The Journal of the Korean Society of
Coastal and Ocean Engineers
Vol. 5, No. 4, pp. 296~301, December 1993

Lateral Spreading of a River Plume and Transport of Suspended Sediments in the Nakdong Estuary
洛東江河口에서의 河川水 플룸의 橫方向퍼짐과 浮游堆積物의 輸送

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Abstract□A hydrodynamic solution for the lateral spreading of a river plume which was developed by assuming a Gaussian distribution of density difference between a turbulent jet river plume and ambient salt water is verified by the field data in the Nakdong river plume. Effect of the river plume on the transport of fine-grained suspended sediment at the Nakdong Estuary is also examined. The analysis of field data showed a reasonably good correspondence with the theoretical solution adopted in this work. Therefore, the hydrodynamic solution can be used as a useful tool in dealing with the lateral spreading of a river plume. The density stratification due to the existence of a river plume seems to cause a retarded settling of the suspended sediments in the water column, and thus a farther transport of the fine sediment is expected than in the normal steady flow.

要　旨: 하수젯트플룸과 주변염수와의 밀도차가 Gauss 분포를 한다는 가정하에 저자들이 구한 플룸의 횡방향 퍼짐에 대한 이론해를 낙동강 하수플룸의 관측자료로 검증하였다. 또한 플룸의 존재가 세립 부유퇴적물의 이동에 미치는 영향도 검토되었다. 현장 관측자료는 이론적인 계산결과와 비교적 잘 맞는 것으로 나타났다. 따라서 본 논문에서 채택하여 검증한 플룸의 횡방향 유동에 대한 이론해가 플룸의 횡방향 퍼짐문제를 다루는데 유용하게 쓰일 수 있을 것이라는 결론을 내릴 수 있었다. 플룸의 존재로 인한 밀도 성층으로 인하여 부유퇴적물은 침전이 지연되고 통상적 정상류의 경우보다 더욱 멀리 운반되는 것으로 생각된다.

1. INTRODUCTION

For the present work we assumed that the density difference and axial velocity component have a Gaussian distribution in the lateral cross-section of the river plume i.e.

$$\Delta\rho(x, y, z) = \Delta\rho_s(x)\, e^{-(y/B)^2/2} e^{-(z/H)^2/2}$$

$$u(x, y, z) = u_s(x)\, e^{-(y/B)^2} e^{-(z/H)^2}$$

Here x is the distance along the plume axis from the river mouth, y is the lateral distance from the plume axis, and z is the depth from the level surface. $\Delta\rho_s$ is the density difference with the ambient seawater at the surface of the axis. H and B are the depth and half width of the plume at whose boundary $\Delta\rho = 0.6\Delta\rho_s$ which is considered to be negligible value in the merging boundary (Fig. 1).

With the assumption, Yu and Lee (1993) developed a hydrodynamic solution for the lateral spreading of the river plume. The result can be arranged as follows. The lateral expanding velocity in the plume cross-section is

$$v_1 = \Delta\rho_s(y/B^2)\, g e^{-(y/B)^2/2} \sqrt{\frac{\pi}{2}} (H^3/\rho_1 N_z) \cdot [(t_i^2 - t^2) - 2\{G(t_i) - G(t)\}] \tag{1}$$

and its surface value is

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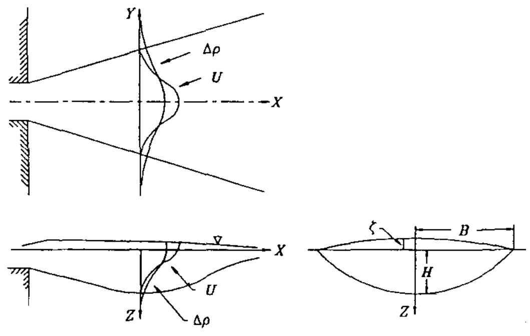

Fig. 1. Definition sketch of the river plume.

$$\nu_s = \Delta\rho_s (y/B^2)\, g e^{-(y/B)^2/2} \sqrt{\frac{\pi}{2}} (H^3/\rho_1 N_z) \cdot \{t_i^2 - 2G(t_i)\} \qquad (2)$$

where

$$t = \frac{z}{\sqrt{2H}},\ G(t) = \iint_0^t erf(t)\ dt\, dt,$$

which can be numerically integrated and the subscript i stands for the interfacial values and

$$t_i = \sqrt{\frac{1}{2} - \frac{(y/B)^2}{2}}.$$

To verify the above results, we carried out field observations and analyzed the field data obtained in the Nakdong Estuary.

In addition, we tried to find the effect of a river plume on the density stratification which causes retarded settling of the suspended sediments and results in a farther transport of the sediment.

2. FIELD MEASUREMENTS AND DATA ANALYSIS IN NAKDONG ESTUARY

The Nakdong river mouth is dammed by a barrage to prevent the salt water from intruding flood tide. The barrage holds the fresh river water during the flood tide and subsequently opens to release the fresh water into the wide estuary basin at the beginning of the next ebb tide. Usually the large amount of released fresh water easily forms a turbulent jet plume and spreads into the estuary basin.

To test the lateral spreading of the plume, a station was held at the Nakdong Estuary (Fig. 2) and

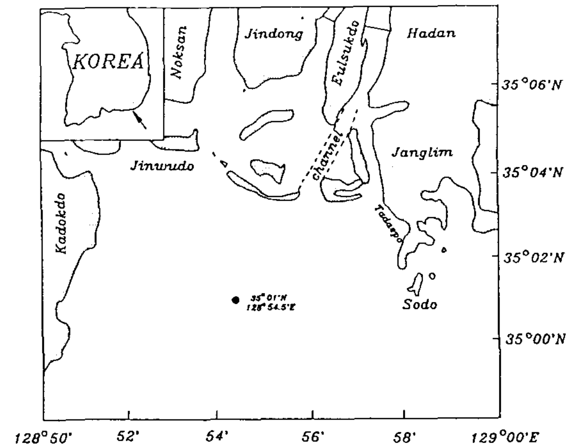

Fig. 2. Location map of the current, salinity, temperature measurement and water sampling.

the change of current, salinity, and water temperature with time and depth were measured for 10 hours on April 4, 1992. Since the river plume is directed southwards and the tidal currents flow east-westwards at Nakdong Estuary, the tidal currents could easily swing the plume east-westwards, and thus the stationary measurement could effectively measure the lateral variation of the plume according to the change of tides. The measurement was carried out at a half hour interval at every half meter from the surface to the bottom while the plume was strong. When the plume was none or weak, the measurement was carried out at an hour and one meter intervals with time and depth, respectively. Water samples at the surface and 1 m above the bottom were also collected every hour to analyze the concentration of suspended sediment.

Since the vertical water temperature variation was so small that no abrupt change in vertical gradient was distinguishable, the vertical variation of salinity and current speed was used to determine the depth of plume layer. The current speed was vectorially divided into east-west and north-south components which were used to determine the lateral expanding velocity of the plume and the plume depth.

3. RESULTS AND DISCUSSIONS

3.1 Spreading of River Plume

Figure 3 shows the vertical distribution of the

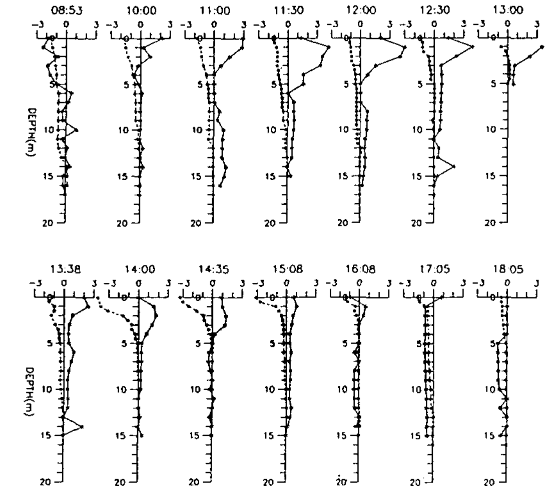

Fig. 3. Vertical distribution of currents in north-south direction (solid line, scale×10 cm/sec) and the salinity difference at each depth from the bottom (broken line, scale×1%).

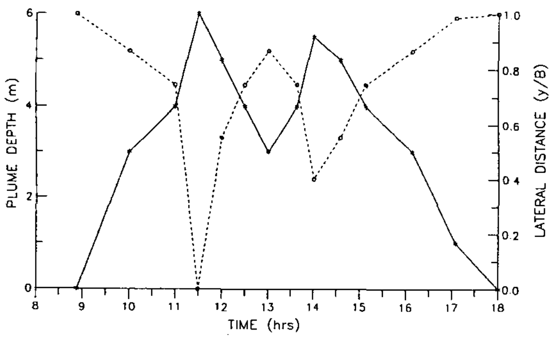

Fig. 4. Change of the plume depth with time (solid line) and the associated lateral position from the plume axis (broken line).

north-south component of the currents and the difference of salinity at each depth from the salinity of the near bottom water. The vertical distribution of the currents shows most evidently the change of the plume depth with time. The abrupt weakening of the current speed in the north-south direction may reflect the diminishing effect of the river plume, and it is also supported by the abrupt change in salinity difference near the same depth as the current weakens. On the day of field measurement the ebb current began at approximately 9:00 in the morning, and the plume began to be observed near 10:00 at the station and the depth of

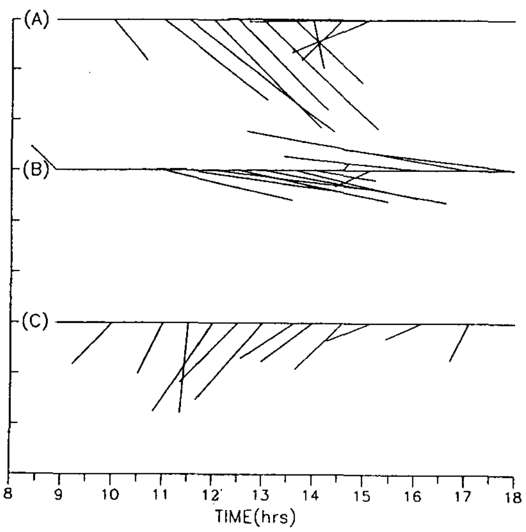

Fig. 5. Depth-mean current speed and direction of the upper layer (A) and lower layer (B) and the difference between upper and lower layers (C). One vertical length scale corresponds to 10 cm/sec of the current speed.

plume changed with time reaching up to approximately 6 m (Fig. 4).

With the lateral components of velocity the net current of the plume was calculated by subtracting the depth-mean current of the lower layer from that of the upper layer above the determined plume depth. Figure 5 shows the directions and speeds of the depth-mean currents of the upper layer (A), lower layer (B), and the difference (C) between the upper and lower layers. The difference (C) was adopted to be the net current by the plume. Figure 5 also shows that the direction of the plume current at 11:30 (Fig. 4), was almost southwards when the plame depth reached at its maximum of 6 m and its east-westward component was almost nil, strongly implying that the plume axis was passing through the station at that time. By the assumption that the plume was steady and its direction was only changed by the tidal currents, the relative lateral distance from the plume axis to the lateral boundary could be calculated from the change of the plume depth (Fig. 4).

Assuming that the plume axis passed through the station at 11:30, the axial and lateral components of the currents at each lateral position were calcula-

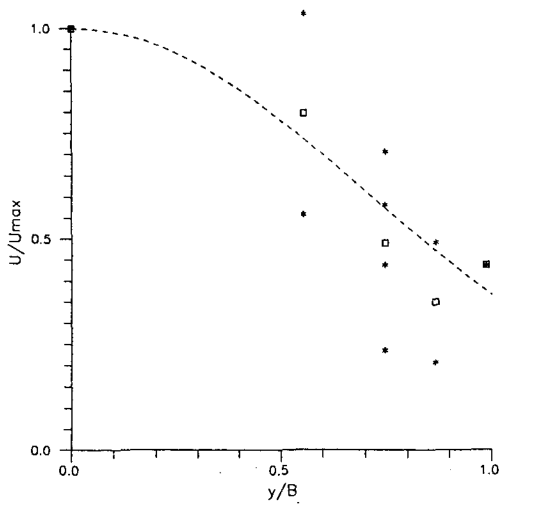

Fig. 6. Axial velocity of the plume layer at each lateral location from the axis. Broken line: theory, asterisks: field measurements, squares: average of the field mesurements.

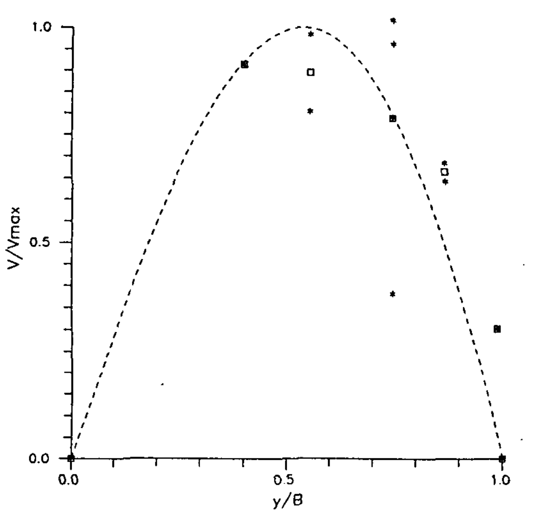

Fig. 7. Lateral velocity of the plume layer at each lateral location from the axis. Broken line: theory, asterisks: field measurements, squares: average of the field measurements.

ted. Figures 6 and 7 show the axial and lateral component of current speed of the plume plotted on the theoretical curve. On the plots, the measurements at 13:00 were omitted because the measurements were only limited to the upper 5 m due to the instrument failure. Even though the measurements show some scatter on the plot, the average of the

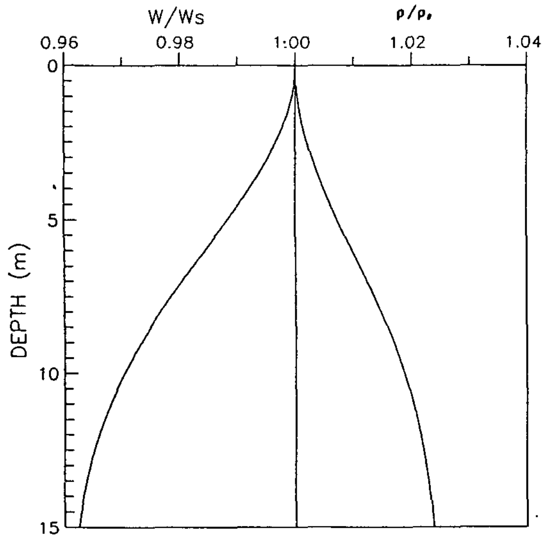

Fig. 8. Change of settling velocity (W/Ws) due to the density difference (ρ/ρ_s) with depth.

measurements at each lateral position roughly follows the theoretical curve. The scatter of the points may be partially caused by the assumptions imposed on the calculation. However, it mostly seems to be the result of the rough estimation of the plume depth since the field measurements were done at half- or one-meter depth intervals.

3.2 Suspended Sediment Transport

Transport and deposition of fine cohesive sediments in a steady flow are largely dependent on the settling velocity of the particles, In the Stokes region, the settling velocity of a sphere is given as

$$W=\frac{gD^2}{18\nu}\left(\frac{\rho_g-\rho}{\rho}\right) \tag{3}$$

where, W : settling velocity of the grain,
g : gravity,
D : grain diameter,
ν : kinematic viscosity of the fluid,
ρ_g : grain density,
ρ : fluid density.

From the above equation, it is obvious that the density stratification due to the river plume may affect the settling velocity of the grains and thus affect the transport and deposition of the suspended sediments. Figure 8 shows the vertical distributions of the settling velocity of a quartz grain ($\rho_g=2.65$ g/cm^3) and the fluid density at the plume axis ($\rho_s=1.0$ g/cm^3, $\rho_a=1.025$ g/cm^3, $H=6$ m) from the surface to the bottom assuming a constant viscosity and the Gaussian distribution of the density difference. The settling velocity is decreased approximately 4% for the increase of fluid density about 2.5% at the depth of 15 m from the surface, which is consistent with the reported decrease of settling velocity by about 5% from the fresh water to the saline water of 35‰ (Dyer, 1986).

The existence of the river plume also causes the vertical temperature gradient, and the effect of temperature gradient is already included partially in the density gradient. However, the settling velocity is also affected by the viscosity of the fluid, which is largely affected by the temperature and changes the Reynolds number WD/ν. The small grains in the Stokes region is most affected by the temperature change, and the settling velocity decreases about 2% as the temperature decreases by approximately 1 degree from 20℃ (Sleath, 1984; Dyer, 1986).

Usually the temperature of the Nakdong River plume is higher than the ambient seawater except for the cold winter time. The vertical temperature difference may be small during spring and fall, but it may be greatest during the summer time. At the Nakdong river plume the measured temperature at the surface was higher than that at the bottom by less than about 0.5℃ during April, 1992. However, the difference was about 2.5℃ during June, 1992, which might considerably decrease the settling velocity as the sediment particles settle down. The turbulence caused by the plume, which affect the drag on the grains, may also affect the settling velocity of the particles and it is expected to reduce the settling velocity. However, the settling velocity of the small particles in the Stokes region are little affected by the turbulent fluctuations (Ludwick and Domurat, 1982).

The concentration of fine cohesive sediments in a steady flow is usually more or less uniform through the whole depth due to the extremely slow

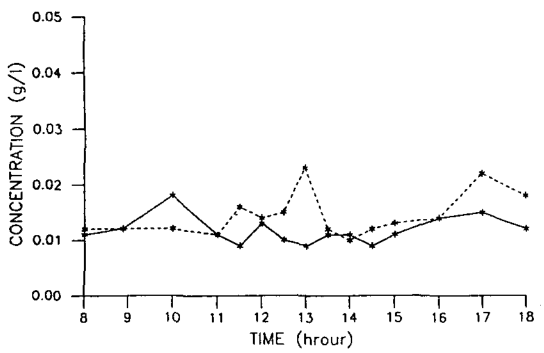

Fig. 9. Concentration of suspended sediments at the surface (solid line) and at the bottom (broken line) (April 4, 1992).

settling velocities of the sediment particles (Sleath, 1984). And the concentration in the water column decreases exponentially with time (Einstein and Krone, 1962; Odd and Owen, 1972) such as

$$\frac{C}{C_o}=exp\left[-\frac{ptW}{h}\right] \tag{4}$$

where, C: concentration at time t,
C_o: initial concentration at time $t=0$,
p: probability of a particle reaching the bed,
h: water depth.

Even though the probability p is usually a function of acting shear stress below the critical shear stress for deposition (Owen, 1977; Krone, 1993), the retarded settling of the particle due to the existance of the river plume may reduce the probability for the sediment particle to reach the bottom, and thus the sediment is held in suspension much longer and transported farther before it reaches the bottom. Fig. 9 shows the variation of suspended sediment concentration at the surface and 1 m above the bottom at the station, and the concentration is kept almost constant with time and depth except for the increase at the bottom during the time of maximum ebb and flood currents (Figs. 5(B) and 9, 13:00 and 17:00). The increase probably seems to be the result of resuspension of the bottom sediment by the strong tidal currents.

4. CONCLUSION

Fresh water effluent from a river mouth into an estuarine basin constitutes a turbulent jet plume, and the jet plume forms density gradient horizontally and vertically from the plume axis. The actual river plume effluent from the Nakdong River mouth barrage was identified by the measurements of currents, salinity, and water temperature at a station in the Nakdong Estuary, and the analysis of the field data showed a reasonably good correspondence with the theoretical solution, which supported the applicability of the lateral spreading velocity of a river plume based on the assumption of a Gaussian distribution for the density difference.

The vertical density gradient due to the river plume seemed to reduce the settling velocity of the sediment particle in the water column. Hence the sediments are held in suspension longer and transported farther into the estuary basin. The measurement of suspended sediment concentration at the Nakdong Estuary also showed a relatively constant concentration with time and depth for a tidal cycle even though an exponential decrease of concentration with time at the plume layer was expected if it were a normal steady flow.

ACKNOWLEDGEMENTS

The research was supported by Non Directed Research Fund, Korea Research Foundation, 1991 Korean Ministry of Education. Current meter was borrowed from the Department of Ocean Engineering, Dong-A University, and the field assistance by Professor K. C. Kim of the Dong-A University is also gratefully acknowledged.

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