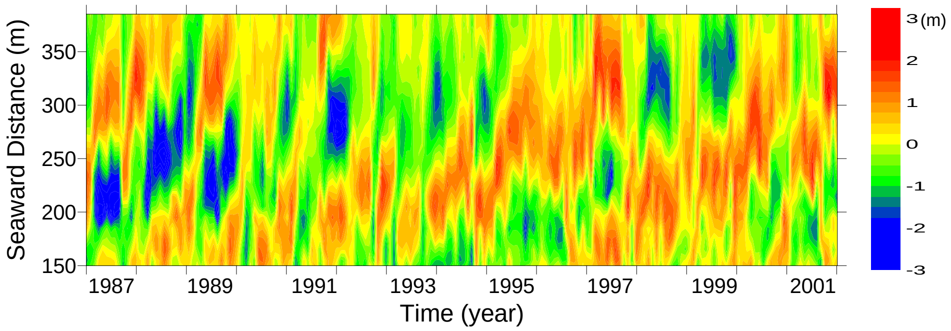

Figure 3 Variation in elevation from the mean beach profile at HORS. The elevations above and below the mean profile are shown by warm and cold colors, respectively.

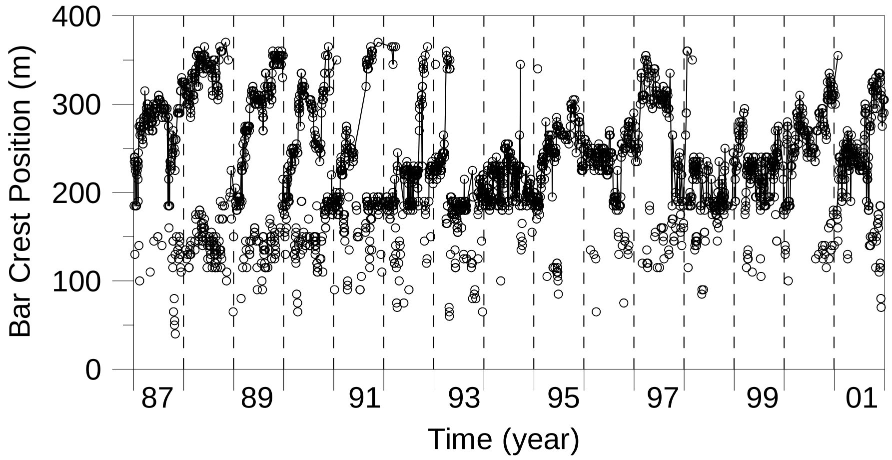

Figure 4 Temporal variation of bar crest position along the HORS pier during a period from 1987 to 2001. The solid lines show the bar crest migrations seaward of P180m.

bars, which were located seaward of P180m, are -2.07 m and 0.83 m, and those of the bar heights are 1.30 m and 0.58 m.

The spatial and temporal variations of the deviation in elevation from the mean beach profile show that areas above and below the mean beach profile moved seaward with a duration time of about 1 year before 1993, but with a time of about 2 years after 1994 (**Figure 3**). The temporal variation of the bar crest position also gave a similar pattern (**Figure 4**).

A Short Time Fourier Transform analysis with a window of 7 years (e.g., *Newland, D.E.*, 1993) was applied to the elevation at P300m, which is located in the middle of the bar movement zone of P180m to P380m. The location of the peak shifted from 1 year (f = 0.0027 cycle/day) prior to 1993 to 1.6 years (f = 0.0017 cycle/day) after 1995 (**Figure 5**).

For more detailed analysis, Complex Empirical Orthogonal Function (CEOF) analysis was applied to the elevation deviations from the mean beach profile. CEOF analysis,

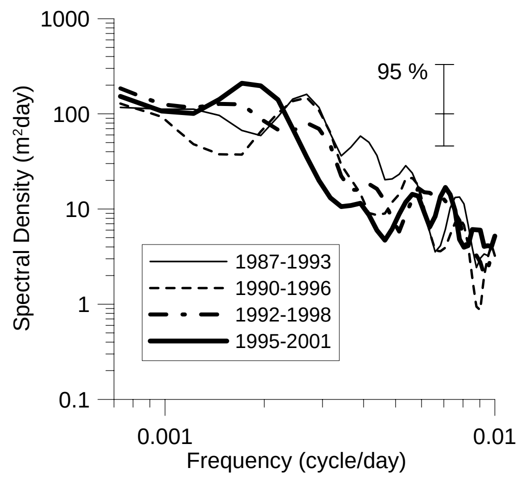

Figure 5 Spectral density of the elevation change at P300m based on a Short Time Fourier Transform analysis for the years of 1987 - 1993, 1990 - 1996, 1992 – 1998, and 1995 – 2001. The vertical line shows the 95% confidence interval.

which is an expansion of Empirical Orthogonal Function (EOF) analysis (*Horel*, 1984; *von Storch and Zwiers*, 1999), decomposes the complex deviation $Z(x,t)$ expressed as Eq. (1) into the products of the complex temporal coefficients and the complex nondimensional spatial eigenfunctions expressed as Eq. (2) (e.g., *Liang and Seymour*, 1991; *Ruessink et al.*, 2000; *Kuriyama and Lee*, 2001; *Ruessink et al.*, 2003).

$$Z(x,t) = z(x,t) + i\hat{z}(x,t), \quad (1)$$

$$Z(x,t) = \sum_n \left(C_{nr}(t) + iC_{ni}(t)\right)\left(e_{nr}(x) - ie_{ni}(x)\right), \quad (2)$$

where $z(x,t)$ is the deviation from the mean beach profile, $\hat{z}(x,t)$ is the Hilbert transform of $z(x,t)$, the subscript n represents the values in the nth mode, $C_{nr}(t)$ and $C_{ni}(t)$ are the real and imaginary parts of the complex temporal coefficient, and $e_{nr}(x)$ and $e_{ni}(x)$ are the real and imaginary parts of the complex eigenfunction.

The deviation expressed by the nth mode is reconstructed as:

$$z_n(x) = \mathrm{Re}\left\{\left(C_{nr}(t) + iC_{ni}(t)\right)\left(e_{nr}(x) - ie_{ni}(x)\right)\right\}. \quad (3)$$

Equation (3) is re-expressed as (e.g., *Ruessink et al.*, 2000):

$$\begin{aligned} z_n(x,t) &= S_n(x)R_n(t)\cos\left\{\theta_n(x) - \psi_n(t)\right\}, \\ S_n(x) &= \sqrt{e_{nr}(x)^2 + e_{ni}(x)^2}, \\ R_n(t) &= \sqrt{C_{nr}(t)^2 + C_{ni}(t)^2}, \\ \theta_n(x) &= \arctan\left(e_{ni}(x)/e_{nr}(x)\right), \\ \psi_n(t) &= \arctan\left(C_{ni}(t)/C_{nr}(t)\right). \end{aligned} \quad (4)$$

The phase of the complex temporal coefficient in $\psi_n(t)$ expresses the temporal phase of the profile, and hence the time derivative of $\psi_n(t)$ represents the frequency of the profile change. The value of $R_n(t)$ expresses the temporal variation of the profile amplitude.

The contribution of the elevation change expressed by the first mode to the measured elevation change is over 50% in the region from P200m to P360m (**Figure 6**), where bars developed, and the amplitude of the complex spatial eigenfunction seaward of P200m is larger than that shoreward of P200m (**Figure 7**). These results indicate that the first mode represents the bar evolution, which was the predominant beach profile change at the investigation site. The first modes of the CEOF analyses applied to beach profile data at Duck in the United States and four Dutch coasts also represent the bar migrations (*Ruessink et al.*, 2001).

The temporal variation of $\psi_1/2\pi$ shown in **Figure 8** is similar to that of the bar crest position (**Figure 4**), and the correlation between the two parameters is strong (**Figure 9**).

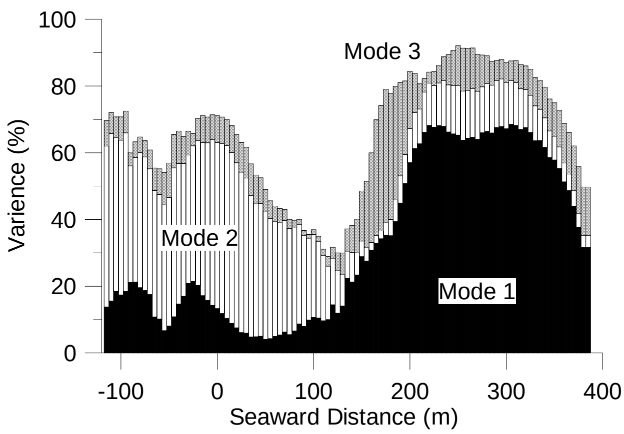

Figure 6 Variance at each location explained by the first three modes of the Complex Empirical Orthogonal Function analysis for the profile data from 1987 to 2001.

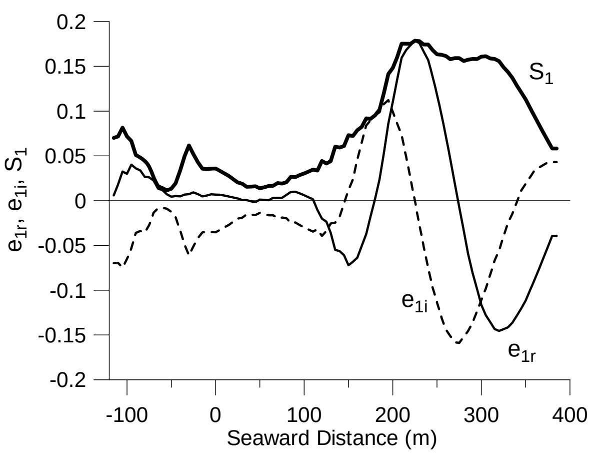

Figure 7 Spatial variations of the real and imaginary parts of the complex eigenfunction in the first mode, e_{1r} and e_{1i}, and the amplitude of the complex eigenfunction S_1.

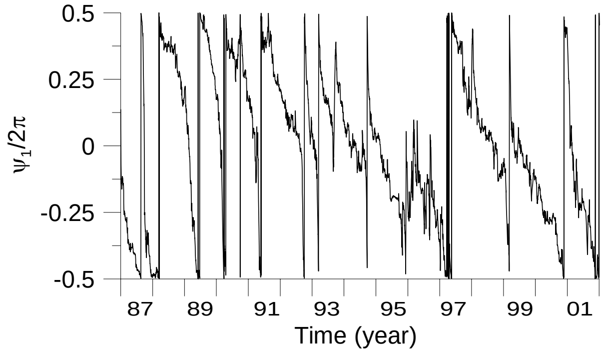

Figure 8 Temporal variation of the phase of the complex temporal coefficient of the first mode $\psi_1/2\pi$.

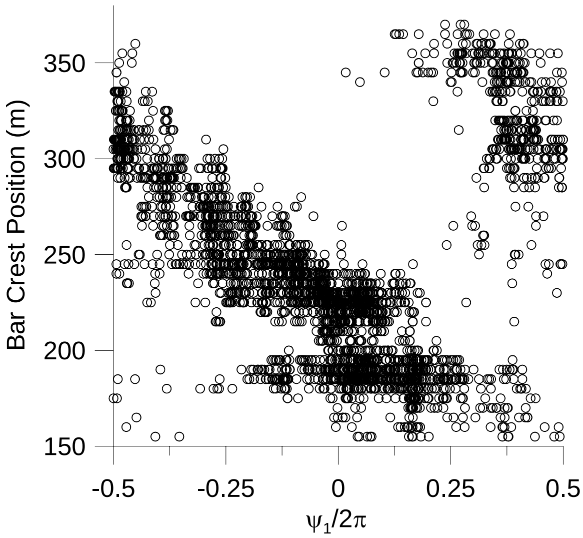

Figure 9 Relationship between the bar crest position and the phase of the complex temporal coefficient of the first mode $\psi_1/2\pi$.

This result indicates that $\psi_1/2\pi$ represents a surrogate for the bar crest position, and $d(\psi_1/2\pi)/dt$ represents the bar migration frequency; which is the reciprocal of the duration time of the bar migration cycle. In the following analysis, the seaward bar migration is represented by the negative value of $d(\psi_1/2\pi)/dt$.

The temporal variation of the bar migration frequency $d(\psi_1/2\pi)/dt$ has relatively large spectral densities at 40 days (f = 0.025 cycle/day), 180 days (6 months, f = 0.0055 cycle/day) and 700 days (1.9 years, f = 0.0014 cycle/day) (**Figure 10**). In order to investigate the medium-term variation of the bar migration frequency, the components with periods longer than 150 days (f = 0.0067 cycle/day) and those with periods longer than 1,000 days (f = 0.001 cycle/day) were reconstructed. The temporal variation of the reconstructed components with periods longer than 150 days shows that the bar migration frequency represented by $d(\psi_1/2\pi)/dt$ fluctuated over a 6-month cycle between -4.0 to 0.5 cycle/year (**Figure 11**). The variation in periods longer than 1,000 days shows that although the bar migration frequency ranged between -1.3 to -0.8 cycle/year (0.7 to 1.25 year/cycle) prior to 1993, it gradually decreased after 1994, and reached -0.1 cycle/year (10 year/cycle) at the end of 1996. It then gradually recovered to the frequency before 1993.

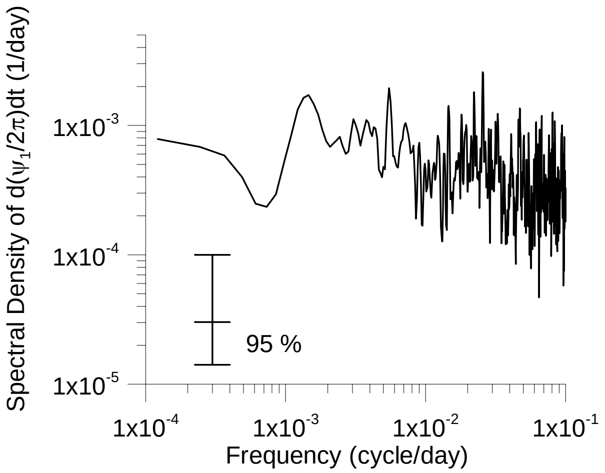

Figure 10 Spectral density of the bar migration frequency $d(\psi_1/2\pi)/dt$. The vertical line shows the 95% confidence interval.

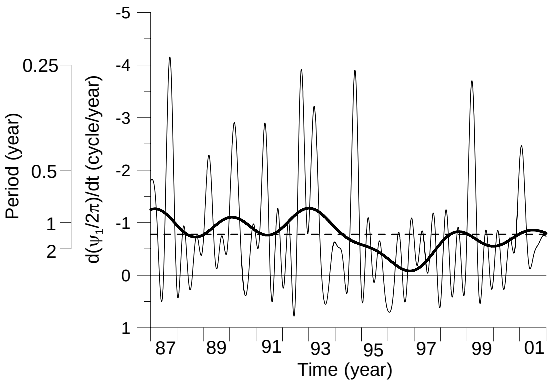

Figure 11 Long period components of the bar migration frequency $d(\psi_1/2\pi)/dt$. The thin and thick solid lines show the reconstructed components whose periods are longer than 150 days and 1,000 days, respectively. The dashed line shows the averaged value.

The value of R_1, which represents the temporal variation of the bar amplitude, has a relatively large spectral density at 400 days (f = 0.0025 cycle/day) (**Figure 12**), and the location of the large spectral density is different from those in $d(\psi_1/2\pi)/dt$ (**Figure 10**). However, the temporal variation of the reconstructed components of R_1 with periods longer than 1,000 days shows that R_1 acted similarly to $d(\psi_1/2\pi)/dt$ in that both were of smaller magnitude during the period from 1995 to 1997 (**Figure 13**).

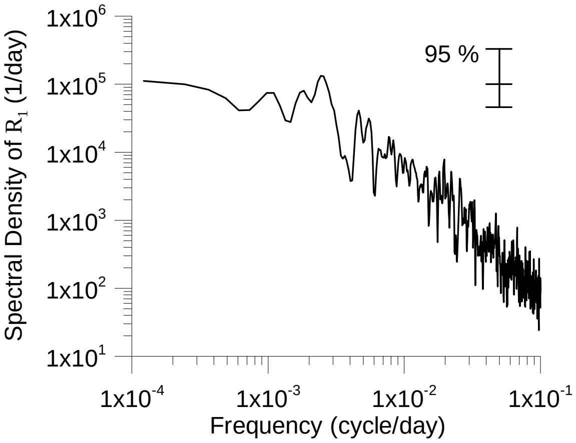

Figure 12 Spectral density of the temporal coefficient of the bar amplitude R_1. The vertical line shows the 95% confidence interval.

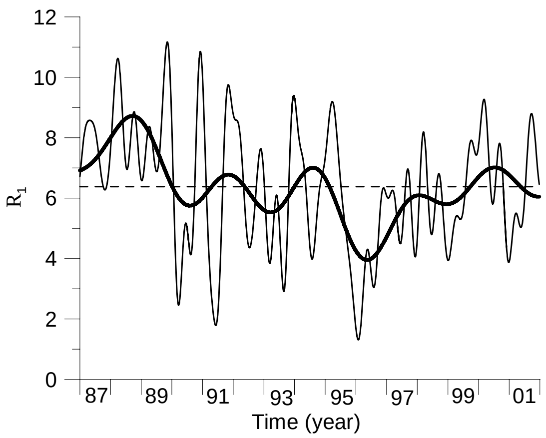

Figure 13 Long period components of the temporal coefficient of the bar amplitude R_1. The thin and thick solid lines show the reconstructed components with periods longer than 150 days and 1,000 days, respectively. The dashed line shows the averaged value.

4. Linkages of bar migration frequency and bar amplitude with environmental factors

4.1 Bar migration frequency

Seaward bar migration is influenced by the offshore wave energy flux (*Kuriyama*, 2002). The increase in the offshore wave energy flux induces more active sediment movement. Furthermore, if a feedback system affects the bar migration, the bar position or the bar amplitude may have an influence on the bar migration frequency. Hence, the correlations between the bar migration frequency $d(\psi_1/2\pi)/dt$, and ψ_1 representing the bar crest position, R_1 representing the temporal coefficient of the bar amplitude and the offshore wave energy flux E_f were investigated.

The value of E_f was given by

$$E_f = \frac{1}{16}\rho g (H_{1/3})_0^2 C_{g0}\,, \tag{5}$$

where $(H_{1/3})_0$ is the offshore significant wave height and C_{g0} is the offshore group velocity. The daily averaged E_f was estimated from the offshore wave data obtained every two hours.

At the 1% significance level, the bar migration frequency had no correlation with the bar crest position, but weak negative correlations with the bar amplitude and the offshore wave energy flux (**Table 1**). Because the positive bar migration frequency was defined to be shoreward, the results shown in **Table 1** indicate that the seaward bar migration frequency increased as the offshore wave energy flux and the bar amplitude increased.

4.2 Bar amplitude

As in **4.1**, we investigated the correlations between the frequency of the bar amplitude change dR_1/dt, and the

Table 1 Correlation coefficients between the bar migration frequency $d(\psi_1/2\pi)/dt$ and the parameters of the bar crest position ψ_1, the temporal coefficient of the bar amplitude R_1 and the offshore wave energy flux E_f. The number of data items is 5476.

ψ_1	R_1	E_f
0.01	-0.21	-0.16

Table 2 Correlation coefficients between the frequency of the bar amplitude change dR_1/dt and the parameters of the bar crest position ψ_1, the temporal coefficient of the bar amplitude R_1 and the offshore wave energy flux E_f. The number of data items is 5476.

ψ_1	R_1	E_f
-0.03	-0.08	0.07

parameters of the bar crest position ψ_1, the temporal coefficient of the bar amplitude R_1 and the offshore wave energy flux E_f. At the 1% significance level, the bar amplitude change frequency had no correlation with the bar crest position ψ_1, but a weak positive correlation with the offshore wave energy flux E_f, and a weak negative correlation with the temporal coefficient of the bar amplitude R_1 (**Table 2**). The result that dR_1/dt had a weak negative correlation with R_1 indicates that a weak negative feedback functioned in the bar amplitude variation; the frequency of the bar amplitude change dR_1/dt increased as the temporal coefficient of the bar amplitude R_1 decreased, and dR_1/dt decreased as R_1 increased.

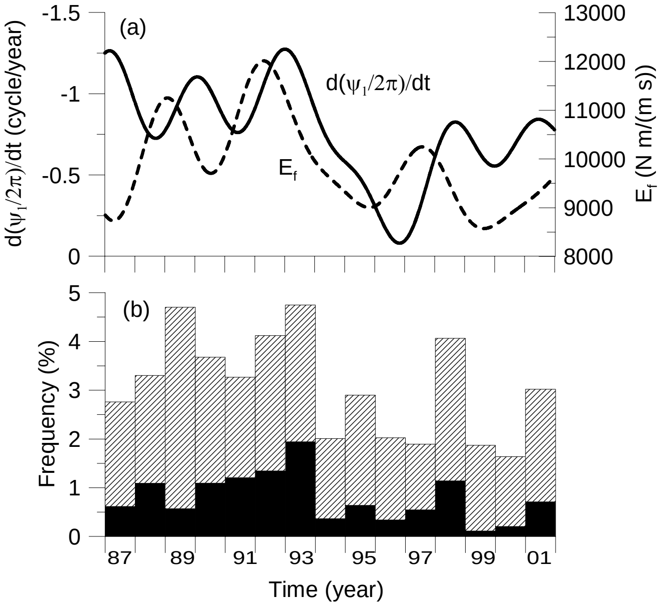

Figure 14 (a) Long period components of the bar migration frequency $d(\psi_1/2\pi)/dt$ (solid line) and the offshore wave energy flux F_f (broken line). (b) Annual occurrence frequency of high waves. Solid bars show the values over 4 m, and the hatched ones between 3 and 4 m.

5. Discussion

The medium-term bar behavior may be influenced by abrupt seaward bar migrations in storms. At the Hasaki coast, however, the correlation between the bar migration frequency and the offshore wave energy flux was relatively low (**Table 2**). Furthermore, the temporal variation of the reconstructed long period components in the bar migration frequency whose periods are longer than 1000 days did not show complete synchrony with those of the long period components of the offshore wave energy flux and of the annual occurrence of high waves (**Figure 14**). These results indicate that the bar did not always migrate seaward in a storm and hence the medium-term bar behavior is not strongly influenced by the number of storms.

The negative feedback in the bar amplitude found in this study is to keep the bar amplitude constant and is different from the negative and positive feedbacks in *Plant et al.* (2001). Although *Plant et al.* (2001) showed that a bar moves seaward and approaches the equilibrium position without the bar amplitude change in the negative feedback, the bar migration frequency in this study was irrelevant with respect to the bar position (**Table 2**), a result which suggests that there was no equilibrium bar position. *Plant et al.* (2001) also described the positive feedback that takes place when a bar migrates shoreward with the amplitude decay. When the offshore wave energy flux was small in this study, $d(\psi_1/2\pi)/dt$ and dR_1/dt became negative, which resulted in shoreward bar migration with bar amplitude decay. However, a small R_1 made dR_1/dt positive, and hence the amplitude decay did not continue. The causes of the difference in the feedback system in the bar evolution are not clear yet, and further investigation is required.

6. Conclusions

CEOF analysis was applied to beach profile data obtained every weekday for 15 years along the 427-meter-long HORS pier at the Hasaki coast in Japan. The seaward bar migration was represented by the first mode of CEOF analysis and the bar crest position had a strong correlation with the phase of the complex temporal coefficient of the first mode $\psi_1/2\pi$.

The temporal variation of the seaward bar migration frequency represented $d(\psi_1/2\pi)/dt$, in which the shoreward migration was defined as being positive, had relatively large spectral densities at 40, 180 and 700 days. The components with periods longer than 150 days showed that the bar migration frequency $d(\psi_1/2\pi)/dt$, which is the reciprocal of the duration time of the bar migration cycle, fluctuated on a 6-month cycle between -4.0 to 0.5 cycle/year. Those with periods longer than 1,000 days showed that although the bar migration frequency ranged between -1.3 to -0.8 cycle/year (0.7 to 1.25 year/cycle) before 1993, it gradually decreased after 1994 and reached -0.1 cycle/year (10 year/cycle) at the end of 1996. It then gradually recovered to the frequency before 1993.

The temporal variation of the bar amplitude represented by R_1 had a relatively large spectral density at 400 days, and the location of the large density was different from those in $d(\psi_1/2\pi)/dt$. However, the temporal variation of the long period components, with periods longer than 1,000 days, had a similar pattern with that of $d(\psi_1/2\pi)/dt$, namely that it was large before 1993, but small from 1995 to 1997, and then returned to the value before 1993.

The bar properties of the bar migration frequency $d(\psi_1/2\pi)/dt$ and the bar amplitude change frequency dR_1/dt had correlations with the offshore wave energy flux and the bar amplitude R_1. The negative correlation between dR_1/dt and R_1 indicated that a weak negative feedback existed in the bar amplitude change, such that the bar amplitude change frequency dR_1/dt increased as the temporal coefficient of the bar amplitude R_1 decreased, and dR_1/dt decreased as R_1 increased.

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