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論文

Current and Long Wave Influenced Plume Rise and Initial Dilution Determination for Ocean Outfall

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해양 배출구에서 해류와 장파에 의한 플룸 상승과 초기 희석도 결정

권석재

Key Words : Ocean Outfall(해양 배출구), Plume Rise(플룸 상승), Initial Dilution(초기 희석), Surfacing Frequency(표면상승 빈도), Significant Wave Height(유의 파고), Resultant Velocity Vector(잔차류 속도 벡터), Diffuser(확산기)

Abstract

In the United States, a number of ocean outfalls discharge primary treated effluent into deep sea water and contribute for more efficient wastewater treatment. The long multiport diffuser connected by long pipe from a treatment plant discharge wastewater into deep water due to the steep slope of the sea bed. However, Plume discharged from the diffuser can have significant impacts on coastal communities and possibly immediate consequence on public health. Therefore, there have been growing interests about the dynamics of plume in the vicinity of the ocean outfalls. It is expected that the ocean outfall should be considered for more efficient and reliable wastewater treatments as soon as possible around coastal area in South Korea.

A number of studies of plume dynamics have used various models to predict plume behavior. However, in many cases, the calculated values of plume behavior are in significantly poor agreement with realistic values. Therefore, in this study, it is recommended that improvements should be made in the application of the plume model to more simulate the actual discharge characteristics and ocean conditions. It should be noted that input parameters in plume models reflect realistic ocean conditions like waves as well as currents. In this study, as one of the new parameters, current and long wave-influenced plume rise and initial dilution have been taken into account by using simple linear wave

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theory under some specific assumptions for more reliable plume behavior description.

Among the improved plume models approved by EPA (Environmental Protection Agency), the RSB (Roberts-Snyder-Baumgartner) and UM(Updated Merge) models were chosen for the calculation of plume behavior, and the variation calculated by both models on the basis of long period wave was compared in terms of plume rise and initial dilution.

1. Introduction

The study site is the Sand Island outfall located on the south coast of Ohau as shown in Fig. 1. This shows the location of the diffuser and the monitoring stations where density profiles were measured along entire depth. The Sand Island outfall has been classified and studied as one of the main outfalls in the United States due to the significantly large discharge flow rate and the importance of location. A number of plume dynamics studies of the Sand Island outfall have been made with much funding from the mainly City and County of Honolulu. One of the studies, Project MB-4 in the Mamala Bay Study made with funding in the amount of $9 million, statistically dealt with the near-field behavior of the plumes at the Sand outfall. In Project MB-4, the RSB model was used to run more than 20,000 near field simulations based on bottom currents measured in Project MB-6, treatment plant flows, and density profiles measured simultaneously on a halfhour time interval (Roberts, 1995).

Sand Island Outfall plume model prediction made by the Mamala Bay Study predicted a high surfacing frequency (how much of the plume discharged from the diffuser hits water surface on the basis of time (generally based on one year)) of 22.4 %. However, this surfacing has not been observed in the ocean, and the frequency of surfacing obtained by model studies by Oceanit Laboratories, Inc. were approximately 2 %. It is suggested that following studies should use reliable and justifiable model and differ in the input data and in the treatment of the new and realistic parameters. In this study, as one of the new parameters to reflect realistic ocean conditions, current and long wave-influenced plume rise and initial dilution have been considered by using simple linear wave theory under some specific assumptions for more reliable plume behavior description. The main objective of this paper is to investigate the combined effects of currents and waves on the plume rise and initial dilution for the Sand Island Outfall. This study will also provide a standard technique to evaluate future data and the plumes of other outfalls.

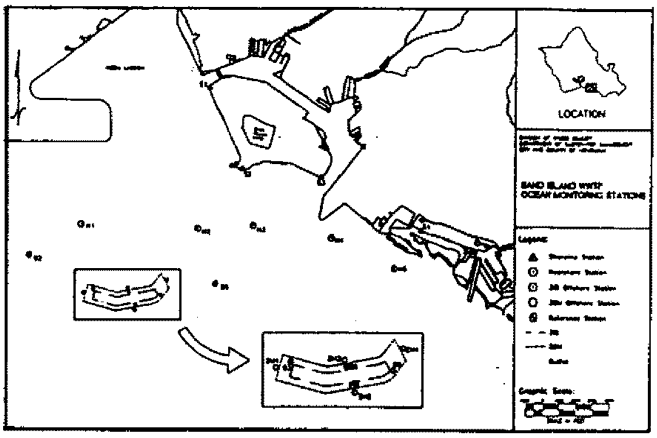


Fig. 1 Plan View of the Sand Island WWTP Ocean Monitoring Stations (City and County of Honolulu)

2. Current Direction and Magnitude

2.1 Description of Mathematical Models

The RSB (Roberts-Snyder-Baumgartner) model approved by EPA (Environmental Protection Agency) is a more suitable model than any other previous model since this model is based on the experimental studies of multiport diffusers in density-stratified currents. The RSB model takes into account the merging of plumes from both sides of the diffuser and re-entrainment and additional mixing in the spreading layer. The surfacing plume generated by stratified or unstratified density conditions can be predicted by the RSB model. However, it should be noted that RSB is based on an uniform current, linear density stratification, and straight line diffusers (Roberts, 1995).

The UM (Updated Merge) model, the latest model approved by the EPA, has been developed for marine applications by Teeter and Baumgartner (1979). Since the UMERGE model has been generalized and improved, the UM model includes the improvements. The features in the UM model includes Lagrangian formulation and projected area entrainment (PAE) hypothesis which is also supported by the experimental data on which the RSB model is based. The UM model is suitable for a similar range of conditions for single port as well as multiport discharges, but only for the ports along one side. The UM model can handle vertical nonuniformities in current speed and direction which are not applicable in the RSB model. However, the limitations are that the UM is less useful for the cases of currents parallel to the diffuser, for shallow water, and for plumes discharging to very cold or fresh water (Baumgartner, 1994).

The UM and RSB models are reliable and recent models which will be used in this study for the prediction of wastefield behavior at both outfalls. This study will also show which model is more suitable for these outfalls. The results predicted by the RSB and UM models will be compared for a range of plume behavior. The details of the general and mathematical descriptions of the RSB and UM models are discussed in the previous study (Kwon & Lee, 1997).

2.2 Input Parameters

Buoyant effluent discharged from the submerged multi-port diffusers rapidly rises in the water column and entrains the surrounding water. The plume stops rising at a level of neutral buoyancy, known as the "trapping level", which is predominantly dependent on the density stratification. The region where mixing is caused by the turbulence generated by effluent momentum and buoyancy, also known as "near field", will be the focus of this study.

The parameters include effluent flow rate, number of ports, port spacing, port depth, effluent salinity, port diameter, current direction, current speed, and density profile. Conservative values of each parameter were taken from the manual, "Dilution Models for Effluent Discharges" (Baumgartner et al., 1994). However, in order to reflect the actual discharge characteristics, the average of measured value of effluent salinity and temperature was taken into account while, in the Mamala Bay Study, the salinity of fresh water was entered as one of the input parameters. Among these parameters, current speed and direction will be differed to reflect realistic ocean conditions like waves as well as currents. The application to consider current and long wave-influenced plume rise and initial dilution will be described by using simple linear wave theory for more reliable plume behavior description in the following sections.

2.3 Mean Current Direction and Magnitude

In the Mamala Bay Study, the dominant direction of near bottom currents measured around the Sand Island diffuser was measured respectively to be 267 deg. (clockwise from North) which is almost parallel to the diffusers (Roberts, 1995). In this study, the Sand Island diffuser is assumed to be parallel to the East-West direction. The diffuser is assumed to be straight. The angle (alpha) between the Sand Island diffuser and the respective mean current direction is +3 deg. (Fig. 2).

The mean current speed in the vicinity of the Sand Island Outfall, 12.7 cm/s, has been taken from De Jesus (1984) and Suarez (1990) since the Mamala Bay Study did not present mean current speed. It is reasonable to use this value since the measured maximum current speed at the diffuser is in good agreement with the maximum value measured in the Mamala Bay Study.

3. Wave Induced Horizontal Water Particle Velocity and Wave angle

In this study, the significant wave height (0.83m) and wave period (16 sec.) around the Sand Island Outfall are based on the wave data measured using a pressure wave gage during the period of August 11 to September 21, 1982 (Zapka, 1984). Even though the wave period of 16 seconds is relatively longer than the wave periods estimated by waverider data (an accelerometer instrument which is much less sensitive to long period and low amplitude waves), they represent a significant contribution to the frequency of occurrence distribution (Zapka, 1984). The significant wave height was estimated as 0.83m ($H_s = 1.63F$, where $\overline{H}$ is the average wave height).

The wave induced horizontal water particle motion at the seabed will have significant effects on plume behavior (as it does on sand motion). The horizontal bottom water particle velocity at the center of the Sand Island diffuser is calculated using linear wave theory under the assumption of straight and parallel depth contours around the Sand Island diffuser. The horizontal velocity under a progressive wave is given by

$$Vh = \frac{H\omega}{2} \frac{\cosh k(d+z)}{\sinh kd} \cos(kx - wt) \quad \cdots\cdots\cdots (1)$$

The bottom (z= -d) horizontal velocity under the wave at a fixed point (x=0) is expressed as

$$Vh_b = \frac{H\omega}{2} \frac{\cos(-\omega t)}{\sinh kd} \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (2)$$

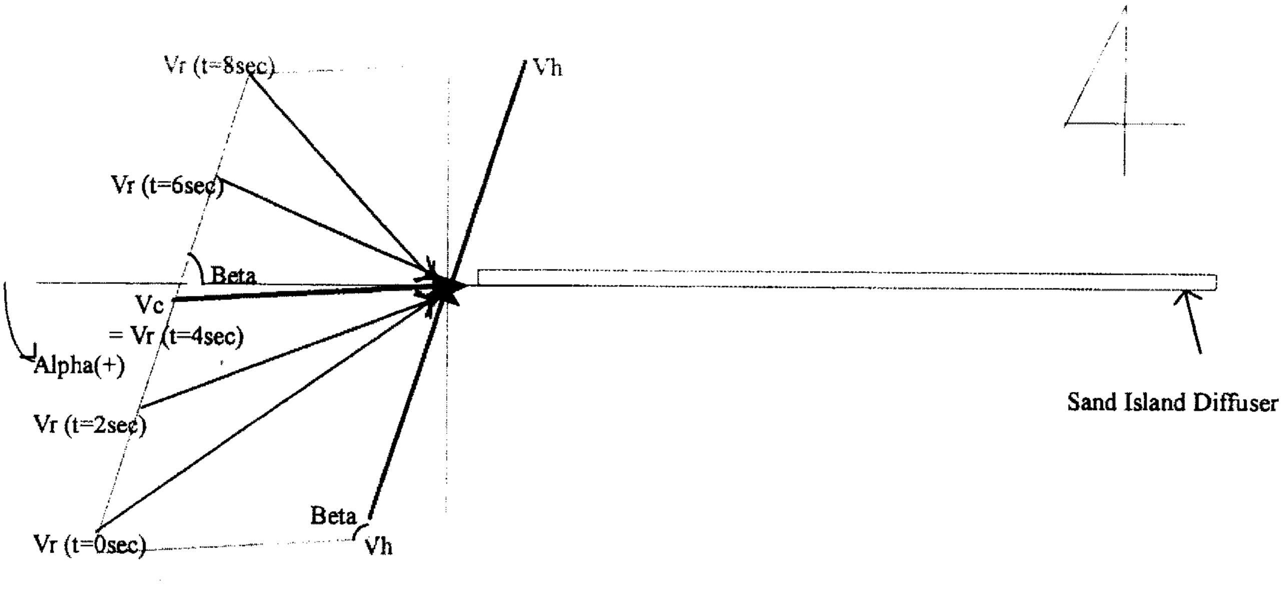
where Vh_b is horizontal bottom velocity, H is significant wave height, ω is wave frequency (= $2\pi/T$, t is time, k is wave number (= $2\pi/L$), d is water depth, T is wave period, and L is wave length. Wave length is computed using Pade approximation, defined as

$$L = \left\{ gd\left[y + \left(1 + \sum_{n=1}^{9} d_n y^n \right)^{-1} \right]^{-1} * T^2 \right\}^{1/2} \quad \cdots\cdots (3)$$

where $y = \frac{\omega^2 d}{g} dk \tanh(kd)$

d1 = 0.66667, d2 = 0.35550, d3 = 0.16084
d4 = 0.06320, d5 = 0.02174, d6 = 0.00654
d7 = 0.00171, d8 = 0.00039, d9 = 0.00011

The maximum horizontal bottom water particle velocity was calculated to be 0.098 m/sec. The wave induced bottom horizontal velocity



(Overhead View)

Fig. 2 Resolution of the Resultant Vector considering Vc and Vh for the Sand Island Diffuser Area

Vc : Mean Bottom Current Velocity Vector (=0.127 m/s)
Vh : The Wave Induced Horizontal Bottom Velocity Vector (Max = 0.098 m/s)
Vr : The Resultant Velocity Vector considering Vc and Vh (Max= 0.179 m/s)
Alpha : The Resultant Counter Clockwise Angle from the Diffuser Axis (deg.)

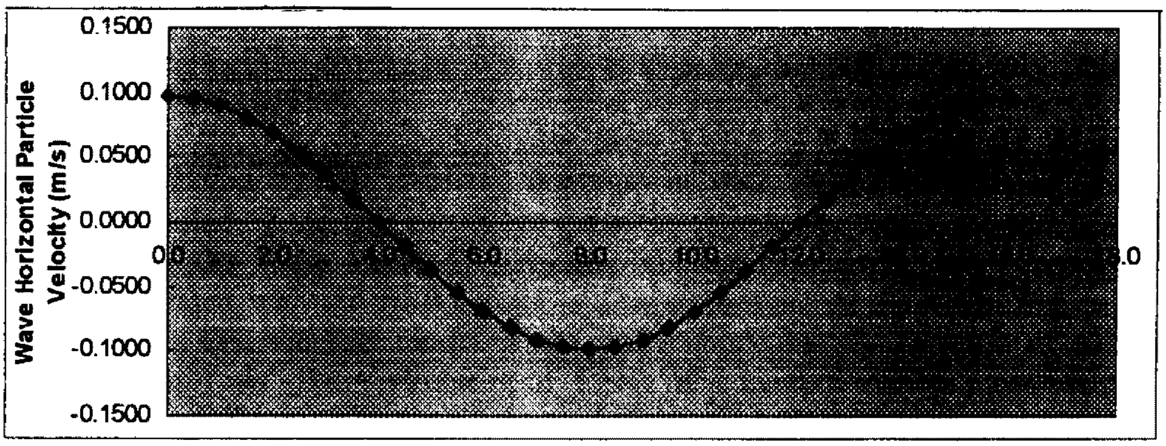


Fig. 3 Wave induced Horizontal Bottom Velocity Variation based on Linear Wave Theory (at the center of the Sand Island Diffuser, Hs = 0.83 m, Tp = 16 sec.)

variation with wave period is shown as a sinusoidal curve (Fig. 3).

The angle between wave direction and North at the center of the diffuser is calculated using a ACES' linear wave theory, Snell's law under the assumption of constant shore slope and parallel depth contours, where the incident wave direction (14 deg. : clockwise from North) and incident significant wave height (1.3 m) have been taken from the "Nearshore Circulation and sediment Transport" (Wang, 1993). The wave angle (the angle between wave direction and the line perpendicular to the depth contour) at the center of Sand Island diffuser was calculated to be 12 deg. which is close to perpendicular to the diffuser.

4. Current and Wave Induced Plume Behavior

The resultant velocity vector can be resolved from two components which are the current velocity vector and wave induced horizontal velocity vector by using the parallelogram law (Fig. 2). The variation of the resultant velocity and direction at the Sand Island diffuser on a wave period basis is presented in Fig 4. The variation is symmetric with respect to half of the wave period, and the difference in the variation at both diffusers is due to the angle difference between the bottom current velocity vector and wave induced horizontal bottom velocity vector. It is assumed that the long period wave has maximum horizontal particle velocity when time equals to 0 sec. Hence, the bottom current velocity and resultant velocity vectors are identical when time reaches a quarter of the wave period (i.e. at t = 4 sec.) as shown in Fig. 4.

The plume rise and initial dilution variation based on a wave period of 16 sec. is predicted by running the RSB and UM models using the variable resultant velocity vectors. It is expected that, in the real world, the plume from each port follows a wave induced zigzag motion around the current direction as the plume rises. In this study, for model calculation purposes, the effluent velocity is assumed to be constant along whole plume path. This study will focus on the vertical plume behavior rather than any horizontal motion since the main objective is to determine the vertical rise distance and dilution. In addition, higher effluent momentum at the initial plume region after discharge will have larger effect on the plume behavior, but will be dissipated soon. In this case, because the model calculation require a steady-state condition, it is assumed that the initial plume direction discharged from multiport corresponds to the resultant direction. Due to the dominant resultant effects on the plume behavior, the resultant velocity vectors were directly entered instead of current speed and direction. The other values of input parameters are identical to the values used in the sensitivity analysis with the exception of the density profile. The density profile entered here was measured at ZM2 on October 10, 1996.

The plume behavior described at each time (t = 0, 1, 2, ...) indicate the plume behavior determined by the resultant direction at each time. The plume behavior variations predicted by the UM model are quite sensitive in the range of 3 seconds to 5 seconds where the wave induced horizontal bottom velocity is low whereas the variation calculated with the RSB model is almost constant as shown in Fig. 5. It should be noted that the UM model is not really applicable for the case of currents parallel to the diffuser (Baumgartner et al., 1994). It is evident that, in most cases, the maximum or minimum effect on plume behavior corresponds to the maximum horizontal velocity (t = 0 second) or the minimum horizontal velocity (t = 4 seconds). The comparison of plume rise and initial dilution predicted by the RSB and UM models is shown in Fig. 5. It is suspected that the initial dilution when time equals to 4 seconds is the lowest even when the plume reaches water surface. However, it is expected that that the horizontal distance and length of time of the initial mixing region are very short in both the RSB and UM models

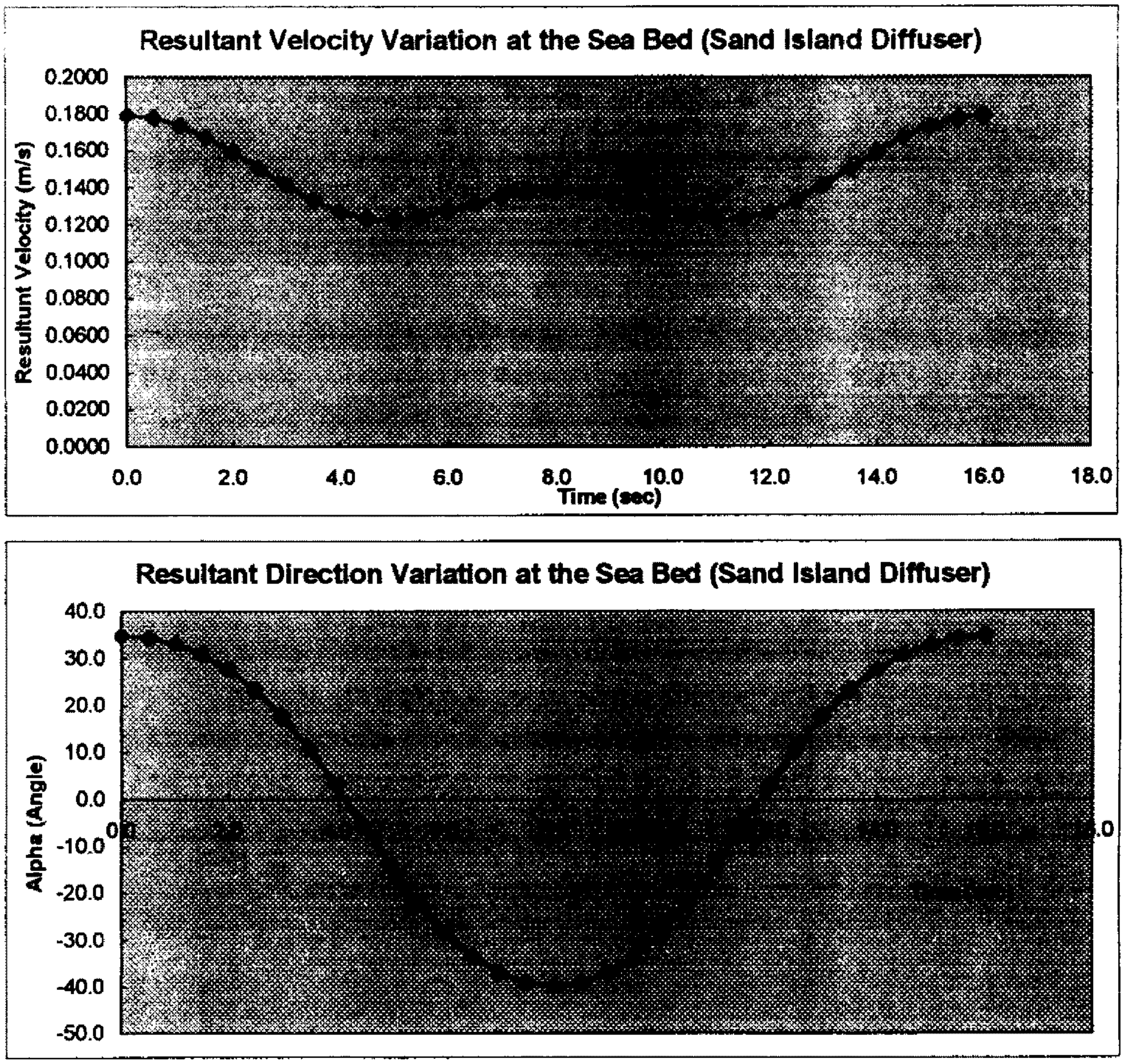


Fig. 4 The Resultant Velocity and Direction Variation at the Sand Island Diffuser

and have no significance in the real world.

5. Conclusion

The current and long wave influenced resultant direction and magnitude variation due to the horizontal bottom water particle velocity variation on a typical wave period (16 sec.) basis at the Sand Island outfall results in somewhat significant variation in plume rise and initial dilution. The RSB and UM models are the most reliable and recent models and have been widely used for the prediction of plume behavior. Based on the long wave period of 16 sec., the variation of the plume rise calculated by the RSB model is almost constant while initial dilution computed by same model is slightly sensitive. It is seen that the plume behavior predicted by the UM model is quite sensitive to the resultant direction close to parallel to the diffuser. Therefore, it is reasonable that plume rise and initial dilution variation based on wave period can provide the range between maximum and minimum values

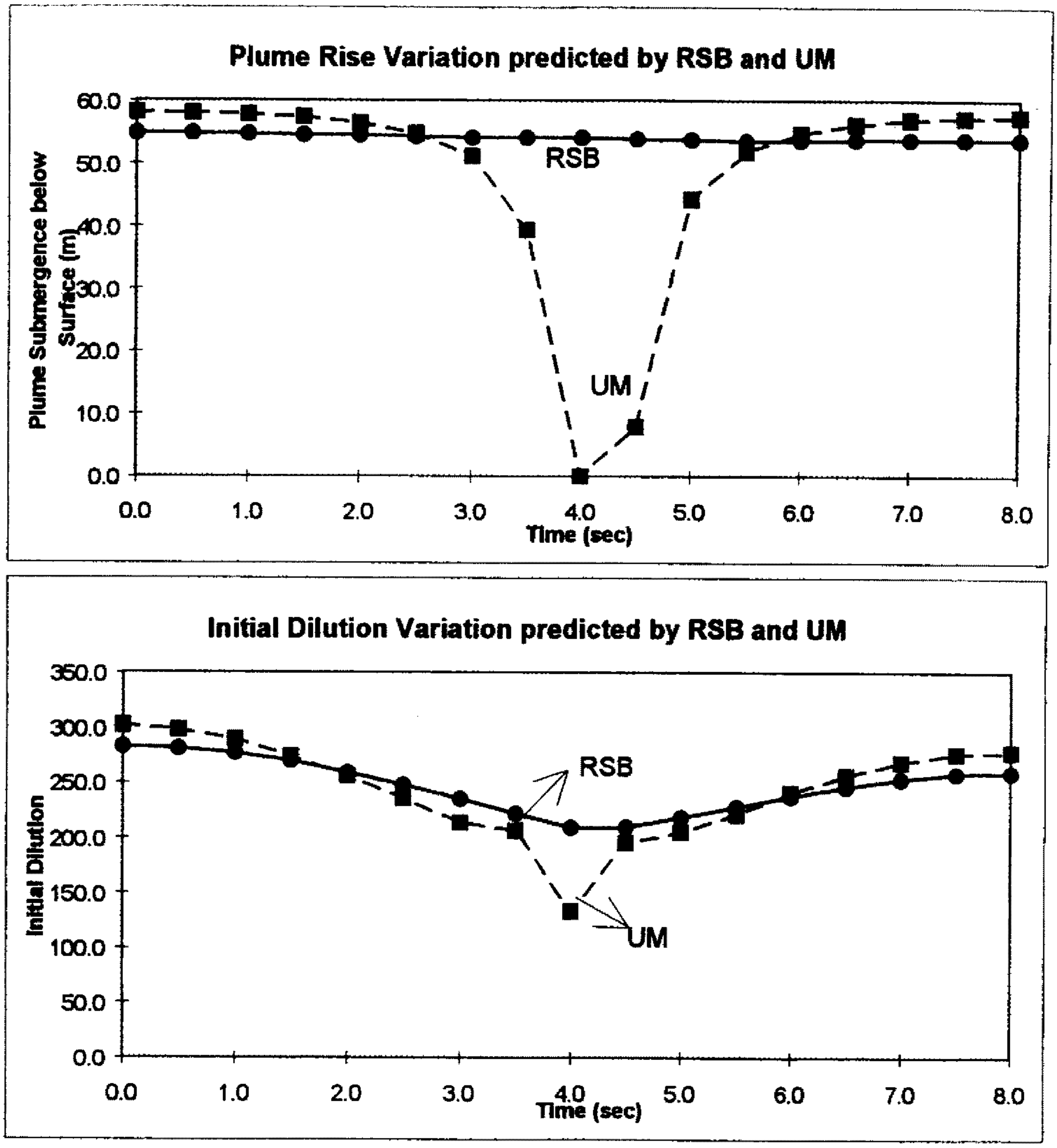


Fig. 5 The Variations of Plume Rise and Initial Dilution Predicted by the RSB and UM models at Sand Island Outfall

of predicted plume behavior which will be more realistic values rather than constant plume behavior calculated by currents only.

It was previously mentioned that the dominant direction of near bottom currents measured in the vicinity of the Sand Island outfall is predominantly parallel to the diffuser. On the basis of the result in this study, it is expected that the RSB model is more suitable for the Sand Island outfall than the UM model since the UM model is inaccurate for the case where the resultant current parallel to the diffuser. In the following studies, the model for the plume behavior analysis should be carefully chosen along with the considerations of ocean conditions around each outfalls and the limitations of all the models.

요 약

미국에서는 오랜 전부터 1차 처리된 폐수를 해양배출구를 통하여 심해저로 흘려보내어 보다 효율적인 폐수처리에 기여하고 있다. 해저의 경사 때문에 연안의 폐수처리장에서 긴 관을 통해 심해저로 다공배출구를 연결시키고 있다. 그러나, 심해저 확산배출구를 통해 흘러 나와 형성된 플룸이 근접한 연안에 간접적으로는 인간의 건강에 해를 줄 수 있다는 보고 때문에 바다의 물리적인 조건을 세심하게 고려한 심해저 확산배출구의 적절한 수심에서의 배치가 요구되고 있다. 우리나라의 연안역에서도 보다 효율적이고 신뢰할 수 있는 폐수처리를 위해 해양배출에 대한 고려를 하여야 할 것이다.

플룸의 거동을 예측하기 위해 일련의 플룸 동역학에 대한 연구에서는 여러 가지 모델이 사용되어 왔으나 대부분의 경우 플룸거동의 계산치가 현실과는 동떨어져 있다. 따라서 본 연구에서는 실제 배출특성과 해양의 조건을 시뮬레이션 하기 위한 플룸모델의 적용에서 개선방안을 제시하고자 하였다. 플룸모델에서 파랑과 흐름과 같은 실질적인 해상조건을 반영한 입력 파라메타를 도입하여야 하는 것이다.

이 논문에서는 최근의 마말라 만 연구에서 선택한 특정 모델의 입력 변수 중에 장파는 고려하지 않고 해류만을 고려한데서 오는 단점을 보완하여 선행파이론에 기초한 장파와 흐름이 공존함으로써 야기되는 해저로부터의 플룸 상승과 초기 희석 계산을 수행하였다. 실제적으로 해저에서 플룸의 형상이 해수뿐만 아니라 장파에 의해서 크게 영향을 받는다는 것을 염료를 넣어 플룸을 사진촬영함으로써 증명하였다. 앞으로의 연구에서는 장파와 같은 현실적인 인자를 세심하게 고려함으로써 계산결과를 더욱 현실 값에 접근시킬 수 있게 되었다. 물론, 장파와 같은 인자를 도입함으로써 야기되는 물리학적인 한계점은 관련된 가정을 통해 어느 정도 보완이 되었지만 그러한 한계점은 향후 3차원적인 플룸 역학을 다룸으로써 보강차원의 실증적 연구가 더 필요하다고 하겠다.

미국환경보전국에서 승인한 개량플룸모델 중에서 RSB 및 UM모델을 플룸거동을 계시하는데 사용하였으며, 장주기파의 조건하에서 계산된 값을 플룸의 상승 및 초기희석의 관점에서 비교하였다.

References

1) Baumgartner, D.J., Frick, W.E., and Roberts, P.J.W. (1994). "Dilution Models for Effluent Discharges (Third Edition)." U.S. Environmental Protection Agency, Office of Research and Development, Washington, DC. EPA/600/R-94/086.

2) Dean, R.G. and Dalrymple, R.A. (1993): Water Wave Mechanics for Engineers and Scientists. World Scientific Publishing Co. New Jersey etc.

3) De Jesus T.M.C. (1984). "Current and Mixing Measurement Techniques for the Sand Island Ocean Outfall." Department of Ocean Engineering, University of Hawaii.

4) Krock, H.J. (1996). "Review of the Mamala Bay Study" Mamala Bay Study, Mamala Bay Study Commission, Appendix II, Appendix B.

5) Kwon, S.J. and Lee, J.W. (1997) "Plume Rise and Initial Dilution Determination Reflecting the Density Profile over Entire Water Column." Journal of the Korean Institute of port Research, Vol. 11, No.2, 1997 26) Pickard, G.L. and Emery, W.J., (1990): Descriptive Physical Oceanography (An Introduction). Pergamon Press, Oxford etc.

6) Roberts, P.J.W. (1995). "Plume Modeling." Mamala Bay Study, Mamala Bay Study Commission, Volume 1, Report No. Project MB-4.

7) Suarez, M.M.N. (1990). "Study of Currents for the Honouliuli WWTP, Barbers Point Ocean outfall." Department of Ocean Engineering, University of Hawaii.

8) Sullivan P.K. et al. (1993). "1990 Sand Island Annual Assessment Report." Coastal & Environmental Engineering Services, Oceanit Laboratories, Inc., Volume 2, Honolulu, Hawaii.

9) Vithanage, D. and Krock, H.J. (1985). "Wave Measurement Comparison between Pressure Cell and Waverider off Oahu." J.K.K. Look Laboratory of Oceanographic Engineering, University of Hawaii.

10) Wang, N., "Nearshore Circulation and Sediment Transport." Department of Ocean Engineering, University of Hawaii.

11) Zapka, M.J. (1984). "Sand Island Sediment Accumulation Study." Department of Ocean Engineering, University of Hawaii.