Prediction on Changes of Seabed due to Sluice Built on entrance of Haiyou Branch in Sanmen Bay

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Abstract: Haiyou branch is the main branch of Sanmen Bay, it is an optional plan to construct sluice at the entrance of Haiyou branch to store fresh water for the utilization of freshwater resources in the Sanmen Bay basin. Basing on the verification of historical tidal currents and seabed erosion and deposition, numerical and physical models are established. Numerical calculations and physical model test show that the impact on hydrodynamic and seabed environment after the construction of sluice will be limited to the local sea area outside the sluice, where the downstream area of sluice, Shepan waterway and Maotou waterway are located, and the siltation strength decreases from the sluice towards Maotou waterway. After the construction of the sluice, the tidal inflow volume of Shepan section will decrease by 11.3% to 17.1%, the tidal volume of Maotou section decrease by 1.7% to 4.3%, and the tidal volume of Qinshan section and Qimen section remain basically unchanged. Within one year, the downstream area of sluice will be deposited with 0.5m~0.7m, Maotou waterway with about 0.15m, and there is also little siltation at Qimen waterway and other waterway. Due to the impact of the sluice construction of Haiyou branch, after a long time, the deposition of deep pool in Maotou waterway is 2.0m~2.5m. A once-in-50-year flood from the upper reaches will not cause significant seabed changes in the deep pool of Maotou waterway.

1. Introduction
In the islands and bay areas along coast of Zhejiang, the river runoff changes greatly during the year. Because mountain reservoirs are mostly small reservoirs or mountain ponds with small storage capacity, there is basically no flood regulation effect during wet seasons, most of the precipitation becomes surface runoff which is discharged into the sea and there is the risk of floods because floods fluctuate sharply. Rivers may be cut off during dry seasons, droughts occur, and there is a shortage of water resources. Since 1950, Zhejiang Province has adopted blocking of branch and reclamation of tidal flat to store freshwater resources during floods, and has built a few marine reservoirs in Sanmen Bay with a total storage capacity of 170 million m³, two marine reservoirs in Yuhuan city with a total storage capacity of 130 million m³. With the social and economic development of coastal cities, the population is concentrated in the coastal area, the contradiction between supply and demand of regional water resources has gradually emerged, and the demand of water supply has further increased. To construct coastal water reservoirs to store floodwater is of great significance. However, the construction of the reservoir will inevitably cause hydrodynamic changes of the sea area, resulting in seabed deposition/erosion in the sea area downstream. This is a significant concern on marine environmental issues for the construction of marine reservoir. Haiyou branch is the main branch of Sanmen Bay, it is planned to build sluice at the entrance of Haiyou branch to construct marine
reservoir storing fresh water. This paper studies the impact of sluice construction on the seabed deposition/erosion and dynamic conditions in Sanmen Bay, especially deep pool at Maotou waterway. It is of great significance for the protection and development of Sanmen Bay and the utilization of water resources.

2. Overview of the study area

The drainage area of Sanmen Bay covers an area of 3160 km\(^2\), and the annual average runoff is 2.68 billion m\(^3\). Haiyou branch is located on the southwest side of the inner bay of Sanmen Bay. At the entrance section, the annual average runoff is 421 million m\(^3\) and the annual average flow is 13.34 m\(^3\)/s, a sluice will be built at the entrance section to build a marine reservoir whose water area is 423.0 km\(^2\), and the average diversion flow after the construction of the sluice is 1.9 m\(^3\)/s. The location is shown in Figure 1. Sanmen Bay opens to the southeast, whose sea area is 775 km\(^2\), tidal flat area accounts for 38% of the total sea area. Sanmen Bay can be divided into inner bay and outer bay by Maotou cape. The river flows upstream maintain the existence of the branch, which profoundly affects the topography of the inner bay of Sanmen Bay. The tongue-shaped tidal flats are arranged alternately and communicate with the outer bay by many waterways. The outer bay of Sanmen Bay is mainly composed of an underwater plain in the south and a waterway in the north. The water from Haiyou branch flows out of the entrance section into the Shepan waterway, which is connected to the waters out of Sanmen bay through Maotou Waterway. The deep pool of Maotou cape is about 9km away from the sluice site at Haiyou branch. Because the cape extends into the Maotou waterway, a deep pool is formed with a maximum water depth of about 45 m at its bottom.

Figure 1. Location of Project and hydrographic stations in December 2007

There have been four large-scale hydrological surveys in Sanmen Bay, in the summer and winter of 1994, the winter of 2007, the summer of 2013 and the winter of 2019. The hydrological survey in 2007 were mainly located in the inner bay and Haiyou branch, the survey in other periods are mainly located in the middle of the bay and the outer bay. The hydrological survey in 2007 can be used as the basis for the prediction. The tidal wave of Sanmen Bay belongs to standing wave, and regular semi-diurnal tide, the tidal range increases gradually from the mouth to the inner of the bay, according to December 2007, the average tidal ranges at Niushan station near the mouth of bay, Jiantiao in the middle and Shepan station at the top of the bay, was 4.13m, 4.18m and 4.47m respectively. The tidal current in Sanmen Bay is mainly restricted by the shoreline and topography and presents a reciprocating flow. In December 2007, the maximum vertically averaged tidal current velocities during tidal flood and ebb at Maotou waterway in December 2007 showed 1.22 m/s and 1.08 m/s
respectively, the values are 1.06 m/s and 0.95 m/s respectively measured in December 2019. The velocity during tidal flood is greater than tidal ebb. There are three measurement stations (C9, C10 and C11) at Haiyou branch from Dayu to the entrance of branch, the maximum vertically averaged tidal current velocities are 0.9 ~ 1.25 m/s during flood of spring tide, and the maximum velocity is 0.6 ~ 0.9 m/s during ebb, the velocity gradually decreases upstream along the branch, which indicates that tidal dynamics gradually decreases as the tide waves propagate upstream. There are many branches in Sanmen Bay, and the sediment mainly comes from the nearby seas. The character of distribution show that suspended sediment concentration (SSC) in the mouth of bay is larger than inner bay, SSC during spring tide is larger than neap tide, SSC at the bottom layer is larger than the surface layer, and the beach area is larger than the open water. In December 2007, the averaged vertically SSC during spring tide in the sea area was 0.13 ~ 0.4 kg/m$^3$. In 2019, the averaged SSC was 0.19 ~ 0.56 kg/m$^3$. In different years, the content is basically similar.

3. Verification of tidal current and seabed deposition/erosion in Sanmen Bay
Sanmen Bay belongs to a strong tide bay, and the stratification of the water body is not obvious. A two-dimensional mathematical model of water flow, sediment and seabed deposition/erosion can be used. The scope of the model is shown in Figure 2. The total area of the computational domain is about 3268 km$^2$. This model uses an unstructured triangular grid. In order to ensure the accuracy of simulated flow field, the small size of grid and more grids are used in sea areas with relatively large gradients of water flow and seabed topography, and the grid is further refined in Haiyou branch. A total of 13374 computing nodes and 24447 meshes are deployed throughout the region. The step length of plane grid is 50m ~ 2000 m, and the step length of time is 0.01 s ~ 60 s in numerical model.

The physical model is shown in Figure 3. According to the shape of Sanmen Bay, tidal current movement and seabed topography, plane scale $\lambda_l$ is adopted as 400 and vertical scale $\lambda_h$ is adopted as 100 in the model whose area covers about 240 km$^2$, including Shepan waterway, Qinshan branch and Liyang branch. The deposition/erosion of seabed in Sanmen Bay depends on the movement of suspended load. Data from many surveys show that the medium size of suspended sand in this sea area ranges from 0.004 to 0.009 mm, which is fine silt. The physical model mainly studies the deposition of seabed from sluice to Maotou pool. The model sand is selected mainly according to the similarity of settlement and starting. Wood powder with a median particle size of 0.05 mm was selected as the model sand, the test dry bulk density was 0.27 g/cm$^3$, and the settle velocity was 0.024 cm/s. There will be time abnormalities. For this reason, a single tidal process is controlled by the time scale of current motion to ensure that the simulated current is similar to the current of prototype; the number of test tides in the simulation depends on the time scale of seabed deposition to meet the requirements of seabed deformation similarity. Experiments were performed under conditions on similarity of geometry, water flow motion and sediment motion, and the conversion of physical variables between the prototype and the model is carried out accordingly.

![Figure 2. Scope of Numerical simulation](image1)

![Figure 3. Scope of Physical simulation and measured location](image2)
The verification of numerical and physical model about water flow adopts the data of hydrological survey carried out inside and outside Haiyou branch in November 2007. The verification includes tidal level process of 5 stations, tidal current process of 11 stations (see Figure 1). The verification results show that simulated tide level processes, current processes, surface flow trajectory are in good agreement with the prototype. Both numerical and physical simulation about seabed erosion/deposition were verified by the change between underwater topography in Maotou Channel and Shepan Channel where there were slightly erosion/deposition during November 2006 and December 2007. For the physical model, there was additional verification of erosion/deposition on the fixed section of Haiyou branch from May 2007 to December 2007, where there is slight siltation. According to the results of many sets of verification tests about erosion/deposition, when $\lambda_S = 0.3$ and $\lambda_{t2} = 400$, the SSC, topographic erosion/deposition and its distribution are in good agreement with the prototype.

4. Hydrodynamic changes in the sea area after the construction of sluice

After the construction of sluice on Haiyou branch, the flow field will be affected at the sea area from the sluice to the front of Maotou cape, including the downstream area of the sluice, Shepan waterway and Maotou waterway, where the tidal current velocities will decrease. The influence of sluice construction on tidal current will decrease with the increase of distance from the sluice, the influence on ebb current is greater than flood current, and the influence on the spring tide is greater than the neap tide, as shown in Figure 4.

The results of numerical model and physical model about velocity variance of representative locations in key areas of Sanmen Bay are listed in Table 1, and the locations are shown in Figure 3. After construction of sluice project, the current velocity at Shepan waterway will be reduced by about 1% to 25%, current velocity at Qimen branch and Qinshan branch will remain basically unchanged according to numerical simulation, and will increase slightly within 5% according to physical model, tidal current velocity at the deep pool of Maotou cape will be slightly reduced with 3% to 4% according to numerical simulation, and 0% to 5% according to physical simulation. The rate of decrease in tidal ebb current is slightly larger than that of tidal flood current. It can be seen that this area will be more likely to form siltation than before the sluice project was implemented.

The control section of tidal inflow volume about some branches in Sanmen Bay show in Figure 3. After the sluice is constructed, due to reduction of tidal storage capacity, the tidal inflow volume of Shepan section will decrease directly, resulting in reduction of the volume at Maotou section as shown in Table 2. Numerical calculations show that tidal inflow volume of Shepan section will be reduced by 16.6% to 17.1%, and physical simulation shows that the section will be reduced by 11.3% to 14.9%. The tidal inflow volume of Maotou section will be reduced by 4.1% to 4.3% according to the numerical model, and is reduced by 1.7% ~ 2.9% according to the physical model. In numerical model, the tidal inflow at Qinshan section and Qimen section will remain basically unchanged, and the tidal inflow of the two sections in the physical model will increase slightly by about 2% to 5%, and the variance of tidal inflow at Qinshan section is smaller than that at Qimen section.
5. Analysis of seabed erosion/deposition changes

5.1. Annual seabed erosion/deposition variance caused by the project

After the construction of sluice project, the elevation change of seabed after one year is subtracted from the natural evolution value of seabed, and the one-year seabed deposition/erosion caused by the project is shown in Figure 5. After construction of the sluice in Haiyou branch, the current velocity of sea area from the sluice to Maotou cape will decrease, the capacity of carrying sediment of the water flow decrease, and siltation will occur in the seabed. In the downstream area of sluice, not only the flow velocity will be reduced, but also a certain scale of backflow will be formed, which will
aggravate sedimentation. It can be seen from the Figure 5 that sluice construction will lead siltation of seabed basically, and its scope of siltation will include the downstream area of sluice, Shepan waterway and Maotou waterway. The thickness of siltation will decrease from the sluice to Maotou cape, and its magnitude is 0.05 ~ 0.7 m/a.

5.2. Final changes of seabed erosion/deposition caused by the sluice

After the construction of sluice in Haiyou branch, the final erosion/deposition distribution of seabed caused by the sluice are shown in Figure 7 according to numerical simulation. After the construction of the sluice, there will be overall siltation in seabed from the sluice to Maotou cape, including the downstream area of sluice, Shepan waterway and Maotou waterway. Qinshan waterway and Manshan waterways are basically not affected. The thickness of siltation decreases from the sluice to Maotou cape. There will be 5.6 m of final siltation in the downstream area near the sluice, 0.4m ~ 1.5 m in the deep trough of Shepan waterway, within 0.2 m in the beach, within 0.6 m in deep trough of Maotou waterway, 1.82 m in the deep pool (the deepest location).
5.3. Deposition trend of local deep pool

The typical local deep pool in Sanmen Bay is Maotou deep pool. The sluices built at the Haiyou estuary to block the tide and store fresh water, the tidal inflow volume of Sanmen Bay will decrease, and the amount of stream flowing into the bay will be reduced at the same time. The reduction of runoff has very little impact on the short-term siltation of the nearby seabed, the annual siltation amount is below 1cm at Maotou deep pool. To consider the operation period of sluice which is 50 years, the siltation of deep pool by blocking of branch and diversion of runoff is 2.3 m according to numerical model.

The final siltation can be predicted according to the fitting method basing on the measurement results of physical model. The fitting method is as follows:

\[ H = H_0 \left(1 - e^{-\lambda t}\right) \lambda \]  

where \( H \) is the accumulated deposition thickness of the seabed (m); \( H_0 \) is the initial deposition rate of the seabed (m/a); \( \lambda \) is attenuation coefficient (1/a); \( t \) is the duration (a). The construction of sluice will cause 2.5 m of the final siltation at the bottom of deep pool.

6. Conclusion

The utilization of Sanmen Bay mainly includes the construction of reservoirs on the upstream of the branch, the construction of marine reservoirs by blocking the branch, and the reclamation of the beach. Numerical calculation and physical model tests show that the impact on the hydrodynamic and erosion/deposition environment caused by the sluice on Haiyou branch will be limited to local sea area where the downstream area of sluice, Shepan waterway and Maotou waterway. The deposition of the local deep pool of Maotou will be about 2.5 m. The construction of marine reservoir in Haiyou branch is an optional plan to increase the utilization of freshwater resources in Sanmen Bay.

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