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FIELD VERIFICATION OF DIFFUSION-INDUCED CIRCULATION IN SOK KWU WAN, HONG KONG

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Abstract: Sok Kwu Wan in Lamma Island, Hong Kong, is a small semi-enclosed bay. Its tidal circulation and flushing characteristics have been studied using 3D numerical models. The hydrodynamic model employed has been validated against a) the experimental flume test results for estuarine salinity intrusion study and b) the field data collected in August 2002. An interesting finding from the study is that the computed wet season flow circulation in Sok Kwu Wan exhibits a vertical three-layer structure, which is supported by the field observations. In line with the previous findings in Baltimore Harbour, the three-layer diffusion-induced circulation leads to better flushing than the classical two-layer estuarine circulation. Numerical experiments show that the main factor that contributes to such circulation in Sok Kwu Wan is its topography and shape, in particular its short length but relatively large width at the outer bay.

Key words: Diffusion-induced circulation, Field verification, Numerical modelling, Stratified flow, Tidal flushing

1. INTRODUCTION

Sok Kwu Wan is a small semi-enclosed bay located at the eastern shore of Lamma Island in the western Hong Kong Waters. It is about 4 km long, 0.5 km wide at the inner bay and 2.3 km wide at its mouth (Fig. 1); the water depth varies from 4 to 20 m. A fish culture zone is located in the relatively well-sheltered inner bay. It has a long history of mariculture activity and the standing stock has been quite high in the past. It is a representative site elected in our study on the environmental management of mariculture in Hong Kong (Lee *et al.* 2003).

Due to freshwater inflow from Pearl River and the oceanic currents, there is significant vertical density stratification in Hong Kong's coastal waters. Thus, three-dimensional (3D) numerical models have been employed to simulate the flow circulation in Sok Kwu Wan. The flow model solves the full 3D hydrodynamic equations with the hydrostatic assumption. A uniform rectangular grid is applied in the horizontal directions and a topographically conformal co-ordinate (sigma-coordinate) system is applied in the vertical direction. The turbulence closure is represented by a zero equation mixing length model. This simpler approach has been found to be adequate in describing the reduction of mixing due to vertical density stratification for the purpose of the present study.

2. MODEL VERIFICATION

To verify that the numerical model developed can properly simulate the flow circulation under tidal action and density stratification, several test cases has been undertaken. They include: salinity intrusion in estuaries of rectangular section and a 26-hour field survey conducted on August 2002.

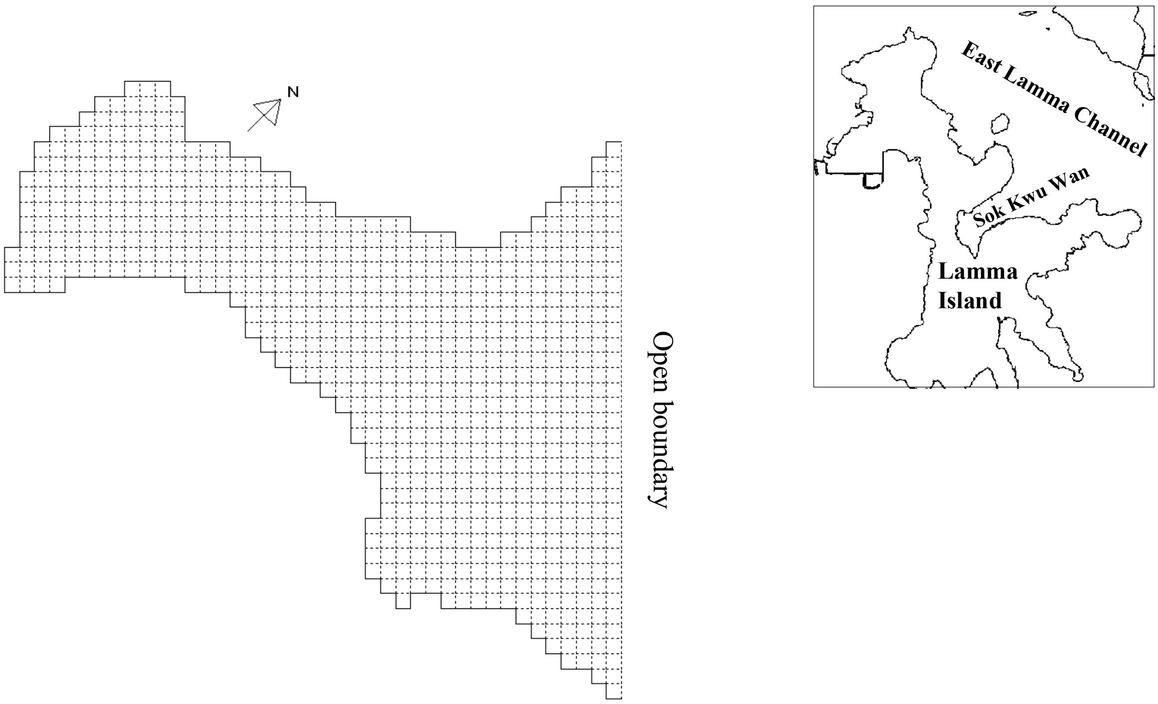

Fig. 1 Sok Kwu Wan, Lamma Island and the model grid for the hydrodynamic study

3. SALINITY INTRUSION IN ESTUARIES OF RECTANGULAR SECTION

There are only limited data sets available for validating the three-dimensional (3D) numerical hydrodynamic models that simulate the salinity transport in the estuaries under the action of tide and freshwater runoff. One available set is obtained from a series of experiments conducted in the U.S. Army Engineer Waterways Experiment Station tidal rectangular flume (Ippen and Harleman 1961, Ippen 1966 and Thatcher and Harleman 1972). The salinity intrusion in a partially or well-mixed estuary was studied. The extent of salinity intrusion, the mean and vertical salinity distributions had been measured. The experimental results provide useful references for verifying 3D flow models in their capability to reproduce the salinity transport in the estuary resulting from the salinity difference existing between the open sea and the freshwater inflow along the intrusion length.

A model with 10 uniform vertical sigma layers are used to model the flume channel. At the upstream end, discharge boundary condition is applied. Freshwater with zero salinity is introduced evenly into the 10 layers. At the downstream or ocean end, tidal boundary condition is prescribed. Six test cases with different ocean salinities, freshwater discharges and tidal amplitudes are carried out, and the original test numbers for the experiments are used as the test case reference.

The measured and computed water levels for Test 29 (with zero freshwater inflow and ocean salinity) are shown in Fig. 2. They agree very well and support that the bottom friction has been properly modelled. It should be noted that the High Water (HW) and Low Water (LW) at different locations do not occur at the same time, so the plots do not represent an instantaneous longitudinal water level profile along the flume. Fig. 3 shows the computed and observed tidally averaged vertical salinity profiles at selected locations, and indicates that the model have reproduced the observed vertical salinity distribution reasonably well. By comparing the instantaneous depth-averaged salinity distributions for the test cases, satisfactory agreement between the model results and the experimental measurements are observed. The minimum and maximum intrusion extents at low and high water respectively are well predicted (Choi 2002).

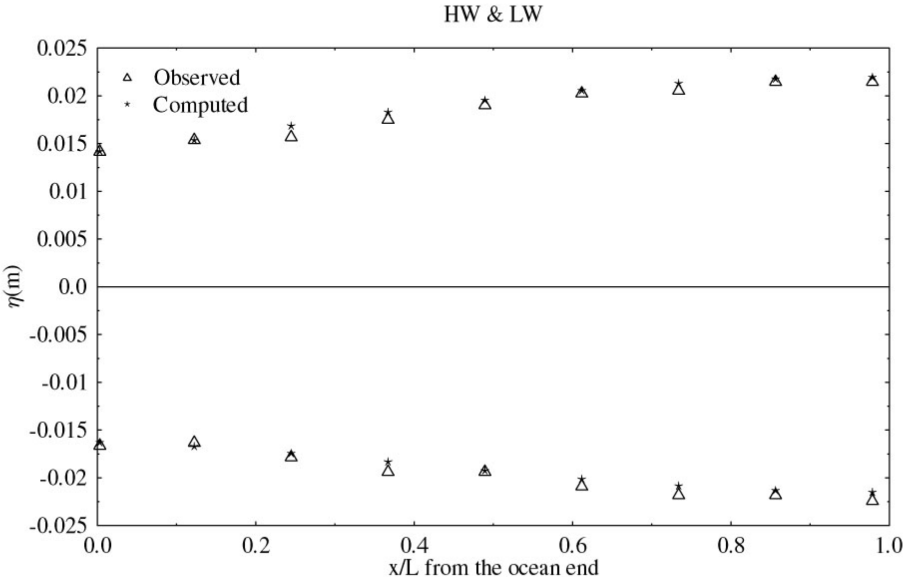

Fig. 2 Comparison of experimental and computed tidal levels for salinity intrusion experiment in tidal flume (Test 29, Ippen and Harleman 1961)

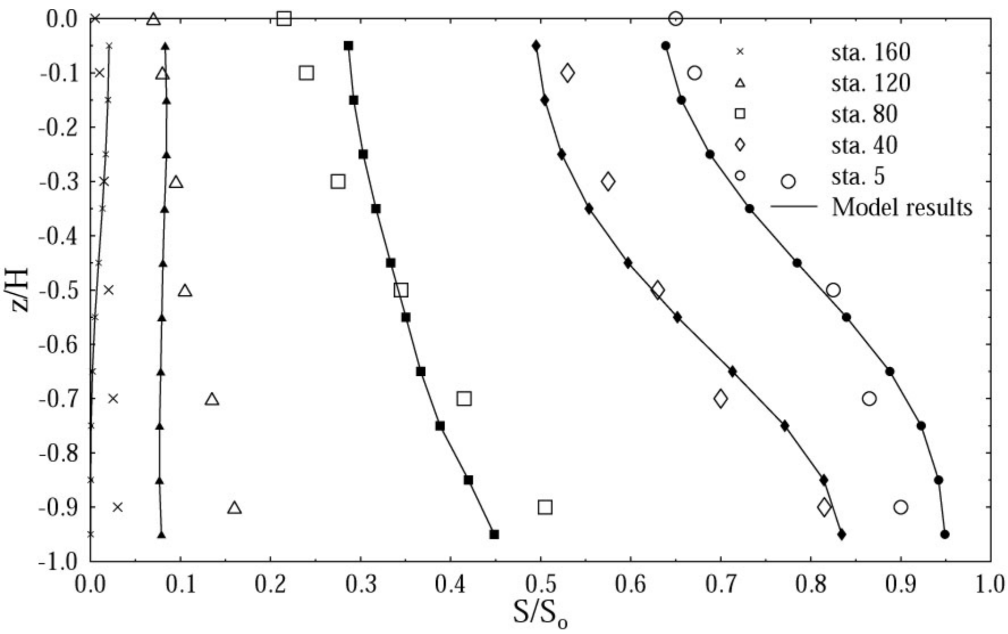

Fig. 3 The measured and computed tidally averaged salinity/ocean salinity vs. relative depth for salinity intrusion experiment in tidal flume (Test 16, Ippen and Harleman 1961)

4. FIELD SURVEY AUGUST 9 – 10, 2002

A 26-hour survey was conducted in Sok Kwu Wan on August 9 – 10, 2002. The spatial distribution of tidal velocities at representative tidal states are obtained by Acoustic Doppler Current Profiler (ADCP) measurements taken from a moving vessel along a circuit around the bay (Fig. 4); each circuit took about two hours. The circuit was sailed clockwise, starting and ending at Point 1. The ADCP recorded current velocities in vertical increments of 0.5 m from just below the sea surface to just above the seabed. Vertical profiles of salinity, temperature, turbidity, dissolved oxygen and Chlorophyll-*a* are measured at survey points 1, 2, 3, A and B (Fig. 4). Point 1 and 2 are located at the entrance of the bay and the other three survey points are situated along the centreline of the bay.

The Sok Kwu Wan model has a uniform horizontal grid size of 50 m (Fig. 1) and ten uniform sigma layers in the vertical direction. The recorded tidal levels during the survey period at Lamma Island power station are used as the tidal forcing at the open boundary, while the measured vertical profiles of salinity at Point 1 and 2 are averaged and used as the salinity boundary conditions.

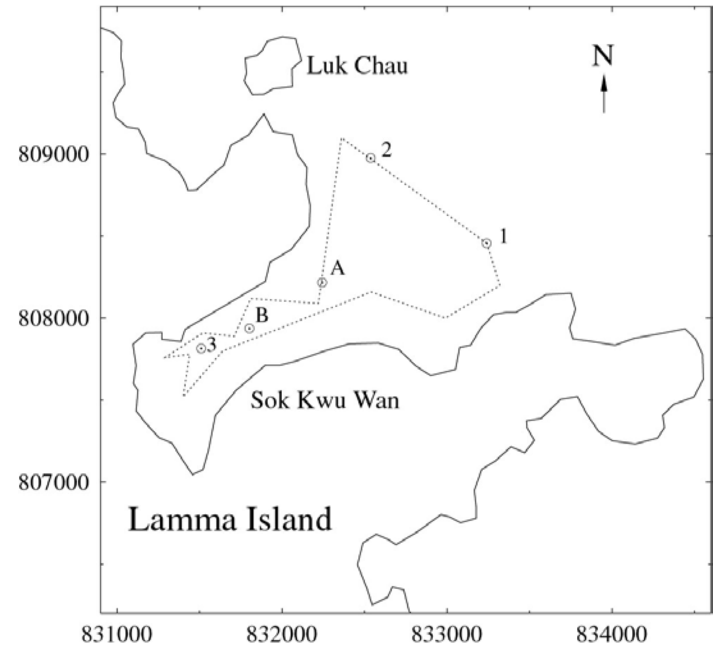

Fig. 4 Location of vertical profiles and ADCP circuit in field hydrographic survey

Fig. 5 and 6 show the comparison between the observed and computed salinity and currents in the upper (top 6m) and lower layer (below 6m); they compare quite favourably. There is good agreement between the measured and computed flow speeds and the dominant flow directions, and the differences in the top and bottom layers. The comparisons are generally better for the bottom than the top layer, probably because the latter is subjected to greater influence by the heavy rainfall during the survey (about 90 mm rainfall was recorded by the Hong Kong Observatory on both August 9 and 10, 2002).

As can be seen in Fig. 5, the flow model is able to reproduce the significant time variations in salinity and stratification. From both the observed and computed results, it is noted that the flow in the narrower inner bay is mainly along its centreline. The flow structure becomes more complex in the wider outer bay; currents differ in both magnitude and direction in different layers. Those at the entrance are influenced by the water movement in the East Lamma Channel. The stratified circulation and the effect of the East Lamma Channel upon the flow in the outer bay for a flood tide are illustrated in Fig. 7.

5. DIFFUSION-INDUCED CIRCULATION IN SOK KWU WAN

Diffusion-induced circulation is a three-layer circulation induced by mixed of stratified water masses in estuarine embayments with negligible fresh water inflow and has been observed in some tributary embayments to large estuarine systems such as Passamaquoddy Bay open to the Bay of Fundy and Baltimore Harbour, an inlet tributary to Chesapeake Bay. Hachey (1934) conducted some laboratory experiments to simulate the three-layer circulation observed in Passamaquoddy Bay. Hansen and Rattray (1972) and Hensen and Festa (1974) examined the phenomenon theoretically using similarity solution techniques and numerical model. Their results compare well with observations on Baltimore Harbour and the existence of this type of circulation is later confirmed by field measurements (Boicourt and Olson 1982). An important finding about the three-layer circulation is that in the absence of this flow, flushing times due to the wind and the tides only would be an order of magnitude longer.

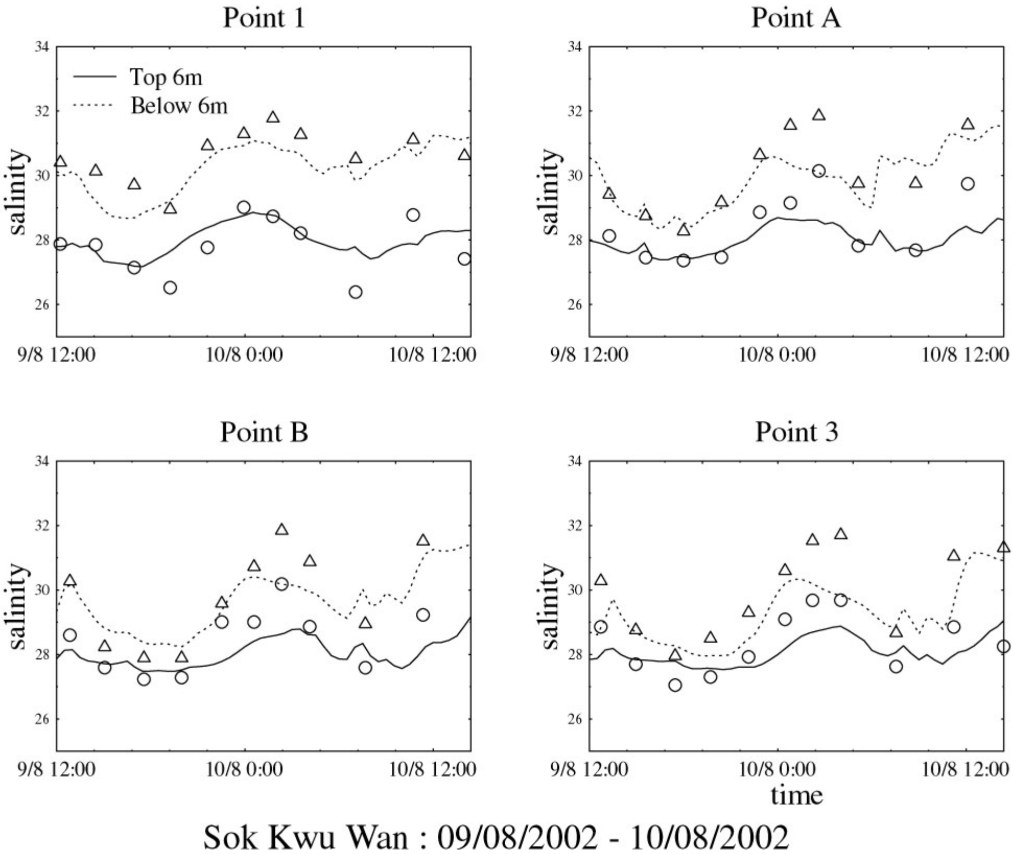

Fig. 5 Observed (symbol) and computed (line) salinities in Sok Kwu Wan

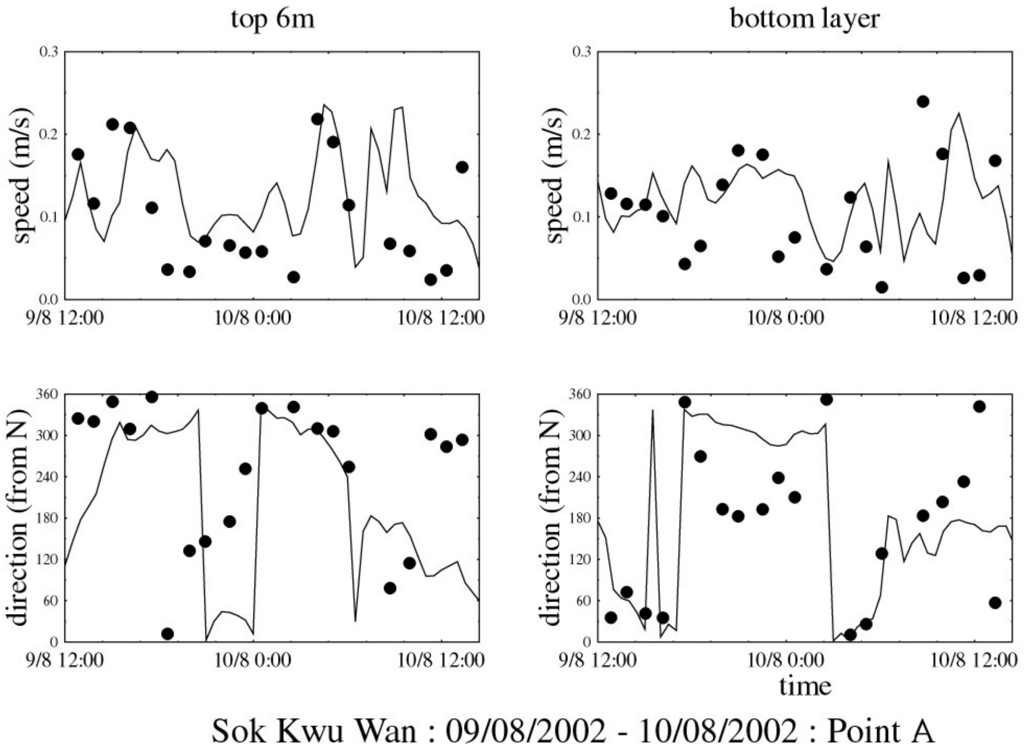

Fig. 6 Observed (symbol) and computed (line) current speeds and directions at point A

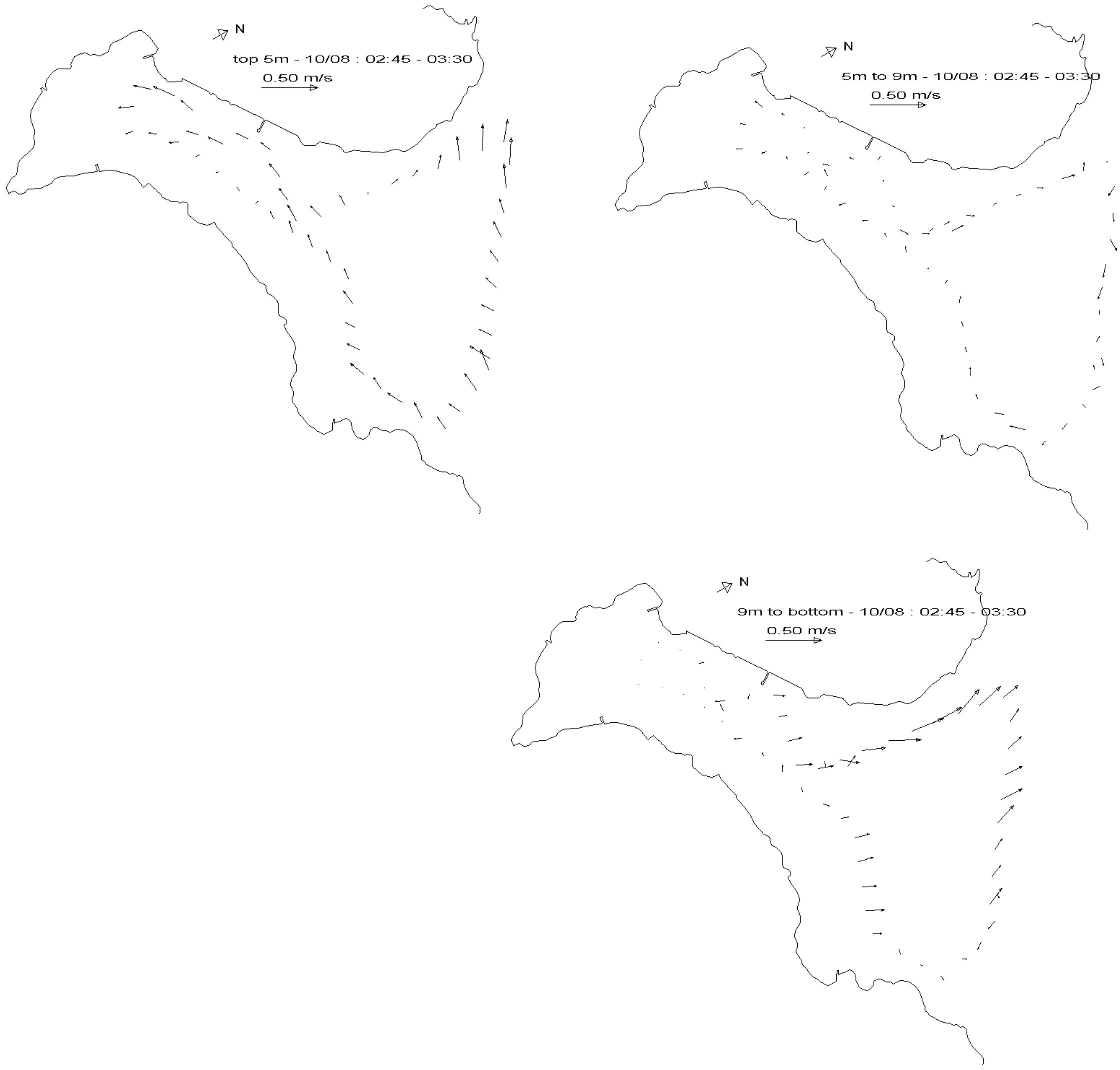

Fig. 7 Observed currents in surface, middle and bottom layers during flood tide

In our study on the flushing characteristics of Sok Kwu Wan using 3D numerical hydrodynamic and mass transport models, it is found that the computed flushing times for the representative wet and dry season conditions differ by an order of magnitude. Also, it has predicted a vertical three-layer structure in the wet season flow (Choi and Lee, 2002).

Besides providing data for verifying the numerical flow model, the field survey is also aimed to determine whether the predicted three-layer circulation actually exists in Sok Kwu Wan. Since the diffusion-induced circulation is a second order effect, it is quite difficult to identify the three-layer flow structure from the vertical profiles of the measured instantaneous velocity. As shown in Fig. 8, by averaging the observed horizontal velocities throughout the survey, it can be seen that at almost all of the five survey points, the vertical profiles exhibit a three-layer flow structure and support that the possible existence of diffusion-induced circulation.

All the previous studies on diffusion-induced circulation dealt with idealized geometry and without tidal action, and as far as we are aware, there has hitherto been no work on the tidal flushing resulting from such three-layer circulations in real estuaries. A series of numerical model study has been conducted to study the various factors that might affect the generation of the three-layer circulation. These include: the vertical salinity differential at the estuary entrance, time variation of the salinity at the estuary entrance, freshwater inflow, and the land form of the basin (Choi 2002). Besides the Sok Kwu Wan model, the models developed for

Tolo Harbour, Hong Kong (Choi and Lee 2000) and simple straight rectangular channels have been employed in the study.

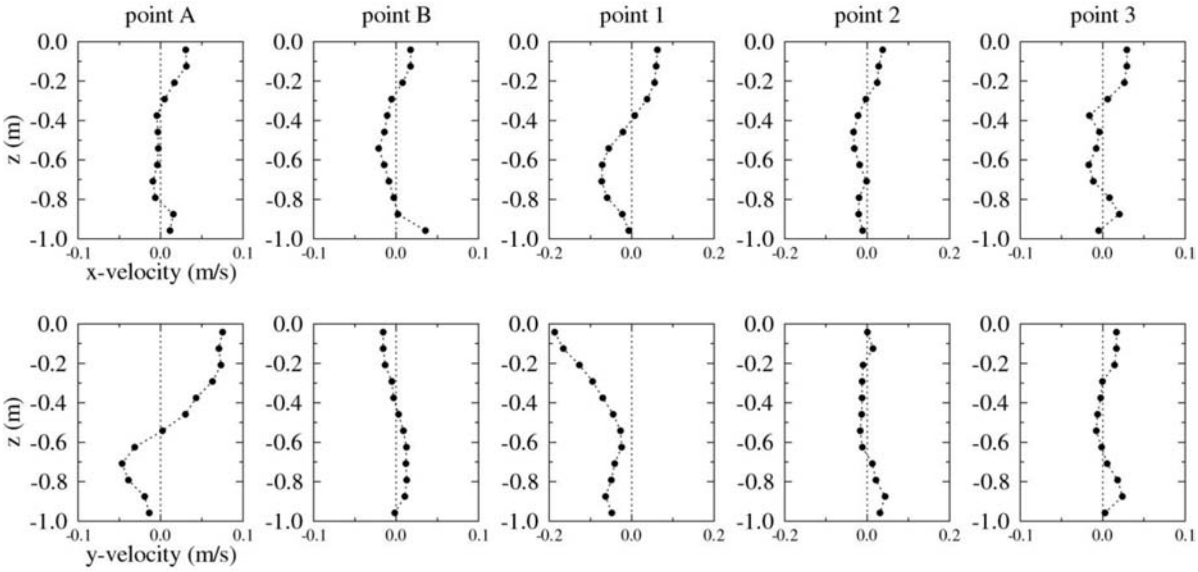

Fig. 8 Vertical Profiles of averaged observed velocity over the survey period

From the results of the numerical experiments, it is found that sufficiently large vertical density differential at the bay entrance is necessary for sustaining the three-layer circulation. The model results also suggested the main factor that contribute to the presence of such circulation in the wet season and the flushing characteristics found in Sok Kwu Wan is its topography and shape, in particular its short length but relatively large width at the outer bay.

6. CONCLUSIONS

In Sok Kwu Wan, Hong Kong, both field survey and numerical simulation have confirmed the presence of a three-layer gravitational circulation in the wet season. The 3D flow model developed for studying the tidal circulation in Sok Kwu Wan has been verified by comparing the computed results with both the laboratory and field data. Detailed numerical experiments are also carried out to study the various factors that affect the generation of the three-layer circulation. The landform of Sok Kwu Wan, relatively wide at the entrance and gradually decreasing in width and depth towards the inner shore, provides favourable condition for the generation of the three-layer flow structure.

ACKNOWLEDGEMENTS

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