Integrated flood risk management on sedimentation, course stabilization and spare-course planning in Yellow River Delta

Yiru Zhang¹, Jing Chen² and Bo Huang¹,³
¹School of Water Conservancy and Environment, University of Jinan;
²Shuifa Planning and Design Company Limited
³Email: stu_huangb@ujn.edu.cn

Abstract. The Yellow River Delta as the youngest land of China was originated in 1855, after the river changed its downstream course and emptied into Bohai Sea. Thereafter, the river channel shifted and swayed naturally due to great silt sedimentation in delta area. High silt concentration and sedimentation is the Yellow River’s major characteristic, which dominates the evolution law of the estuary, and lead to river bed rising, tail channel extending, swaying and even course diversion on the end. Dike heightening, enforcing projects and river regulation works have improved the discharging capability of river channel, but the fundamental measures to decrease flood risk in delta are sediment reduction in reservoir, sediment conservation in middle reaches and measures for course stabilization and spare-course planning. The paper gives a comprehensive analysis on water and sediments relationship, evolution process of tail channel, and presents possible solutions on flood risk management.

1. Introduction
The Yellow River delta is normally referred to a fan-shape area and covers about 5400 km² (Figure 1). During a very long period, there had been no levees along the channel and the river shifted its course freely in delta area. The river flow loaded a large amount of sediments to the estuary, and caused continuous riverbed rising and channel seaward extending. With decrease of discharging capacity, the river would shift its course once meeting a big flood. So the evolution process of the tail channel always follows a periodic cycle that silting, extending, swaying and diverting, and the delta therewith growing, expanding continuously.

Land-accretion is the major characteristic for the Yellow River delta. The average amount of the sediments entrained to the sea is about 0.8 billion tons and the average area of land-accretion is about 25 km² each year. The total area of the new land created from 1855 to 1996 amounts to 2400 km² and the new land area created from 1976 to 1999 is about 405 km² (Figure 2).

2. Main problems in Yellow River Delta

2.1. Instability of the river course
For the Yellow River Delta, the primary problem on flood management is relatively instability of the river course. 10 times course-shifting in large scale were happened after 1855 within the delta region, three of which were artificial diversions in 1953, 1964 and 1976, in case of high flooding risk (Figure 3). The present course has been working for 43 years since the previous shifting in 1976, and it always followed the natural evolution process of silting, extending, swaying and diverting. The channel silting
and seaward extending ratio has been slowed down dramatically under the variation of water-silt
condition and artificial channel regulation. How long the present course could be kept running is still
uncertain. Therefore, how to prolong the running age of the present course as long as possible and
secure from flooding is the primary task and a huge challenge.

Figure 1. The Yellow River delta (2004).

Figure 2. Overlapping remote sensing images of the delta in 1976 and 1999(1).

Figure 3. Courses diversions after 1855(1).
2.2. Channel sedimentation and riverbed rising
Continuous channel sedimentation and then caused riverbed rising is the major flooding risk in delta. The design discharge of the current channel is 10,000 m$^3$/s in the delta region, and the flood level at Xihekou cross-section should not exceed 12m when meeting design discharge, otherwise safety from design flood would not be guaranteed and man-made channel-diversion should be taken [1]. The defence works constructed after 1980’s increased the discharging capacity, improved the river channel regime and the stabilization of the river course, which played positive influence on channel evolution, and slowed down the speed of riverbed rising in a certain extent.

All the measures implemented in the past couples years have not solved the problem and changed the situation completely. The natural evolution law are still no radical change, which are the continuous sedimentation of the riverbed and the seaward channel stretching. The water level meeting the same flow is rising and discharging capacity has decreased. It means the developing trend is discharging capacity decrease and water level rising at the same discharge. In one word, the flood risk still exists and the local social-economy development are confronting more flooding threat.

3. Analysis of the problems

3.1. Water-sediment relationship
The Yellow River is best-known for its high silt content of the river flow. The average annual silt quantity delivered through Sanmenxia dam is about 1.61 billion tons, the average silt content up to 35 kg/m$^3$. However, the total annual runoff in volume is only 58.52 billion m$^3$ within the river basin.

The water-silt characteristic of the yellow river is mainly connected to the following four aspects: (1) the first is less water and much silt; (2) the second is the source difference for water and silt. The majority of the water is from the upstream, but the most of the sediment is from the middle stream; (3) the third is huge variation in water and silt volume, and distribution is great uneven along the whole year. For instance, the maximum water volume measured in 1937 is 65.95 billion m$^3$, the minimum is 20.22 billion m$^3$ in 1928, then the difference up to 3.2 times; however, the maximum sediment distribution is 3.92 billion tons in 1933, the minimum is 0.486 billion tons in 1928, the difference up to 8 times. Besides. The water and sediment distribution shows great interannual variation, the most of which accumulated in flood season or minor big floods; (4) the fourth is that the water-silt relationship shows the same trend to the delta. The average annual water volume is 32.5 billion m$^3$, the sediment is 0.81 billion tons, and the silt content is 25 kg/m$^3$ according to the long-term statistics [2].

3.2. Sedimentation
With the analysis of measured data, the total silt volume deposited in the downstream had reached to 9.2 billion tons from 1950 to 1998. The downstream riverbed has lifted 2~4m since 1950s and is 4~6m higher than the land surface outside the dike, hence is called “hanging river”. For example, the riverbed in Xinxiang reach is 20m higher than the land surface and 13m higher in Kaifeng city.

Due to the influence of natural causes and human activities in the past decades years, the uncoordinated water-silt relationship caused increasing sedimentation in the main channel and then create a 3~5 high “hanging channel”, which characterized as the channel higher than beach and the beach higher than land surface. The downstream channel has completely become a “hanging river” at the present. The rising situation of the riverbed in delta region is not much serious due to frequent course diversion. In general, the channel level in the delta is equal or lower than land surface but the beach is higher than land surface.

3.3. Water and silt decrease to delta
Since 1980s, the water and silt coming from upstream decrease gradually. The Table 1 shows that the total annual runoff and sediment volume is only account for 24.8% and 11.7% of the 1950s. The silt content kept stable and shows no significant changing trend before 2000, but with the Xiaolangdi
reservoir came into function on silt retention since 2000, the silt content decreased substantially from 25 kg/m³ to 13.5 kg/m³ during the year 2000~2005 (Table 1) [3].

The decrease of water and silt amount flowing into the delta is determined by natural factors and human activities of upper reaches, but not the estuary situation. The reasons concerned mainly as follows: (1) decrease of rainfall and runoff. The average annual runoff of the river basin was 58 billion m³ from 1919 to 1975, and the rainfall volume and annual runoff decreased 10% after 1986; (2) increase of water diversion. Under the situation of runoff decrease of the river basin, the great development in society and economy from 1950s~1990s caused remarkable increase of water demand from 12.24 billion m³ to 30.75 billion m³; (3) Water storage and sediment retention of Xiaolangdi reservoir. The total storage capacity of the reservoir is 12.64 billion m³, in which silt retention capacity is 7.56 billion m³. It needs 30 years to store 10 billion tons silt and therefore reduce 7.62 billion tons silt deposited in the channel, which is equivalent to 20 years non-sedimentation in the downstream channel.

Table 1. Water and sediment into delta.

| Year       | Annual water volume (billion m³) | Annual sediment volume (billion t) | Sediment content (kg/m³) |
|------------|----------------------------------|-----------------------------------|--------------------------|
| 1950-1959  | 46.36                            | 1.32                              | 28.4                     |
| 1960-1969  | 51.29                            | 1.10                              | 21.5                     |
| 1970-1979  | 30.42                            | 0.89                              | 29.2                     |
| 1980-1989  | 29.07                            | 0.65                              | 22.2                     |
| 1990-1999  | 13.15                            | 0.38                              | 28.9                     |
| 2000-2005  | 11.48                            | 0.16                              | 13.5                     |
| 1950-2005  | 32.00                            | 0.80                              | 25.0                     |

4. Flood risk management

4.1. Sediment reduction

4.1.1. Sediment retention in the reservoirs. Sediment retention is not a thorough solution to solve the silt problem, but it is the most effective measure to reduce sedimentation temporarily in lower reaches. The basin authority had planned seven trunk projects to deal with sediment, in which Longyangxia, Liujiaxia projects in upper reaches and Sanmenxia, Xiaolangdi projects in middle reaches had constructed and put into operation. Xiaolangdi reservoir has a total water storage of 12.68 billion m³, put into operation in 2000. The silt retention capacity is 7.52 billion m³, which is equivalent to 20 years non-sediment in the channel of lower reaches.

The Xiaolangdi reservoir would reach a balance situation in silt retention after 20 years operation and then Guxian and Qikou projects (Figure 4) will put into construction. The design storage of Guxian reservoir is 15.44 billion m³, silt retention capacity is 10.52 billion m³. The project could reduce sedimentation in middle reaches to 5.46 billion tons, and is equal to 52 years sediment amount, which will also reduce sedimentation 77 billion tons in lower reaches, equal to 20 years sediment amount. Furthermore, the Qikou reservoir could prevent sedimentation for further 20 years in middle and lower reaches. Therefore, on the purpose to improve and coordinate the water-silt relationship and reach a relatively balance situation, the construction of reservoir group in middle reaches would guarantee 100 years non-sedimentation in lower reaches.

4.1.2. Water and sediment conservation in the middle reaches. The majority of the silt is from middle reaches, the Loess Plateau. Therefore, sustainable water and silt conservation measures should be implemented in the local district in order to reduce silt transportation to the downstream. Engineering measures such as gully regulation, silt arrester dam system, tree planting and terrace building on slope protection are efficient ways to reduce soil erosion. But, it is indeed a long way to solve the problem of soil erosion in the Loess Plateau due to the impact of natural reasons and funds shortage.
4.2. Measures for course stabilization

The research of the course running mode in the Yellow River delta is a long-term and complicated task. The core point of the study is what methods and approaches could be taken to maintain the channel stable and running as long as possible. It is necessary to determine the direction and the goal of river training and what engineering measures should be taken. According to the evolution history of the Yellow River estuary, each course in delta has its own unique running mode. Even the same channel, it may be different under artificial intervention. In order to prolong the running life of the current course as long as possible, two alternatives can be chosen, which are long-term stable running or relatively stable running of the Qingshuigou course (Figure 5).

4.2.1. Long-term stabilization of Qingshuigou course. The main principle of this alternative is to keep a main channel and a secondary channel, then fix the river in two channels for a long term, which can divert flood to the secondary channel when encountering high water level. The specific operating mode of this alternative is as follows: Taking the current Qingshuigou course as the main channel and constructing secondary dike to guide and restrain the flow. The controlling discharge of the main channel is 3000 m$^3$/s and building spur dikes to form a composite riverbed; Diaokouhe course as a supplementary channel, a diversion gate is built near the Xihekou cross-section, with a discharge of 3000 m$^3$/s, and continuous dredging and desilting need to be carried out in the downstream of the Xihekou section to ensure the river channel stable and smooth discharging.

4.2.2. Relative stabilization of Qingshuigou course. The main principle of this operation mode is to maintain the stability of the current Qingshuigou course, on the basis of the safety of flood control and ecological environment protection, which could give full play of the resource advantages and promote the sustainable development of social-economy in the region. Through necessary engineering measures, channel dredging and desilting, to minimize the feedback influence to downstream channel that resulted by estuary sedimentation and channel extension, trying to control the water level not exceed 12 m under the flood discharge 10000 m$^3$/s.

Through the comparison and analysis of the above two alternatives, the second is more practical and feasible, which prolong the running life on the basis of the safety of flood control, meets the demand of local socioeconomic development, reduces the negative influence resulted by course changing, and also takes into account natural protection and sustainable development. Therefore, it is suggested that the relatively stable running mode of the Qingshuigou course should be adopted in the long term planning of the Yellow River delta.

Figure 4. Location of water-sediment regulatory. Figure 5. River courses and artificial bifurcations projects.
4.3. **Spare courses**

Less water and more sediment is the most significant characteristic of the Yellow River. The evolution of the tail channel at delta region still follows the natural law of "silting, extending, swinging and course shifting", and no any signs of obvious changing. Therefore, spare courses should be considered in Yellow River regulation planning and Delta development planning. On the basis of comprehensive consideration of historical conditions, characteristics of the sea area and social and economic development, three possible paths for spare course are reserve as Diaokou river, Maxin river and Shibahu river [4] (Figure 6).

**Figure 6.** Spare courses in delta (4).

4.3.1. **Diaokouhe course.** Diaokouhe River is an old channel running from January 1964 to May 1976 in the delta, which has stopped running for more than 40 years. During this period, the oil companies carried out large-scale oil exploitation near the areas along the channel, and many production facilities and infrastructure were built. At the same time, the local government also carried out agricultural and forestry development. The topography and landform of the original river course had great changes, resulted severe channel shrank and embankments damage.

During the running period of Diaokouhe course, levees were built along the both sides of the channel, and the dike spacing is about 8.5-14.4 km. After course shifting of the river in the delta, most of the defense works have been abandoned. Due to abundant oil reserves in the delta, large-scale infrastructure were built and a large area were developed for farmland, forest and grassland, and the region near the estuary was planned into delta nature reserve. In 2010, the Diaokouhe river has been kept flowing again after restoration as a water supplement passage to Delta Ecological Protection Area.

4.3.2. **Maxinhe course.** Maxinhe river is a man-made drainage and flood discharging channel with a total length about 60 km from planned diversion point to the entrance into Bohai sea. The Maxinhe course is based on the existing Maxinhe river channel, with a riverbed width of 14~18 m. The planned Maxinhe course need to be widen and the distance between both embankments is 3~4 km. All embankments both sides must be newly built, with a length of about 54 km. The project would cause 75 villages, 26 thousand people and 540 hectares farmland affected.
4.3.3. Shibahu course. Shibahu course is located in the south of current course of Qingshuigou, which is an artificial river channel flowing into Laizhou Bay. It is the shortest passage with a length of 32 km from diverting point to the estuary. The north dike of the planned course can be built on the basis of the existing south dike, and the new south dike needs to be built completely. The estimated impact area of the planned course is about 160 km², involving 15 thousand people and 35 thousand hectares of cultivated land. At present, no oil field has been found in the region and no large infrastructure existed. In addition, a comprehensive storm surge defense system has been built along the coast.

By comparing in channel length, sea condition, running life, possible total cost and negative impact of the three planned courses above, it can be concluded that the Diaokouhe course should be preferred after the current course, Qingshuigou, reaches the running life (including three artificial bifurcations).

5. Conclusions

After construction and put into operation of Xiaolangdi reservoir in 2001, the overall flood risk of Yellow River downstream and the delta has presented remarkable decrease. The annual runoff and sediment volume deposited in delta has reduced gradually, therefore, the speed of estuary extending seaward and riverbed rising has slowed down. However, the evolution law of the river channel in deltaic region has no essential change and course diversion as a risk will be faced in long term, although the running life for each individual course can be prolonged by integrated engineering management. But, with the social-economic development of the deltaic region, especially in consideration of the oil industry in coastal area, engineering measures and spatial planning should be taken into account to control and decrease the flood risk, which should include three aspects: the first is to strengthen and heighten the dikes, enhance the discharging ability of the channel in deltaic reach, then prolong the running life of the present course as long as possible; the second is to reduce the silt quantity transported to delta by reasonable regulation of the present reservoirs or constructing new reservoirs in middle reach, thereby slowing down the speed of course extension, channel sedimentation and riverbed rising in delta; the third is to make a long term plan of spare courses, and determine the priority of the spare course scenario, which better be integrated to the overall development plan of the delta. Thus, once a course diversion have to be made when encountered a flooding risk or facing some urgent situation in the future, the engineering cost, economic lost and negative impacts to local society could be reduced to the least.

Reference

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