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Outflow Characteristics of Nakdong River Plume
낙동강수의 유출특성에 관한 연구

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Abstract□CTD measurements were conducted in the Nakdong estuary on the several sections of along-plume and cross-plume directions in 1993 and 1994. Internal Froude number Fi=0.22 - 0.35 in ebb tides and 0.14 in flood tides suggest that Nakdong river plume may go farther seawards in the along-plume direction with little mixing with the adjacent sea water after the construction of Nakdong river barrier. From Dadae-Po to Gaduk-Do section of cross-plume direction, three cores of low salinity were found. The main plume outflows from the newly made channel by cutting Ulsuk-Do after the construction of barrier. The low salinity core found near Gaduk-Do is the plume patch advected by tidal currents. Rossby deformation radius varied with the tidal cycle so that Coriolis effect is strengthened in flood tides to deepen the isohalines westwards to the Gaduk-Do site. Internal wavelike shape was found in the section of cross-plume direction during ebb tides. Richardson number of the section suggests the possibility of forming internal wave but more precise observations are necessary.

요 지 : 1993년과 1994년에 낙동강 하구둑 하류부에서 낙동강수 플룸의 방향과 가로지르는 방향을 따라서 몇개 단면을 설정하여 CTD 관측을 행하였다. 하구둑 건설전에는 낙동강수는 낙조시 상하의 entrainment 혼합이 활발히 일어나 장자등과 나무싯등 부근에 이르기도 전에 완전히 혼합되어 빠져나갔지만 본 조사자료에서는 낙동강수는 표층에서 1 m 정도의 깊이의 플룸의 형태로 장자등과 나무싯등 사이를 빠져나가 훨씬 남쪽까지 내려감을 알 수 있었다. 이것은 하구둑에서 조시에 따라 주로 낙조동안 강수가 방출이 되고 낙조류의 방향과 플룸의 방향이 어느 정도 일치하기 때문이며 또한 internal Froude number가 썰물시 0.22 - 0.35, 밀물시 0.14로서 상하층의 성층상태가 썰물과 밀물시 모두 아주 안정적인 값을 나타내는 것으로서도 알 수 있다. 플룸을 가로지르는 방향의 다대포와 가덕도남단을 잇는 단면에서 3개의 저염축이 발견되었는데 가장 저염축은 주된 플룸을 나타내며 하구둑 건설후 을숙도를 절개하여 새로 만든 수로를 나와 장자등과 나무싯등을 거쳐 나옴을 알 수 있다. 가덕도 부근의 저염은 patch 형태로 밀물에 의해 이류된 강수플룸의 영향이다. Coriolis 효과를 나타내는 Rossby deformation radius는 조시에 따라 달라지는데 창조시에 Coriolis 효과가 강하게 나타나 가덕도 부근에서 등염분선을 가덕도쪽으로 깊어지게 한다. Internal wave 형태의 형상이 썰물시 단면에 나타나 Richardson number를 구하여 그 가능성을 확인하였는데 좀 더 자세한 관측 및 분석이 필요하다.

1. INTRODUCTION

Nakdong estuary, which is located at the southeastern part of Korea, is the interface between fresh Nakdong river water and saline coastal water of Southeastern Sea of Korea (Fig. 1). Nakdong river, which is the second longest river in Korea, transports large amount of suspended materials into Nakdong estuary and this has been the main source of sediment and variations in topography of Nakdong estuary. Fresh water of Nak-

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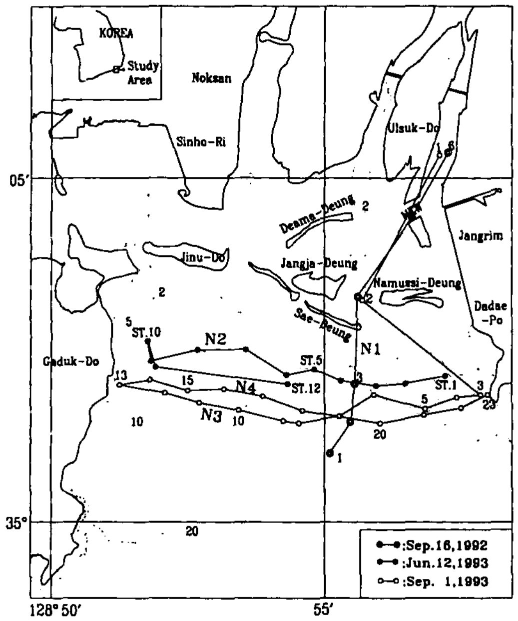

Fig. 1. N1, N2, N3 and N4 of CTD sections. The numbers in each section are station numbers which are numbered in the measuring sequence. Newly made channel by cutting Ulsuk-Do after construction of Nakdong river barrier is denoted 'NEW'.

dong river forms a surface plume with well defined frontal zone and mixes continuously with the existing saline water.

Nakdong estuary has experienced dramatic environmental changes since the construction of Nakdong river barrier in 1987. Nakdong river barrier was constructed mainly to prevent intruding of salt water upstream the Nakdong river. Mixing and circulation patterns in the estuary have been changed fundamently after the construction of barrier. Before the construction of barrier, seawater intrude upstream during flood tide while during ebb tide, river and sea water mix sufficiently to flow out of the estuary as nearly homogeneous water mass (Yu *et al.*, 1993). But after the construction of barrier, discharge of fresh river water is controlled artificially depending on the tidal period, the amount of river runoff, etc. Intermittent release of fresh water causes much different structure of river plume from continuous release case. Kim (1992) suggested that because of sudden and intermittent release of fresh river water after the construction of barrier, surface plume of low salinity water spreads farther down the estuary keeping its shape.

Circulation pattern in the estuary may be varied by the factors such as river discharge, density difference between fresh water and sea water, tidal range, wind, waves, and Coriolis force, etc. Construction of barrier altered several factors of the above such as river discharge and density difference resulting in fundamental changes in circulation pattern. Because dissolved and suspended materials are transported into the estuary with the prevailing circulation pattern, it is important that the effect of each factor on the circulation should be determined.

Yu *et al.* (1993) solved the hydrodynamic equation for the lateral spreading of the Nakdong river plume. From the observations of current and salinity for 10 hours at the selected station in Nakdong estuary, it was suggested that Nakdong river plume which is directed southwards could be swung east-westwards as the directions of tidal currents. Han *et al.* (1993) discussed two factors-tides and wind-which affect the structure of the Nakdong river plume, by analyzing the serial time series measurements of current and salinity taken at the selected station for 1 tidal cycle. It was also suggested that Nakdong river plume is not continuous but patch-like because river water is discharged intermittently from the barrier according to the tidal cycle.

The present study is concerned with the change of the oceanographic environment of Nakdong estuary after the construction of Nakdong river barrier. Especially, the physical characteristics, outflows and spreading of Nakdong river plume in the presence of tidal flows were sought which are thought to be the major factors that control the oceanographic environment of Nakdong estuary. CTD data collected on the several sections of along-plume and cross-plume directions in 1993 and 1994 are analyzed and discussed.

2. MEASUREMENTS AND PROCEDURES

Bathymetry of Nakdong estuary is somewhat complicated near Nakdong river barrier but main direction of isobath is east-westwards as shown in Fig. 1. The main channel (denoted by 'NEW' in Fig. 1), through which two-thirds of river water discharged from the barrier flow, was newly made by cutting the Ulsuk-Do after the construction of Nakdong river barrier. Before the construction of the barrier, most of river waters discharged out through the channel between Ulsuk-Do and Dadae-Po. This change of main channel of river waters must be a significant factor determining the environmental change of Nakdong estuary.

CTD measurements were conducted on the several vertical sections which were denoted in Fig. 1 and Fig. 2 as N1, N2, N3, N4, N5, N6. Positions for the denoted stations were determined by Sony IPS-360 GPS (Global Positioning System) and was accurate to about 50 m. At each station, SBE 19 CTD of Sea-Bird Electonics was lowered to 1 m above the bottom, taking two samples of temperature, conductivity and pressure per second. N1 section which was measured on September 16, 1992 during ebb tides for one hour was setup along the line on which Nakdong river plume was considered to spread. N2, N3 and N4 sections were taken between Dadae-Po and Gaduk-Do (Island) to investigate the structure of the Nakdong river plume in the cross-plume direction according to the tidal cycle. N2 section was measured during flood tides for two hours on June 12, 1993. N3 and N4 section were measured on September 1, 1993, but different tidal cycle-N3 during ebb, N4 during flood tides. N6 section (Fig. 2) was measured by the Department of Ocean Engineering, Korea Maritime University on September 20, 1993. This measurement provides several cross sections of plume structure in the outward directions of the estuary.

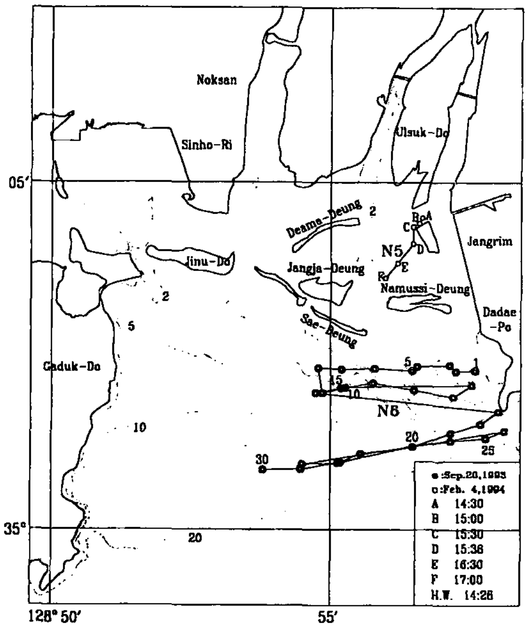

Fig. 2. N5 and N6 sections. N5 section is also drogue tracking line. N6 section was measured by Department of Ocean Engineering, Korea Maritime University on September 20, 1993.

In order to find out the movement of the plume, drogue was tracked at the surface near the barrier down the estuary while conducting the CTD and current measurements at the same time. Tracking line is denoted as N5 in Fig. 2 and observation time at each station is given in the legend. Tracking was conducted during flood tides when the barrier was closed. Plume structure of diffrent tidal cycle in the along-plume direction was analyzed using N1 and N5 sections. Drogue used for tracking the plume was basket type drogue. The time and tidal hours for each measurement are presented in Table 1.

Table 1. Measuring time and tidal hours.

Date	Start	End	High tide	Low tide	Section name
Sep. 16, 1992	15:29	16:20	10:48	16:31	N1
June 12, 1993	10:03	12:30	14:07	07:49	N2
Sep. 1, 1993	10:35	13:00	08:49	14:32	N3
Sep. 1, 1993	14:30	16:20	08:49	14:32	N4
Feb. 4, 1994	12:00	15:30	14:28	08:20	N5
Sep. 20, 1993	10:44	17:06	11:23	17:10	N6

3. ALONG-PLUME SECTIONS

The structure of Nakdong river plume along the direction of propagation was investigated using N1 and N5 sections which were measured in the along-plume direction.

In N1 section (Fig. 3), low salinity layer of below 25‰ is up to 5 m from the surface at stations 4 and 5 which are located near the barrier, but it is confined surface layer of only 1 – 2 m from the station 4 to seaward stations. This structure might show a salt wedge structure of the estuary. This section was measured at the last stage of ebb tides when the discharges of river water from the barrier reached its maximum. The typical salt wedge structure is that river water of upper layer goes out seaward while sea water penetrates below the river water in the reverse direction. But in Nakdong estuary, the outflow of river water from the barrier is mainly during ebb tides. The direction of river water plume of upper layer coincides with that of ebb currents of lower layer so that salinity structure of N1 section is not real salt wedge structure. Plume layer is thickened near the barrier by continuous supply of river water, but it is more and more confined to the surface layer as it goes down the barrier because of buoyancy effect mainly-not the mixing with existing seawater.

The interface between the upper fresh water layer and the sea water underneath is relatively stable. The stability of the interface depends on the value of the densimetric Froude number Fi given by

$$Fi = \frac{U}{\sqrt{\gamma g h}} \tag{1}$$

where U is the mean velocity of the upper layer, g is the acceleration of gravity, h is the depth of the interface below the surface and γ is the density ratio

$$\gamma = \frac{(\rho_s - \rho_f)}{\rho_s} \tag{2}$$

where ρ_s is the density of salt layer and ρ_f is that of fresh water layer. The interface has generally been thought to be stable when densimetric Froude number values are subcritical, i.e., $Fi < 1.0$, but if Fi exceeds unity, interfacial waves form and break and active vertical mixing occurs (Stommel and Farmer, 1952; Wright and Coleman, 1971). Typical values in this section are: U= 50 cm/s, γ=0.15, h=5 m near the barrier, 2 m at seaward station, so that Fi=0.22 – 0.35 which indicates subcritical value of strongly stable condition. This implies that the thinning of plume layer seawards is not the result of mixing between upper and lower layer but buoyancy effect.

In N5 section (Fig. 4), which was measured during flood tides, salt wedge-like structure disappears because

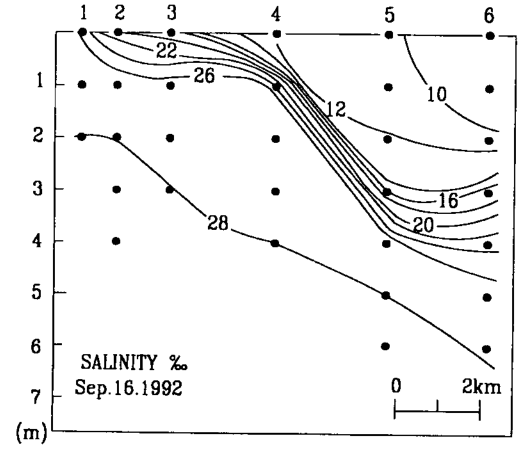

Fig. 3. N1 section of salinity. Station number denotes measuring order. Station 6 is barrier site and seaward direction is to the left.

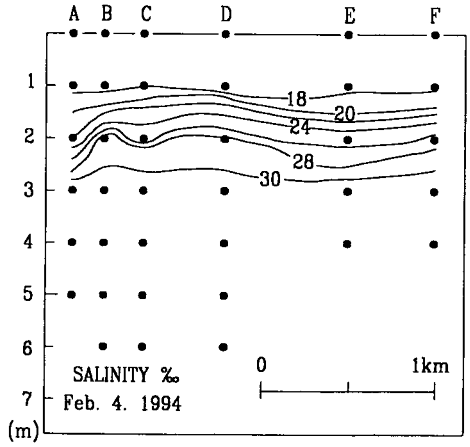

Fig. 4. N5 section of salinity. Seaward direction is to the right. Drogue tracking was done in alphabetical order.

the supply of river water from the barrier stopped. Boundary of upper layer is 30‰ contour and vertical section shows uniformly stratified structure. If plume structure was compared with N1 section inside the Jangja-Deung and Namussi-Dueng, the plume layer is flattened keeping layer depth of about 2.5 m, which indicates that the river plume can propagate farther southwards inspite of the opposing direction of flood currents. Typical values of N5 section are: U=20 cm/s, γ= 0.08, h=2.5 m, so that Fi=0.14 of subcritical value that are also strongly stable condition. Therefore, Nakdong river plume can propagate farther down the estuary without mixing with lower layer of sea water regardless of tidal cycles. Before the construction of barrier, Nakdong river plume in ebb tides discharges southwards at the surface layer while ebb tidal currents keep northwards flow in the lower layer. This results in entrainment mixing between upper and lower layer extensively because of velocity difference between upper and lower layers so that near the Jangja-Deung and Namussi-Deung, homogeneous water flows down the estuary due to complete mixing (Yu *et al.*, 1985). But after the construction of barrier, upstream flow at lower layer become impossible and the Nakdong river plume can spread farther southwards as indicated in N2, N3 and N4 sections (Figs. 5, 6 and 7).

N5 section also represents the Lagrangian drift of the surface plume obtained by drogue tracking. Even when there is no input of river water from the barrier and flood tidal currents flow upstream, surface plume moves down the barrier which is denoted as 'A' to 'F' in Fig. 2.

4. CROSS-PLUME SECTIONS

Three cores of low salinity exist in the N2, N3 and N4 sections (Figs. 5, 6 and 7). These are at southwards of Sae-Deung, near the coast of Dadae-Po and near Gaduk-Do. Lowest salinity core exists at station 6 in N2 section, station 7 in N3 section and between stations 18 and 19 in N4 section. Lowest salinity core means that the main flow of Nakdong river plume passes through this core. Distribution of lowest salinity core indicates that Nakdong river water discharged from the Nakdong river barrier mainly flows along the passage which was newly made by cutting the Ulsuk-Do and down through the channel between Janja-Deung and Namussi-Deung. Before the construction of barrier Nakdong river water flowed out through the channel between Ulsuk-Do and Dadae-Po. Low salinity core near Dadae-Po-between stations 1 and 2 in N2 section, station 3 in N3 section and between stations 22 and 23 in N4 section-is thought to represent the effect of the outflow from the previous channel.

Ebb current enters Nakdong estuary northeastwards

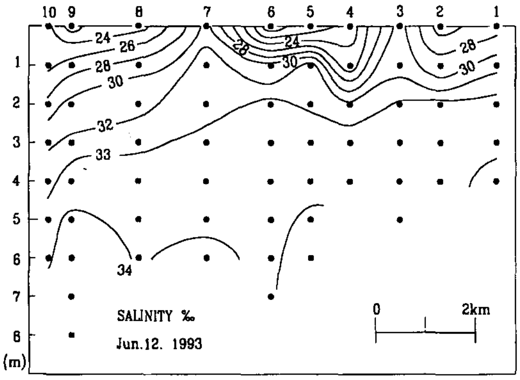

Fig. 5. N2 section of salinity. Station 1 is Dadae-Po site and station 10 is Gaduk-Do site. Stations are numbered as measuring order.

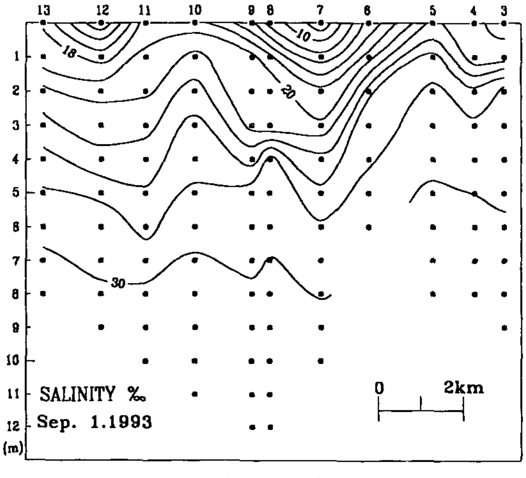

Fig. 6. N3 section of salinity. Station 3 is Dadae-Po and station 13 is Gaduk-Do site. This section was measured during ebb tides.

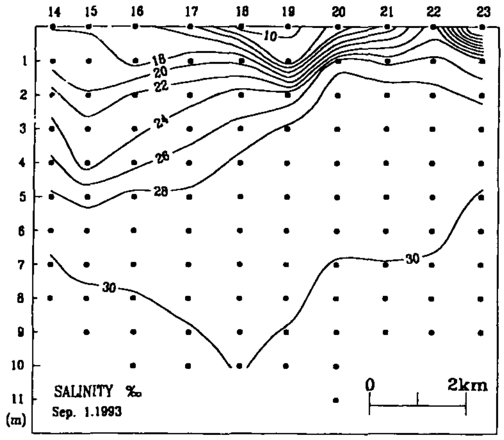

Fig. 7. N4 section of salinity. This section was measured from Gaduk-Do (station 14) to Dadae-Po (station 23) during flood tides on the same day as N3 section.

and flows out southeastwards while flood current enters northwestwards and flows out the estuary southwestwards. The tidal flow in the Nakdong estuary causes significant changes in salinity structure through the tidal cycle, as shown in N2, N3 and N4 section of Figs. 5, 6 and 7. N2 and N4 sections were measured during flood tides while N3 was measured during ebb tides. Low salinity layer-referred to the layer above 28‰ line which is the boundary of sharp gradient zone under the influence of Nakdong river water-is thicker up to 6 m in N3 section than in N2 section where the layer reaches only up to 2 m, despite the fact that N3 section is located more southward than N2 section. N4 section was measured from the beginning of flood tides after measuring N3 section, so that the change of the structure of river plume with the tidal cycle can be found by comparing N3 and N4 sections. Low salinity layer in N 4 section becomes thinner eastwards to the Dadae-Po site because flood tides progress more than in N3 section. The spreading direction of Nakdong river plume is nearly coincident with the direction of ebb flow. Consequently, the plume spreads farther down with the aid of tidal flow without much mixing with the ambient sea water, maintaining the depth of low salinity layer.

In addition, the lowest salinity cores in N2 and N4 sections are somewhat shifted westwards-to the Gaduk-Do-as compared with N3 section. This is thought to be the result of mixing between river water plume and tidal current. When flood current flows, the plume moves northwestwards to the Gaduk-Do and turbulent mixing between the plume and sea water, which arises from the opposed direction of flow, results in thinning of the low salinity layer.

Low salinity core found near the Gaduk-Do-between stations 9 and 10 in N2 section and station 12 in N3 section-is somewhat strange in the sense that there is no source of low salinity water near the place. Intermittent release of river water from the barrier causes patch-like horizontal structure of river plume. van Alphen *et al.* (1988) found from salinity measurements in the Rhine river estuary that the river plume becomes detached from the river mouth as it is carried with the strong flood currents and sometimes the plume breaks into several patches. In Nakdong estuary, when the supply of river water from the barrier stops during the flood tides, the river plume becomes detached from the barrier and easily breaks down into smaller patches. Han *et al.* (1993) discussed the patch-like structure of the Nakdong river plume from the time series measurements of salinity and current in one station in the Nakdong estuary. Flood currents advect these patches to the land boundary of Gaduk-Do, which seems to be the cause of the low salinity core near the Gaduk-Do.

In estuarine outflow, important length scale for a buoyant river plume is the Rossby deformation radius r_d which is defined as (Gill, 1982):

$$r_d = \frac{1}{f}\left[\frac{\Delta\rho}{\rho}\, g\, \frac{h\,(D-h)}{D}\right]^{1/2} \qquad (3)$$

where $f=2\Omega\sin\phi$(Ω: angular velocity of the earth, ϕ: latitude) is Coriolis parameter, $\Delta\rho$ is the density difference between upper and lower layer, ρ is sea water density, h is upper layer depth, D is the total depth and g is gravity acceleration. The Rossby deformation radius is the horizontal length scale over which the horizontal pressure gradient force arising from the horizontal density gradient and the Coriolis force become an equal order of magnitude. If there is not any other motion in the estuary, river waters discharged from the river mouth behave as jet-like motion at first and then spread radially up to the distance comparable to the Rossby deformation radius, but over this distance the Coriolis force comes into play so that they are deflected to the right in the northern hemisphere. Matsuno and Nagata (1987) investigated numerically the effect of earth's rotation on the behavior of heated water discharged into the ocean. It is shown that horizontal spreading of the heated water is suppressed to the offshore and leftward direction, but accelelated in the rightward direction. The thickness of the warm water mass increases rightwards with increasing the Coriolis parameter f. The characteristic values for the Nakdong river plume are (Jang, 1994): ρ=1025 kg·m^{-3}, $\Delta\rho$=20 kg·m^{-3} in ebb tides, 10 kg·m^{-3} in flood tides, D=8 m, h=5 m in ebb tides, 2 m in flood tides. So the Rossby deformation radius r_d=7.18 km in ebb tides, 1.3 km in flood tides. As N2, N3 and N4 sections are located over 8 km from the barrier, Coriolis force may have an important role in these sections especially in flood tides. The change of tidal cycle from low to high tides causes the same effect as increasing Coriolis parameter f as the Rossby deformation radius decreases.

The low salinity core near Gaduk-Do of N3 section in Fig. 6 shows V-shaped structure of which trough is located at station 12 at surface being the result of advection of low salinity patches by the eastward flowing ebb currents and it is shifted eastwards to station 11 as the depth increases. More widely, the plume shows W-shaped structure from station 5 to station 13. In N4 section, the V-shape structure still remains because this section is measured from the beginning of flood tides and is considered to disappear as flood tides progress. The trough of V-shape is shifted from station 16 at surface to station 15 at depths and W-shaped structure as in N3 section disappears which is considered as the result of Coriolis effect thickening the isohalines toward the Gaduk-Do site. The V-shaped structure is not seen in N2 section as shown in Fig. 5 because this section was measured in the midst of flood tides. Isohalines slope down and low salinity layer is getting thicker from station 9 to the Gaduk-Do site because of the Coriolis effect.

Fig. 8 shows four successive sections of N6 denoted as I, II, III and IV. These sections were measured during ebb tides except section I which was measured during transition time from flood to ebb tides. The low salinity core found between stations 2 and 5 as a very thin layer of less than 1 m depth is not the main plume but the influence of river water discharged through the channel between Ulsuk-Do and Jangrim which was the main channel before the construction of barrier. The main plume is not found in section I because it is advected westwards by flood currents, but its influence seems to be seen at station 8 as low salinity. In section II, the main plume appears at stations 14 and 15 as it is advected eastwards by ebb currents. The other plume found in section I outflowing from the previous channel is not seen in section II because it is advected to Dadae-Po site. In section III, two cores of low salinity are found. One core between stations 21 and 23 is the main plume and the other core at station 19 is the plume outflowing from the previous channel. The main

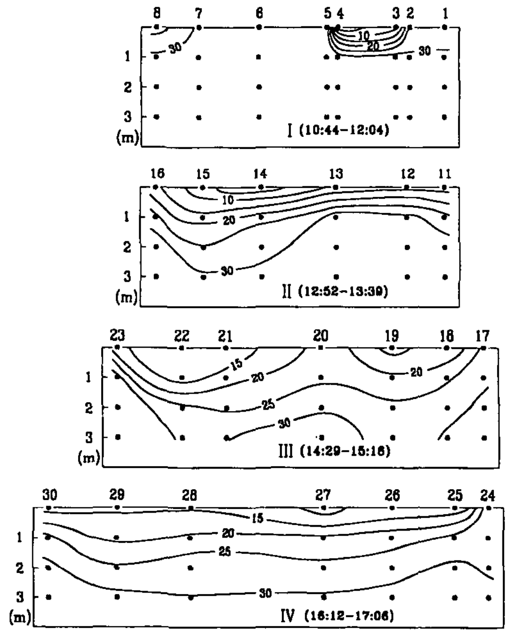

Fig. 8. N6 section of salinity measured by Department of Ocean Engineering, Korea Maritime University on September 20, 1993. It consists of four sections denoted as I, II, III and IV.

plume is shifted somewhat westwards as compared with section II despite the fact that ebb currents flow southeastwards more strongly than in section II. Section III is located over the Rossby deformation radius so that Coriolis force plays an important role to deflect the plume to the right overcoming the ebb currents. Section IV is nearly the same place as section III but different measuring time. Isohalines are nearly parallel all over the section as compared with section III where they are W-shaped. This is thought to be the result of Coriolis effect which flattens and deepens the salinity structure rightwards as similar to the structure of Gaduk-Do site.

5. SUMMARY AND DISCUSSION

Nakdong river plume which is the major factor that controls the oceanographic environment of Nakdong estuary is analyzed using CTD data collected on the several sections of along-plume and cross-plume directions.

In the along-plume direction, internal Froude number Fi=0.22∼0.35 in ebb tides and 0.14 in flood tides-both subcritical values-indicates that Nakdong river plume can go farther down the estuary-far down Namussi-Deung-without mixing with the adjacent sea waters in both ebb and flood tides. Before the construction of barrier, extensive entrainment mixing in ebb tides makes homogeneous waters before arriving at Namussi-Deung.

From Dadae-Po to Gaduk-Do, three cores of low salinity are found. Main river plume outflows through the newly made channel by cutting Ulsuk-Do after the construction of barrier. The low salinity core found near Gaduk-Do is considered to be the plume patch advected by flood currents. The low salinity core near Dadae-Po is the plume outflowing from the channel between Ulsuk-Do and Dadae-Po which was the main channel before the construction of barrier.

In ebb tides, as spreading direction of plume and direction of ebb currents nearly coincide, river plume can go far down southwards keeping its layer depth with little mixing with seawater while in flood tides, spreading direction of plume is opposite to the direction of flood currents so that plume layer is thinned as a result of mixing and shifted westwards to Gaduk-Do site.

In Nakdong estuary, Rossby deformation radius is varied with tidal cycle. Coriolis effect is more enhanced during flood tides. Isohalines slope down toward Gaduk-Do site deepening the low salinity layer during flood tides by Coriolis effect.

Internal waves are observed in several estuaries (Kranenburg, 1988; New and Dyer, 1988; New *et al.*, 1987). Abraham (1988) showed that internal wavelike motions occur when the Richardson number Ri (e.g., Officer, 1976) defined by:

$$Ri = \frac{N^2}{\rho(\partial u/\partial z)^2} \tag{4}$$

is 1 to 2.5 Here, N is the buoyancy frequency (e.g., Turner, 1979) defined by:

$$N = \left(-\frac{g}{\rho}\frac{\partial \rho}{\partial z}\right)^{1/2} \tag{5}$$

and $\partial u/\partial z$ is the vertical shear in the horizontal velocity field. Typical values in N3 and N4 sections-corresponds to ebb and flood tides-are: $\partial\rho/\partial z = 2\ \mathrm{kg \cdot m^{-2}}$, in N3, $4.5\ \mathrm{kg \cdot m^{-2}}$ in N4, $\partial u/\partial z = 10^{-1}\ \mathrm{s^{-1}}$ in both ebb and flood currents (Lee, 1994) so that Ri=2 in N3, 4.5 in N 4 section. It is expected that in ebb tides, internal wavelike motion may occur. In Fig. 6, the wavelike motion is observed, but it is not obvious that it is really internal wave. It should be measured more precisely by stationary CTD and echo sounding measurements at several points. Growth and breaking of internal waves in both along and cross plume directions are so important to the mixing processes in estuary that the measurement and analysis of internal waves are expected to be the necessary subject for the future.

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