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SHORELINE CHANGES OF THE YELLOW RIVER DELTA AND ITS SUB-DELTA AREA FORECAST

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Abstract: Comparisons were made among comprehensive shoreline changes during the high-tidal periods of the Yellow River Delta in 1855, 1954, 1976 and1992. The results show that the shoreline moves towards the sea in the river-flowing period, and retreats in the non-flowing period because of the wind, wave, tidal current and the deflection force of the Earth. The dynamic process of the sub-delta along the Qingshuigou Course was also analyzed by using the isobath of –2m. From the analysis it is found that the sub-delta is progratading towards the southeast but the land-forming rate is becoming slower than before, indicating a tendency that the river mouth is developing from the original increasing to the terminal atrophy. A mathematical model is presented for calculating the changes in volume of sediment discharge and the sub-delta landing area. It shows the two variables are closely related with each other, and the sediment discharge is the key parameter governing the evolution of the sub-delta. According to the water-sediment quantity an analytical model is used to forecast the area growth of the sub-delta in the future.

Key words: The Yellow River Delta, Sub-delta, Shoreline changes, Area forecast

1. INTRODUCTION

The Yellow River, China's second largest river, originates in the northern part of the Bayankala mountains and the Northeast of the Tibetan Plateau, is 5,464 km long, and drains a total area of 752,443 km^2. The river traverses the Inner Mongolian Plateau, the Loess Plateau, and the North China Plain and finally discharges into the Bohai Sea. The Yellow River, which is characterized by a high concentration of suspended sediment of about 25kg/m^3 on average and more than 200 kg/m^3 in flood stage at Lijin station, about 100 km from the river mouth, supplies a huge sediment load to the Bohai Gulf through the North China Plain forming a macro-delta toward to the Bohai Sea coast.

Due to the serious on-going aggradation, the lowland reach is highly unstable, and the lateral course has diverged and migrated dramatically more than 10 times (Fig 1) since 1855, and consequently, a large delta consisting of at least ten sub-deltas or lobes has developed along the coast (Pang Jiazhen, 1979). For the past 137 years, nearly 2500km^2 of land area is formed till 1992. The last lateral course shift diverged artificially in 1976 caused an increment of land and formed a big river mouth sandy body like an elongated bird's foot pattern (Guo Yongsheng, 1980)).

As we know, a river delta is an important part of "channel-estuary-delta" system and its evolution is dominated by many factors. The Yellow River with its huge sediment discharge has being formed a macro delta. Since the estuary of the Yellow River is within a weak tidal area, the tidal flux is smaller than the runoff flowing into ocean with the proportion of 1: 5.40 (Qian Ning, 1981). At the same time, the Effective Index of water discharge, which means the delta-reforming ability of the water discharge visas to that of the wave dynamics, is larger than other Chinese estuaries. So the flow of Yellow River and its carrying sediments discharged into the ocean play an important role to the evolution of the delta.

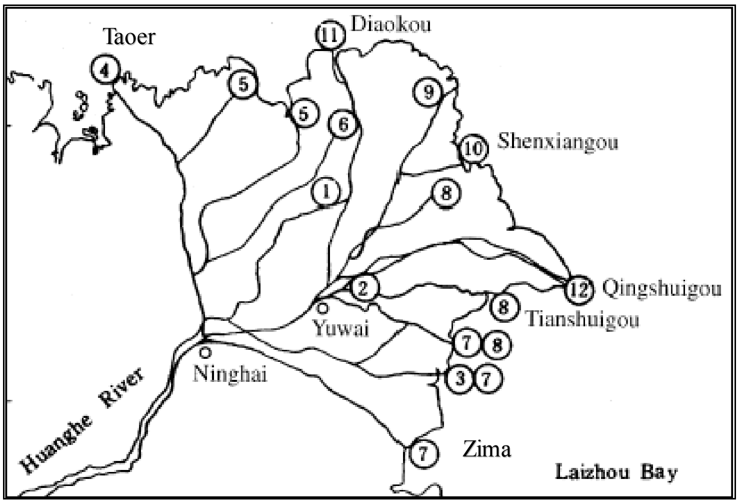

Fig. 1 Index map of the Yellow River Delta (①-Course No.)

Pang Jiazhen (1979) first studied the evolution of the Yellow River estuary. Guo Yongsheng (1980) reviewed and studied the historical migration along the delta coast. From then on, many scientists did a lot of research work from the angle of the channel shift in the river and the sediment transports in the ocean but rare from the macro-process and the progradation trend of the sub-delta (Guo Yongsheng, 1992).

However, the purpose of this paper is to show the general status of shoreline changes in the Yellow River Delta, and then calculate the deposit amount of the sub-delta and forecast its developing trend in the future. It must be mentioned that the macro river delta is formed after the year of 1855, and the sub-delta, which is also called lateral river delta lobe is formed in the Qingshuigou Course since 1976.

2. METHOD

Shoreline position of the Yellow River delta can be circled by many methods including the satellite imagery, history chart, topographic map and field survey. So the shoreline can be remarked by the high tidal line, theoretical high tidal line, 0m contour and -2m counter.

Shoreline changes of the macro delta are analyzed by using the high tidal line obtained from the historic survey and the maps in this paper. The high tidal mark of the river delta in 1855 was roughly determined by the position of the former fishing forts in history learned though the field investigation. The shoreline in 1954 comes from the high tidal mark on the topographic map with the proportion of 1:50000 measured by the Survey Bureau of General Staffer Department of CPLA. The Shorelines in 1976 and 1992 come from the isobathic map with the proportion of 1:100000 measured by the Shandong Bureau of Hydrology and Water Resources, Yellow River Water Conservation Commission.

However, the -2m counters gained by measured data were used to analyze the dynamic process of the sub-delta. The scientific software of Graph and Suffer 7.0 were used to calculate thousands of measured data in October of 1976, 1982, 1987, 1990 and 1995. Based on the statistic data, the Analytical Model was used to forecast the evolution trend of sub-delta.

3. SHORELINE CHANGES

Shoreline changes of the Yellow River Delta result from two factors, of which one is the shifting of the lateral river course and the other is sediment transportation. The former causes the abrupt changes of shoreline, showing that delta protrudes in the period of on-flowing course and delta eroded toward to the land in the period of off-flowing course or an abandoned course. The later causes slow changes of shoreline, showing that certain part of shoreline gradually protrudes and eroded.

The Yellow River discharges into Bohai Sea after depriving the course of Daqinghe River since 1855. From then, the Yellow River has bursted and changed its lateral course owing to the natural and artificial factors for more than 50 times, in which the bigger shifts are about 10 times. This below is to analyze the whole changes of shoreline based on the contrasts of the high tidal marks in 1855, 1954 and 1976 (Fig.2).

The river delta with the whole shoreline length of 128km in 1855 started from the Taoer River mouth to the Nanwang River mouth. The maps measured in 1954, 1976 and 1992 were more accurate. Contrasted with the four high tidal marks, it is found that the shoreline was rapidly protruded toward to the sea in some coastal areas, which the river passed by. It is also found that the shoreline was retreated by the attack of waves, currents, wind and other dynamic factors in some other coastal areas, which there is no river passing by. The protrusion and erosion of the delta shoreline are shown in Fig.2 and Table 1.

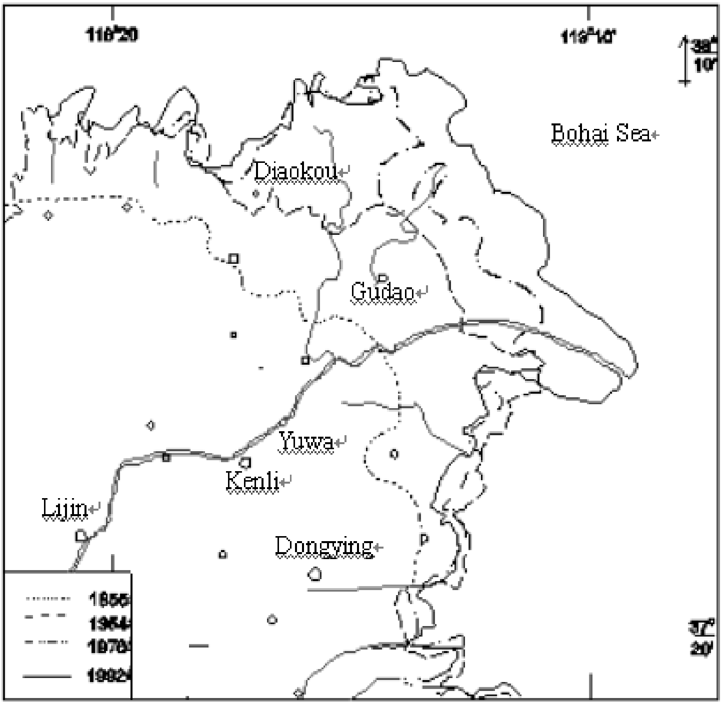

Fig. 2 Shoreline changes of the Yellow River Delta (High-tidal line)

Table 1 Protrusion and erosion area of the Yellow River Delta (high-tidal line)

Period	Protrusion area (km^2)	Erosion area (km^2)	Net landing area (km^2)	On-flowing time (a)	Landing rate (km^2/a)
1855-1954	1510	/	1510	64	23.6
1954-1976	650.7	-102.4	548.3	22	24.9
1976-1992	499.9	-120.6	364.4	16	22.8
1855-1976	2160.7	/	2058.3	86	23.9
1855-1992	2660.6	/	2422.7	102	23.8

It can be seen from the Fig.2 and the Table 1 that the shoreline protruded with an increasing area of about 2160.7km^2 and retreated with 102.4 km^2 during the period of 1855−1976. The net progradating area is 2058.3 km^2 with the rate of 23.9Km^2/a. From 1976 to 1992, the net landing area is about 364.4 km^2 with the rate of 22.8km^2/a. On the other hand, it can also be seen from the plain changes that the south area of the delta is dominant with protrusion bounded by the Shenxiangou Course. The coastal area from the west of the Shenxiangou mouth to the Western-Pole Oil Field maintains relatively steady, whereas from the Western-Pole Oil Field to Diaokouhe mouth and to Wanwangou mouth belongs to the erosion coast.

4. SEDIMENTATION OF THE SUB-DELTA

Detailed analysis is given on the shoreline changes and the silting topography of the shallow marine area in order to appeal the whole process of the evolution of the sub-delta in the Qingshuigou Course. The data is surveyed as a matter of fact and –2m-isobathic contour represents the shoreline.

4.1 CHANGES OF –2M ISOBATH AND LAND REBUILDING

The changes of –2m-isobathic contours in 1976, 1982, 1990 and 1995 are respectively calculated and mapped based on Beijing coordinate system. The included area is 60km*60km. The section ranges in shallow marine areas (from cs18 section to cs31 section) are shown in Fig3.

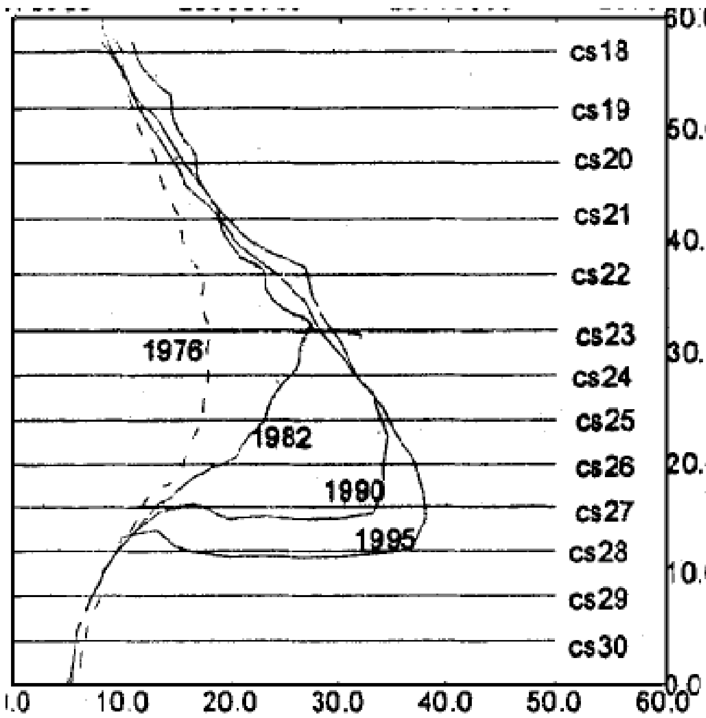

Fig. 3 Shoreline changes in Qingshuigou Course (-2m)

It can be found that the sub-delta is gradually shifting to the southeast when it prorogates seaward. The main axes of prorogation is gradually shifting to the southward, which is affected by waves, tidal currents and deflection force caused by the earth's rotation in a long time. The landing areas of –2m-isobathic contour in the calculated area is listed in Table 2.

As it can be seen in Fig. 3 and Table 2, the rates of landing area in the Qingshuigou Course is fast since October 1976 and then gradually slow, which indicates a tail channel experiencing its evolution from the primary period to the withering period. This also reflects that the ocean dynamics have the trend of strengthening with the sub-delta prorogating from the near shore to the sea and indicating a tendency that the river mouth is developing from the original increasing to the terminal atrophy.

Table 2 Sediment discharge and the landing area in the Yellow River estuary

Period	Time interval (a)	Sediment discharge (Million ton)	Increasing area of –2m isobath (km^2)	Area landing rate ($km^2/10^8$ ton)	Area landing rate (km^2/a)
1976.10—1982.7	5.8	4370	205.0	4.7	35.3
1982.8—1990.9	8.2	5280	201.5	3.8	24.57
1990.10—1995.10	5.0	2480	81.0	3.3	16.2
1976.10—1995.10	19.0	12,130	487.5	4.0	25.66

4.2 VERTICAL TOPOGRAPHY OF SECTIONS

The sediment transported to the sea from the river, which is controlled by the land-ocean interaction, causes the evolution of the river delta. The factors result in the delta changes includes the river sand transport rate, wave condition, tidal current, seabed topography and the deflection force caused by the earth's rotation. The silting process from the shallow water to the deep water is reflected though the detected sections (Fig.4).

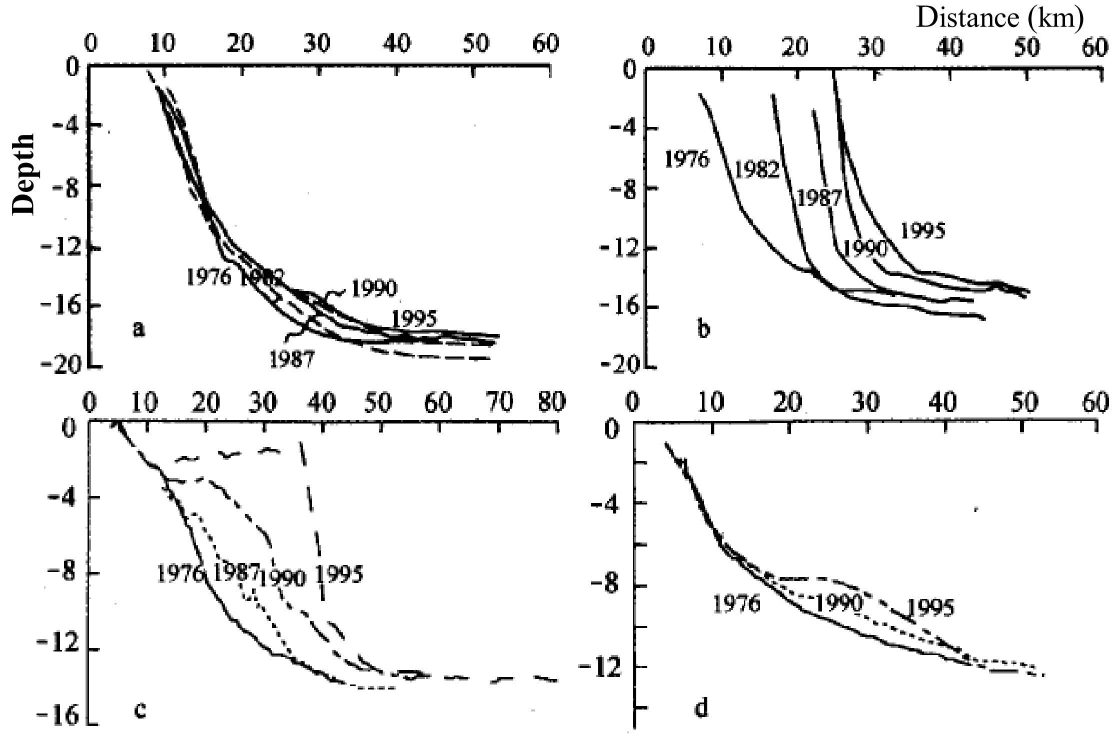

Fig. 4 Aggraded topography of the sections
(a--section 18, b-- section 25, c-- section 28, d-- section 31)

It can be seen from Fig.4 that little changes has occurred in the north area of the section 18 and the south area of section 31since 1976. It shows that the silting scope is located in the area between the section 18 and section 31, where the silting dimension and the shape varied from each section. The fundamental cause of the silting topography is attributed to the suspended sediment diffusion and the sand transport at the different site of the river mouth. Thus, the silting process always centers on the sand spits of the river mouth and gradually expanding to each side.

4.3 SPATIAL TOPOGRAPHY OF SILTING

Regarding 1976 as a base year, the silting volume of the sub-delta was calculated in Simpson method by the year of 1982, 1987, 1990 and 1995. The isoline of silting thickness in the estuary is given in Fig.5.

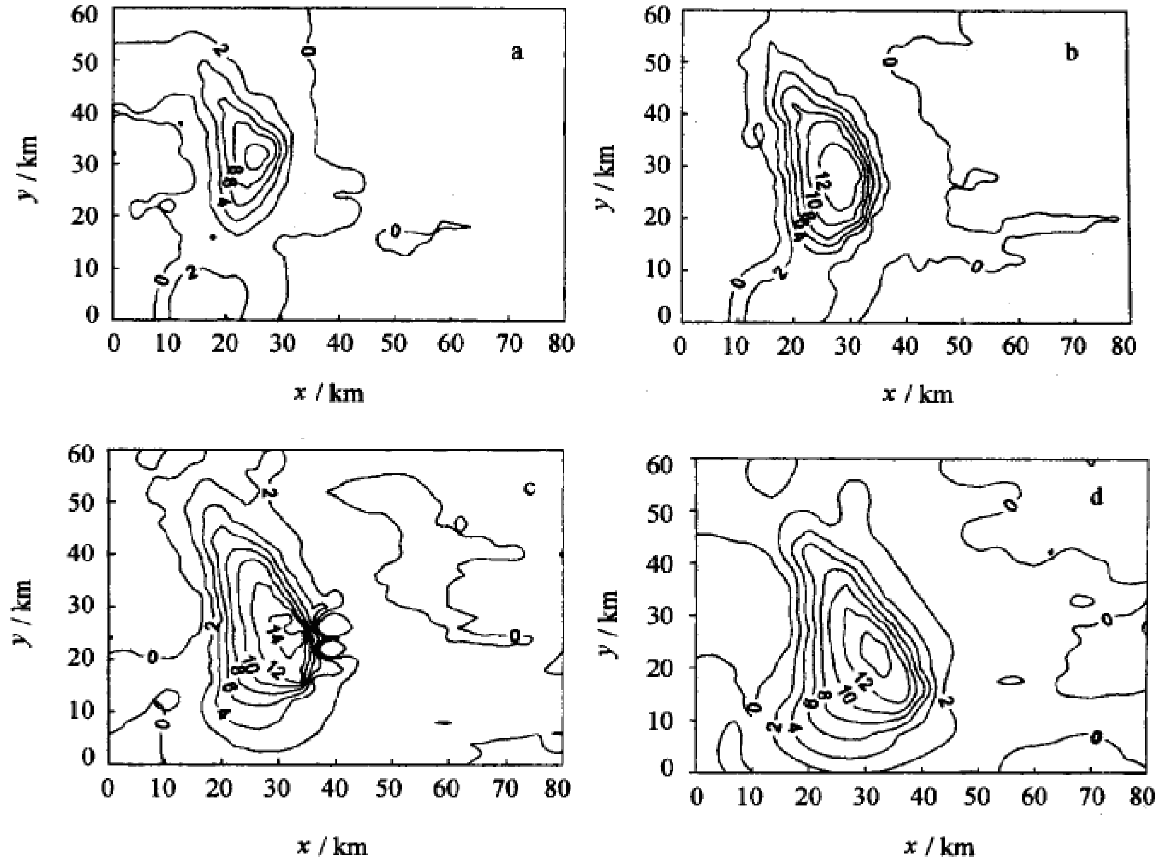

Fig. 5 The isoline of silting thickness in the Yellow River estuary
(a. 1976-1982, b. 1976-1987, c. 1976-1990, d. 1976-1995)

The silting topography shows straightly extending to the seaward in the period of 1976-1982. The volume of sediments in the research area is about 2970 million ton. The area surrounded by the -2m-thickness isoline is small, where the length from the north to the south is about 35km and the width of 15km from the west to the east. The silting center is located in the east side of the river mouth with the biggest thickness of about 10m.

In the year of 1987 and 1990, the silting area was expanding and increasing rapidly with the biggest thickness of above 12m and 14m respectively and the silting form became an irregular ellipse. By the end of 1995, the volume of sediments in the research area is about 7180 million ton. The area surrounded by the -2m-thickness isoline became larger, where the length from the north to the south is about 50km and the width of 25km from the west to the east. The silting center turned to the right (south) side with the biggest thickness of about 15m. It can be seen from Fig.4 that the -2m-thickness isoline became dense from the silting center to the east, and became gradually sparse to the southwest and to the northwest. This indicated the basic trend of sediment transport in the estuary.

The above silting property is relative to the hydrodynamic condition of land-ocean interaction. At the beginning of the course formation, the river discharged into the sea freely and the suspended sediment diffused and deposited in the wide estuary. As a result, the river-mouth sand spit did not jutted out from the shore to the sea obviously and the –2m isoline expanded smoothly (1976). Along with the continuous silting, the lateral channel of the river is bound by the nature landform and the riverbank, the sand only silted near the river mouth. The sand spit jutted sharply to the sea and the depth isoline is curved (1982). Thereafter, the sand-spit jutted and turned to the right affected by the northern orientate wave dynamic and the Earth's deflection force (1987, 1990). By the end of 1995, the water deepened at the front edge of the spit and the ocean dynamic increased, so the spit increased slowly with long and narrow topography indicating a tendency that the river mouth is developing from the original increasing to the terminal atrophy. The spatial distribute of sediments indicates the macro-behavior of the Yellow river delta evolution, which complies with the basic rule of sand transport effected by the factors of river dynamic, tidal current, wave condition and other factors.

5. ANALYTICAL MODEL AND FORECAST

The flow and the sediment discharge mostly dominate the increasing area of sub-delta. So a quantity analysis was made on the relation between the increasing area of the river delta and the sediment discharge into the estuary. It is found that the landing area surrounded by the –2m isoline is tightly related to the sediment discharge after a lot of simulating tests (Table 3). The relative coefficient between the periodical sediments and the landing area is about 0.66, however, of which between the accumulate sediments and total landing area is 0.968. In order to come up with the analytical model describing the macroevolution rule of the river delta, a basic formula is presented in equation (1).

Table 3 The landing area of the sub-delta and the sediments discharge in Lijin Station

Period	Area (km^2)	Sediment (10^8t)	Accumulate area (km^2)	Accumulate sediment (10^8t)
1976.10-1977.9	15	10.5	15	10.5
1977.10-1979.9	116.2	16.7	131.2	27.2
1979.10-1980.8	-3.06	2.69	128.14	29.89
1980.9-1981.7	30.21	3.9	158.35	33.79
1981.8-1982.7	48.5	9.93	206.85	43.72
1982.8-1983.8	20.65	8.6	227.5	52.32
1983.9-1984.5	81.75	6.61	309.25	58.93
1984.6-1985.6	54.35	14.0	363.6	72.93
1985.7-1990.9	42.82	23.62	406.42	96.55
1990.10-1995.10	81.08	24.75	487.42	121.3

$$Q = \sum_{i=1}^{n} [y_i - \hat{y}(x_i)]^2 \quad (1)$$

Where, $\boldsymbol{Q}$—Sum of Square Data Deviation (DEVSQ)

y_i—increasing area (km^2)

x_i—accumulate volume of sediments (10^8t)

y—analog value of increasing area (km^2)

The equation (1) will be the best if the simulated value $\boldsymbol{Q}$ is access to zero. The approximate value of $\boldsymbol{a_j}$ in $\boldsymbol{y(x)}$ can be acquired though the method of minimized two-multiplication by making the equation (1) minimized. So the equation (1) becomes another function given below.

$$\frac{\partial Q}{\partial a_j} = \frac{\partial}{\partial a_j}\{\sum_{i=1}^{n} [y_i - \hat{y}(x_i)]^2 \quad (2)$$

The simulating curve is drawn in Fig.6.

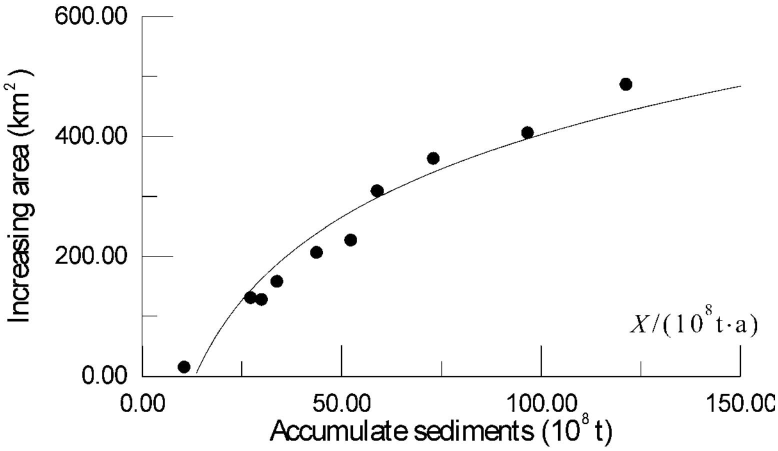

Fig. 6 Relation of sub-delta area and sediments

The analog function is given in equation (3).

$$Y=199.56\lg(x)-515.803 \quad (3)$$

Where the parameters are,

Average lg(X) = 3.80416

Average Y = 243.373

Regression sum of squares = 179862

Residual sum of squares = 11906.2

Coef of determination, R-squared = 0.937913

Residual mean square, sigma-hat-sq'd = 1488.28

It can be seen from the Fig.6 that the landing area will initially increase rapidly when the accumulate sediments is larger than 13×10^8 ton. But the increasing rate of sub-delta will be slow along with the rise of sediment discharge, which indicates the ocean influence strengthening gradually. This simulating result is in accordance with the process of area landing described before.

Now the landing area can be predicted. For example, if we want to forecast the increasing area of sub-delta in 2010, we should know the amount of sediments discharged into the sea in the future. The first step is to calculate the current flow and sand discharge into the sea. The annual average amount of sediment discharged into the sea in Lijin Station is about 5.8×10^8 ton/a in the period of 1981−1995. By the relative research result, the amount of water diverting from the Yellow River is increasing to 5 billion cubic meters per year by 2010, of which the sand loss is about 0.49×10^8 ton. In the other side, there is another kind of sand loss, which is about 1.0×10^8 ton because of the water and soil conservation in the whole Yellow River basin. Thus the annual average sediment discharged into the sea is about 4.31×10^8 ton and the total sediment is 64.65×10^8 ton in the future.

There are two conditions should be considered. One is that the Yellow River continuously flows in the present lateral channel and the process of the area landing will be slowly. So the predicted landing area of the sub-delta will rise up to 527.0km^2 with the increasing area of 39.6km^2 and landing rate of about 2.6km^2/a in the period of 1996−2010 based on the former analytical model. The low rate indicates a tendency that the river mouth is developing from the original increasing to the terminal atrophy. The other situation is the river shifts its lateral channel and the process of the area landing will be rapidly. The predicted landing area will be 316.2km^2 with the high increasing rate of about 21.1km^2/a respectively.

6. DISCUSSIONS

Since a natural course shifted in 1855, the Yellow River has being emptied into the Bohai Sea and formed a huge cuspate delta along the coast. Evolution of the Yellow River Delta is governed by land-ocean interactions but key dominated by the high concentration of sediments. The present delta lobe has been undergoing the primary fast developing stage to the terminal atrophy stage. According to the determined sediment discharge, an analytical model was introduced in this paper for describing the changes of the sub-delta along with the variety of sediments. In this regard, the model can forecast the developing trend of the Yellow River Delta lobe and may serve as the planning and design work for the whole delta region.

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