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Near-Field Mixing Characteristics of Submerged Effluent Discharges into Masan Bay

See Whan Kang[+], Seung Hyup You[*], and Jung Yul Na[*]

Coastal and Harbor Engineering Laboratory, KORDI
Ansan P.O. Box 29, Seoul 425-600, Korea

[*]*Department of Earth and Marine Sciences, Hanyang University, Ansan, 425-791, Korea*

Abstract: Hydrodynamic mixing characteristics of submerged effluent discharges into Masan Bay were investigated by both field observations and numerical model simulations. CORMIX model, a length-scale mixing model, was adopted to obtain the near-field dilution and wastefield characteristics of the effluent discharges into Masan Bay. Model predictions of the near-field dilution rates were in a good agreement with field observations in summer and winter seasons. Seasonal variations in the dilution rates showed that the highest dilution rate was obtained in winter while the lowest dilution rate was in summer. As the effluent discharges are increased with the treatment capacity expansion to be completed by 2011, the dilution rates are expected to be much reduced and the near-field stability of the wastefields will become unstable due to the increased effluent discharges.

Key words: Submerged effluent discharge, Masan Bay, Near-field dilution, CORMIX, Near-field stability.

1. Introduction

The primary goals of sea outfall diffusing system are to accomplish a rapid initial mixing of the effluent with the receiving seawater and thus to minimize detrimental effects of the effluent discharges on the environment. In engineering practices, sea outfall system with a submerged multiport diffuser (Fig. 1) has found a most efficient way of maximizing near-field initial dilution by enhancing the rapid initial mixing of the effluent discharges with the ambient waters (Doneker and Jirka 1991). Recently, a submerged multiport diffuser consisting of many closely spaced ports through which wastewater effluent is discharged at high velocity has been widely used to meet regulatory requirements of increasingly stringent water quality criteria (Roberts *et al.* 1989; Wood *et al.* 1993). Since the early 1990's, 21 municipal wastewater treatment facilities along the coastal cities of Korea have been in operation to reduce and to control the pollutant loads directly discharged into the coastal waters where water quality has been worsening. As a part of the efforts for improving water quality in Masan Bay, a Masan-Changwon municipal wastewater treatment plant with a sea outfalls has been in operation since 1993, first in Korea. Five sea outfalls of municipal wastewater treatment facilities are in operation or to be operated at Ulsan and Sokcho coastal waters (Kang *et al.* 1999b).

Hydrodynamic mixing processes of the outfall

[+]Corresponding author.

E-mail : swkang@kordi.re.kr Fax : +82-31-408-5827

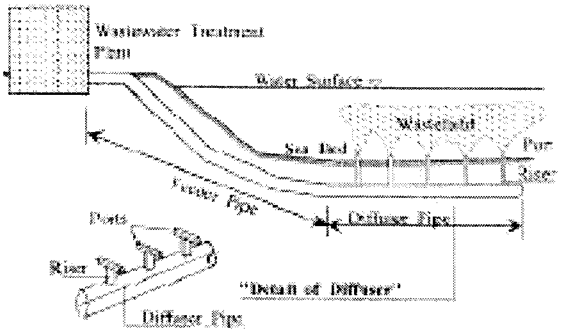


Fig. 1. Sea outfall system with a submerged multiport

discharges depend primarily on the discharge condition, diffuser length, the depth at discharge, and the ambient conditions of ocean current and density. A wastefield is established at the end of the initial mixing region, and then it drifts with the ocean currents and is diffused by oceanic turbulence in the far field. The near-field initial dilution of the discharges can be controlled by outfall design, but the wastefield behavior in the far field is subjected to the turbulent diffusion and transport processes which are dependent on the local in-situ ocean currents. Near-field mixing processes of the submerged effluent discharges have been mostly studied through laboratory experiments by Roberts *et al* (1989), and Jirka and Akar (1991). A few field studies at sea outfall sites have been also reported (Proni *et al* 1994; Tsai and Proni 1997).

In this paper, hydrodynamic mixing characteristics of submerged effluent discharges into Masan Bay were investigated by both field observations and numerical model simulations. A prediction scheme for near-field dilution and mixing characteristics was applied to Masan sea outfalls. The environmental factors such as water temperature, salinity and currents were measured at the Masan outfall site during the summer of 1998 and the winter of 1999. The field-measured dilutions of effluent discharges were compared with the predictions made by a CORMIX model (Akar and Jirka 1991). Seasonal variations in the dilutions of effluent discharges were also predicted. Dilution changes and the stability of the near-field flow structure were investigated for the treatment capacity expansion of Masan-Changwon wastewater treatment facilities to be completed by 2011.

2. Hydrodynamic Mixing Characteristics of Submerged Effluent Discharges

Hydrodynamic mixing behavior of submerged effluent discharges is determined by the interplay of ambient conditions existing in the receiving water body and by the outfall design characteristics such as diffuser length and alignment, and discharge depth. The ambient conditions are given by geometric and dynamic characteristics of the water body. Geometric parameters include plan shape, vertical cross-sections, and bathymetry of the discharge location. Dynamic characteristics are given by the velocity and density of the water body. In many cases, these conditions can be considered as steady or as in equilibrium state because the time scale for the mixing processes is usually in the order of minutes or up to an hour (Roberts *et al* 1989; Jirka *et al* 1996).

Hydrodynamic mixing processes of an effluent can be separated into two regions as" near-field" and " far-field" as shown in Fig. 2 (Roberts *et al* 1989; Doneker and Jirka 1991). In the near-field or initial mixing region, near to the diffuser, where a strong initial mixing takes place, the initial jet characteristics of momentum flux, buoyancy flux, and outfall geometry may influence the buoyant jet trajectory and mixing. The dilution at the end of this region is called the near-field initial dilution (Roberts *et al* 1989). For a large discharge in the coastal waters, typical length scales of the near-field and the far-field are in the order of hundred meters and kilometers, respectively.

The assessment of near-field stability, i.e. stable or unstable discharge conditions are important for understanding the behavior of the two dimensional plumes resulting from multiport diffusers (Jirka and Harleman 1979). Unstable discharge conditions which cause restratification or

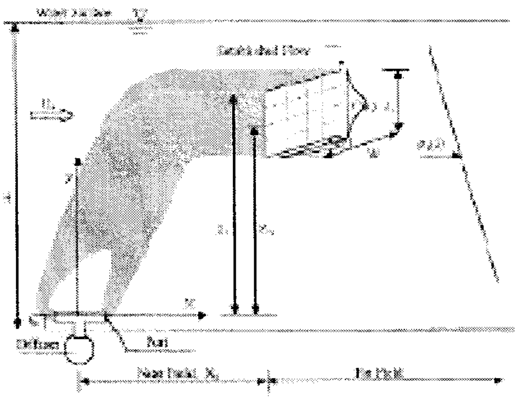


Fig. 2. Wastefield characteristics discharged from a submerged diffuser.

full vertical mixing of effluents are occurred by a combination of low buoyancy, high momentum and shallow water depth of effluent discharges. It is often called as" shallow water" conditions. Stable discharge conditions occurring from a combination of high buoyancy, low momentum and deep water, are referred to as " deep water" conditions. Three important types of near-field processes are a submerged buoyant-jet mixing, boundary interactions and a surface buoyant jet mixing (Jirka *et al* 1996).

3. Mathematical Mixing Models

In order to predict the near-field characteristics of effluent discharges, mathematical mixing models have been developed (Winiarski and Frick 1976; Teeter and Baumgartner, 1979; Frick, 1981; Mullenhoff *et al* 1985). As shown in Fig. 2, the most important wastefield parameters of submerged effluent discharges are the height to the top of the established wastefield, z_e, the height to the level of maximum dilution concentration(and minimum dilution), z_m, and the thickness, h (Roberts 1996). The minimum dilution at the end of the initial mixing region(x_i) is S_m which is defined as the smallest value of the dilution observed in a vertical plane through the wastefield at the end of the initial mixing region. There have been two different approaches for developing the prediction models: the one is based on the jet integral theory and the other is on the dimensional length scale arguments. As shown in Table 1, the jet integral models mostly of previous mixing models, thus far have not been successful due to their limited applicability (Jirka *et al* 1996). More recently, the length scale models such as CORMIX (Jirka *et al* 1996) and RSB (Roberts *et al* 1989) are widely used by U.S. EPA to determine near-field, initial dilution for setting effluent limits in the mixing zone.

In this study, a CORMIX model was introduced to investigate the Masan sea outfalls' case study. CORMIX, Cornell Mixing Zone Expert System(Doneker and Jirka, 1991), has been developed for the analysis, prediction, and design of aqueous toxic or conventional pollutants, e.g. BOD, COD, discharges into river, lake and coastal water. It was developed jointly by U.S. EPA and Cornell University during the period of 1985-1995. CORMIX model is based on the length scales of hydrodynamic mixing processes that determine the effluent fate and distribution in the physical aspects(Doneker and Jirka 1991). This model can resolve in details important dynamic parameters such as diffuser configurations and environmental factors to simulate effluent behaviors distinctly and has been successfully applied to cover 80~95% of practical discharge designs while other integral models covered only 10~20% of very limited applicability(Jirka *et al* 1996). CORMIX consists of three subsystems. These are (1) CORMIX1 for the analysis of submerged single port discharges, (2) CORMIX2 for the analysis of submerged multiport diffuser discharges, and (3) CORMIX3 for the analysis of buoyant surface discharges.

4. Masan Sea Outfalls Study

The Masan outfalls in Fig. 3 are located off the coast of Masan city and in Masan Bay, one of the most polluted water bodies in Korea, where most of the regional pollutants are loaded in. This semi-enclosed bay with the adjacent Chinhae Bay opens to the Korea Strait and has the total area of ~500 km^2 with shallow water

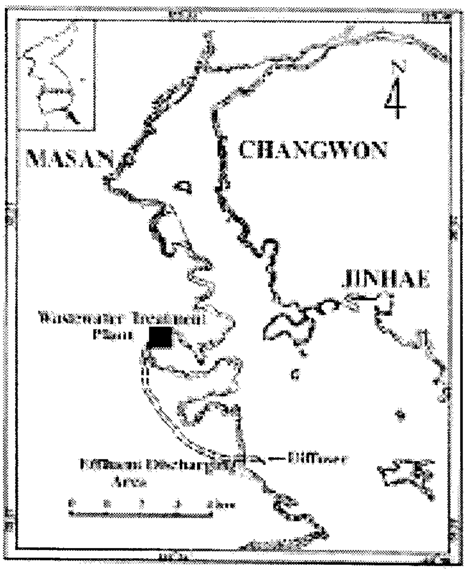


Fig. 3. Location map of the submerged ocean outfalls of Masan- Changwon wastewater treatment plant

depth, i.e., the average depths of ~5 m in the inner parts of Masan Bay and ~20 m in Chinhae Bay. The mean tidal range in a semi-diurnal tide is 180 cm and 45 cm for spring and neap tides, respectively, and its observed maximum tidal currents are up to 100 cm/s in the deep channel of Chinhae Bay while the currents in Masan Bay are very weak with less than 20 cm/s (Kang 1991). The water columns are well-mixed in winter, but highly stratified in summer with thermocline depths of 5~7 m (Kang 1993).

Since 1993, primary treated sewage effluents in the average of ~200,000 tons/day have been discharged through the outfalls. The treatment information is summarized in Table 1. Because of the primary treatment which removes only some of the solids from the sewage effluents, the removal rates of BOD and COD are very low, with less than 50%. The Masan outfalls are installed 680 m away from the nearest shore at 14 m water depth. The submerged multiport-diffuser in the length of 210 m consists of 21 risers equipped with 4 ports for each riser at 10 m intervals. Two current meters at the water depths of 5 m and 10 m, respectively were moored at the outfall site to measure oceanic currents for one month in 1982 (Fig. 4). A recent field survey showed that water and sed-

Table 1. Sewage treatment status of Masan-Changwon municipal treatment plant.

Construction Phase (year)	Treatment capacity (m^3/day)	Wastewater amount (m^3/day)			Treatment level
		Daily average	Daily maximum	Hourly maximum	
First phase (1993)	280,000	281,105	312,659	480,085	Primary process
Second phase (2001)	500,000	517,873	569,979	927,231	Primary process
Third phase (2011)	720,000	619,571	721,491	1,117,608	+incineration

Construction Phase (year)	Water quality (mg/l)				Removal rates (%)
	Parameters	Influent	Effluent	Design water quality	
First phase (1993)	BOD	173	100	-	42
	COD	303	175	-	42
	SS	222	68	-	69
Second phase (2001)	BOD	117	18	130	86
	COD	110	17	125	86
	SS	113	16	130	87
Third phase (2011)	BOD	117	18	130	86
	COD	110	18	130	86
	SS	113	16	130	87

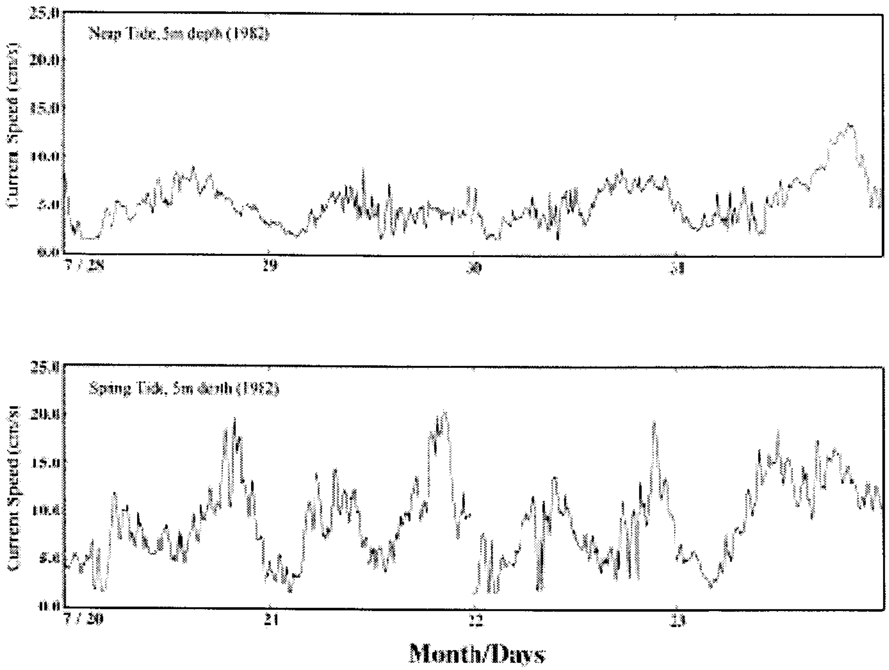


Fig. 4. Ocean currents measured during the spring and the neap tidal periods.

iment qualities in the outfalls area have been deteriorating since the effluent discharges began in 1993 (Kwon and Lee 1998).

Field Observations

Field measurements of ambient conditions at the Masan outfalls site and its vicinity were conducted during neap tidal periods of two seasons, the summer of 1998 and the winter of 1999. They included vertical and horizontal distributions of temperature and salinity measured by CTD. As shown in Fig. 5, the precise locations of 16 stations with 400 m grids for CTD measurements were determined by GPS (Global Positioning System). Fig. 6 shows vertical profiles of temperature and salinity measured in the summer and winter seasons. In the summer season, typical stratification appeared at the 4~7 m depth. On the other hand, as stratification disappears, uniform density profiles are observed in the winter season.

Near-field dilution of submerged effluent discharges can be obtained through two types of field measurements, dye and salinity (Proni *et al* 1994; Tsai and Proni 1997). In this study, salinity deficit was taken as a tracer to determine near-field dilutions. The salinity deficit method used the equation (1) to obtain the dilution rate from field data;

$$D_m = \frac{S_{ac} - S_e}{S_e} = \Delta$$

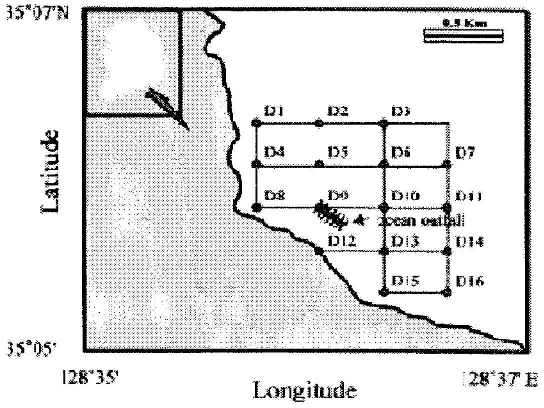
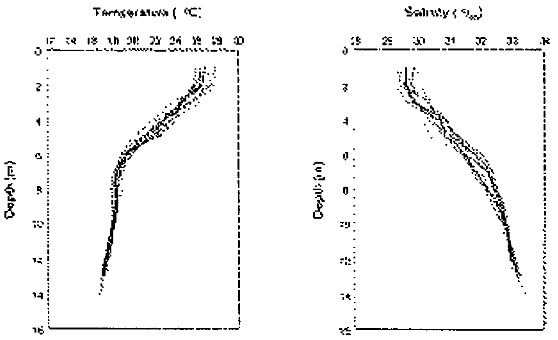
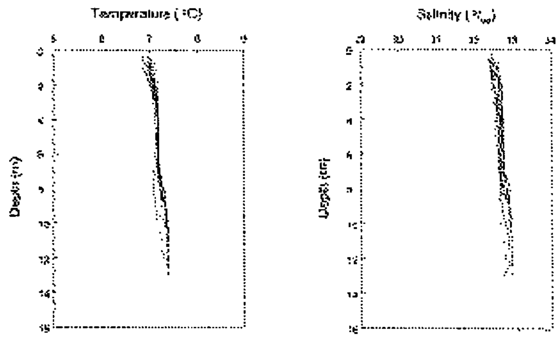


Fig. 5. Station map of field measurements at Masan sea



(a) Summer



(b) Winter

Fig. 6. Temperature and salinity profiles at Masan sea outfalls in summer and winter.

where D_m is the initial dilution, S_{ac} the characteristic ambient salinity, S_m the minimum salinity, S_e the effluent salinity, ΔS_m the maximum salinity deficit, and ΔS_e the salinity deficit in effluent.

Fig. 7 shows the isohaline contours of salinity data measured at the outfalls and its proximity. Fig. 7a and 7b are the isohaline contours of 1998 summer measurements at the thermocline depths of 6m while Fig. 7c and 7d are the contours of 1999 winter measurements at the 1 m depth. Summer and winter dilutions associated with weak ambient currents during the neap tide were obtained from the isohaline contours using the salinity deficit method. Two assumptions are considered: one, maximum salinity is considered as the ambient salinity, and two, the ambient water is affected by discharging fresh waters. Minimum salinity is produced by isohaline contours and then calculated field dilution rates as a preceding salinity deficit equation. Table 2 shows observed dilution rates in the summer for 5~7 m layer and winter seasons for surface to 2 m layer.

Table 2. Observed dilution rates in summer and winter

Depth	Summer	
	Morning	Afternoon
5 m	57*	33
6 m	39	24
7 m	27	20

Depth	Winter	
	Morning	Afternoon
Surface	108	136
1 m	96	181*
2 m	125	204*

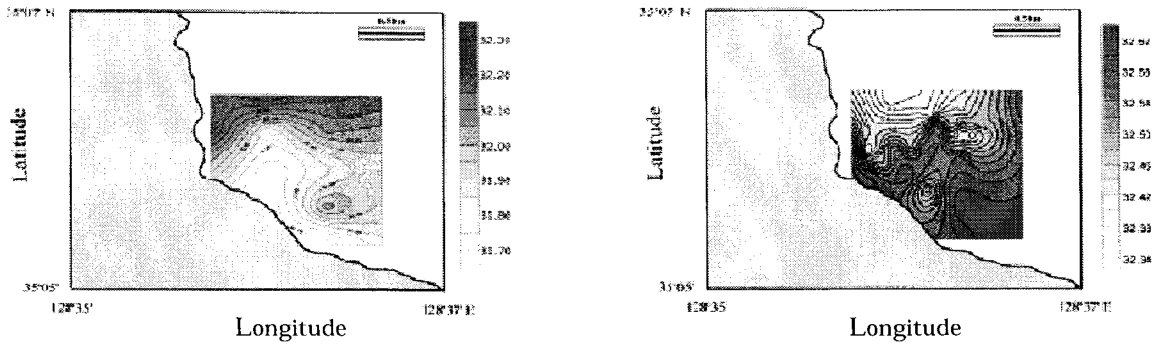
The observed dilution rates in summer were in the range of 27~57 and 20~33 for the morning and afternoon surveys, respectively. The dilution rates in winter were in the range of 95 ~125 and 136~204 for two field measurements. There were some uncertainties in the field data for the high dilution ranges, and they were not used for the comparison of model predictions.

Model Predictions

In order to compare with the observed dilution rates, CORMIX2 was used to calculate the near-field dilution of the wastewater discharges and the wastefield characteristics. For the ambient flow velocity, the mean current velocities measured at the mid-depth of 5 m were used; a weak current of 6.0 cm/s for the neap tide and a strong current of 15.5 cm/s for spring tide(Fig. 4).

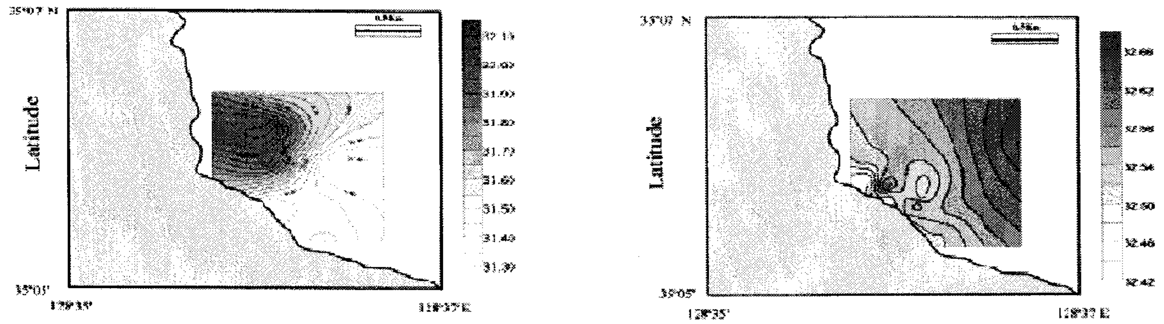
Table 3 shows the predicted results of dilution rates and wastefield characteristics at the five stations in Fig. 5. The plume position at the edge of near-field region is represented by X, Z coordinates and others are plume characteristics such as BV vertical thickness, BH horizontal half-width, ZU upper boundary, and ZL lower boundary.

The dilution rates predicted by CORMIX2 model during the summer are in the range of



(a) Summer (morning depth: 6m)

(c) Winter (morning depth: 1m)



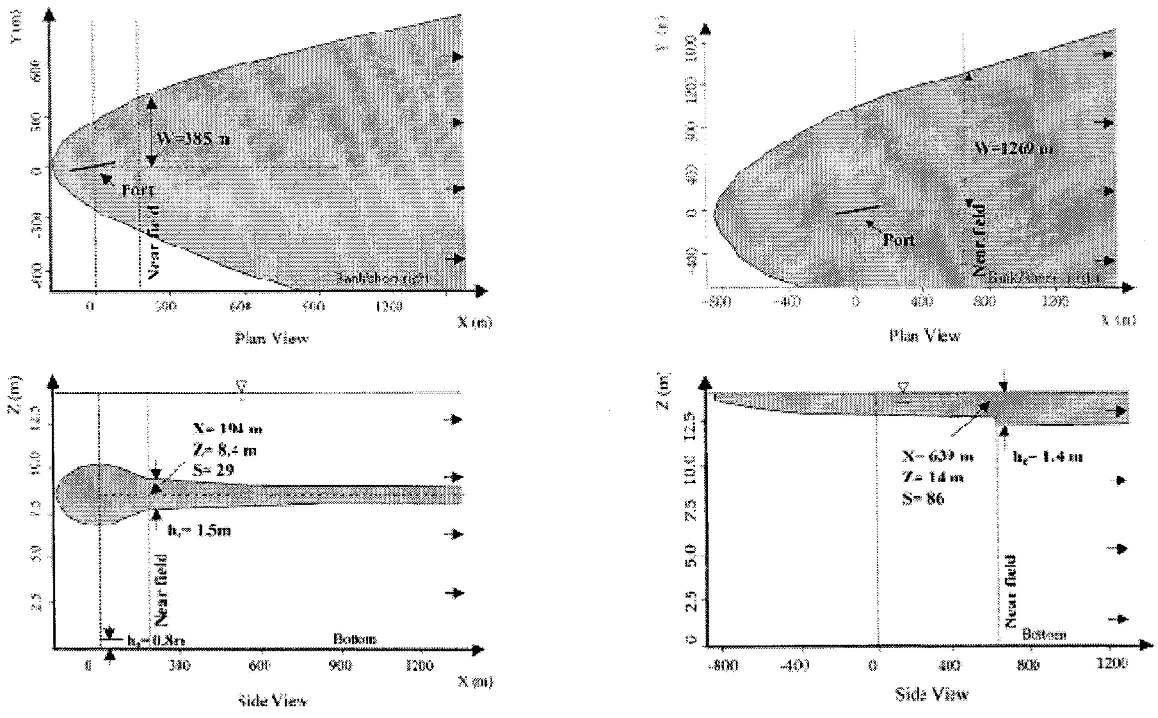
(b) Summer (afternoon depth: 6m)

(d) Winter (afternoon depth: 1m)

Fig. 7. Isohaline contours of salinity field data.

Table 3. Wastefield characteristics and near-field dilution rates predicted by CORMIX2.

Season	Time	Station	Plume position		Dilution	BV	BH	ZU	ZL	Accumulated time	
			X (m)	Z (m)						sec	hrs
Summer	Morning	D05	194.5	8.4	29	1.5	385.3	9.1	7.6	3227	0.9
		D06	190.0	8.0	27	1.4	376.4	8.7	7.3	3151	0.9
		D09	201.2	8.9	32	1.6	398.3	9.7	8.1	3336	0.9
		D10	197.5	8.6	30	1.5	391.1	9.3	7.8	3275	0.9
		D13	196.9	8.5	30	1.5	390.0	9.3	7.8	3266	0.9
	Afternoon	D05	201.6	8.9	33	1.6	399.1	9.6	7.1	3343	0.9
		D06	185.9	7.6	25	1.3	368.5	8.3	7.0	3084	0.9
		D09	195.4	8.3	29	1.5	387.0	9.1	7.6	3240	0.9
		D10	195.3	8.4	29	1.5	386.8	9.1	7.6	3239	0.9
		D13	188.2	7.8	26	1.4	373.0	8.5	7.1	3123	0.9
Winter	Morning	D05	639.7	14.0	86	1.4	1269.9	14.0	12.6	10616	2.9
		D06	642.1	14.0	86	1.4	1274.8	14.0	12.6	10657	2.9
		D09	642.3	14.0	87	1.4	1275.3	14.0	12.6	10661	2.9
		D10	642.9	14.0	86	1.4	1276.4	14.0	12.6	10670	2.9
		D13	643.5	14.0	87	1.4	1277.8	14.0	12.6	10681	2.9
	Afternoon	D05	644.0	14.0	90	1.5	1273.3	14.0	12.6	10650	2.9
		D06	645.2	14.0	90	1.4	1275.7	14.0	12.6	10670	2.9
		D09	644.1	14.0	90	1.4	1273.5	14.0	12.6	10652	2.9
		D10	644.3	14.0	91	1.4	1273.9	14.0	12.6	10655	2.9
		D13	644.2	14.0	91	1.4	1273.8	14.0	12.6	10655	2.9



(a) Summer

(b) Winter

Fig. 8. CORMIX2 prediction of the wastefield transport.

25~33. On the other hand, dilution rates during the winter are in the range of 86~91. Fig. 8 shows the side and plane views of the predicted wastefields in the weak currents of summer and winter. Even the weak ambient currents of ~6 cm/s, buoyant jets gradually deflected into the current direction and induced additional mixing. Since the ambient stratification is very strong in the summer, it leads to trapping of the wastewaters at thermocline depth of 4~7 m. In the winter, the buoyant jet rises and forms a stable layer at the sea surface due to the isopy-

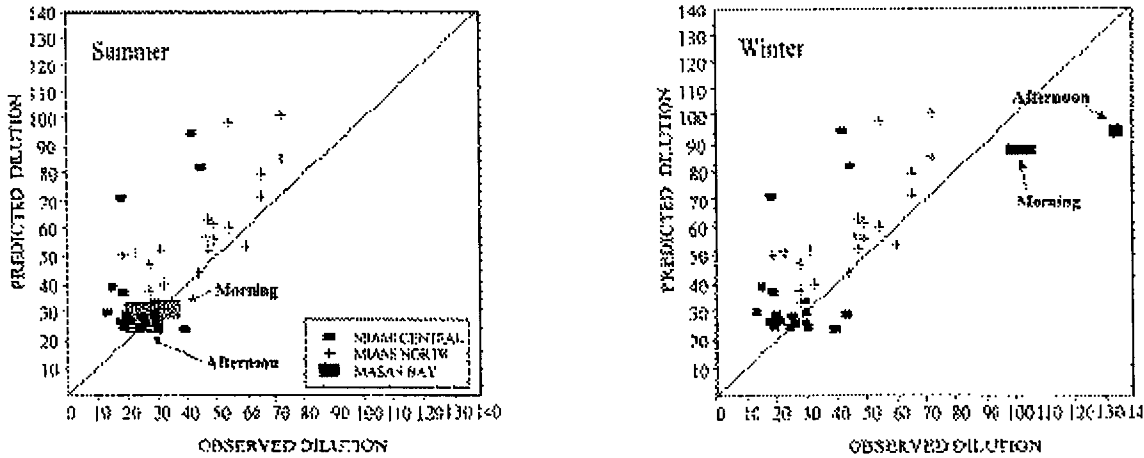


Fig. 9. Comparisons of Masan outfalls dilutions with Miami outfalls results.

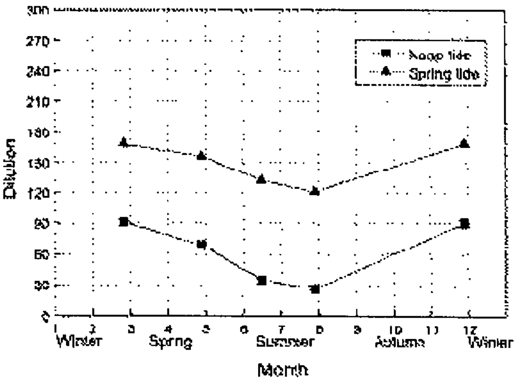


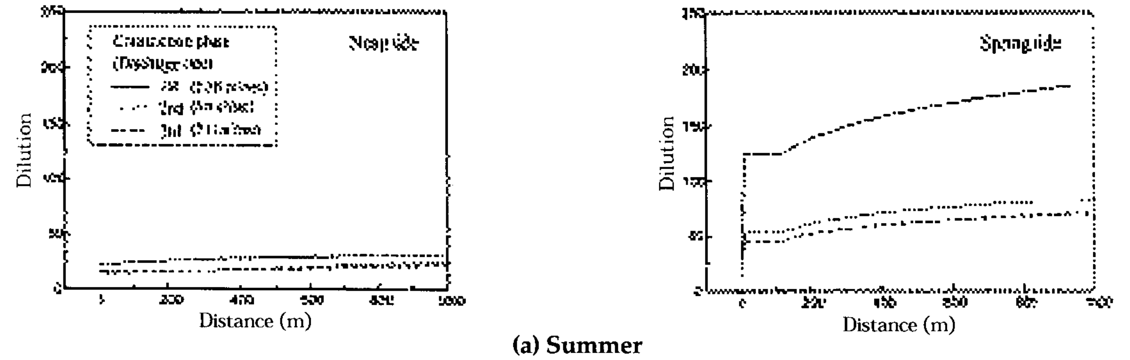
Fig. 10. Seasonal changes of near-field dilution under the neap and the spring tidal currents.

cnal water density.

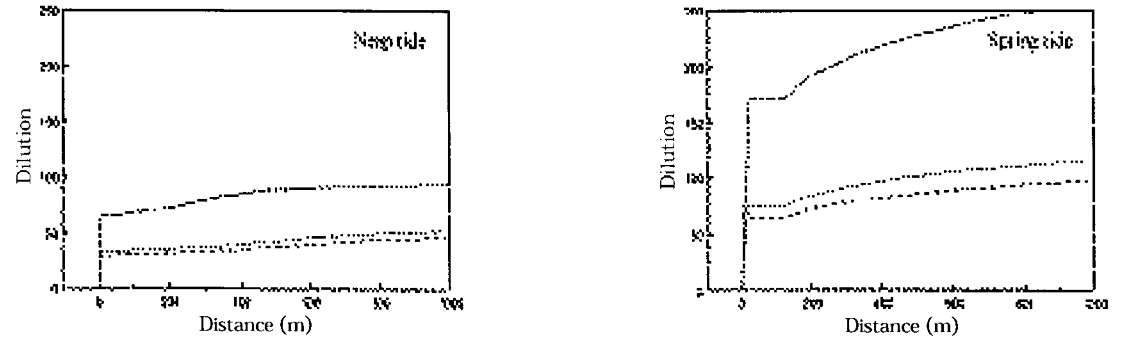
Fig. 9 shows the comparisons between the observed dilutions of summer and winter seasons with CORMIX2 predictions, and also includes the Miami outfalls data obtained during the Southeast Florida Ocean Outfalls Experimental II (SEFLOE II, 1991~1994) project (Fergen and Huang 1994). The model predictions agree well with the Masan outfalls case than with Miami outfalls. Both results in summer and winter seasons were in a reasonably good agreement with the field observations although the predictions in the winter tended to underestimate the dilution rates (Kang *et al.* 1999c; Kang *et al.* 2000).

Seasonal Changes of Near-field Dilutions

Seasonal changes of near-field dilutions were also simulated by CORMIX2 model using the ambient field data observed in the Masan outfalls area (Kang *et al.* 1993). Fig. 10 shows seasonal variations of near-field dilutions with two ambient flow conditions, that is, the strong current of 15.5 cm/s during a spring tide and the weak current of 6.0 cm/s for a neap tide. Under the weak ambient currents seasonal variations in the near-field dilutions were in the range of 26~91 with the low dilution in summer and the high dilution in autumn and winter



(a) Summer



(b) Winter

Fig. 11. Near-field dilution rates along the downstream for the future treatment expansion cases of Masan-Changwon

(Kang *et al.* 1999a). The dilution difference between summer and winter seasons is very large, by fourfold only due to the effect of density stratification. Under the strong ambient currents, seasonal variations in the near-field dilutions were in the range of 120~168 and the difference between summer and winter seasons becomes relatively small, by 30%, compared with the large difference in the weak ambient current condition.

These results indicated that the near-field dilution is more governed by ambient current conditions than density stratification at the outfalls. Similar results of seasonal dilution changes were also reported by Roberts and Snyder(1993) from the hydraulic model tests for the Boston Harbour outfalls.

Dilution Changes due to Treatment Capacity Expansion

According to the expansion plan of Masan-Changwon wastewater treatment plant(Masan city 1996), the treatment capacity will be increased from currently 280,000 m^3/day(Q_0 = 2.315 m^3/s) to 500,000 m^3/day(Q_0 = 6.0 m^3/s) with the completion of the second construction phase in 2001, and to 720,000 m^3/day(Q_0 = 7.17 m^3/s) after the third construction phase in 2011. CORMIX2 model was simulated to predict the dilution changes due to the increase of effluent discharges for the second and third expansions of the treatment capacities. Fig. 11 shows the summary of the predicted results for the present, the second and the third facility expansions. More details of this study can be found elsewhere (You 2000). It is predicted that the near-field dilution rates would be drastically reduced as the effluent discharge rates were to be increased. Even under the strong ambient currents (~15.5 cm/s) of spring tide at the outfall site, the dilution rates are to be decreased from 120 to 46 in summer and from 168 to 63 in winter at 200 m downstream. The dilution rates were also expected to be lowered under the weak currents (~6.0 cm/s) of neap tide from 26 to 15 in summer and from 90 to 43 in winter. For the environmental concerns, a feasibility study for selecting a new outfalls site is needed for the future expansion of treatment facilities.

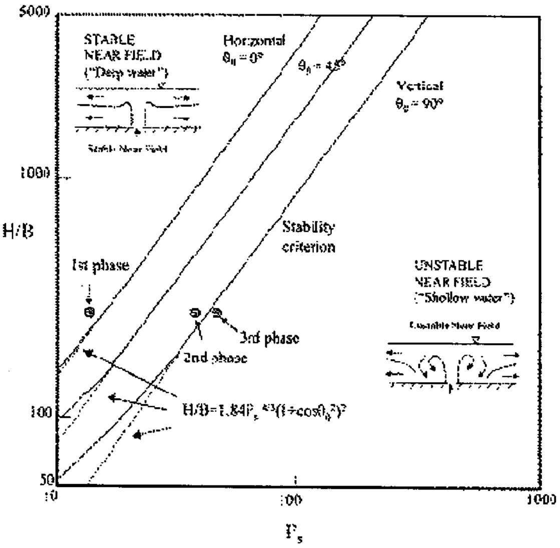


Fig. 12. Near-field stability criteria diagram for slot buoyant discharges from submerged multiport diffuser. The stability of Masan outfall discharges are marked as the 1st, 2nd, and 3rd expansion phases.

Stability of Masan Sea Outfall Discharges

The near-field stability criteria for slot buoyant discharges from submerged multiport diffuser have been obtained from the theoretical and experimental studies of Jirka and Harleman(1979) and Jirka(1982). Fig. 12 shows the stability diagram using the parameters of a discharge slot densimetric Froude number($F_s = m_0^{1}/j_0^{2}B^{1}$) and relative depth H/B with the discharge angle θ_0. $B(=D\pi/l)$ is the slot width, D the port diameter, l the port spacing, m_0 the momentum and j_0 the buoyancy flux for the unit diffuser length. As shown in Fig. 12, the near-field of submerged effluent discharges is defined as stable if a buoyant surface layer is formed which does not interact with the initial buoyant jet zone. However, it is defined as unstable if the layered flow structure breaks down forming recirculating zones or mixing over the entire water depth. For low F_s and large H/B, the near-field becomes stable thus it can be called as a" deep water" discharge.

An unstable discharge is called as a" shallow water" discharge.

For the Masan outfalls, $\mathcal{B}$ is 0.013, and H/B is 279. The slot densimetric Froude numbers are 14.6, 38.5 and 46 for the first, the second, and the third treatment expansion phases, respectively. As marked in Fig. 12, the near-field of the 1st phase(present) discharge is stable, however it becomes unstable for the second and the third phase discharges. Since the discharge depth of Masan sea outfalls is ~14 m and the diffuser length is 210 m which is relatively long compared to the discharge depth, the near-field will become unstable as the effluent discharges are to be increased with the future treatment capacity expansion.

5. Conclusions and Discussion

Hydrodynamic mixing characteristics of submerged effluent discharges into Masan Bay were investigated by the field observation studies and by the numerical simulations of CORMIX model. The near-field mixing behavior of the effluent discharge is governed by the environmental factors existing in the coastal water and by the discharge conditions associated with geometric and flux characteristics of the outfalls installation. Because of many variables involved in the dynamics of submerged buoyant-jet flows, mathematical model predictions of near-field dilution and wastefield characteristics have been an extremely difficult task. In this study, a CORMIX model was utilized to obtain the near-field dilution rates and wastefield characteristics of the effluent discharges into Masan Bay. The model predictions were compared with the observed dilution rates under the summer stratification and the winter isopycnal mixing conditions at the outfalls. The results showed that the CORMIX model can be applied to the complicated sea outfalls installations such as Masan outfalls with a submerged multiport diffusing system.

The highest dilution rates in the seasonal variations were found in winter while the lowest dilution rates were found in summer due to density stratification. As shown in Fig. 8, the winter isopycnal mixing of water density causes increases in the near-field dilution of the effluent discharge as they rise to the sea surface. On the other hand, the summer density stratification causes to inhibit the near-field mixing by trapping the effluent discharges at the thermocline depth of 5~7m at Masan outfall site. However, the near-field mixing and dilution rates were found to be more influenced by ambient currents than by ambient density stratification at the outfalls. For the weak ambient currents of ~6.0 cm/s, summer dilution rates were reduced by 70% of the winter rate while the difference between two seasons became much less, by 30%, under the strong ambient currents of ~15.5 cm/s. Similar results to our findings were also reported from the hydraulic model tests for the Boston outfalls(Roberts and Snyder 1993)

Since the low dilution of ~20 was found in summer with nearly stagnant currents at the outfalls, most of the contaminants discharged from Masan-Changwon muni-cipal wastewater treatment plant would be accumulated in the vicinity of the outfall. According to recent field surveys of Kwon and Lee(1998), the discharged contaminants such as heavy metals have been increasingly accumulated in the recent surface sediments. The sediment quality in the outfall areas has been worsened by the factor of 4.7 since the effluent discharges began in 1993. As the treatment capacity expansion by the year of 2011 is planned, the effluent discharges will be increased from current 280,000 m^3/day (first phase) to 720,000 m^3/day in 2011 after the third expansion phase. The model predictions showed that the dilution rates become much lower than the present rates. The near-field stability of the wastefields will become unstable due to the increased effluent discharges. Even with the current discharges of ~200,000 m^3/day, we have found that the near-field dilution rates at Masan outfalls were in the much lower range than the obtainable dilution in a well-designed outfalls elsewhere, which is in the order of 100 or more. After a feasibility study by surveying ocean environmental conditions and model simulations, a new site for Masan outfalls should be searched carefully to maximize the dilution rate and to obtain the stable near-field flow structure even with the increased discharges.

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References

Akar, P. J. and G. H. Jirka. 1991. CORMIX2: An expert system for hydrodynamic mixing zone analysis of conventional and toxic submerged multiport diffuser discharges. Tech. Report, DeFrees Hydraulics Laboratory, School of Civil and Environmental Engineering, Cornell University, Ithaca, N.Y.

Doneker, R. L. and G. H. Jirka. 1991. Expert system for mixing-zone analysis and design of pollutant discharges. *J. Wat. Resour. Plann. and Manag.*, 117, 679-696.

Fergen. R. E. and H. Huang. 1994. Comparison of SETLOE II field initial dilution data with two EPA models: UM and CORMIX. p. 249-254. In *Proc. WEFTEC '94* NOAA.

Frick, W. E. 1981. A theory and users' guide for the plume model MERGE, revised. Tetra Tech Inc., Environmental Research Laboratory, Corvallis, OR.

Jirka, G. H. and D. R. F. Harleman. 1979. Stability