Characteristics of long-period flow velocity fluctuations around Tomakomai Harbor

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1. Abstract

Studies of flows near the coast from the viewpoint of coastal engineering have focused on tidal currents and nearshore currents that are generated by waves in breaker zones.However, on-site observations have shown that there also exist strong flows with long periods of several days. As these long-period flows have a high velocity even at deep water levels outside breaker zones,they are thought to play an important role in the offshore drift-sand phenomenon and in the convection and diffusion of floating larvae of marine organisms.Through analysis of observation date on wind velocity and flow velocity recorded around Tomakomai Harbor, the temporal and spatial characteristics of long-period velocity fluctuations of these flows were clarified.We confirmed the existence of and clarified the characteristics of long-period flow velocity fluctuations around Tomakomai Harbor that have a period of 3～4 days and propagate in a westerly direction at a phase velocity of approximately 2.0km/h. These long-period flow velocity fluctuations can be estimated by the storm surge formula that assumes wind stress to be the extemal force and Coriolis force to be the restoring force.

2. Introduction

Studies of flows near the coast from the viewpoint of coastal engineering have focused on tidal currents and nearshore currents that are generated by waves in breaker zones. However, on-site observations have shown that there also exist strong flows with long periods of several days.Adams and Buchwald (1969) pointed out that wind stress parallel to the coastline is

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important for the occurrence of shelf waves. Nakamura (1990) showed from the results of on-site observations carried out over a period of many years on the coast of Fukushima that there exist southward-propagating flow velocity fluctuations with a period of 3 or 4 days, propagating the direction with the shoreline on the right,and he reported that these flows correspond to the second mode of shelf waves. He also pointed out that these flows affect the drifting and diffusion of floating bivalve larvae. Sato (1995) reported the existence of a strong flow at a depth of 15m off the Hokuriku coast that reaches a speed of up to 1m/s along the coastline and reported that this flow is mainly caused by wind stress and Coriolis force. Yasuda et al. (1995) pointed out that not only wind stress but also the effect of momentum transportation due to offshore breakers is important in the generation of strong flows outside the breaker zone. As these flows with long periods of several days have a high velocity even at deep water levels outside breaker zones, they are thought to play an important role in the offshore drift-sand phenomenon and in the convection and diffusion of floating larvae of marine organisms. However, there have been very few field studies conducted on these flows. Moreover, these strong flows are caused not only by a large variety of factors such as wind stress, offshore breakers, differences in density and shelf waves but also by combinations of these factors, making it difficult to clarify the physical mechanisms of flow occurrence.

Therefore, in this study, through analysis of observation data on flow velocity and wind velocity recorded around Tomakomai Harbor, we attempted to clarify the temporal and spatial characteristics of long-period velocity fluctuations of these flows, and the correlation between flow velocity and wind velocity. Next, we performed numerical calculation of these flows using a storm surge formula, and by a comparison with the observation results, we were able to investigate the mechanisms that generate these flows.

3. On-site observation data

The observation data used for the analysis were flow and wind velocities measured at the sites around Tomakomai Harbor shown in Fig. 1. Flow velocity data included long-term continuous observation data collected at one site and short-term observation data collected at multiple sites. The long-term continuous observation data of flow velocity were measured by an NC-2 current meter set at 23.5 m under the sea surface and at 1m above the sea bottom at site A, which is located 2.5km offshore from the west harbor (see Fig. 1). Velocity data (90-sec mean velocity) collected every hour from January 1990 to August 1995 were used for the analysis. The short-term data were measured by a RCM-4 current meter set at 5m below sea surface at

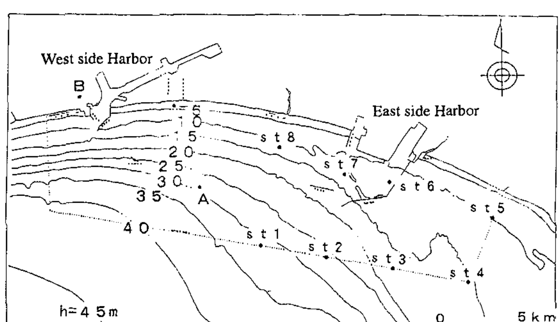


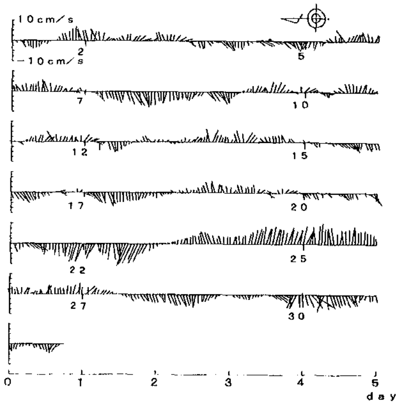
Fig.1 Observation sites around Tomakomai Harbor

eight observation sites (St. 1～St. 8) around the east harbor (see Fig. 1). The offshore sites, St. 1～St. 4, run almost parallel to the shoreline, and the water is shallower on the east side. At St. 1～St. 8, 20-min mean flow velocities were measured at 20-min intervals over a period of 30 days four times a year (in June, July, October and February). Wind velocity was measured at 10m above the ground at site B (see Fig. 1). Wind velocity data obtained every hour during the same period as the recording of long-term continuous flow velocity were used for the analysis.

4. Characteristics of long - period flow velocity fluctuations

4.1 Temporal characteristics of flow velocity fluctuations

Fig. 2 shows flow velocity data obtained over a one-month period in October 1993. As can be seen in the figure, there were flow velocity fluctuations with periods of 12.5 hours and 25 hours attributed to the tides. There were also flow velocity fluctuations with shorter periods and flow velocity fluctuations with long periods of 4～6 days. The flows with long-period flow velocity fluctuations were mainly in an east-west direction, parallel to the shoreline. In the present study, we focused on these flow velocity fluctuations with a long period of several days. In order to show the components of these long-period fluctuations, we calculated the 25-hour moving averages of the flow velocity raw data used in Fig. 2 and extracted the flow velocity fluctuations with periods shorter than tidal periods. The results are shown in Fig. 3. As can be seen in the figure, the periods of the flow velocity fluctuations are 4～7 days.



1 ～ 31 Oct. 1993

Fig.2 Temporal characteristics of flow velocity

Next, we divided the raw data of flow velocities for October 1993 shown in Fig. 2 into two components: the component of flows in a direction parallel to the shoreline and the component of flows in a direction perpendicular to the shoreline. Fig. 4 shows the power spectrums for these

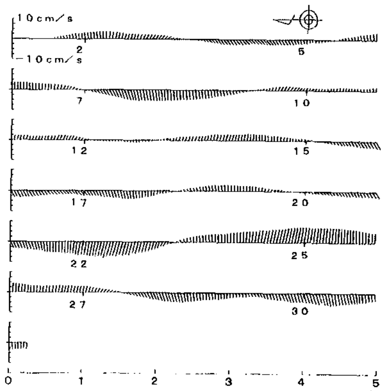


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Fig.3 25-hour moving average of flow velocity two components. The spectrums were calculated by MEM using 700 data values obtained every hour over a period of 30 days. For the flow velocity component in a parallel direction to the shoreline, the spectrum density is greatest at a period of about 150 hours (about 6 days).These long-period fluctuations correspond to the velocity fluctuations with periods of 4～7 days in Figs. 2 and 3 and were dominant flow fluctuations in October 1993. A comparison of the parallel and perpendicular components of flow velocity shows that the parallel components of these long - period flow velocity are dominant. A spectrum of flow velocity fluctuations observed every month over a period of 6 years showed that strong flow velocity fluctuations with a long period of several days were dominant throughout the year except in the early summer and mid-summer months from May to July. Nakamura (1990) reported that flow velocity fluctuations with long periods of several days could be observed off the coast of Fukushima throughout the year except for summer, when there is a great difference between daily maximum and minimum water temperatures caused by thermocline. These observation results are similar to the results of our observations of flow velocity fluctuations off the coast of Tomakomai.

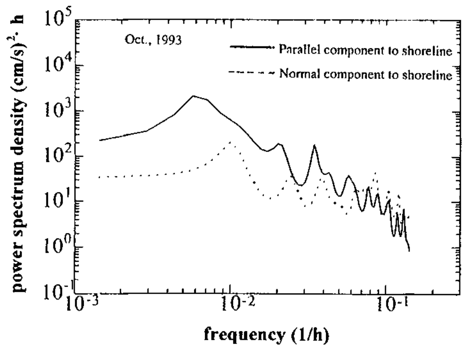


Fig.4 Power spectrum of flow velocity

4.2 Spatial characteristics of flow velocity fluctuations

Fig. 5 shows the measurements of flow velocity from September 28 to October 7, 1993 at St. 1 ～ St. 8 around the east harbor. This observation period is almost the same as the first ten days in Fig. 2. As can also been seen in this figure, the dominant flow velocity fluctuations were those with a period of several days, and most of these flows were in an east-west direction. As can be seen in Fig. 5, flow velocity fluctuations have the following spatial characteristics. St. 1 ～ St. 4 (offshore sites) showed almost the same tendencies in flow velocity fluctuations. The intensities of flow velocity fluctuations were almost the same at St. 1 and St. 4, while St. 2 and St. 3 showed larger flow velocity fluctuations. For example, on September 28, when there was a dominant eastward flow, the maximum flow velocity fluctuation at St. 1 and St. 4 was about 15cm/s, while the flow velocity fluctuation at St. 3 reached a maximum of 30cm/s. This difference is thought to be due to the acceleratory effect caused by the breakwater in the harbor; this effect should be considered when dealing with the issue of drift sand around a breakwater, especially in deep water around the end of the breakwater. As can be seen in the figure, St. 5 also showed similar flow velocity fluctuations to those at St. 1 ～ St. 4.

On the other hand, St. 8 showed similar flow velocity fluctuations to those at St. 1 ～ St. 4 when an eastward flow was dominant at the offshore sites, but the flow direction at St. 8 was opposite to that at St. 1 ～ St. 4 on September 29, October 4 and October 7, when an westward flow was dominant at St. 1. It is thought that a westward flow with a velocity fluctuation period of several days changes direction at St. 8 after circling around the back of the breakwater. This type of circulatory flow around a large harbor could be effective for preventing the drifting and diffusion of floating larvae of bivalves such as surf clams. A flow in the opposite direction to that at St. 1 was rarely seen at St. 5. This is thought to be due to the shape of the breakwater, although many points still remain unclear. However, this phenomenon is thought to be an important factor in assessing the effects on the coastal environment, and especially the hydraulic environment, of large harbors, and further investigation of this phenomenon is needed. The flow velocity fluctuations at St. 6 and St. 7 (nearshore sites) are much smaller than those at other sites; most of the flow velocity fluctuations at these two sites have short periods that accord with the tides.

A comparison of the flow velocity fluctuation data from October 1 to October 7 in Figs. 2 and 5 for site A and St. 1, which are located relatively close together (see Fig. 1), shows that although these two sites have similar flow velocity fluctuations, the flow velocity at site A, where measurements were conducted near the sea bottom, is only about half that at St. 1. The vertical distribution of flow velocity fluctuations with long periods is also important for transport problems of matter such as drift sand.

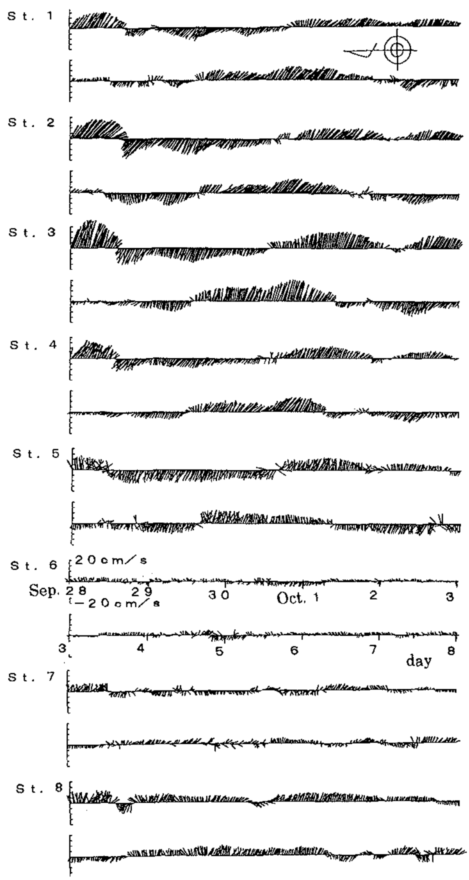
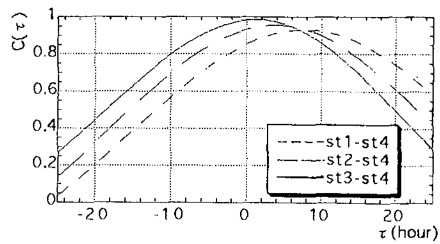


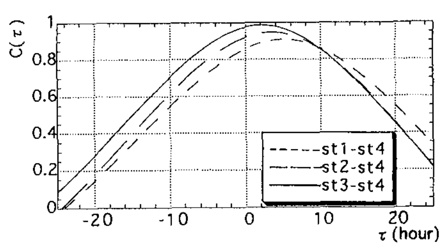
Fig.5 Spatial characteristics of flow velocity fluctuations around the east side of Tomakomai Harbor

Since St. 1 ~ St. 4, sites that are not affected greatly by the harbor (see Fig 5), showed very similar flow velocity fluctuations, we calculated the correlations of east-west and north-south flows between these sites using 25-hour moving averages of the observation data obtained at each site. Fig. 6(a) and (b) show the correlation coefficients C(τ) between flow velocities at St. 4 and those at St. 1 ~ St. 3 for a 30-day period in October 1993. The distances between St. 3 and St. 4, St. 2 and St. 4, and St. 1 and St. 4 are 4.0km, 7.5km, and 10.9km, respectively. As can be seen in the figures, the correlation coefficients between all of the sites are high (over 0.9) for both the east-west and north-south components. Also, the time lag (τ) increases as the westward distance from St. 4 increases, and the correlation coefficient decreases slightly as the distance between sites increases. These results indicate that flow velocity fluctuations with long periods propagate about 10km to the south with little change in form. This property is the same as that of shelf waves along coasts in the northern hemisphere, the direction of propagation being with the shoreline on the right.

Table 1 shows the time lags between sites in various observation periods and the phase velocities of flow velocity fluctuations in these observation periods. The table shows that flow velocity fluctuations were always in an east-to-west direction and that the phase velocity ranged from 1.5~3.0 km/h.



(a) East - West velocity component



(b) North - South velocity component

Fig.6 Cross correlation of long - period flow velocities between these sites

Table 1 Correlation coefficient and phase velocity

Month	Year	Sites	Correlation coefficient	Time lag (min)	Phase velocity (km/h)
May	1993	st2-st4	0.88	300	1.5
May	1993	st3-st4	0.97	90	2.7
Oct.	1993	st1-st4	0.93	460	1.4
Oct.	1993	st2-st4	0.95	240	1.9
Oct.	1993	st3-st4	0.98	80	3.0
Jan.	1994	st1-st4	0.91	300	2.2

4.3 Correlation between flow and wind velocities

Fig. 7 shows the raw data of wind velocities recorded during the same period in October 1993 as that in Fig. 2. As can be seen in the figure, wind velocity data also have fluctuations with periods of several days. A comparison with the data in Fig. 2 shows that there is a clear correlation between flow velocity and wind velocity fluctuations and that wind velocity fluctuations is slightly faster for change in phase than flow velocity fluctuations.

Fig. 8 shows the same power spectrums for wind velocity as those calculated for flow velocity in Fig. 4. The majority of winds blowing in a direction parallel to the shoreline had a velocity fluctuation period of about 150 hours.This is similar to that of the flow velocity fluctuations shown in Fig. 4.

We calculated the correlation coefficients between flow velocities at site A and wind velocities at site B.Table 2 shows the correlation coefficients that were greater than 0.8. The correlation coefficients between flow and wind velocities in the months not shown in the table were also relatively high; for example, the correlation coefficients were 0.7～0.8. for other months in 1993. The time lags of flow velocity are also shown in the table. In the case of a high correlation coefficient between flow and wind velocities, there was a time difference of 6 to 11 hours between sea flow and wind.The above results show that a sea flow is generated approximately 6 to 11 hours after a strong wind starts to blow, suggesting that tangential stress acting on the sea surface due to wind is important for the external forces that cause flow velocity fluctuations with long-term periods.

Velocity fluctuations in flows off the coast of Tomakomai with periods of 4～7 days showed a strong correlation with wind. As possible factors affecting wind, we investigated the positional relationship between low and high atmospheric pressures and the relationship between wind and flow velocities. The following results were obtained. When low and high atmospheric pressures pass over

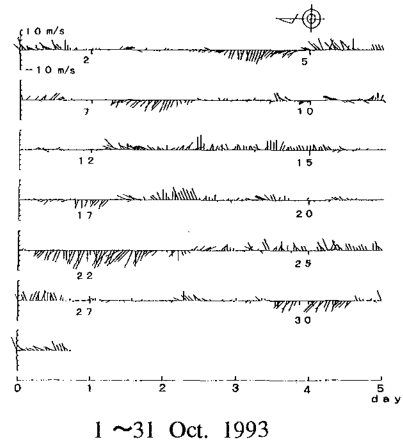


Fig.7 Temporal characteristics of wind velocity

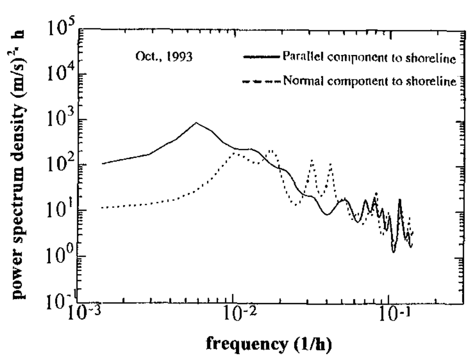


Fig.8 Power spectrum of wind velocity

Table 2 Correlation coefficient and time lag

Month	Year	Correlation coefficient	Time lag (hour)
Nov.	1990	0.89	11
Oct.	1991	0.83	9
Apr.	1992	0.83	10
May	1992	0.89	6
Aug.	1993	0.85	6
Mar.	1994	0.84	8
Aug.	1995	0.81	10

Tomakomai together, flow velocity fluctuations with long periods occur. When there is low pressure to the west and high pressure to the east of Tomakomai, westward wind and sea flows occur, and when there is low pressure to the east and high pressure to the west of Tomakomai, eastward wind and sea flows occur. These results suggest that wind velocity, which is largely determined by the atmospheric pressure pattern, and fluctuations in the sea surface due to changes in atmospheric pressure affect flows.

5.Numerical calculation of long-period flow velocity fluctuations

A flow velocity fluctuation with a long period of several days is thought to be generated by wind stress and atmospheric pressure fluctuations accompanying the passing of a low atmospheric pressure, and Coriolis force as restoring force.At a first step, numerical calculation was performed by similar method with Sato (1995) using a basic formula for storm surge.An outline the numerical calculation is as follows:

$$\frac{\partial M}{\partial t}+\frac{\partial}{\partial x}\left(\frac{M^2}{d}\right)+\frac{\partial}{\partial y}\left(\frac{MN}{d}\right)-fN+gd\frac{\partial \eta}{\partial x}+\frac{d}{\rho_w}\frac{\partial p_0}{\partial x}-\frac{\partial \tau_{sx}}{\rho_w}-\frac{\partial \tau_{bx}}{\rho_w}-\varepsilon\left(\frac{\partial^2 M}{\partial x^2}+\frac{\partial^2 M}{\partial y^2}\right)=0$$

$$\frac{\partial N}{\partial t}+\frac{\partial}{\partial x}\left(\frac{MN}{d}\right)+\frac{\partial}{\partial y}\left(\frac{N^2}{d}\right)-fM+gd\frac{\partial \eta}{\partial y}+\frac{d}{\rho_w}\frac{\partial p_0}{\partial y}-\frac{\partial \tau_{sy}}{\rho_w}-\frac{\partial \tau_{by}}{\rho_w}-\varepsilon\left(\frac{\partial^2 N}{\partial x^2}+\frac{\partial^2 N}{\partial y^2}\right)=0$$

$$\frac{\partial \eta}{\partial t}+\frac{\partial}{\partial x}M+\frac{\partial}{\partial y}N=0$$

Where, x , y : the parallel and the vertical co-ordinates to shoreline, d : water depth, f : coefficient of Coriolis force, g : acceleration of gravity, ρ_w : density of sea water, τ_s :shear stress on the sea surface, τ_b : shear stress on the seabed, and ε : horizontal coefficient of eddy viscosity.Subscripts x and y represent the components of flow that are parallel to the shoreline and perpendicular to the shoreline, respectively.

The topographical conditions were simplified to a shoreline running parallel to the x direction with a 1/100 uniform slope and no harbor. Coriolis factors within the area of calculation were assumed to be constant, and we used f-plane approximation and values at 42° North Latitude. An square area of 600km × 600km was used for the calculation. At the shoreline boundary, M and N = 0, and all other boundaries were closed. The grid width was 10km, and time steps were 30 sec. As the results of past calculation showed that fluctuation in atmospheric pressure has little effect on flows, atmospheric pressure was not included in the present calculation.Observed date of wind velocity were used as extemal force in this calculations.

Fig. 9 shows observed flow velocity, 25-hour moving average flow velocity, observed wind velocity, 25-hour moving average wind velocity (all at site A in Fig. 1), and calculated flow velocity 10km offshore for the period from Oct. 1 to Oct. 15, 1993. Although a direct comparison between observed and calculated flow velocities is not possible, since observation data of flow velocity were obtained at a site approximately 2.5km offshore and calculations of flow velocity were made at a point 10km offshore, the qualitative agreement between observed and calculated flow velocities is good. Moreover, the phase velocity of the calculated flow velocity fluctuations at a point 10km offshore is 2.5 km/h, which agrees well with the results of on-site observations (see Table 1, Oct. 1993). However, there are time differences of a half day to one day between the calculated and observed flow velocities. Further study is required to resolve this discrepancy.

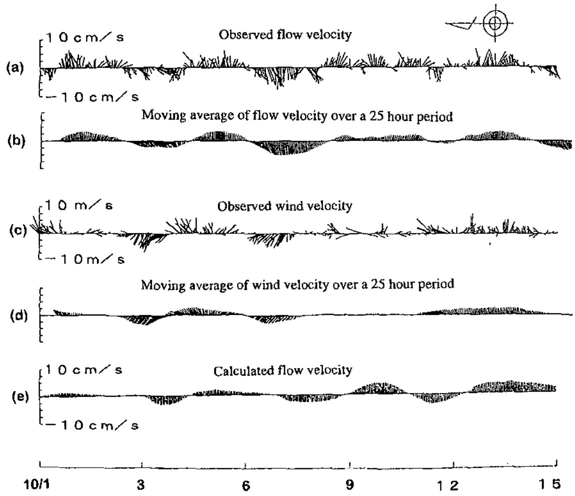


Fig.9 Relationship among observed flow velocity,observed wind velocity and calaculated flow velocity

6.Conclusions

We confirmed the existence of and clarified the characteristics of long-period flow velocity fluctuations around Tomakomai Harbor that have a period of 3～4 days and propagate in a westerly direction at a phase velocity of approximately 2.0km/h. These long-period flow velocity fluctuations can be estimated by the storm surge formula that assumes wind stress to be the external force and Coriolis force to be the restoring force.

7. References

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