International Journal of Hybrid Information Technology
Vol.9, No.1 (2016), pp. 21-30
http://dx.doi.org/10.14257/ijhit.2016.9.1.03

Study on the Evolution and Preliminary Equilibrium of the Delta Deposition

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Abstract

The delta deposition pattern is the most important and universal sedimentation type in reservoirs, yet it is still unclear to engineers and researchers concerned about its evolution, adjustment and preliminary equilibrium of the sedimentation. Taken the reservoir named Xi Luodu as a typical case study the whole deposition processes of the delta evolution can be divided into two stages according to the time the delta arrives at the dam site, corresponding to the formation of the wedged shape deposition. Sedimentation in the first stage composes the majority deposits of the reservoir total accumulation volume. Although in the second stage the deposition rate is much slower than the first one it is the period for the reservoir to rebuild its new equilibrium mainly by changing the configuration of its cross-section to regain sufficient sediment carry capacity. The delta profile and the cross-section deformation were both discussed in detail during the two stages. Characteristics of the deposition/erosion along with the sediment delivery ratio were also analyzed throughout the whole processes.

***Keywords**: reservoir sedimentation, deposition evolution, preliminary equilibrium, delta profile*

1. Introduction

Sediment deposition is the primary problem affecting the useful life of reservoirs. In order to estimate the sedimentation extent in a reservoir both the rate and pattern of sediment deposition is required. Longitudinal deposition patterns have four basic types depending on the inflowing sediment characteristics and reservoir operation: delta deposits, wedge-shaped deposits, tapering deposits and uniform deposits [1]. Among them the delta deposits is considered the most common type occurred in reservoirs.

Field datum shows that delta profiles have been spotted in many natural reservoirs [2]. Experiment results also reveal that the longitudinal development of sedimentation shows the delta type [3]. Numerical models from different researchers also obtain the typical type of delta sedimentation in reservoirs [4-6]. Although the delta deposit is one of the most commonly phenomena in reservoir sedimentation, its basic development and evolution process is still unclear and need to be explored more profoundly.

Traditionally the sediment distribution in the reservoir is achieved by using the empirical area reduction method [7] or the analytical procedure [8]. Since the sediment deposition process can usually take a long time and greatly varies spatially, few scale model (or physical model) has been constructed due to the high cost. However, with the establishment of mathematic model more and more reservoir sedimentation problems have been studied through numerical approaches. The HEC-6 model is a one-dimensional movable-boundary open-channel flow model that computes sediment scour and deposition [9]. Other sediment transport models include GSTARS [10], FLUVIAL [11]. Up to now the cognition of the characteristics of delta deposits are mostly based on empirical or schematic models. Studies of the evolution, preliminary equilibrium and

ISSN: 1738-9968 IJHIT

adjustment of the delta sedimentation in natural reservoirs have not been systematically reported in the literature.

This paper is intended to explore the evolution and characteristics of delta deposits in natural reservoirs obtained by mathematical model. The numerical model adopted in this study is a one-dimensional hydrodynamic and sediment transport model [12]. The model was calibrated and then was applied in the study of the sedimentation problem of the Three Gorge Project. By taking a natural reservoir named Xi Luodu as the typical one some useful recognitions and regularities of the delta deposition evolution and its adjustment has been systematically studied in the paper.

2. Background

During the flood season (usually from June to October) both the water inflow and the sediment discharge account for the majority of the total year in most natural rivers in China due to the specific characteristics of the hydrological and meteorological conditions. In order to alleviate the sedimentation in reservoirs the Chinese sediment engineers and researchers have brought forth the so called operation mode of "storing the clear water and releasing the muddy water". On the Yangtze River it is appropriate to adopt this operation scheme because of its plenty runoff for discharging sediment during the flood season and also because it can be relatively easy to fulfill water impoundment goal for implementation its benefit in the non-flood season. Of all the reservoirs in Yangtze River the Xi Luodu reservoir is a very typical one. It is suitable to be taken as the representative for the study of the delta evolution and its regularities.

The Xi Luodu reservoir, located in the upstream of the Yangtze River, southwest of China, is a mountainous type reservoir with backwater length approximately 210km long for the main purpose of hydropower, flood control and water supply etc. The reservoir has a drainage area of 454.4×103 km2 and a normal capacity of 11.57×109 m3. The annual amount of suspended load is 247×106 t and bed load 1.82×106 t. The annual runoff at the dam site is 143×109 m3 and annual mean sediment concentration is 1.72 kg/m3. The representative pool levels are: the normal pool level (NPL) 600 m, the dead pool level (DPL) 540 m and the flood control level (FCL) 560 m. The operation mode of "storing the clear water and releasing the muddy water" will be applied in order to reduce the reservoir sedimentation. During the flood season the pool level is maintained at FCL (560 m) for the purpose of flood prevention. The reservoir impounding begins in September 11 until the end of the month to raise the pool level to NPL (600 m). Then the rest of the year is the reservoir supply water period until the end of May the pool level is released to the DPL (540 m).

3. Evolution Prosecess

The reservoir sedimentation calculated by the numerical model clearly shows that the whole process can be divided into two stages (Figure 1). The first stage is from the beginning use of the reservoir to the end of the 70 year. In this stage the curve is comparatively steep with the annual sedimentation rate of 1.18×108 m3/y. In the second stage (from the 70 year to the 100 year) the curve is approximately a horizontal line with the annual sedimentation rate of 0.16×10^8 m^3/y. The 70th year is obviously a pivot point for the reservoir sedimentation. Before the very point the reservoir lose its volume rapidly and after the pivot point the reservoir volume decrease very slowly. So the whole sedimentation process can thus be separated into two stages.

3.1. First Stage of Deposition

In the first stage longitudinal delta profiles were obtained by numerical model (Figure 2). From Figure 2 it will be taken 70 years for the sedimentation delta to approach at the dam site, just corresponding the time to the pivot point in Figure 1. Comparing Figure 2 to Figure 1 the most serious sedimentation occurs during the first stage before the delta arriving at the dam site. Due to the great variation of the pool level, the inflow of water and sediment discharge between flood season and non-flood season the evolution, adjustment and characteristics of the delta sedimentation should be discussed separately.

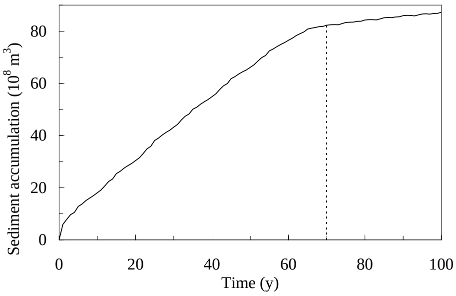

Figure 1. Timewise Pattern of Sediment Accumulation in Reservoir

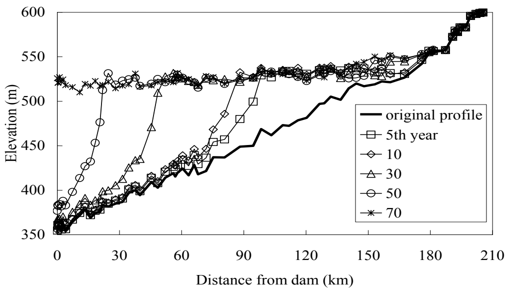

Figure 2. Delta Profiles of Xi Luodu Reservoir in the First Stage

During the flood season the pool level will be maintained at FCL (560 m) and the average inflow discharge is about 8,000 m3/s. Delta profile of the 10th year and its section velocity distribution were achieved (Figure 3). The velocity distribution is corresponding to the longitudinal delta profile. The velocity on the topset area of the delta is obviously faster than that in the region from the foreset area of the delta to the dam site. At the tail region of the reservoir the velocity became much faster than that of the other reaches because of the steep gradient and narrow cross-section both in the natural condition and after the reservoir's impoundment. Further more the flow area distribution is also corresponding to the delta profile (Figure 4). The flow area is just accord with the local hydrodynamic conditions both on the topset reach and in the foreset reach. In the topset region the flow area reveals to become small because the section was heavily deposited and the original bed was considerably raised up. Before the pivot point of the delta the flow area shows to be much larger than that of the topset area due to the large water depth.

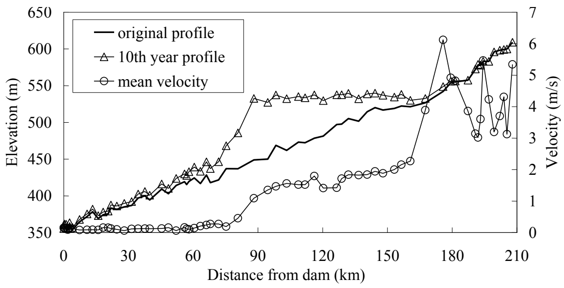

Figure 3. Delta Profile of the 10th Year and Velocity Distribution (Flood Season)

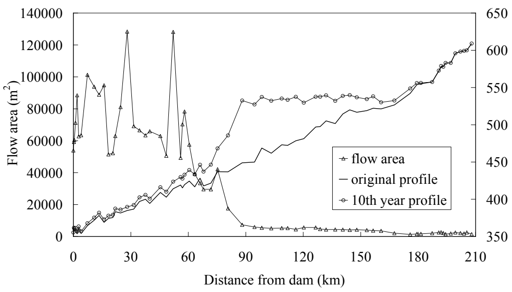

Figure 4. Delta Profile of the 10th Year and Flow Area Distribution (Flood Season)

The velocity and flow area distribution in different years are all corresponding to the delta profile demonstrated in Figure 2 (Figure 5 and Figure 6). As soon as the delta appraoching to a certain section the topset section is immediately adjusted to decrease its flow area and to increase the velocity to enhance the sediment carry capacity. Thus the topset reach of the sedimentation delta functions just like a kind of conveyer to uninterrupted transport sediment from the topset to the foreset. Deposition then mainly occurs in front of the delta foreset reach because the water depth and flow area varies abruptly. However, on the topset reach of the delta the cross section approximately achieves its preliminary equilibrium and sedimentation rarely happens (Ref to Figure 2).

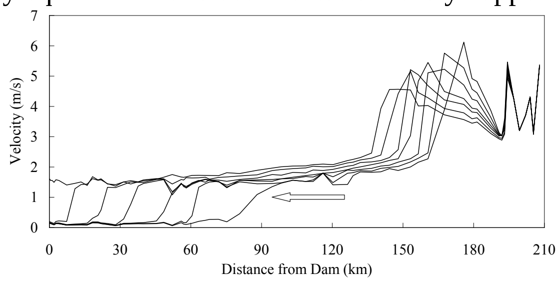

Figure 5. Velocity Distribution in Different Year (Flood Season) (The Arrow Direction Represents the 10th-70th Year)

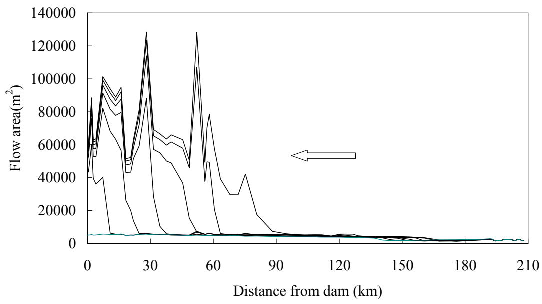

Figure 6. Flow Area Distribution in Different Year (Flood Season) (The Arrow Direction Represents the 10th-70th Year)

In the flood recession period the pool level will be raised to NPL (600 m) and the average inflow discharge during the non-flood season is about 2,000 m3/s. The velocity and flow area distribution can then be calculated (Figure 7 and Figure 8). In most region of the reservoir the velocity is slow and the flow area is quite large due to great water depth. The flow area decreases greatly just after the delta head approaching forward to make the foreset section transforms into topset section. Flow area at the topset section during non-flood season is still much larger than that in the flood season. So sediment carry capacity is greatly reduced and sedimentation occurs nearly in all the reservoir regions.

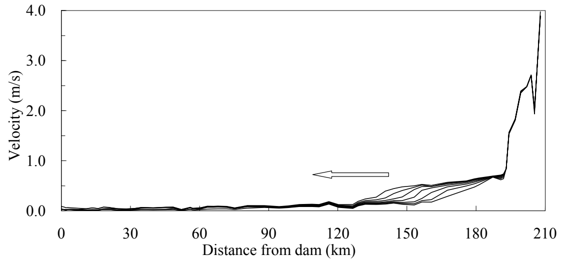

Figure 7. Velocity Distribution in Different Year (Non-flood Season) (The Arrow Direction Represents the 10th-70th year)

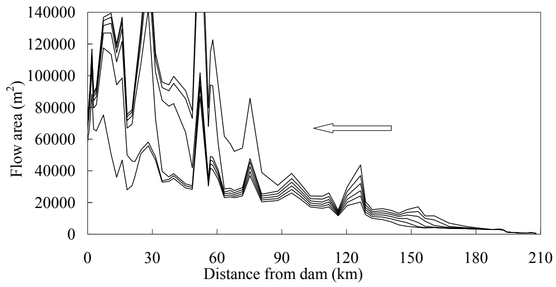

Figure 8. Flow area Distribution in Different Year (Non-flood Season) (The Arrow Direction Represents the 10th-70th Year)

In the approaching processes of the delta toward the dam both the longitudinal profile of the river bed and the cross section configuration are greatly modified by reservoir sedimentation. With respect to the delta topset section sedimentation occurs in the entire section developing a near-horizontal surface configuration regardless of the original cross section shape (Figure 9). In the delta foreset section sedimentation occurs mainly in the deepest part of the section and the bed configuration alters slightly (Figure 10).

From Figure 9 and Figure 10 it is apparent that as the delta head advancing toward the dam the cross-section changes a lot. Yearly deformation area of each section can then be calculated from the beginning of the delta formation to the sedimentation preliminary equilibrium is attained, that is, when the delta approaching at the dam site (Figure 11). With respect to a specific year the location where the deformation area achieves the maximum value is just the position of the pivot point illustrated in Figure 2 in that very year. During the entire period of the delta approaching to the dam site the reservoir is mainly faced with deposition.

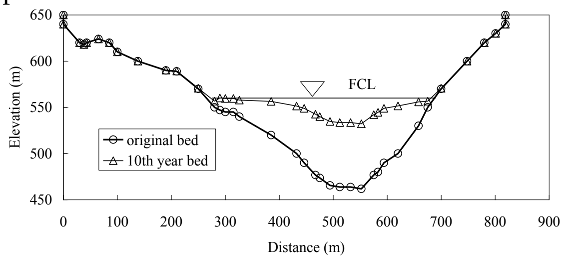

Figure 9. Cross-section Deformation of the Topset Section in the 10th Year

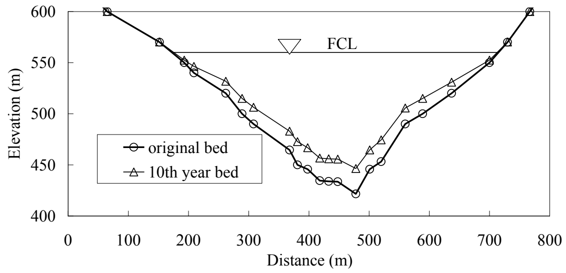

Figure 10. Cross-section Deformation of the Foreset Section in the 10th Year

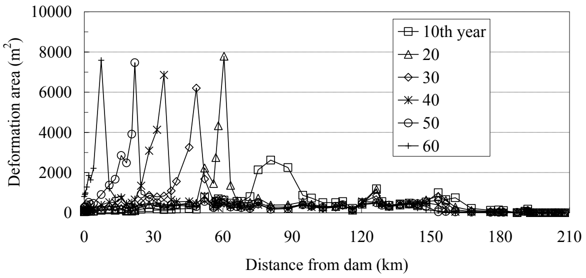

Figure 11. Yearly Deformation Area of Each Section (from 10th -60th Year)

3.2. Second Stage of Deposition

The second stage refers to the period after the sedimentation delta has already arrived at the dam site to get its preliminary equilibrium. In this period the sedimentation rate is greatly reduced (Figure 1) and the delta profile only changes slightly from the 70th year to the 100th year (Figure 12). Yearly deposition area of each section is calculated in this period (Figure 13). Comparing with the first stage the sedimentation intensity is greatly reduced due to the preliminary equilibrium sedimentation balance between the inflow condition and the cross section.

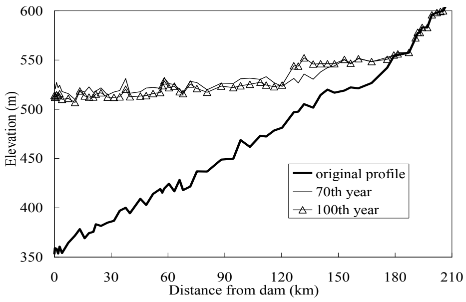

Figure 12. Delta Profiles of the Second Stage

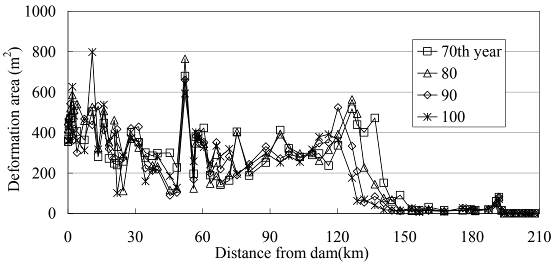

Figure 13. Yearly Deformation Area of Each Section (from 70th-100th)

Flow area were calculated both in the flood season operation (Q=8,000 m^3/s, WL=FCL) and in non-flood season operation (Q=2000 m^3/s, WL=NPL) (Figure 14) to compare the evolution of the delta development during the second stage. In the flood recession period the pool level is raised to NPL characterized by large flow area and low flow velocity in each cross section. Local hydrodynamic condition tends to decrease the local sediment carry capacity in most area of the reservoir so the floodplain and the main channel are all faced with sedimentation. While during the flood season the pool level is maintained at FCL and the flow is nearly confined in the main channel characterized by small flow area and great flow velocity in each cross section. The hydrodynamic condition intends to increase the local sediment carry capacity and the main channel is faced with erosion. With the development of deposition in the whole cross-section and erosion only confined in the main channel the high flood plain and the deep channel configuration is thus gradually come into shape.

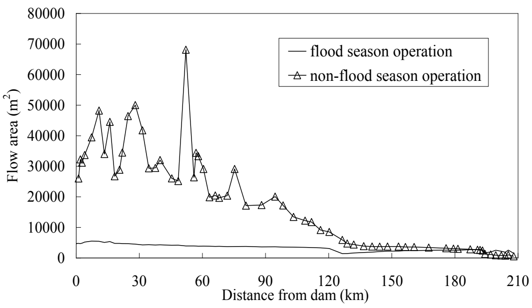

Figure 14. Flow Area Distribution in the End of the 100th Year

3.3. Further Discussion

A typical cross section was selected to demonstrate the deformation through the entire operation (Figure 15). It should be indicate that the deformation area mentioned here is the deposition/erosion area just in one year. In this case before the operation of 40 years the cross-section is all faced with deposition of which most occurs in the flood season. At the 40th year the section deposition intensity achieves the maximum value because the delta profile has just approached to the section. From the 50 year to the 100 year the section is still faced with deposition mostly during the flood season. In the later period of operation the section deformation area is decreased due to the new equilibrium the reservoir has approximately achieved.

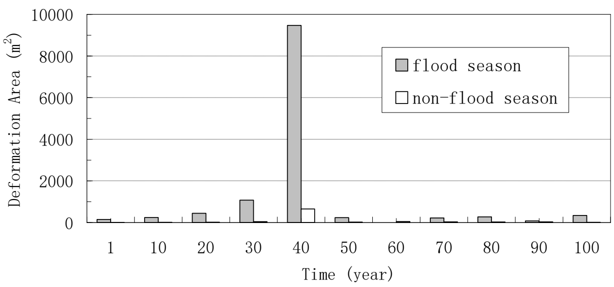

Figure 15. Yearly Deformation Area of a Typical Cross Section

Two representative cross-sections were taken as the typical sections to illustrate the lateral deformation (Figure 16 and Figure 17). In the first sedimentation stage the cross section begins with slight deposition focused in its main channel. As soon as the longitudinal delta approach at the given section the whole section is heavily deposited developing a near-horizontal surface bed regardless of the original cross section shape. After the delta approaching further to make the section become delta topset reach the cross-section is faced with sedimentation during non-flood season and erosion during flood season. This contributes to transform the section to the high flood plain and deep channel shape.

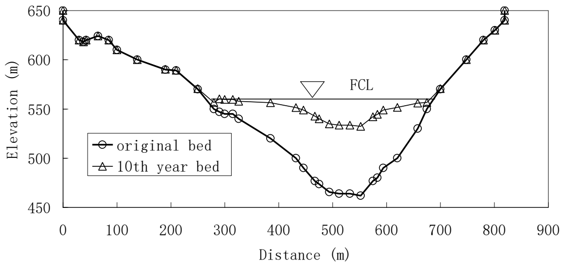

Figure 16. Cross-section Evolution of Topset Section

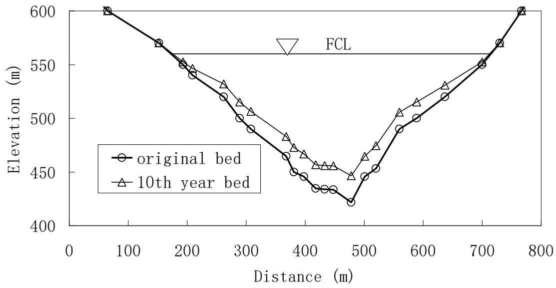

Figure 17. Cross-section Evolution of Forest Section

Sediment discharge ratio during the entire evolution and adjustment of the sedimentation was calculated (Figure 18). The variation diagram can be divided into two phases corresponding to the two stages of the delta evolution. The first stage is defined from the beginning operation of the reservoir to the time the delta arrives at the dam site, that is, about 70 years. During this period the sediment discharge ratio is small because the whole reservoir is faced with deposition. In the second stage after the delta approaches to the dam site the sediment discharge ratio is raised to about 70% and then changes slightly hereafter.

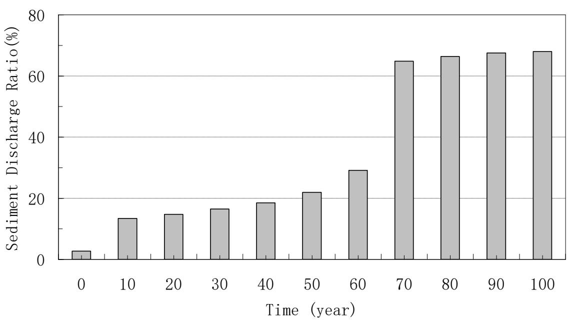

Figure 18. Sediment Discharge Ratio in Different Year

4. CONCLUSIONS

By taking the Xi Luodu reservoir as the typical case to study the delta evolution, adjustment and development the main conclusions can be summarized as follows:(1)The whole evolution of the delta sedimentation can be divided into two stages according to the time the delta arriving at the dam site to attain its preliminary equilibrium. This specific time is just corresponding to the pivot point in the diagram of the time wise pattern of the sedimentation accumulation volume (2). During the first stage the reservoir is fully faced with sedimentation with the cross-section surface near-horizontally raised regardless of the original section shape. The main characteristic during this stage is the universal sedimentation in the reservoir and low sediment delivery ratio (3). During the second stage the reservoir has reached its preliminary balance characterized by large sediment delivery ratio. Because of the operation scheme of "storing the clear water and releasing the muddy water" the cross-section will be shaped into the configuration of high flood plain and deep main channel due to the deposition of the whole section during the non-flood season and erosion only confined in the main channel during the flood season.

Acknowledgements

This work was partly supported by the Supporting Program of the "Twelfth Five-year Plan" for Sci & Tech Research of China (2012BAB05B03).

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