二重層海洋における内部波について(Ⅰ)

緑川　弘毅[*1]　　榊田　尚志[*1]

流れが海底に砂漣を作ることはよく知られている。浅海では砂漣は海面の波による水の動きにより，少し深い海域では流れによって形成されるものと考えられている。
しかし，当研究において，内部波によって発生する躍層の下の流れで，直径数cmの小石を含む底質が運ばれたり，硬い海底に規模の大きな波紋を形づくったりすることが分かった。

キーワード：内部波，二重層海洋，水の運動，底質，砂漣(砂紋)

On Internal Waves in a Two-Layer Ocean (Ⅰ)

Koki MIDORIKAWA[*2] **Naoyuki SAKAKIDA**[*2]

It is well known that the current generates sand ripples on the sea bottom. It is thought that in shallow waters sand ripples are generated by the movement of water associated with surface waves, and in deeper waters by the current.
It was found that the horizontal motion caused by internal waves below the pycnocline could transport stony sediments having the size of several centimeters in diameter, and form big scale ripples on the hard bottom.

Key Words: Internal wave, Two-layer ocean, Water movement, Sediment, Sand ripple

1 Introduction

Internal waves rise in all oceans, bays and lakes. They usually travel more slowly than surface waves, but they may have a greater height and length. Internal waves occur at surfaces between different density layers within the sea, because the density difference leads to a gravitational pressure restoring force if fluid is displaced vertically. In a two-layer density area, maximum amplitude of internal waves exists at the boundary of the two layers, and decreases linearly with distance above and below.

In shallow waters, horizontal velocities of flow generated by internal wave motions were estimated theoretically and they were partly confirmed by means of observations (Midorikawa (1975[1], 1977[2][3])). When thermocline approaches the bottom, the increased current below can be effective in moving the sediment. But, it is thought that then the internal wave troughs approach the bottom, they become flat and broad by the conflict of the current through the constriction between the trough and sea

＊1　海洋観測研究部
＊2　Ocean Research Department

floor, so the effect of sediment-moving current is reduced. The horizontal wave motion below the pycnocline could transport the sediments containing stony sand and mud with a size of several centimeters in diameter. In coastal stratified areas, since the pycnocline is stable, the large kinetic energy from upper layers can be transported to the deeper water through the wave motion of pycnocline. On stormy days in stable stratified areas, the internal wave height becomes larger and the wave trough approaches the bottom, consequently the effect of internal wave on sediments becomes greater.

2 Internal wave velocities

2.1 Wave speed

The boundary surface of two layers are in the thermocline, where the density difference is chiefly due to temperature difference. The internal wave measurements were made by thermistors in a small triangular array as shown in figure 1. We can see from the records that there were two significant modes of the internal fluctuations. One is the short period internal wave of 2 or 3 minutes, and the other is a larger scale motion having the period of several tens of minutes.

The observed internal wave speeds are compared with the theoretical speeds using an equation for phase speed of free internal waves propagating at the discontinuity with small wave height. The theoretical speeds are estimated in a range of values between 0.2−4.4 m/sec, while observed speeds are 0.19−3.1 m/sec. The largest numbers of wave speed distributions were obtained from 0.20 to 0.25 m/sec which are smaller than the result of other investigators. Ufford (1947)[4] got the value of the speed less than 0.5 m/sec, however Gaul (1961)[5] got values from 0.37 to 0.65 m/sec in his measurements.

The observed speeds were generally smaller than the theoretical value. It would be conspicuous in the case the density structure is soft instead of a sharp discontinuity. So the case of this phenomenon might be due to change to high mode[2].

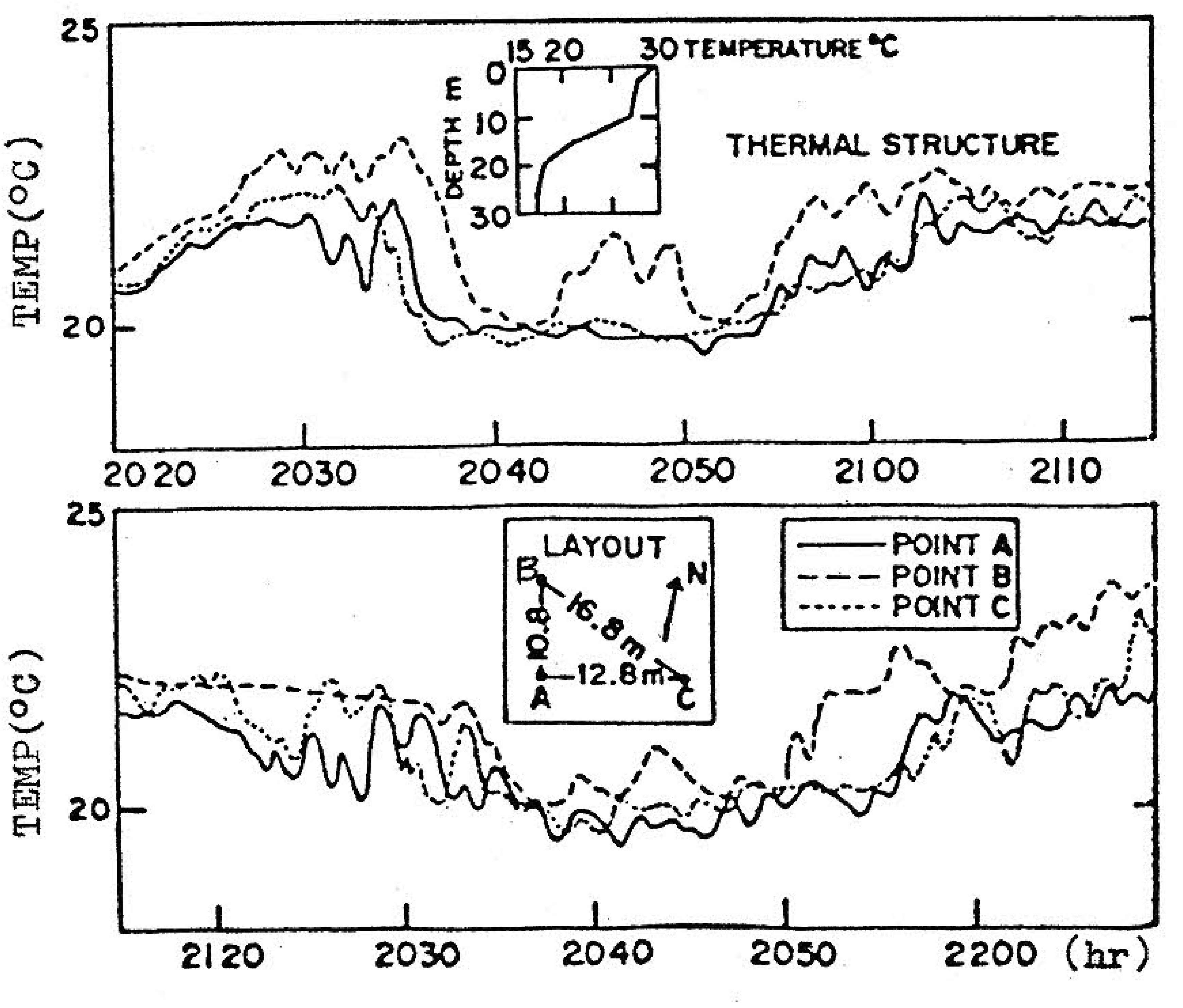

Fig.1 Temperature records obtained by a small-triangular thermistor array as shown in the figure (Midorikawa, 1975[1]).

2.2 Horizontal coherence

The temperature data recoreded at each point as mentioned above were analyzed. The coherences were generally high in lower frequency range from zero to 0.5 cpm(cycle per minute) and decreased gradually in the higher frequency range.

The reduction of horizontal coherence in high frequencies may be mainly caused by the interference of internal waves coming from various directions. The change of phase velocity, by the change of mode, of variations in density structures and the effects of variable currents, would cause the additional decrease of the coherence.

3 Water movement caused by internal waves

3.1 Horizontal water motion

Internal waves are the vertical oscillation of pycnocline in sea water and the circulations of water occur accompanied with internal waves. We consider the movement of water due to an internal wave at the boundary surface using a two layered model.

Assuming that there is no appreciable net transport of sea water across a vertical section perpendicular to the direction of wave propagation, the same volume of water per unit width must pass over the crest as under the trough, the horizontal velocities over the crest and under the trough must be inversely proportional to the respective thickness of both layers, and the former increases with the increase of the amplitude of internal wave.

Calling the density, the thickness of layer, the horizontal velocity and vertical displacement as ρ_1, h_1, u_1, and η_1 for the upper layer, and ρ_2, h_2, u_2, and η_2 for the lower layer, respectively, the equations of continuity and the equations of motion of the upper and lower layers are, taking the x-axis in the direction of wave propagation, given respectively by,

$$h_1 \frac{\partial u_1}{\partial x} + \frac{\partial}{\partial t}(\eta_1 - \eta_2) = 0$$
$$h_2 \frac{\partial u_2}{\partial x} + \frac{\partial \eta_2}{\partial t} = 0 \qquad (1)$$

$$\frac{\partial u_1}{\partial t} = -g \frac{\partial \eta_1}{\partial x}$$
$$\frac{\partial u_2}{\partial t} = -g \frac{\rho_1}{\rho_2}\frac{\partial \eta_1}{\partial x} - g\left[\frac{\rho_2 - \rho_1}{\rho_2}\right]\frac{\partial \eta_2}{\partial x} \qquad (2)$$

where g is the acceleration of gravity. From these equations, the horizontal velocities in the x-direction in the upper and lower layers are given by the following formulae.

$$u_1 = \frac{1}{c^2/gh_1 - 1}\frac{cA}{h_1}\cos(kx - \sigma t) \qquad (3)$$

$$u_2 = \frac{cA}{h_2}\cos(kx - \sigma t) \qquad (4)$$

Taking $c(= \sigma/k)$ as the phase velocity of the internal wave, equation (3) can be reduced to

$$u_1 = -\frac{cA}{h_1}\cos(kx - \sigma t) \qquad (5)$$

Equation (5) indicates that the horizontal velocity in the upper layer is inversely proportional to the thickness of the upper layer and proportional to the amplitude of the internal waves. The value of u_1 becomes maximum when the phase angle $(kx - \sigma t)$ is zero, and its direction is opposite to the direction of propagation of internal wave. From equations (4) and (5), we can get

$$\frac{u_1}{u_2} = -\frac{h_2}{h_1} \qquad (6)$$

This equation indicates that the horizontal velocity in each layer is inversely proportional to the thickness of individual layers.

The water motion over the crest of internal waves is more active for the smaller thickness of the upper layer and the effect of the motion reaches the sea surface, consequently, the circulation of water associated with the internal wave generates convergences and divergences on the sea surface. Divergences appears at the front of the crest and convergences at the back of crest of internal progressive wave. The convergence has an effect on the sea surface of reducing the surface tension and capillary waves disappear, thus slicks are formed at the active surface convergence zone. The smoothing effect of slicks is mostly attributed to the absorption of energy from the wind-produced capillary waves by the alternate expansion and contraction of surface film. The slicks move shoreward parallel to the depth contours with the same speed as the internal waves.

When the upper layer is thin, the water motion in the upper layer becomes active and the shear of vortex-sheet around the internal wave crest increases. In this case, the maximum value of u_1 can be derived from equation (5) as follows,

$$u_1 \max = -\frac{A}{h_1 - A} c \qquad (7)$$

when the crest approaches the sea surface, this horizontal velocity becomes greater.

If the internal waves propagate downward along the descending thermocline, an active convergence in the upper layer is generated. When the descending thermocline approaches the sea bottom, the water motion near the bottom becomes active. From equation (4), the maximum value of u_2 is given by

$$u_2 \max = -\frac{A}{h_2 - A} c \qquad (8)$$

The maxima of u_1 and u_2 have a phase difference of π, and the maximum velocity in the lower layer occurs at the trough and is always in the opposite direction of wave propagation. It becomes stronger as the trough approaches the sea bottom.

3.2 Water movement in thermocline of the equator

On the equator itself there is a powerful eastward-flowing subsurface current in the region of the thermocline, the Equatorial Undercurrent, or Cromwell Current, as the Pacific Equatorial Undercurrent is often called. This current is like a thin ribbon, perhaps 200 m thick and 300 km wide, with peak speeds of up to 150 cm/sec. The core of the current usually coincides with the thermocline, and it is generally centered on, or very close to, the equator. The depth of the core of the current varies from 50 m or less near its eastern terminus to 200 m or more in the western Atlantic and Pacific.

Often, but not always, there is a spreading of the thermocline with the undercurrent, as well as an apparent mixing of properties, such as oxygen, across the thermocline. In both the Atlantic and Pacific Oceans, the sea surface slopes along the equator to the east. Slope of the sea surface in the Pacific along the equator can be found by calculating the height of the sea surface in dynamic meters. The height of sea surface is 0.7 dynamic meters higher in the west region than the east (Knauss(1978))[6].

The subsurface thermocline descends by the increase of the surface pressure in the west of the equator. The surface pressure may spread the descending thermocline, and the funneling of water in it flows to the east strongly as it is called jet flow.

4 Effect on the bottom sediment

The nature of the thermocline is influenced by a number of factors and therefore varies in depth and magnitude from place to place and from time to time. Tidal current and storms also influence the depth of the main thermocline (LaFond(1961))[7].

Strong stratifications are generally formed in coastal area, especially, near an estuary harbor. The thermocline develops in late spring and becomes stronger in summer. The horizontal motion associated with internal waves below the trough becomes stronger as the thermocline approaches the sea bottom. The values of the horizontal motion are estimated by equation (8) for various thicknesses of the lower layer. The thickness of the lower layer, the phase velocity and the amplitude of internal wave are taken to be 30 m, 0.4 m/sec and 20 m respectively. These values are put into equation (8) to estimate the theoretical water motion and get the maximum value of 0.8 m/sec, and will be still faster for the thinner lower layer.

Interesting features of broad ripples have been investigated such as the sediments of gravels of several centimeters in diameter were scoured at the trough on the hard bottom at 20 m depth. The distances between the troughs were about 180 cm and the troughs (and crests) stretched more than 300 m parallel to each other (Midorikawa (1975[1], 1976[8], 1995[9])). It has not been clarified whether internal waves were a cause of the big scale ripples or not in those days.

We made sure that the horizontal motions caused by internal tides were over 1 knot near the bottom, and the sediments of sand and stone on the sea floor were scoured by the strong current (Midorikawa et al. (1986[10], 1988[11])). Besides, the thermocline in the area was not destroyed while it was right in the middle of strong storms (Midorikawa (1976[8]), 1986[10])). Through these facts, we found that those ripples were generated by water movements associated with internal waves.

5 Consideration

The horizontal wave motion below the pycnocline could transport sediments which are several centimeters in diameter. In coastal stratified areas, since the pycnocline is stable, the large kinetic energy from the upper layer can be transported to the deeper water through the wave motion of pycnocline. On stormy days, the pycnocline is still maintained in the stable stratified area, and internal wave height becomes larger, so the effect of internal waves on sediments becomes greater.

The water motion generated by internal tidal waves having large amplitude also has a great effect on the tidal current through the superposition. It seems that the effect of sediment transportation becomes great when the internal tidal waves break at the steep sea floor(Midorikawa(1995[9]))).

References

1) Midorikawa, K. and T. Miyazaki : On Internal Waves in Suruga Bay, Internal wave-motion and marine sediments. The 3rd International Ocean Development Conference, preprint Vol. V, 11-20. (1975).

2) Midorikawa, K.: Observations of Internal Wave Velocities. JAMSTEC R 1 , 109-114. (1977).

3) Midorikawa, K. : The Effect of Tidal Currents on Internal Waves. J.. of Oceanogr. **33**, 311-319, (1977).

4) Ufford, C, W.: Internal waves measured at three stations. Transact. Amer. Geophys. Union, **28** (**1**), 89-95. (1947).

5) Gaul, R. D.: Observations of internal waves near Hudson Canyon. J. Geophys. Res. **66** (**11**). 3821-3830. (1961).

6) Knauss, J. A. : Introduction to physical Oceanography. Prentice-Hall, Inc. 338pp. (1978).

7) LaFond, E. C. : Internal Wave Motion and its Geological Significance. Makadevan Volume, A collection of geological papers, Osmania University Press, 61-77. (1961).

8) Midorikawa, K. : Observations of Longshore-Current and Marine Sediments. Bull. Coastal Oceanogr. **13** (**1**), (1976).

9) Midorikawa, K. : On the phenomenon occured in Shiome and two-layer ocean. Folktale on the sea and fishery. JAMSTEC R **32**, (in press), (1995).

10) Midorikawa, K. and T. Matsumoto : On the Relation Between Deep Sea Currents and Bottom Sediments. -Observation of Bottom Current-. JAMSTECR Deep-sea Research, (1986).

11) Midorikawa, K., H. Momma, K. Mitsuzawa and H. Hotta : Meassurment of the Deep-sea Current near the Bottom in the Suruga Trough. JAMSTECR Deep-sea Research, (1988).

(原稿受理：1995年７月27日)