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NUMERICAL SIMULATION ON THE EFFECTS OF PUMPING SEA WATER TO SCOUR THE LOWER REACH ON THE YELLOW RIVER MOUTH

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Abstract: In order to mitigate the sedimentation of the lower reach and to stop the outward extension of the river mouth of the Yellow River, a new way has been proposed, that is, pumping sea water to a reservoir near Lijin, and using it to scour the lower reach. The velocity distribution and sedimentation as well as density flow of the Yellow River Mouth have been calculated by a two-dimensional mathematical model. The results show that the new way is effective in increasing flow kinematic energy, developing density flow, and relieving sedimentation of the Yellow River Mouth.

Key words: Pumping seawater, Two-dimensional model, Mitigating the sedimentation, The Yellow River Mouth

1. INTRODUCTION

Because the Yellow River is short of water and contains high sediment concentration, the lower reach of the Yellow River has kept aggradation for a long period, and has formed a well-known suspended river, and this has caused serious problem to flood control. Based on previous experiences, a new regulation way has been proposed recently. That is, pumping sea water from Bohai Bay to a reservoir near Lijin firstly, then pouring a large discharge at Xihekou(or Lijin) into the Yellow River to scour the sink of channel cooperating with the operation of Xiaolandi Reservoir. The aim is to make the downstream channel of the pouring point generating streamwise scouring, and the upstream channel of the pouring point generating head erosion, thus to mitigate the aggradation of the lower reach of the Yellow River. Here a two-dimensional non-equilibrium sediment mathematical model is used to simulate the effect of the new regulation way on the evolution in the river mouth.

2. MATHEMATICAL MODEL

2.1 GOVERNING EQUATIONS

To-dimensional Equations of flow continuity and momentum are

$$\frac{\partial Z}{\partial t}+\frac{\partial}{\partial x}[(Z-Z_0)U]+\frac{\partial}{\partial y}[(Z-Z_0)V]=0 \quad (1)$$

$$\frac{\partial U}{\partial t}+U\frac{\partial U}{\partial x}+V\frac{\partial U}{\partial y}+g\frac{\partial Z}{\partial x}+\frac{U(U^2+V^2)^{1/2}}{C^2(Z-Z_0)}=0 \quad (2)$$

$$\frac{\partial V}{\partial t}+U\frac{\partial V}{\partial x}+V\frac{\partial V}{\partial y}+g\frac{\partial Z}{\partial y}+g\frac{V(U^2+V^2)^{1/2}}{C^2(Z-Z_0)}=0 \quad (3)$$

Non-equilibrium sediment transport equation is

$$\frac{\partial[(Z-Z_0)S]}{\partial t}+\frac{\partial[(Z-Z_0)US]}{\partial x}+\frac{\partial[(Z-Z_0)VS]}{\partial y}=\alpha\omega(S_*-S) \quad (4)$$

Bed deformation equation is

$$\gamma_0 \frac{\partial \eta}{\partial t} = \alpha\omega(S - S_*) \tag{5}$$

Sediment carrying capacity equation is

$$S_* = K\left(\frac{U^3}{gh\omega}\right)^m \tag{6}$$

Where Z is water level, Z_0 is bed elevation; U and V are flow velocities along x and y direction, respectively; g is gravity acceleration， C is Chezy resistance coefficients， $C = 1/n(Z - Z_0)^{1/6}$, n is Manning resistance coefficients， S and S_* are the mean sediment concentration and sediment carrying capacity in vertical, respectively, K and m are coefficients， ω is settling velocity of sediment particles， η is thickness of scour and silting.

Vertical-integrated two-dimensional density flow equations are

$$\frac{\partial h}{\partial t} + \frac{\partial uh}{\partial x} + \frac{\partial vh}{\partial y} = 0 \tag{7}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{(\rho_s - \rho_w)g}{r_s \rho_f}\frac{\partial sh}{\partial x} - \frac{\rho_w g}{\rho_f}\frac{\partial \zeta}{\partial x} + \frac{(\rho_s - \rho_w)gs}{\gamma_s \rho_f}\sin\theta_x - \frac{\tau_x}{\rho_f h} + fv \tag{8}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -\frac{(\rho_s - \rho_w)g}{r_s \rho_f}\frac{\partial sh}{\partial y} - \frac{\rho_w g}{\rho_f}\frac{\partial \zeta}{\partial y} + \frac{(\rho_s - \rho_w)gs}{r_s \rho_f}\sin\theta_y - \frac{\tau_y}{\rho_f h} - fu \tag{9}$$

$$\frac{\partial sh}{\partial t} + \frac{\partial suh}{\partial x} + \frac{\partial svh}{\partial y} = \alpha\omega(E_s - s) \tag{10}$$

$$\gamma_0 \frac{\partial \eta}{\partial t} = \alpha w(s - \mathrm{E}s) \tag{11}$$

Where θ_x, θ_y are slopes along x and y direction respectively， τ_x, τ_y are shear frictions along x , y directions respectively， t is time， h is thickness of density flow， ζ is tide level， ρ_s ， ρ_w and ρ_f are sediment densities, clear water density and fluid density， respectively, γ_s is specific weight of sediment particles， γ_0 is dry density of sediment particles, E_s is saturation concentration of sediment, α is saturation coefficient, f is Coriolis parameter, shear friction stress τ_x and τ_y are resultant friction stresses of boundary surface of density flow, and E_s for the Yellow River Mouth is expressed as $E_s = 9.83(V^2/h)^{0.23}$, V is resultant velocity of density flow.

2.2 VERIFICATION OF THE MATHEMATICAL MODEL

In the research, tidal characteristics and topographical change were verified. The main representative component tide used in the model is principle lunar semi-diurnal constituent. Table 1 shows the differences of calculated and measured amplitude of tide and tide phase at nine alongshore-tidal stations. Both calculated tidal amplitude and phase are in good agreement with the measurement.

Table 1 Difference of calculated and measured data

Station	Yantouwa	Taipingjiao	Yinkou	Huludao	Juhuadao	Qinhuangdao	Tanggu	Longkou	Changxin-gdao
Amplitude(m)	0.06	-0.03	-0.09	0.02	-0.02	-0.08	0.01	0.00	-0.02
Phase(rad)	0.07	0.33	-0.05	0.05	0.16	1.29	-0.087	0.03	0.17

3. SEDIMENT TRANSPORT AT THE RIVER MOUTH

3.1 SEDIMENT TRANSPORT IN THE RIVER MOUTH IN DIFFERENT HYDROLOGIC CONDITIONS AND DIFFERENT PUMPING PLANS

Pumping sea water to scour the lower channel may increase sediment in the Yellow River Mouth. The effect of pumping seawater is closely relative to the route of sediment to the sea and the shape of sediment deposition. Pouring seawater at Xihekou will change the hydrologic condition in the section Qing 7, which will be different from natural condition. In order to study the influence of the change of hydrologic condition on the development of the Delta, several typical cases had been studied. Table 2 shows the results. Duration of calculation is ten tide cycles.

3.1.1 Distribution of sediment concentration

In the research, the sediment concentration distribution corresponds with the pattern of velocity field. The sediment concentration at entry position is the largest, and as sediments propagate, sediment concentration decreases.

3.1.2 Distribution of sedimentation

Sediment transport capacity decreases greatly from the river mouth to the sea with the channel becoming wider and deeper and the existence of the opposite tidal flow. Consequently, the sediment deposits quickly. Deposition rate decreases as the distance increases seaward. Under the joint action of runoff and tide flow, sediment propagates to the open sea along runoff, and at the same time, it propagates to the two sides of the river mouth along ebb tide.

3.1.3 Comparison of accumulation and propagation of sediment in typical pumping plans

From the distribution of sediment concentration and sedimentation, we can see that whether in natural condition or pumping seawater, deposition is the main tendency in the river mouth. What we should concern is that how to change the shape of sedimentation and transport the most part of sediment to the far sea to reduce the extension of the river mouth. In order to find out the optimal regulation plans, several typical cases had been studied in the research. Table 2 shows the sedimentation in natural condition, and pumping discharge of 1000m^3/s of seawater, and pumping discharge of 1500m^3/s of sea water. The rate of sediment transport is used to describe the capacity of sediment transport, which is the proportionality of sediment transported to the far sea to the total sediment.

Table 2 Accumulation and transport of sediment in the Yellow River Mouth

Series	Ipumping Discharge (m^3/s)	Discharge (m^3/s)	Sediment Con. (kg/m^3)	Total Water (10^{8}m^3)	Total Sediment (10^{8}m^3)	Sediment Accumulation (10^{8}m^3)	Sediment Transport Rate (%)	Accumulation Area (km^2)
1	0	199.4	2.82	0.86	0.002	-0.153	>100	50.0
	1000 m^3/s	1191	11.36	5.15	0.045	0.034	28.3	93.8
	1500 m^3/s	1708	13.77	7.38	0.078	0.039	24.5	112.5
2	0	1000.8	12.14	4.32	0.040	0.031	22.9	81.3
	1000 m^3/s	1899.3	11.31	8.21	0.071	0.016	77.8	56.3
	1500 m^3/s	2386.2	10.98	10.31	0.087	0.009	90.0	56.3
3	0	1496.4	18.87	6.46	0.094	0.063	33.1	143.8
	1000 m^3/s	2364.7	19.84	10.22	0.156	0.053	66.1	143.8
	1500 m^3/s	2820.1	20.31	12.18	0.190	0.038	80.2	131.3
4	0	2740.7	30.55	11.84	0.278	0.126	54.7	256.3
	1000 m^3/s	2809.3	30.84	12.14	0.288	0.127	56.0	250.0
	1500 m^3/s	2974.9	31.73	12.85	0.314	0.129	58.8	256.3

Pouring sea water at Xihekou arouses scouring downstream, and this will increase the sediment in the river mouth, and also increase sediment accumulation outside the river mouth, and sediment transport rate increases. As the pumping discharge increases, the sediment transport rate increases.

3.2 DENSITY FLOW IN THE RIVER MOUTH

3.2.1 The effect of density flow on transporting sediment

In order to show the effect of density flow on transporting sediment, several typical cases had been studied. Table 3 shows that sediment transport rate of density flow is higher than that of non-density flow, and the bigger the sediment concentration is, the bigger the difference between density flow and non-density flow is. Because density flow maintains higher sediment capacity, it can carry more sediment to the sea and reduce the accumulation in the Yellow River Mouth. Thus, density flow is effective on transporting sediment. However, the formation of density flow needs some conditions.

Table 3 Comparison of Sediment Transport of Density Flow and Non-Density Flow

Item / Type	Series	Discharge (m^3/s)	Sediment Con. (kg/m^3)	Total water (10^8m^3)	Total Sediment (10^8m^3)	Sediment Transport Rate of Non-Density flow（%）	Sediment Transport Rate of Density Flow（%）
Fresh water	1	2000	80	8.64	0.53	18.9	41.5
	2	2000	60	8.64	0.40	22.4	43.5
	3	2000	40	8.64	0.27	37.3	46.1
Salt water	4	2000	30	8.64	0.20	41.7	47.2

3.2.2 Immersion depth of density flow in the Yellow River Mouth

Based on Prof. Fan's study, when the density flow occurs, the critical Froudes at immersion point is

$$F_{r_0}^2 = \frac{u_0^2}{\eta_g g h_0} = 0.60 \quad (12)$$

where u_0, h_0 is velocity and water depth at immersion point, respectively, η_g is correct gravity, $\eta_g = \frac{\rho_f - \rho_w}{\rho_f}$, ρ_f is flow density of sediment-water mixture, ρ_w is salt water density。

Table 4 shows the critical immersion depth in the different discharge and sediment concentration conditions. It can be seen that when discharge and sediment concentration are the same, the immersion depth of density flow in salt water is smaller than that in fresh water. The larger the discharge is, the larger the immersion depth is, as contrast, the larger the sediment concentration is, the smaller the immersion depth is. Thus, pumping seawater to scour the river channel will increase salinity and sediment concentration, which will cause density flow easily.

3.2.3 The formation condition of density flow in the Yellow River

The formation and transport mechanism of density flow in the Yellow River Mouth is much more complicated than that of reservoir and there is few measured data. So we just try to have a brief understanding of density flow in the river mouth from limited measured data and background in studying the sediment transport mechanisms in reservoirs. As usual, the formation of density flow needs following conditions: Endurance flow dynamic force, that is, a certain amount of discharge and bed slope; Density difference, that is, a certain amount of flow sediment concentration; and Suspended grain size.

Table 4 Critidal Immersion Depth of Density Flow at Different Discharges

Items	Qing 7		Sea outfall			Immersion Depth (m)
	Discharge (m^3/s)	Sediment Con. (kg/m^3)	Average Sediment Con. (kg/m^3)	Average Velocity (m/s)	Average Density (t/m^3)	
Fresh water	2000	60	27.8	0.35	1.017	3.40
	2000	80	39.6	0.39	1.025	2.98
	3000	80	49.6	0.54	1.031	3.48
Salt water	2000	40	19.4	0.40	1.027	2.49
	2000	20	11.5	0.32	1.022	2.78
	2000	10	8.0	0.29	1.020	3.00
	3000	20	14.9	0.42	1.024	3.30
	3000	80	49.6	0.54	1.046	1.67
	3000	5	7.5	0.32	1.020	4.00

According to reservoir measurement, the minimum necessary sediment concentration is about 10−15 kg/m^3, and the grain size is less than 0.02mm in the density flow. In the Yellow River Mouth, it is necessary that the mixture flow density should be larger than that of salt water, to generate the density flow. Density of seawater depends on temperature, salinity and sediment concentration, etc. Table 5 shows the comparison of the density of mixture flow and salt water.

Table 5 Comparison of density of flow from Yellow River and salt water（20℃）

Sea Water		Mixture Flow with Same Density
Salinity(‰)	Density(kg/m^3)	Sediment Concentration (kg/m^3)
20	1013.4	21.5
25	1017.2	27.6
30	1021.0	33.7

When pumping seawater, the flow will compose of both fresh water and salt water. Taking sea water density as 1,020kg/m^3, for generating density flow, the minimum sediment concentration for fresh water is 32 kg/m^3, and the one for salt water is about 15kg/m^3, and the one for mixed water will be between 15−32kg/m^3.

3.3 ACCUMULATION OF THE YELLOW RIVER DELTA FOR PUMPING SEA WATER IN TYPICAL YEARS

Two typical years from a ten-year sequence after construction of Xiaolandi Rservoir, including a low flow rate and low sediment hydrologic year and a medium flow rate and high sediment hydrologic year were chosen to predict the sediment accumulation in the Yellow River. Three plans with different pumping discharge were calculated to study the effect of the intensity of pumping discharge on sediment accumulation in the Yellow River Mouth. The first plan does not consider the seawater pumping, that is the plan in the natural condition, and the other two plans consider the different pumping seawater discharge of 1,000m^3/s and of 1500m^3/s, respectively. Fig.1 shows the scour and silting pattern in the medium flow and high sediment year. The calculated results are shown in Table 6, where year 1 represents the low water and low sediment year, and year 2 represents the medium water and high sediment year. For the low water and low sediment year, pumping seawater will scour the lower channel, which results in the increase the coming sediment in the river mouth. Consequently, it will increase the sedimentation in the river mouth. In the natural condition, the sedimentation in the river mouth is only $0.31\times10^8m^3$. However, pumping seawater to scour the lower Yellow River channel increases the sedimentation to 1.28×10^8–$1.47\times10^8m^3$ in the river mouth. In the medium water and high sediment year, pumping seawater may improve the shape of sedimentation, and make sedimentation decrease. As the pumping seawater increases, it will show more effective in decreasing sedimentation and increasing sediment transport rate. In the natural condition, the sedimentation in river mouth is $5.96\times10^8m^3$, but pumping seawater will decrease the sedimentation to 3.08×10^8–$3.31\times10^8m^3$.

For the plan in natural condition and pumping seawater, the amount and area of sediment accumulation in the low water and low sediment year is smaller than that in medium water and high sediment year. In the low water and low sediment year, the sediment accumulation is smaller and the sediment transport rate is higher, pumping seawater increases the sediment accumulation and decreases the sediment transport rate. In the medium water and high sediment year, the sediment accumulation of natural state is large and the sediment transport rate is rather low, pumping sea water decreases the sediment accumulation and increases the sediment transport rate, and the larger the pumping discharge is, the more effective to decrease the sediment accumulation. This shows that different natural condition may make pumping seawater get different effects on decreasing sediment accumulation. Generally, pumping seawater to scour the lower channel, encountering with higher sediment flow can get more effective in decreasing sediment accumulation in the river mouth.

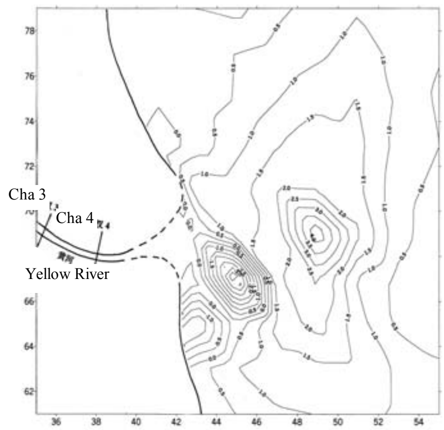

Fig. 1 Scour and silting pattern (Pumping discharge Q=1500m³/s)

Table 6 Comparison of sediment accumulation in the Yellow River Delta

Year	Plan	Average Discharge (m^3/s)	Average Sediment Con. (kg/m^3)	Total Water Volume (10^8m^3)	Total Sediment Volume (10^8m^3)	Sediment Accumula-tion (10^8m^3)	Rate of Sediment Transport (%)	Area of Accumula-tion (km^2)
1	0	506	14.1	157.3	1.44	0.31	78.8	187.5
	1000 m^3/s	1486	7.2	462.1	2.57	1.47	42.7	1437.5
	1500 m^3/s	1986	6.5	615.9	3.08	1.28	58.4	1605.0
2	0	1021	28.6	317.4	6.98	5.96	14.6	475.0
	1000 m^3/s	1939	14.8	602.9	6.86	3.31	51.7	1987.5
	1500 m^3/s	2422	12.2	753.1	7.09	3.08	56.6	2050.0

4. CONCLUDING REMARKS

Based on the above study, some knowledge of the effect of pumping seawater on sediment accumulation in the river mouth can be understood. Pumping seawater to scour the channel make dynamics increase in the river mouth, at most time it will decreases the accumulation of sediment of the river mouth. It also increases the chance of generating density flow, which transport more sediment to the far sea and decrease sedimentation in the river mouth. If fresh water discharging into the river mouth, the minimum sediment concentration to generate density flow is about $32kg/m^3$, but if coming flow from upper reach is salt water, the minimum sediment concentration is about 15kg/m^3. Once the density flow occurs, the sediment transport rate may increase of about 5%−20%. Pumping seawater in different hydrological condition may get different effect on the evolution of river mouth. For example, pumping seawater in the medium water and high sediment year will decrease deposition in the river mouth effectively.

REFERENCES

Fang,C.M, 1997. Sediment mathematical model of reservoir, China Institute of Water Resources and Hydropower Research.

Hu,C.H. and Deng,G.L,1997. The study on evolution of flow route of Cha River of Yellow River Mouth. Office of River regulation of Yellow River Mouth of Shenli oil administration .

Pang,C.G. and Yang,Z.S, 2000. Numerical test of basic control parameter of Yellow River density flow, *Journal of Sediment Research, IWHR.*

Yang, Z.S, 1997. Research on utilization of ocean dynamics to transport sediment of Yellow River to sea, Qingdao ocean university.

Zhang, S.Q, 1996. Flow and sediment transport mathematical model of the Yellow River Mouth, China Institute of Water Resources and Hydropower Research.

Zhang, S.Q. and Zhang, Y. J, 2001. Study on the effect of pumping sea water by a two dimensional mathematical model, China Institute of Water Resources and Hydropower Research.