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A PRELIMINARY STUDY ON THE MECHANISM OF SILTATION IN THE LEADING EDGE OF ALONGSHORE OPEN-TYPE PILED WHARF IN MUD BED ESTUARY

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Abstract: Alongshore pile wharf is widely used in most docks in China, but there occurs serious deposition when the wharf is built in the leading edge of the dock. Based on the analysis of field data, physical model results, and numerical simulation for the open-type piled wharf of the Waigaoqiao Port in the Yangtze Estuary, the characteristic of deposition and the reasons for serious siltation in the leading edge of the wharf in recent years are studied in this paper. The results show that the weak current near the dock, induced by the resistance of piles on flow, is one of the important reasons, and the deflecting effect of piles on current is another one. Besides, the increase of bank slope in the back of the wharf after its construction speeds up the beach moving forward, enhancing the siltation in this area too. For this type of dock, owing to the dredging of harbor basin is executed on the beach slope, the process of sediment siltation is very complex, and the deposition of suspended sediment is only one part of it. The collapse of slope resulted from the breaking of equilibrium beach profile is the primary reason for the serious deposition in the leading edge of wharf after it is dredged.
Based on analysis of the features of sediment deposition for the alongshore open-type wharf and the silting verification, a model for silting calculation is discussed and used to estimate sediment siltation in front of the dock edge after harbor basin dredged.

Key words: Alongshore open-type piled wharf, Siltation, slope of beach underwater, Dredging, harbor basin

1. INTRODUCTION

Estuary merges river and ocean together, and it plays an important role both in flooding discharge and water transportation. For an example, Shanghai City is not only the center of economic, but also the center of water transportation in China. On the other hand, the economic zone adhere to it has made the Yangtze River being a gold channel for water transportation in China.

For most wharfs near estuaries and tidal channels, the form of alongshore open-type piled wharf is often adopted so as to lessen the influence on flooding discharge and the effects of wharf structures on flow current and river bed. There is often a good condition of water depth in the site of dock building before its construction. However, with the analysis of field survey, there is a strong siltation occurred after the dock built, especially in the Yangtze Estuary.

What's more, there is a severe siltation occurred again after the harbor basin dredged in the leading edge of the dock.

In this paper, an investigation on the siltation in the alongshore piled wharfs in the Yangtze Estuary is given, and the silting process and mechanism in the leading edge of the dock for its construction and dredging of harbor basin is studied. In addition, an estimating calculation of sediment siltation is done.

2. SURVEYS AND ANALYSIS OF SEDIMENT SILTATION

2.1 ANALYSIS OF CHARACTER OF SEDIMENT SILTATION AND SCOUR IN THE PROCESS OF CONSTRUCTION

The Waigaoqiao Port is located in the south bank of the south port channel in the south branch of the Yangtze River. Fig. 1 shows the layout of the first phase construction of the wharf. The dock is an alongshore piled wharf, and it is 900 m in length and 42 m in wide. It is connected with the bank by use of 4 access trestles, and there are 4 berths will be built in the first phase construction.

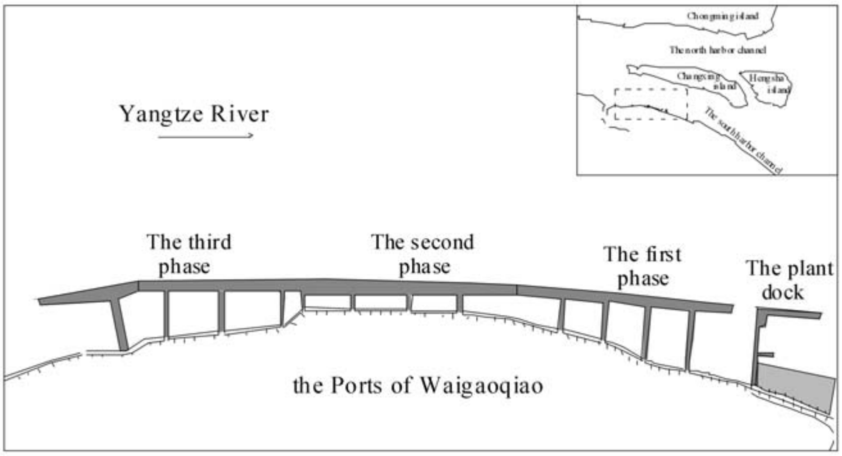

Fig. 1 The layout of coast and Waigaoqiao Port

The construction began on July 1, 1991, finished on December 24, 1993 and the wharf was put into service on Oct. 11, 1994. The water depth in wharf was 12 m before its construction, but it was lessened gradually in the leading edge of the wharf during and after the construction. Table 1 shows the monitor results within the 30 m before the leading edge of the dock.

Table 1 Water depth in 30 m before the wharf in the first phase of the Waigaoqiao Port (in the process of harbor construction)

position / time	1#	2#	3#	4#	Average water depth	Averaged silting height
Before construction	12.00	12.00	12.00	12.00	12.00	
17 months after the begin of construction	10.90	9.76	10.55	11.73	10.40	1.6
24 months after the begin of construction	9.93	8.62	9.76	10.03	9.59	2.42

In the first 17 months, the average silting height is 1.6 m in the leading edge of the dock, and 0.81 m in the back part of the dock. From the beginning to the end of the construction, nearly 3 years, the average height of siltation is 2.42 m in the leading edge of the dock, and the maximum height is 3.38 m. The analysis of silting shape shows that the main silting zone is near to the dock in the leading edge. The larger the distance leaving from the dock is, the smaller the height of siltation.

2.2 ANALYSIS OF CHARACTERISTIC OF SEDIMENT SCOUR AND DEPOSITION AFTER HARBOR BASIN DREDGING

After the construction is finished, there were 3 times dredging executed in June of 1994, July of 1996, and August of 1997, respectively. Fig. 2 shows the profile evolution of the underwater topography monitored after the first dredging. From the begin of June 1994, the water depth was silted up from 12.5 m to 10.7 m in the 16 months. The average silting height is 1.60 m within 40 m forward from the leading fringe, 2.2 m within 30 m, 2.9 m within 20 m, 3.7 m within 10 m, and 4.2 m in the leading fringe, respectively. Furthermore, there is small siltation occurred outside of 30 m, in fact, there is even a bit local scour in the outside of 40 m. The water depth maintains the original before the dredging even shallower in some place one year later. The analytical results of the other two times of dredging are similar to the first one in the silting shape.

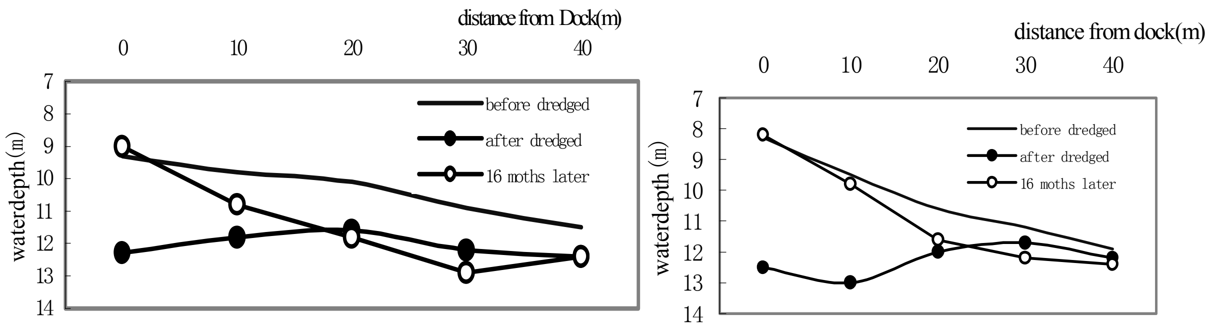

Fig. 2 Beach profile evolution in the first phase of Waigaoqiao Port after dredging in 1994

Neighboring to the upstream of the first phase project, the second phase project of the Waigaoqiao Port has a similar dynamic and sediment environment. The mean water depth is 13.8 m after dredging, and it is silted up to 13.00 m after 8 months (1.01 m within 20 m from the front fringe); 11.4 m after 12 months, the average silting height is 3.2 m in the front fringe, 2.01 m within 20 m, and the silting height is sharply small outside of 30 m and even a bit scour occurs. The results shown in Table 2 have a good agreement with that of the first phase of the Waigaoqiao Port.

Table 2 Silting process after the dredging in August of 1998 unit: (m)

Time interval	1999.8.10	9 months later	13 months later
Averaged water depth	13.8 m	13.00 m	11.4 m
Averaged silting height/ the most of the silting height	/	0.8 m/2.4 m	2.4 m/3.2 m

Table 3 shows the results for the dredging in December of 2000. From the analysis of the data after the dredging, the water depth is silted up to 11.8 m from 12.9 m in the first 4 months, 10.7 m after 6.5 months, and 10.1 m after 9.5 months. The maximum silting height is 5.1 m. Fig. 3 is the profile of the water depth, showing the strongest silting zone is at front fringe of the dock.

Table 3 Slting status in the front fringe of the dock after the dredging in December of 2000

	Water depth after dredging	4 months later	6.5 months later	9.5 months later
Averaged water depth	12.9 m	11.8 m	10.7 m	10.1 m
Averaged silting height/ the largest silting height	/	1.1 m/2.9 m	2.2 m/4.1 m	2.8 m/5.1 m

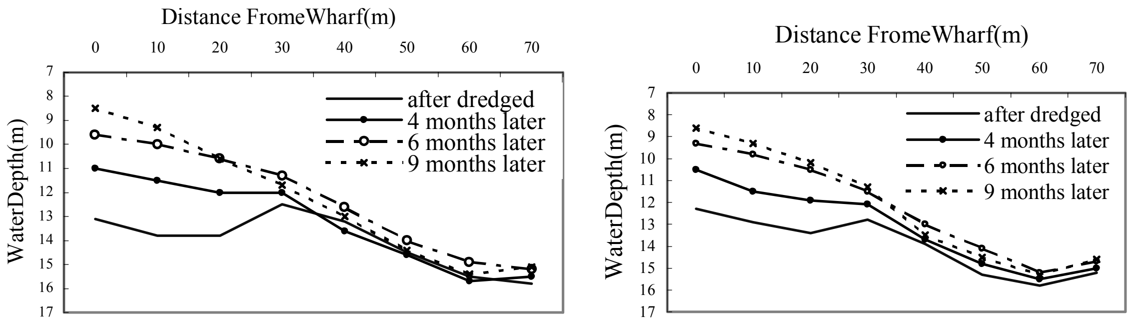

Fig. 3 Beach profile evolution in the second phase of the Waigaoqiao Port after dredging in 1994

According to the analysis of the underwater topography for the first phase and the second phase of the Waigaoqiao Port, it shows that the area within 30 m away from the front fringe of the dock is the most serious silting zone. Over 80% of the total silting amount occurs here, however, there is a small siltation and even a small scour after dredging in the zone outside of 40 m.

3. MECHANISM OF SERIOUS SILTATION FOR CONSTRUCTION AND DREDGING IN FRONT FRINGE OF DOCK

3.1 DYNAMIC AND SEDIMENT ENVIRONMENT

The Waigaoqiao Port is located in the south bank of the south port deep channel, and the current moves under the action of tidal flow and river runoff flow. The duration of ebb is longer than that of the flood, and the maximum current velocity is over 2.0 m/s in spring tide.

The sediment content is affected by the sediment in runoff flow from the upstream and the sediment induced by tidal dynamic in estuaries. In general, the average sediment content in vertical line in flood season is larger than that in dry season, and larger in rising tide than in ebb tide in dry season; the average sediment content in spring is the largest, followed in medium tide, and the smallest in neap tide. According to the surveyed data, the maximum sediment content averaged in vertical is near 1.0 kg/m^3, the minimum sediment content averaged in vertical is smaller than 0.2 kg/m^3, but the average suspended sediment content in one year is no more than 0.5 kg/m^3.

The diameter of suspended sediment here is very fine, varying from 0.002 mm to 0.015 mm with a medium diameter of 0.006 mm, the suspended sediment possesses the characteristic of cohesive sediment. The deposition in bed is silting clay, and its diameter varies from 0.014 mm to 0.0286 mm. The most part of deposition is fine sediment, and the diameter of deposit is near to that of suspended sediment.

3.2 INFLUENCE OF PILES ON FLOW AROUND PILE DOCK

The near shore deep channel is maintained by hydrodynamic in estuary. If the flow condition changed, the river bed would be scoured or silted synchronously. The deep channel in the Waigaoqiao Port is closed to the bank, and a strong dynamic flow condition exists there. The resistance of piles on the current around the dock increases evidently after dock construction. It is shown (Zhao1996,Li 2001) that the eddy turbulence of flow is strengthened, the structure of the current around piles is more complicated and thus the flow velocity decreases because of dock piles. It is estimated that the resistance of piles may increase 5−10 times than before, reducing the flow discharge sharply, forcing the main stream moved away the bank, and enhancing the siltation near the dock obviously.

The results from physical models (Wu et al. 1994,1995) showed that the velocity is reduced by 15%−40% in the dock leading edge, and the results of numerical simulation suggest that the velocity can be decreased by 40% also. It can be(Wu 1994,1995)also shown that, after the construction of dock, there is a local current deflection in ebb and flood, and the angle between flow and the dock line increases.

Several measurements of sediment and current in spring and neap tides were made in the waterway, the leading edge of the dock, and the back edge of the dock after the first phase of the Waigaoqiao Port built. The results of measurement are listed in Table 4.

Table 4 Velocity and sediment content in the leading and the back edge of dock after the first phase of the Waigaoqiao Port

	Waterway	Leading edge of dock	Back edge of dock
Velocity (m/s)	0.59−1.40	0.03−0.42	0.26−0.95
Sediment content （kg/m^3）	0.25−0.92	0.017−0.98	0.16−0.58

The wharf is set up in the deep channel in the first phase of the Waigaoqiao Port. The water depth in the deep channel was about 12 m before the wharf construction, and the velocity there should be equal to that in the waterway. However, there was a large difference appeared after the wharf construction. The velocity in the leading edge of the dock is smaller than that in the waterway and even in the back fringe of the dock, showing that there is a strong effect on velocity around piles for the dock construction. The resistance of piles on flow results in a large difference of hydraulic and sediment conditions after the dock construction.

From the results of physical model tests, numerical model and the comparison of field data between before and after the dock construction, it can be concluded that the decrease of the velocity around the dock makes the sand carrying capacity of flow reduced and the siltation of suspended sediment increased largely. This is one of the key reasons for the strong siltation around the dock after its construction.

3.3 INFLUENCE OF SLITATION IN THE BACK OF THE DOCK ON THAT IN THE FRONT

During the evolution of river bed, a relative stable equilibrium bed profile is formed, and the stability of profile section varies with the stability of hydrodynamic conditions simultaneously. If the flow conditions changed, a new equilibrium would be formed to adapt to the new dynamic condition through an adjustment of river bed. According to the above analysis, the zone of piles is the most serious area affected by the flow current, so that the siltation there is much larger than that in the back or the front edge of the dock, and siltation in the back is larger than that in the front, resulting in obvious increase of the slope around pile foundation and forming a new equilibrium profile.

According to the hydrodynamic and sediment conditions, the natural equilibrium slope is about 1:30−1:40. However, after the dock is constructed, there is a inverse trough formed between the bank and the dock, and the slope changes mild. What is more, the slope of the front of the dock is much steeper than before.

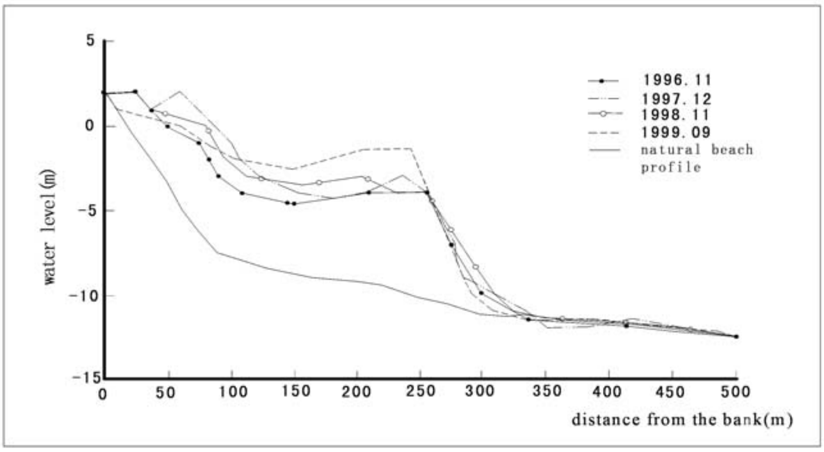

Fig. 4 Beach profiles at the dock of theWaigaoqiao power plant

Fig. 4 shows the profile of river bed for the dock of the Waigaoqiao Power Station, located in the downstream of the first phase. The slope before was 1:30−1:40, but reached 1:5−1:6 in the area of foundation after the dock building, increasing the siltation there largely, especially around the dock. The average silting height is over 2.0 m every year. The slope outside of the dock is a bit milder than that of the pile zone and it is about 1:6−1:10.

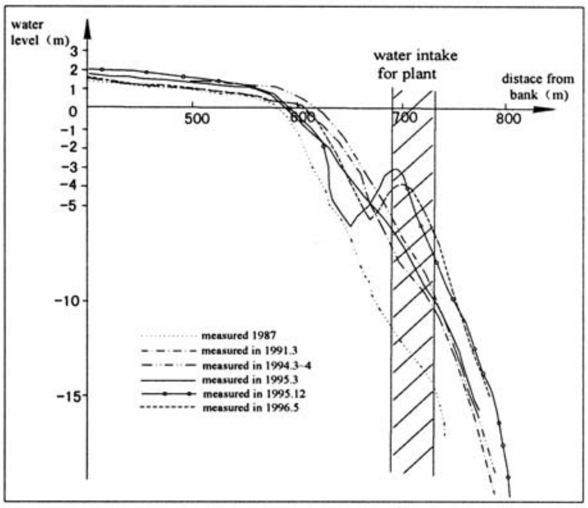

Fig. 5 Beach profile evolution in the water intake of Beilun Power Station

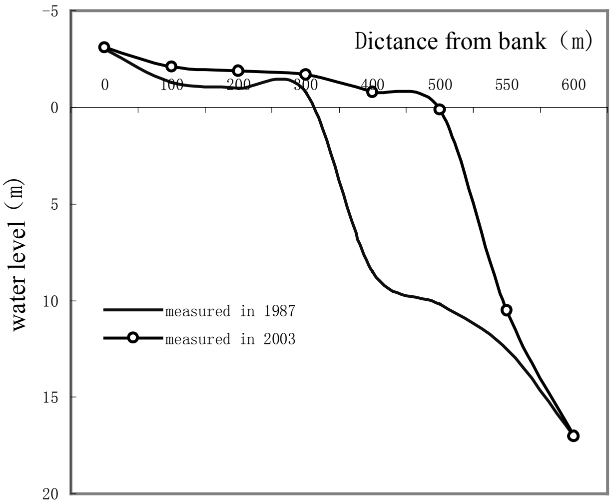

Fig. 6 Beach profile of Shuini Dock in Beilun

Figs. 5 and 6 show the beach profiles in the zone of water intake of the Beilun Power Station and Shuini dock. The slope in the Beilun beach is much steeper than that the Waigaoqiao Port.

It is shown that dock built in strong hydrodynamic zone would lessen velocity and overflow, inducing the increase of siltation in the back of the dock, making the profile slope of underwater topography steep and putting the beach profile moved forward to the front of the dock.

3.4 REASONS FOR THE SILTATION IN THE LEADING EDGE OF THE DOCK AFTER HARBOR BASIN DREDGED

As mentioned above, Fig. 7 shows a new equilibrium formed after the wharf construction to keep the continuity of profile. The steepest slope occurs around the piles and its value is about 1 : 5. The slope of the topography of underwater in harbor is milder than the slope around piles, but it is steeper than itself before. The slope is about 10º around piles and 5º−10º in harbor basin. After the dredging in the harbor basin, the slope changes steep and its stability decreases, easily resulting in slope collapse in the edge of the harbor basin.

In Fig. 7, the continuity of the slope is broken after dredging in the harbor basin. The change of hydrodynamic conditions induces an adjustment of topography to adapting to the new hydrodynamic condition. The nearer to the dock in the leading edge is, the larger the dredging height, and the stronger the adjustment and the siltation in the area.

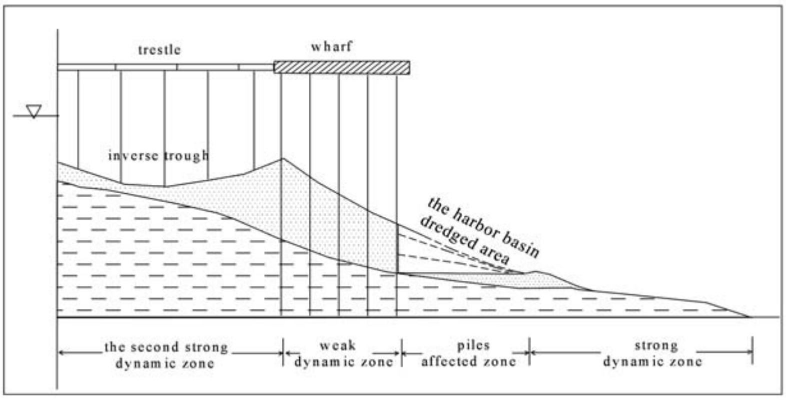

Fig. 7 Sketch of beach evolution and harbor dredging in pile dock

Figs. 2 and 3 are the monitoring maps of the evolution process after dredging in harbor basin for the first phase and the second phase of the Waigaoqiao Port respectively. From the figures, it can be seen that the strongest of adjustment occurs within 10 m outside of the front dock, and the siltation is the most rapid. According to the time of evolution, the most of siltation occurs in the first 4 months, and the water depth in the dredged area will restore to the former after 14 months. The maximum height of siltation is over 5 m. The farther away from the front line of the dock, the smaller is the siltation. There is little siltation or even a bit scour outside 40 m away from the dock.

The restoring duration after a dredging is about one year, meaning that the water depth in harbor basin would restore to the original after about one year from the dredging. It can be concluded that there are two reasons responsible for the serious siltation. The first, dredging on the slope breaks the equilibrium profile and increases the adjustment speed of beach profile to a new equilibrium, making the slope unstable and easy to collapse. Besides, the ships berthing and mooring will stir up the current in the front of the dock and also make the slope collapse more easily. The second, after dredging in the harbor basin, the growing of the area of cross section will reduce the velocity, lessen the capacity of sediment carrying, and enlarge the siltation of suspended sediment in harbor basin.

4. ESTIMATION OF SEDIMENT SILTATION STRENGTH

Physical model experiment and numerical simulation are widely used to study the effect of piles dock on current, but the accuracy depends on the generalization of dock piles. A good result only can be obtained based a good solution for the simulation of piles.

In this paper, a two-dimensional numerical model is used to simulate the effects of piles on flow, and the method of group piles is adopted for simulation. The model is verified by comparing the velocity and the tidal level with the field data(Zhang et al., 2002). Table 5 shows the average velocities for some points along with the dock in the leading edge, before and after the wharf construction and after dredging in the berth.

Table 5 Average velocities for different engineering schemes (m/s)

Points	Point A	Point B	Point C	Point D	Point E	Point F
Before dock construction	0.60	0.56	0.60	0.64	0.64	0.62
After dock construction	0.47	0.40	0.48	0.55	0.54	0.55
After dredging	0.39	0.34	0.43	0.54	0.48	0.51

There is a certain decrease for average velocity in the leading edge after wharf constructed and dredged, and the largest is over 30%. The wharf in the Waigaoqiao Port is built along the shoreline, and the berth parallels to the waterway and the angle between flow and the waterway is small. The formula provided by Liu (1997) can be used for the prediction of siltation in harbor basin:

$$P = \frac{k_2 S \omega t}{\gamma_0}[1 - \frac{V_2}{2V_1}(1 + \frac{d_1}{d_2})] \quad (1)$$

where, V_1 and V_2 are the average velocities before and after the dock construction respectively; d_1 and d_2 are water depths in navigation before and after its dredging respectively; γ_0 is the dry density of deposition mud in the channel; ω is the sediment settlement velocity; S is the average sediment content in an interval; t is the duration of siltation (in second); k_2 is an empirical coefficient for siltation.

The averaged sediment content is no more than 0.5 kg/m^3 in ordinary season. Considering the effect of abnormal weather like wave or windstorm, the annual averaged sediment content of 0.5 kg/m^3 can be adopted (Lu, 1999; Luo, 2000).

It is very necessary to verify the rationality and applicability of the formula in this zone. Siltation in the first phase during the dock construction is used for the verification. The original water depth is 12 m, and d_1/d_2=1 for the area not be dredged. 1.88 m and 2.45 m are obtained from the formula for the silting heights of 17 months and 22 months later respectively. They are very close to the observed heights, 1.6 m and 2.4 m respectively, showing that the formula is adoptable to predict the silting height in this area.

The averaged water depth can be set as 8.5 m before dredging in the leading edge of the dock, it is estimated that the silting height is 1.31 m in the area. 2.1 m and 1.9 m are obtained by the formula for the dredging of 4 m and 3 m respectively.

According to the above data, after 16 months of the dredging in June, 1996, the largest silting height in the leading edge is over 4 m. The average silting height is 4.2 m in the leading edge, 3.69 m within 10 m, and 2.9 m within 20 m. It can be calculated that over 30% of the silting substance in the berth is not resulted from suspended sediment, and it may come from the slope collapse because of the instability of slope. It is shown that there is a big proportion of siltation coming from abnormal siltation in the Waigaoqiao Port.

5. CONCLUSIONS AND DISCUSSION

In this paper, is given a brief analysis for the sediment siltation in the leading edge of the dock in the Waigaoqiao Port according to the investigation of silting status after dock construction and harbor basin dredging. It is suggested that the main reasons for the siltation in alongshore open-type piled docks is the increase of resistance on current after offshore piles construction, which breaks the equilibrium profile of river bed and induces the river bed adjustment. In additional, the siltation in the back of the dock increases the siltation in front of the dock.

The siltation in the dredged harbor basin is a process of sediment siltation in a excavated pool on slope, and it is composed of not only suspended sediment siltation, but also the slope collapse due to unstable bank. The serious siltation in front edge of the dock in short time mainly comes from suspended sediment siltation induced by dredging in harbor basin and abnormal siltation of slope collapse.

Based on the measurement of underwater topography, calculation and analysis, a formula is recommended for prediction of silting, and the results show that over 30% of the total siltation resulted from the slope collapse after dredging.

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