Sea-going Navigation Channel Sedimentation Formula

Weimin Li, Power Planner, U.S. Army Corps of Engineers, Northwestern Division,

1201 NE Lloyd Blvd #400, Portland OR 97232

Abstract

Navigation channel is one of the main components of any harbor to facilitate the access of ships to harbor. The depths of most navigation channels gradually decrease over time due to the sedimentation since these channels behave as a sediment trap. Sedimentation problem in navigation channel is considered a crucial issue according to economic and environmental point of view, which depends on geometric of navigation channel and hydrodynamic parameters.

Sediment movement and tide/wave conditions are balanced in most natural systems. Many natural systems are equilibrated and free of sedimentation or scour. When a navigation channel is deepened and widened on a shoal, the sedimentation on the channel is the result of sediment movement change caused by the movement of wave and tide on the shoal. To estimate the sedimentation on the channel, one studies the sediment transport and finds a unit sediment transport rate using the measured data. Then, the sedimentation formula is derived based on the assumption of the sedimentation induced by the sediment transport capacity reduction due to the navigation channel deepened and widened on the shoal.

Shan Wei Harbor is located on the northeastern of Hong Hai Bay in China. The harbor would be expanded into medium-sized harbor of 3000 to 5000 tons. One of key issues was the sedimentation after the sea-going navigation channel from the harbor was deepened and widened. The sedimentation formula developed in this article was successfully adopted to estimate annual sedimentation rate and study the feasibility of the project.

1.Introduction

Navigation channel is one of the main components of any harbor to facilitate the access of ships to harbor. The depths of most navigation channels gradually decrease over time due to sedimentation since these channels behave as a sediment trap. Periodic maintenance is required to remove sediment trapped in navigation channel to maintain the required depth of channel. Maintenance costs are a critical element in the economic feasibility of a harbor, particularly when a relatively long access channel requires frequent dredging. So, sedimentation problem in navigation channel is considered a crucial issue according to economic and environmental point of view, which depends on geometric of navigation channel and hydrodynamic parameters.

Sediment movement and tide/wave conditions are balanced in most natural systems. Many natural systems are equilibrated and free of sedimentation or scour. Sedimentation occurs when flow velocities are not strong enough to keep sediment moving (usually a result of deepening for navigation/harbor development). Sediment deposition is close related to the exchange water between the basin and the surrounding environment.

When a navigation channel is deepened and widened on a shoal, the sedimentation on the channel is the result of sediment movement change caused by the movement of wave and tide on the shoal. To estimate the sedimentation on the channel, one needs to study the sediment transport and find a unit sediment transport rate using the measured data. Then, the sedimentation formula is derived based on the assumption of the sedimentation induced by the sediment transport capacity reduction due to the navigation channel deepened and widened on the shoal.

Shan Wei Harbor is located on the northeastern of Hong Hai Bay and entrance of Pin Qing Lake in China. Pin Qing Lake is a lagoon with area of 22 km^2. There are no major rivers flowing into the lake. The harbor is the system of lagoon, tide channel and natural sand bar. The harbor is in the 3 km tide channel and behind 1.8 km natural sand bar, and water depth is above 5 meters. There is a lot of shoals outside the tide channel. The harbor would be expanded into medium-sized harbor of 3000 to 5000 tons. One of key issues was the sedimentation after the sea-going navigation channel from the harbor was deepened and widened.

The shallow water equations were used to simulate the two-dimensional depth-averaged tidal flow before and after the navigation channel was deepened and widened with the hydrological data of spring tide in November of 1988. And the sedimentation formula developed in this article was adopted to estimate annual sedimentation rate and study the feasibility of the project. At the end, it was shown that it was feasible to expand Shan Wei harbor into the medium-sized harbor of 3000 to 5000 tons.

2.Navigation Channel Sedimentation Formula

There is a small harbor available. Then it would be expanded to larger harbor. The sea–going navigation channel is needed to facilitate the access of vessels to harbor. The sediment transport is dynamically in balance. It is out of balance with the new dredged navigation channel available. Generally, the water velocity becomes smaller in the channel area, sediment transport rate is to be reduced and the sedimentation occurs. The formula used to quantify the sedimentation is derived in this paper.

There are some available sediment transport formulae [1 – 3]. The sediment transport formula below is exploited in this study.

$$q_s = k(\frac{V^3}{gh\omega})^m \quad (1)$$

where q_s = unit sediment transport rate, kg/ms

V = depth averaged velocity, m/s

g = gravity acceleration, m/s^2

h = water depth, m

ω = sediment settling velocity, m/s

k = local parameter, $^{kg}/_{ms}$

m = local parameter

Knowing the information of water and sediment, one can have the sediment transport rate, such as the above formula (1). Then one can derive the sedimentation formula. There are many available formulae for harbors and navigation channels [1, 4 – 10].

Based on the common concept, the balance of water movement and sediment transport is broken after a navigation channel is dredged. This causes the sedimentation in a navigation channel. Generally, there is an angle between channel axis and water movement direction. The navigation channel and the water flow direction are drawn in the Figure 1.

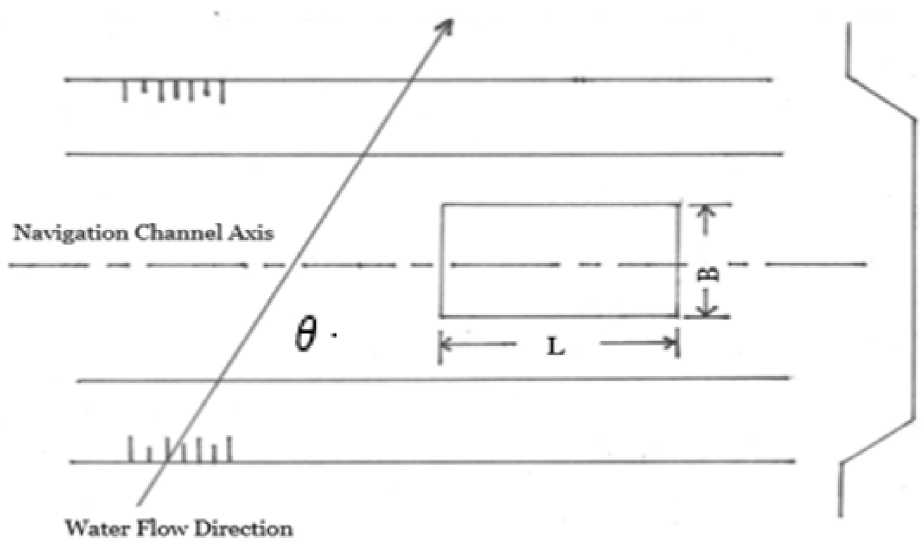

Figure 1 Schematic Diagram of Water Flow Crossing Navigation Channel

The sedimentation on a navigation channel is the sum of sedimentation along with the channel axis and the direction vertical to the channel axis.

$$\Delta W = \Delta W_T + \Delta W_n \quad (2)$$

where ΔW = sedimentation after a navigation channe is dredged

ΔW_T = sedimentation caused by water moving along with a channel axis

ΔW_n = sedimentation caused by water moving along with the direction vertical to the channel axis

It is assumed that there is an element with the length of L and width of B. The quantities of unit discharge, unit sediment transport rate, water velocity and water depth are represented by q, q_s, V and h, respectively. The subscripts of 1 and 2 are adopted to represent the values before and after the navigation channel is dredged, respectively. The angel between the channel axis and water flow direction is defined by θ.

After the navigation channel is dredged, the reduction of unit sediment transport rate is $q_{s1} - q_{s2}$. Let's consider the sedimentation caused by the water flow component along with the channel axis.

The width of the element is B. So, the possible sedimentation caused by this direction water flow component is written below.

$$\Delta W_T{}' = B(q_{s1} - q_{s2})cos\theta \quad (3)$$

And the actual sedimentation on the navigation channel is proportional to sediment settling probability α [11], the ratio of sediment settling velocity and water velocity $\frac{\omega}{V_1}$ and the ratio of the element length and water depth $\frac{L}{h_1}$. So, one has actual sedimentation caused by this direction of water flow component below.

$$\Delta W_T = \frac{\alpha\omega L}{V_1 h_1}\Delta W_T{}' = \frac{\alpha\omega LB}{V_1 h_1}(q_{s1} - q_{s2})cos\theta \quad (4)$$

Similarly, one has actual sedimentation component caused by the direction vertical to the channel axis below.

$$\Delta W_n = \frac{\alpha\omega LB}{V_1 h_1}(q_{s1} - q_{s2})sin\theta \quad (5)$$

The substitution of (4) and (5) into (2) becomes below.

$$\Delta W = \frac{\alpha\omega LB}{V_1 h_1}(q_{s1} - q_{s2})(cos\theta + sin\theta) \quad (6)$$

With definition, one has

$$q_{s1} = s_1 V_1 h_1 \quad (7)$$

and

$$q_{s2} = s_2 V_2 h_2 \quad (8)$$

where $s =$ sediment concentration, $^{kg}/_{m^3}$

From the formula (6), one has

$$P = \frac{\Delta WT}{LB\gamma_c} = \frac{\alpha\omega s_1 T}{\gamma_c}\left(1 - \frac{q_{s2}}{q_{s1}}\right)(cos\theta + sin\theta) \quad (9)$$

where $P =$ sedimentation depth per unit area in the period of T, m

$\gamma_c =$ dry sediment density, $^{kg}/_{m^3}$

Substitution of (1) into the above (9) becomes below.

$$P = \frac{\alpha \omega s_1 T}{\gamma_c}\left[1 - (\frac{h_1}{h_2})^{4m}(\frac{q_2}{q_1})^{3m}\right](cos\theta + sin\theta) \quad (10)$$

When there is no unit discharge change after the channel is dredged, one has below.

$$\frac{q_2}{q_1} = 1 \quad (11)$$

Then, one has below.

$$P = \frac{\alpha \omega s_1 T}{\gamma_c}\left[1 - (\frac{h_1}{h_2})^{4m}\right](cos\theta + sin\theta) \quad (12)$$

3. Application of Shan Wei Harbor in China

Shan Wei Harbor is located on the northeastern of Hong Hai Bay (shown in the Figure 2). It is at the entrance of Bing Qing Lake, which is a lagoon, and behind natural sand bar. It is a harbor of lagoon and tide channel.

Shan Wei harbor is a complete system of lagoon and sand bar. There are no major rivers flowing into the harbor and surrounding area in the Hong Hai Bay. The averaged sediment concentration is less than 0.2 kg/m^3. It is shown that the sedimentation mainly comes from sea and local sediment movement on the shoal after the navigation channel is dredged [12].

The tide is nonregular diurnal in Hong Hai Bay. The average tidal amplitude is 0.91 meters, average flood tide lasts 7 hours and 20 minutes, and average ebb tide does 5 hours and 28 minutes. The tidal velocity inside the harbor is different from the one outside the harbor. For example, the maximum velocity of measurement station 3 (see the Figure 2) is 1.58 m/s at the half depth level in the tide channel during flood tide, and the one is 0.82 m/s during the ebb tide from the measurement made in November of 1988. However, the velocity outside the harbor in Hong Hai Bay is only 0.1 – 0.3 m/s. The storage of Bing Qing Lake is 20 million cubic meters.

The Shallow Water Equations were adopted to simulate the tidal flow before and after the navigation channel is dredged. The tidal flow in the flood tide and ebb tide are shown in the Figures 3 and 4, respectively. The tidal flow moves from south to north, passes the tide channel and pours into Bing Qing Lake during spring tide while the movement is the opposite during ebb tide. The Figure 5 is used to show the depth averaged velocity field in the Hong Hai Bay to help understand the tidal flow movement.

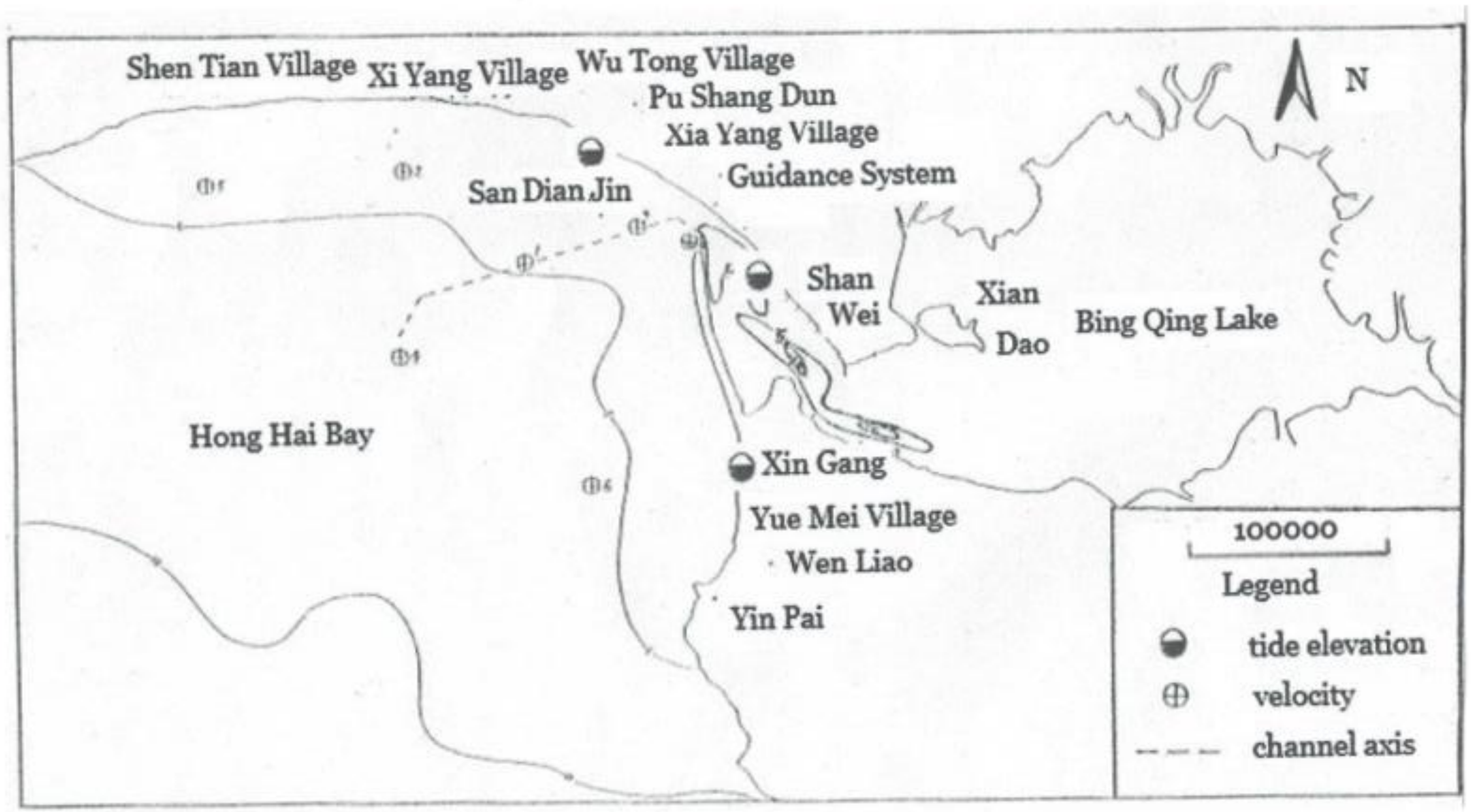

Figure 2 Topography, Navigation Channel Axis and Measurement Stations of Hong Hai Bay and Shan Wei Harbor

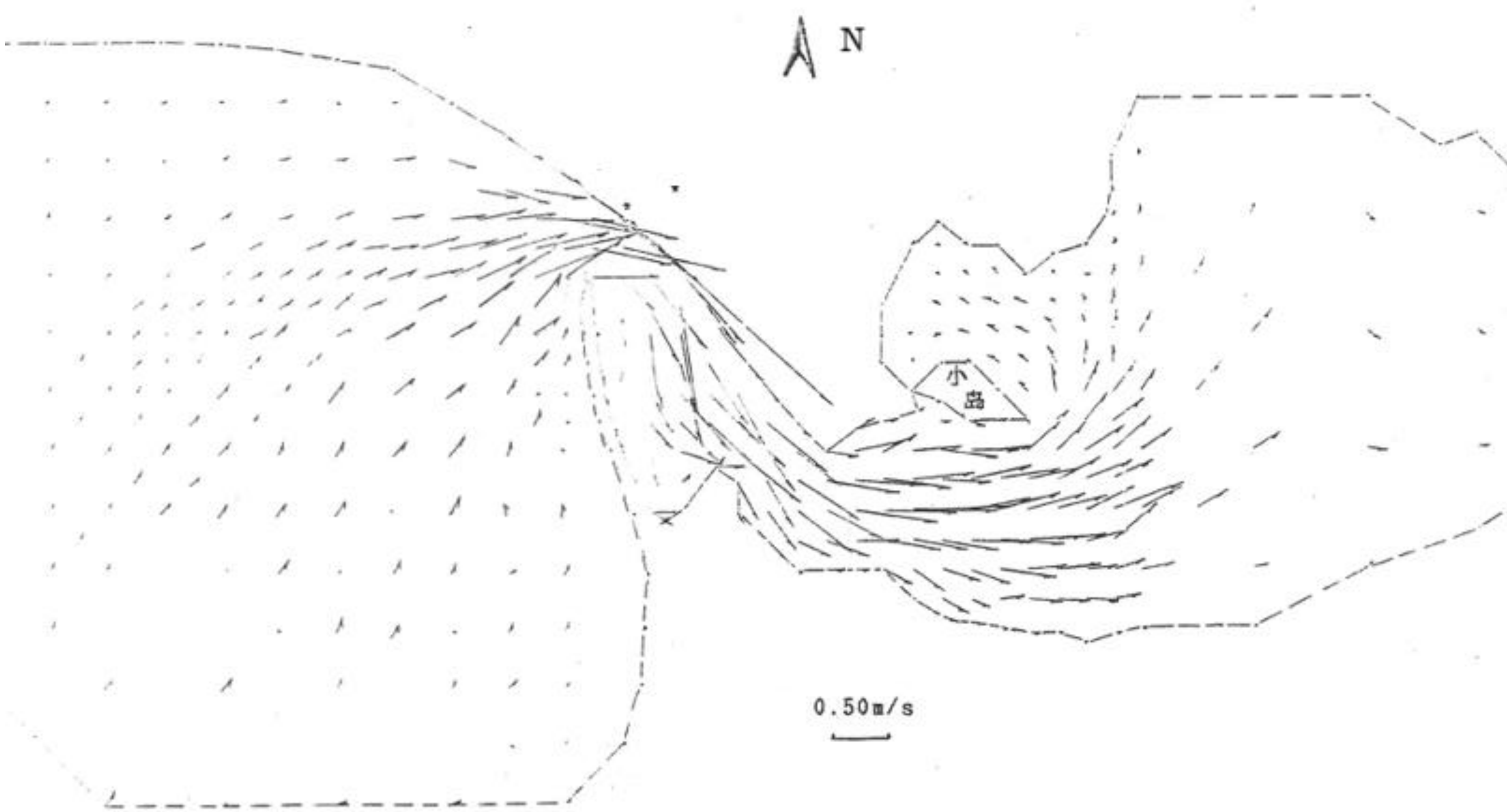

Figure 3 Tidal flow regime of spring tide in Shan Wei
Harbor water area, 16:00 of November 23, 1988

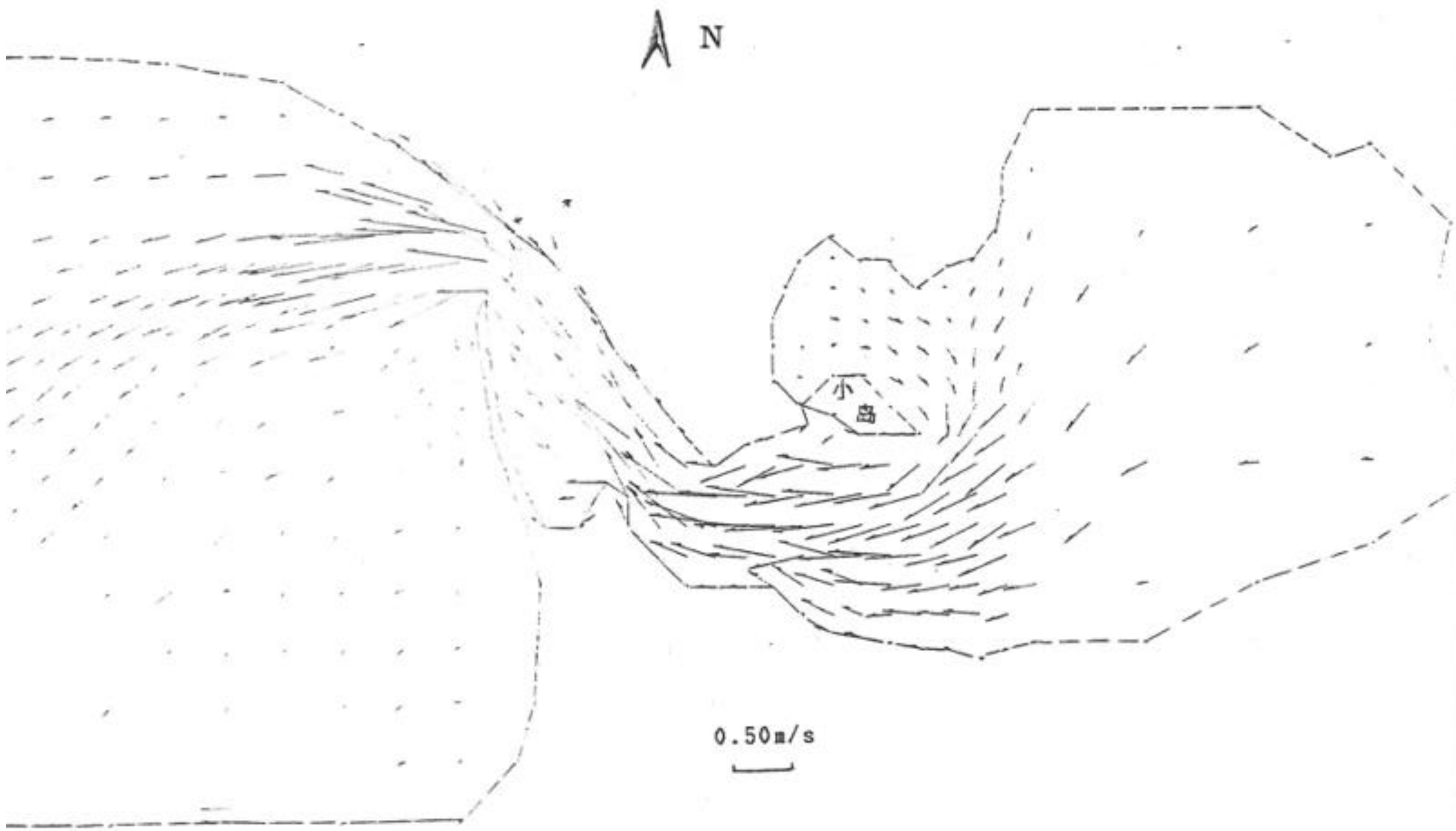

Figure 4 Tidal flow regime of ebb tide in Shan Wei

Harbor water area, 16:00 of November 23, 1988

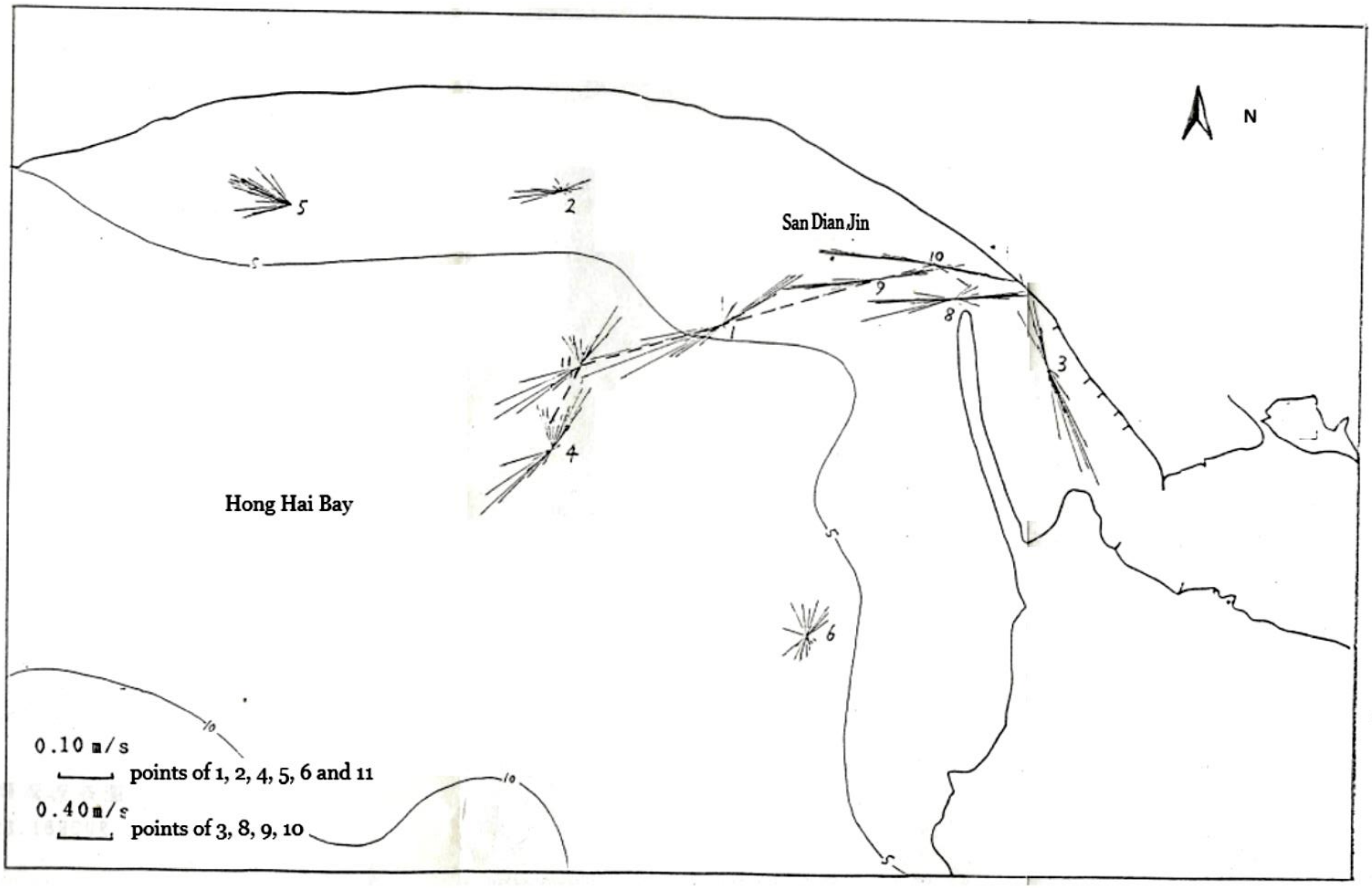

Figure 5 Computed depth averaged velocity vector field in Hong Hai Bay and Shan Wei Harbor water area

The data of sediment and tidal flow measured in November of 1988 was analyzed and utilized to have the local parameters of the sediment transport formula (1). It is shown below.

$$q_s = k(\frac{U^3}{gh\omega})^m \quad (13)$$

where $k = 0.18$ kg/(ms) and $m = 0.3$

The fitting is good (see the Figure 6 below).

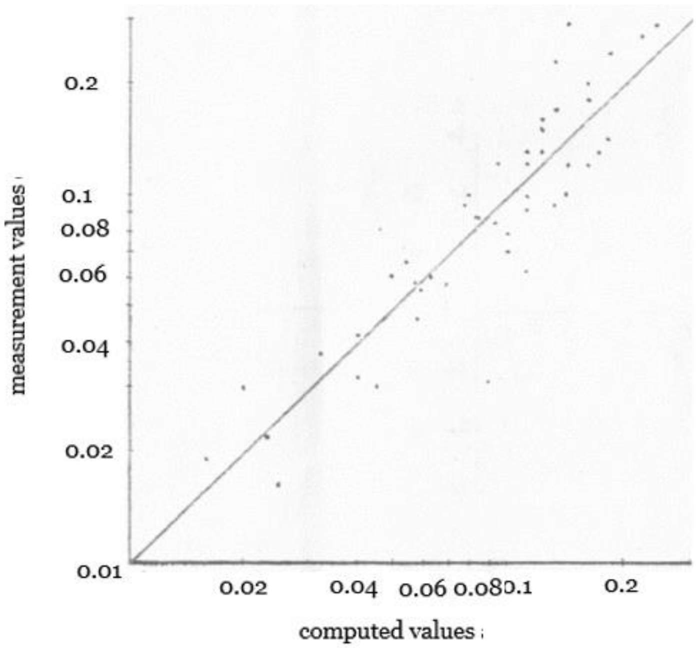

Figure 6 Unit sediment transport rate comparison between computed and measurement

The navigation channel axis is drawn with dash line in the Figure 2. The direction of navigation channel is N72°36'. The bottom elevation of the channel used for 3000 tons is – 5 meters (the datum is 0.36 meters under the theoretical depth datum). and the channel bottom width is 80 meters. And the bottom elevation of the channel used for 5000 tons is –6 meters and the channel bottom width is 90 meters. The side slope is 1:5.

Based on the local topography and information of hydrology and sediment, the navigation channel is divided into 9 pieces with the length between 350 meters and 610 meters. The values of water depth and velocity were adopted from the result of tidal flow simulation [13]. The parameters of the formula (10) are tabulated below [12].

Table 1 Parameters used in the Formula (10)

	d_{50} (mm)	s_1 (kg/m^3)	r_c (kg/m^3)	α
shallower than 5 m	0.024	0.1033	1775	0.69
deeper than 5m	0.0094	0.1798	877	0.69

The sedimentation computation was carried out. The topography of the navigation channel, the velocity ration of $\frac{V_2}{V_1}$ and the annual sedimentation rate are drawn below.

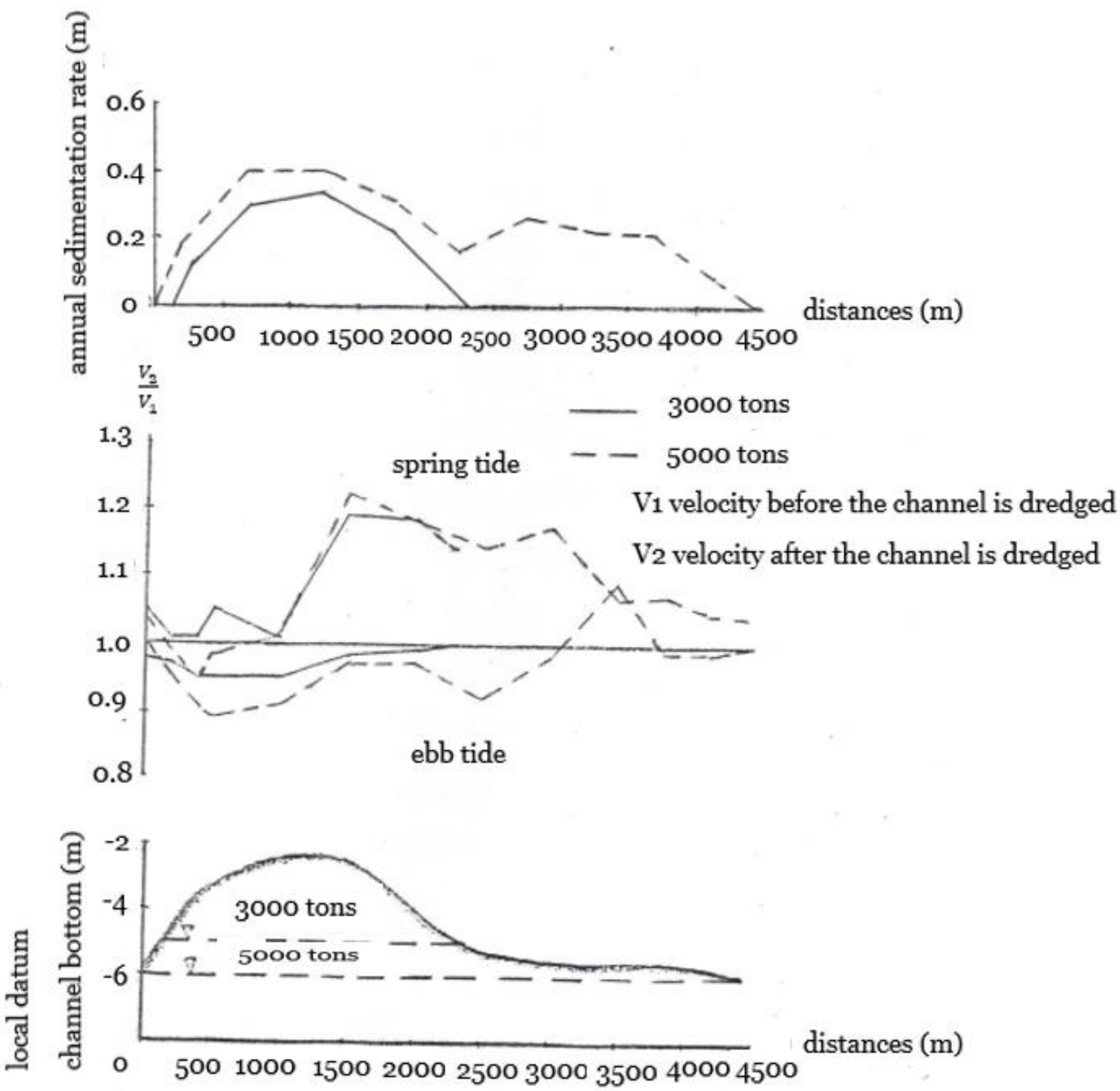

Figure 7 Velocity ratio after and before the channel is dredged and annual sedimentation rate

From the above the Figure 7, it can be seen that the sedimentation rate is larger when the channel is dredged more. Finally, it was proved from this study that it was feasible to expand the Shan Wei Harbor into the harbor of 3000 tons and 5000 tons. Now, the expanded Shan Wei Harbor is being utilized.

4. Conclusion

In a bay, the sediment transport is dynamically in balance. The balance of water movement and sediment transport is broken after a navigation channel is dredged. It is out of balance with the dredged navigation channel available. This causes the sedimentation in a navigation channel. The navigation channel sedimentation formula is derived in this paper. It has been successfully applied to the feasibility study of the sea-going navigation channel sedimentation of Shan Wei Harbor in China.

5. References

1.Jia Ju Liu (1980), The Computation and Forecast of sedimentation of Lian Yun Harbor Navigation Channel, Water Conservancy and Water Transport, No. 4, p.31 (in Chinese).

2. Peter M.J. Kerssens, Ad Prins, Leo C. Van Rijn (1979), Model for Suspend Sediment Transport, Journal of the Hydraulic Division, ASCE, Vol. 105, No. Hy5, p. 461.

3.River Sediment Engineering Teaching and Research Office of Wu Han College of Water Conservancy and Electric Power (1981), River Sediment Engineering, Water Conservancy Publisher (in Chinese).

4.Lars Mikkelsen, Preben Mortessen, Torben Sorensen (1980), Sedimentation in Dredged Navigation Channels, Proceedings of the Seventeenth Coastal Engineering Conference, Vol. II, March 1980, Sydney, Australia, p. 1719.

5.Niao Jin, Ghi Ying Wu, De Chang Chen (1985), Exploration of Sedimentation Computational Methods of Dredged Channel on Silty Coastal Shoals, International Journal of Sediment Research, No. 2, p. 12 (in Chinese).

6.Zhao Seng Luo (1987), Sedimentation Calculation of Dredged Navigation Channel of River Outlet, International Sediment Research, No. 2, p. 13 (in Chinese).

7.Zhan Fulaizhifu, etc. (1987), Technical Status of Dredged Navigation Channel Sedimentation Prediction, Wei Hao Gu translated, Shanghai Navigation Channel Science and Technology, No. 3, p. 18 (in Chinese).

8.Ren Zhan Liu (1988), Sedimentation Process of Port Basin of Jin Jiang Harbor, International Sediment Research, No. 4, p. 30 (in Chinese).

9.Gia Gu Liu and Jing Chao Zhang (1989), Sedimentation Prediction and Verification of Silky Coastal Open Port Basin, Water Conservancy and Water Transport Scientific Research, No. 4, p. 105 (in Chinese).

10.Pei Jiu Le and Jin Xiang Yan (1990), Computational Method of Sedimentation Dredged Navigation Channel, International Journal of Sediment Research, No. 2, p. 38 (in Chinese).

11. Guo Ren Dou (1963), The computation of Tidal Flow Suspended Sediment Movement and Sedimentation, Journal of Water Conservancy, No. 4, p.13 (in Chinese).

12.Li, Weimin (1989), The Feasibility Study of Sea Going Navigation Channel for Shan Wei Harbor: Computation of Navigation Channel Sedimentation, Technical Report, Guangdong Provincial Consulting Institute of Water Resources, Guangzhou, P. R. China (in Chinese).

13.Li, Weimin (1989), The Feasibility Study of Sea Going Navigation Channel for Shan Wei Harbor: Numerical Simulation of Tidal Current and Analysis, Technical Report, Guangdong Provincial Consulting Institute of Water Resources, Guangzhou, P. R. China (in Chinese).