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# ANALYSIS ON EVOLUTION OF MODAOMEN OUTLET OF PEARL RIVER ESTUARY BY APPLYING REMOTE SENSING INFORMATION

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**Abstract:** The Modaomen outlet is the largest outlet among the eight outlets and the most important flood-discharging channel of the Pearl River Estuary. The water flow and the sediment transport in the channel are extremely complicated due to influences of the runoff, the tidal flow, the south west longshore current and wind waves. This paper analyzes the change of boundary lines of the outlet, the variations of the flow pattern, the flow field and sediment concentration, and the evolution of the Modaomen outlet during the past 20 years by applying the remote sensing information and field hydrological and geographical data.

**Key words**: Pearl River Estuary, Modaomen, Estuary evolution, Remote sense information

## 1. INTRODUCTION

The Modaomen outlet is the largest outlet among the eight outlets and the most important flood-discharging channel of the Pearl River Estuary. Its annual runoff is about $923\times10^8 m^3$, among which 79.7% comes in the flood period from April to September. The annual sediment is about $2{,}500\times10^4$t. It discharges 25% water coming from the West River and the Northern River. The average tide difference at Modaomen is about 0.86m, hence it is belong to the weak tidal outlet. The salt and fresh water mix at the outlet forming high stratifying flow. The flow at the outlet is influenced by the strong wind-driven waves (see Fig.1).

In 1980s, in order to prevent flooding upstream and salt-water intrusion, a large regulating project was carried out on the outlet channel and a regime of "one stem and one branch" was formed. This paper studies new changes and problems brought by the project during the 20 years. The remote sensing information and limited field hydrological and geographical data are used to analyze changes of boundary lines of the outlet channel, changes in flow pattern, flow field, sediment concentration, and the evolution of the Modaomen outlet during past 20 years.

## 2. HYDRO DYNAMIC INTERACTION OF BETWEEN FRESH WATER AND SEA CURRENT AT THE OUTLET

Due to the variations of the density, temperature and water amount of the upstream coming water at Modaomen, a complex circular flow is formed near Hengzhou (downstream of Modaomen), and hence a mouth bar is formed there. Some hydro-dynamic features are as follows:


**Fig. 1** Ilustration of Modamen outlet and its situation at Pearl River Estuary

## 2.1 HYDRO DYNAMIC FEATURES UNDER THE INTERACTION BETWEEN RUNOFF AND TIDE

During the period that the upstream flood meets the low tide, the whole outlet reach of Modaomen is full of fresh water. When the water passes near the mouth bar, its velocity declines rapidly due to the increased friction of the bed. In the downstream of the mouth bar, the freshwater flows over the salt water, forming a high density gradient, and hence producing density current. Because of the reduction of the bed friction, the fresh water can flow and disperse to the 40m deep water area and form obvious fresh water plume flow. This shows that the dynamics on the inner and outer sides of the mouth bar are different.

When the upstream flood encounters the high tide, the fresh water can pass the mouth bar for a short distance but the water level at the outlet is increased. If encountering typhoon, the water level can be increased by 1.6−1.8m. According to related study, during the period when the salt water flows upstream or when it flows downstream, the water flow at estuaries tends balance through changing the density Froude number which can be expressed as:

$$F' = \frac{U}{\sqrt{\frac{\rho_s - \rho_f}{\rho_s} g h'}}$$ Where $\rho_f$ and $\rho_s$ are densities of the flow and ambient ware, respectively; $h'$ is water depth at the interface; U is the flow velocity. During ebb tidal period, the balance is reached by the increased flow velocity and increased interface water depth; and during flood tidal period, the balance is reached by the reduced flow velocity and reduced interface water depth; thus, Froude number can be kept around 1. When the upstream flood encounters huge tide, under the inter-effect between the large upstream flow gradient and the downstream salt water against, the balance can not relay on only adjust of U and $h'$ but others such as dam-breaks, diversions or variations of river beds, so that the Froude number can be kept around 1. The Froude number on the inner side of the mouth bar at Modaomen reaches 2.6 or 1.3 during the period when the upstream flood meets the large tide or the low tide. However, the Froude number in the upstream river can be infinitive. Therefore, the flow

near the mouth bar and its front is turbulent dispersion. Only when the flow reaches deeper area, can the dispersion be changed as buoyant dispersion over the salt water. Hence, the Froude number during the upstream flood period is gradually decreased outwards. This shows that the velocity is decreased and the density difference is decreased, implying the buoyant layer is decreased. The Froude number during the upstream dry period is kept around 1, implying the flow during ebb tide period is similar to buoyant dispersion (see Fig.2).

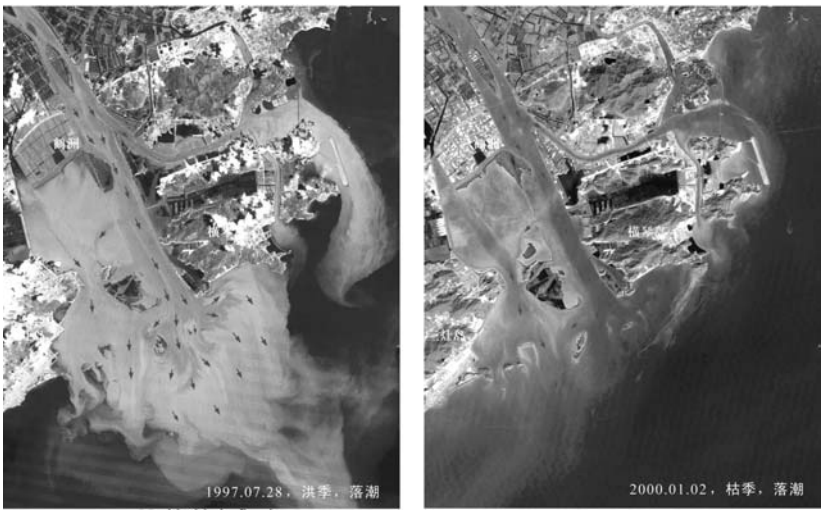


**Fig. 2** Sediment transport in the Modaomen Outlet Area

During the upstream dry period, the upstream reach of the mouth bar becomes mixing area of fresh water and salt water. The flow takes circulating motion with the flood and ebb tide. The freshwater flow is stronger than that in upstream flood period and the flow direction is slanted to the west under the influence of the coastal boundary and the sea waves (see Fig.1).

### 2.2 HYDRO-DYNAMIC FEATURES UNDER THE INTER-EFFECT BETWEEN RUNOFF AND WAVES

The mouth bar of the Modaomen outlet is directly influenced by sea waves. The dynamics of waves decrease that of the upstream runoff, especially during the dry season. But the variation of the valid index of the annual discharge is still similar to that of the discharge, implying the Modaomen still belongs to the river flow type. But it is located between the river and the river wave types, showing the waves play an important role at the outlet.

In addition, as the large discharge period (in the summer) and the large wave period (in the winter) are different, the outlet is affected by the upstream runoff and the sea waves alternatively. This makes the evolution of the mouth bar more complex. Due to the injecting flow of the outlet and the feature of the convex shape of the mouth bar, there is an “angle effect” near the mouth bar and the incoming waves radiate and break there (see Fig.3).

## 3. SEDIMENT TRANSPORT AND SEDIEMNTATION

The inner sea area at Modaomen is the settling region of the sediment coming from the West River. The mouth of the Modaomen extends outwards more than 100m annually in recent hundred years. During upstream flood period, the large runoff carries a large amount of sediment to the mouth bar area and disperse outwards. During dry period, the settled sediment near the mouth bar is suspended by the tide flow and waves and is brought to the inner sea area and resettles there. During the period from 1960−1980, more than $100\times10^6$t sediment settles in this area.

After the reclamation engineering in the inner sea, most of the suspended sediment coming from upstream can be transported to the out of the mouth and enter into the fresh-salt-water

mixing region where due to the flocculation effect the sediment settles down quickly. The flocculated sediment could move along the sea bed near the mouth with the current. Part of this sediment is brought to the area near the mouth bar by the deep circulating flow and settles down, and other part joins upper-lays and continue to circulate. The sediment mainly settles in the front of the mouth bar and forms the underwater delta. The some fine sediment and flocculated sediment can be brought to the southern-western area by the transverse coastal flow and become one of the sediment sources of the Jitimen outlet and the Huangmaohai Bay.


**Fig. 3** Waves and their broken phenomenon near the sand-bar at Modaomen

The sedimentation of the mouth bar area at Modaomen has experienced long historic process. This water area had received the sediment from the West River before the mouth extended to present position. According to the geographical profile record, this area experienced the developing stages of the pro-delta, delta front and delta plain. The drilled data at the Denglongshan best shows such historic process. This settling process is currently continuing in the area outside of the present mouth bar.

## 4. RECENT CHANGES OF THE MODAOMEN OUTLET

In order to prevent upstream flood and salt intrusion, control the sedimentation and improve the navigation, a large regulating project was carried out in the Modaomen outlet in 1980s and a regime of “one stem and one branch” was formed by building the guided-dams. This regulation accelerates the extension of the Modaomen outlet.

The regulation project in 1992 extended the Modaomen outlet more than 20km. Since then, the features of multi-mouths, multi-flow courses and multi-confluences of tides have been changed. The freshwater flow becomes stronger while the tidal flow becomes weaker. The velocities in the channel increase. The hydro-dynamic environment of the outlet is changed.

With the regulation and the extension of the outlet, some new phenomena occur. Examples include: New underwater channels are developing at the mouth of the outlet; Some new

shoals occur in the extended channel; The width of the outlet near Hezhoudong is narrowed to around 2100m due to the sedimentation and the reclamation, which has a serious influence on the flood discharge; The mouth bar at the Modaomen outlet is developing. These new changes are analyzed below.

### 4.1 ANALYSIS ON THE WATER LEVEL VARIATION

In recent decades, the water level in the upstream of the Modaomen Channel is increasing. Comparing to the situation before the regulation, the water level in the upstream of the Modaomen Channel has increased by 10−20cm, corresponding to the discharge 20000~25000$m^3$/s at the Makou hydrological station (on the West River). This is mainly coursed by the extension of the outlet, which courses the datum of the erosion increasing and results in the sedimentation in the channel. In historic regulations, when branches were blocked and channels were narrowed the water level changed according to the stages "increasing — decreasing — increasing". Within past 30 years, the width of the Modaomen channel was narrowed by 100m on average but the discharge at the Makou hydrological station increased slightly. Therefore, the changes of the boundaries and the variation of the water flow and the sediment transport have serious influences on the water level. However, with the self-adjustment of the outlet, the water level will stop increasing and may decrease slightly.

### 4.2 ANALYSIS ON THE SHOALS IN MIDDLE OF MODAOMEN CHANNEL

There are many shoals in the Modaomen channel such as the Daao Shoals, the Haixinsha Shoals, the Qinyu Shoals, the Liuquan Shoals, the Zhupai Shoals, the Dapai Shoals, the Shangsha Shoals, the Shazaimian Shoals, and etc. These shoals are formed due to the sedimentation of the channel to adapt the specific water and sediment coming from the upstream. They are results of the self-adjustment of the channel. With the extension of the outlet and the increase of the water level, the sedimentation occurs in the middle of the channel and with the development of sedimentation, the channel changes its ratio of the width to the depth, and hence the "W" shape complex channel bed is formed. However, after the regulation, the lateral expansion is limited. Some shoals are based on underwater rocks and form underwater shoals at the first stage and then during the flood period, a lot of sediment comes from the upstream and settle down there enlarging those shoals.

### 4.3 ANALYSIS ON THE DEVELOPMENT OF THE MOUTH BAR AT THE OUTLET

Since 1970s, a large scale of reclamation in the Modaomen inner sea area has been carried out. The water and sediment amount discharging from the Hengzhou channel has increased. The mouth bar moves forward fast. With the disappearance of the Modaomen inner sea area, the runoff becomes stronger and discharges into the sea in the form of buoyancy plume. The water flow stagnant point and the sediment stagnant point are located at the same place, accelerating the sedimentation there. Due to the long term sedimentation, settled sediment has formed a huge mouth bar at the Hengzhou mouth of Modaomen outlet.

There are some underwater channels or sub-channels in the mouth bar area. The underwater channels are formed due to the erosion to the mouth bar during the flood period. And the sub-channels are formed due to the lateral erosion to the weaker sides of the mouth bar during the flood period. During the dry season, the sediment is carried to the eastern side of the mouth by the lateral waves and the transverse flow along the coast and forms a shoal there. The eroded sediment is brought by the flow to the eastern side of the mouth bar and then is transported to the western side of the mouth bar and settles there. This special geography and the special way of the sediment movement show that the Modaomen outlet is now at the transient stage from the river-type estuary to the river-wave type estuary.

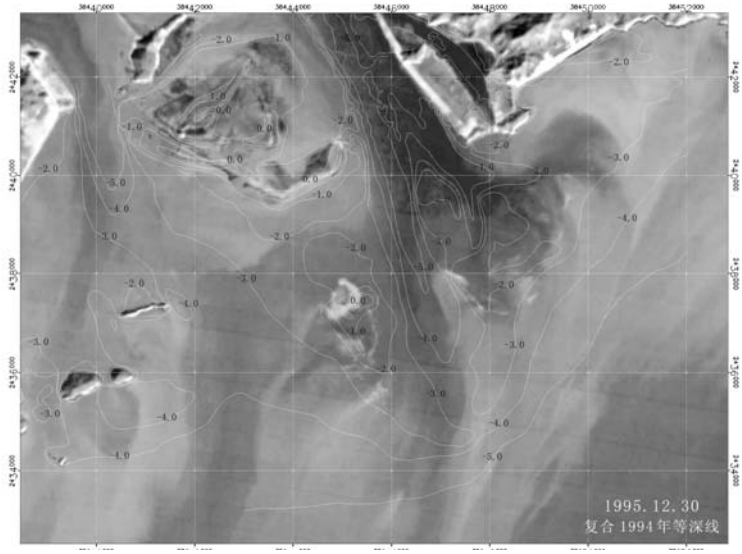


**Fig. 4** Comparasion between measured contour-depths and remote-sensing image near sand-bar at Modaomen

It can be seen from the recent remote sense image (Fig.4) that the center of the mouth bar is appearing above the water and on both sides of the sand two sub-channels are formed in the south-west and south-east directions, respectively. During flood periods, these two sub-channels will be further eroded. Since the development of the mouth bar has deep influence on the development of the Modaomen outlet, it is worthy of studying the regulating measures.

## 5. CONCLUDING REMARKS

This paper analyzes the futures of hydrodynamics between freshwater flow, the tidal flow and the sea wave current at the Modaomen outlet of the Pearl River estuary. And then the changes of boundary lines of the outlet, the variations of the flow pattern, the sediment transport and the evolution of the Modaomen outlet during past 20 years are analyzed based on the remote sensing information and field hydrological and geographical data. The analysis indicates that the changes of the boundaries and the variation of the water flow and the sediment transport in the Modaomen outlet area have a serious influence on the water level. After the regulating project, in the extended channel grass-shoals are growing and with the extension of the Modaomen outlet, a large mouth bar has been formed at the mouth of the Modaomen outlet and has been growing nearly above the water surface. On both sides of the mouth bar two underwater channels or sub-channels are developing. Since the development of the mouth bar has deep influence on the development of the Modaomen outlet, it is worthy of studying the regulating measures.

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