Flow and Sediment Movement Characteristics on the Varisized Plain of Compound Channel

Zuwen Ji*, Dangwei Wang, Qing Lu and Anjun Deng
State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research (IWHR), 20 Chegongzhuang West Road, Beijing, 100048, China

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Abstract: In this paper, river reaches are generalized into two types: the straight and lotus-root-shape compound channels according to plane characters of the Lower Yellow River and the Songhuajiang River. It can be seen from some experimental data of flow and sediment in two kinds of channels. The difference arises from the fact that the momentum transfer is stronger in the louts-root-shape channel than in the straight channel. Thus, the relative velocity of plain to channel type, still increases with increment of the relative depth, their differences are large at the lower relative depth, but close at the higher one. The distributions of flow velocities in two channels are similar with water depth, and the mean velocities are on the decline from main channel to flood plain. At two sides of floodplain, the change ranges from maximal to minimal velocities. Transverse velocity gradient in the interface area is bigger in the straight channel than in the lotus-root-shape channel. This is largely because, relative sediment concentration in both compound channels go up with the increase of the relative velocity and depth. The relationship of sediment concentration to depth, is such that, the enlarging speed is more rapid in the straight channel than in the lotus-root-shape channel. The transverse variation of the vertical average sediment concentration is smaller in the lotus-root-shape channel than in the straight channel, and are bigger on the plain than in the channel.

1 INTRODUCTION

The average annual sediment load in the Lower Yellow River was 1.6 billion tons before 1980s, and ranked first in the world. The average sediment concentration was 35 kg/m^3 and the highest sediment concentration was recorded at 911 kg/m^3. Large quantities of sedimentation have resulted in "suspended rivers" and frequent shift of the river courses in the lower reaches. The average level of riverbed is 4 to 6 m higher than that of normal ground level, and the maximum has reached 13m in some places. This explains why Throughout the history of China, the Yellow River has been associated with floods and famine. It has been a difficult problem to harness the Yellow River because, the whole length of the lower reach is about 878 kilometers. In its plane form, it is involved in mainly meandering and wandering, and their configurations of cross-section include two parts: main channel and floodplain. The area of floodplain is about 3,544 km^2, accounting for 84 % in the total area of the river. Thus, it is very important to study flow and sediment in the compound channel in the Lower Yellow River.

Compound channels are universal forms of fluvial river, and are often in areas that are densely populated and economically developed. Compound channels are different in form of expression from those in the natural rivers. From the point of view of cross-sectional shape, although all compound channels have basic forms like main channel and flood plain, other variants exist such as, one plain with one channel, two plains with one channel, and even much more channels and plains; For plane form, there are equally many expressions, such as straight channel, lotus-root-shape channel, meandering channel and so on, increasing the complexity of the research. The problems that overbank flooding of compound channels causes necessitates water resource planning, floodplain planning, flood level design, channel improvement and so on. At present, the research on the overbank flow in the compound channels mainly focuses on the study of the flow structure and the interaction mechanism of the plain channel. The bed shear stress and resistance characteristics of the

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compound channel were also observed (Lyhess et al., 2001; Knight, 1999). The relationship between flow structure and flow distribution characteristics and bed morphology were studied (Hu et al., 2010; Wormleaton et al., 2004; Ji et al., 2016). The basic exchange model and distribution characteristics of flow and sediment were put forward (Armugha et al., 2018; Chen & Zhang, 1996; Knight, 2005; Moron et al., 2017). The influence of overland flow on bed morphology, surface slope and sediment transport were analysed (Tang & Knight, 2006; Ji et al., 2019; Wu et al., 2020). The above results lay a good foundation for related researches of compound channel, as presented by the analysis of two generalization physical model experiments.

2 EXPERIMENTAL METHODOLOGY

This experimental study conducted on a 30m long circulating straight channel, with basic dimensions of width of 0.3m, floodplain width of 0.7m and beach channel bed height difference of 0.06m. The bed surface and side wall of water channel are both cement surfaces, and the water channel structure is shown in Figure 1 (a) to (c). For lotus-root-shape channels, the width of main channel was 0.3m and the width of floodplain was 0-0.7m. The whole water channel is composed of four lotus roots with each having a length of 4m. The transition section with the length of 1m exists between every two lotus roots. The outer boundary of each lotus root is symmetrical about the axis of the main channel circular arc and curvature of 0.17m. The water channel structure is indicated in Figure 1(b) and Figure 1 (c), and 7 cross sections are arranged on experimental measurement section.

In this experiment, cross-sections of straight channel and lotus-root-shape channel are both considered, rectangles with equal main channel width and beach channel height difference. However, the outer boundary of straight channel is unchanged along the way, and that of lotus-root-shape channel is curved with a great change along the way. In order to facilitate comparison, the lotus-root-shape channels adopt 4 # cross section, and the size of this section is exactly consistent with that of straight channel. During the experiment, the experimental water depth of straight compound channel is taken as 0.02 m~ 0.13m, and the sediment concentration is 4 ~ 83kg/m^3; the experimental water depth of lotus-root-shape compound channel is given by 0.07 ~ 0.12 m, while the sediment concentration is 4 ~ 25kg/m^3. Both compound channels use the same experimental sand with a median grain size of 0.014mm.

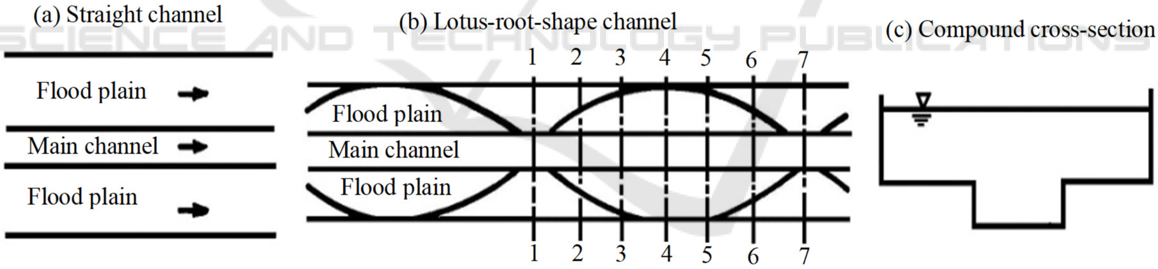

Figure 1: Sketches of the straight and the lotus-root-shape compound channels.

3 COMPARATIVE ANALYSIS ON FLOW MOVEMENT CHARACTERISTICS OF TWO TYPES OF COMPOUND CHANNELS

3.1 Cross-section Flow Capability

According to the water level flow relationship between straight channel and lotus-root-shape channel, it can be known that under the same water depth, whether for main channel or floodplain, the flow capacity of lotus-root-shape channel is less than that of straight channel. The greatest difference lies in total flow capacity of cross section, closely followed by the flow capacity of main channel, relative to the smallest difference in the flow capacity of floodplain. In case of small water depth of floodplain, the difference in the flow capacity of the two channels is small. As the water depth increases, that difference becomes gradually greater.

Figure 2 shows the water level flow relationship between three channels, i.e., single channel, straight compound channel and lotus-root-shape compound channel. Among them, the water level flow relationship of straight channel and lotus-root-shape channel are measured from data acquired by the author, while that of single channel is the calculation result obtained from the Manning formula assuming the water depth to flow area is same as straight channel to lotus-root-shape channel. It can be seen from the figure that under the same water depth and flow area, the single channel has the largest flow capacity, followed by straight channel, and the least is lotus-root-shape channel. Meanwhile, the difference in the flow capacity of the three channels becomes greater with water depth. In the case where the relative water depth of floodplain is about 0.14 ~ 0.51, the flow capacity of straight channel is reduced by 7% - 21% compared with single channel; the flow capacity of lotus-root-shape channel is reduced by 11% - 48% over single channel; the flow capacity of lotus-root-shape channels is reduced by 4% - 34% over straight channel.

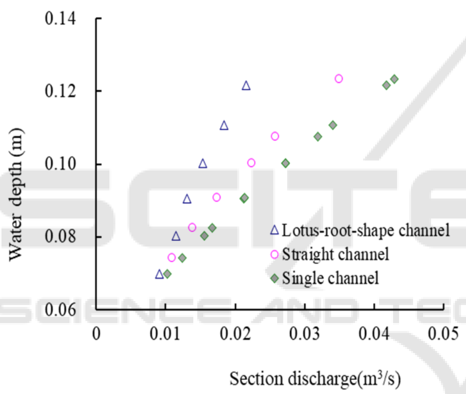

Figure 2: Stage-discharge relations in single.

3.2 Average Flow Velocity of Floodplain

The change in average flow velocity of lotus-root-shape channel floodplain is basically like that of straight channel. The flow velocity of main channel and cross section increases first and then decreases and then increases again with water depth. However, the flow velocity of floodplain indicates monotonic increases with water depth. The characteristics of this change show that there is momentum exchange between the floodplains of the two channels, but the intensity is different, as shown in Figure 3. It can be seen from the figure that regardless of water depth on floodplain, the flow velocity of lotus-root-shape channel is larger than that of straight channel. This shows laterally, momentum exchange between the lotus-root-shape channels is stronger than that of the straight channel. Because the outer boundary of the straight channel is straight, the longitudinal change of floodplain flow is not large. In the lateral direction, there is a certain difference in the flow velocity of floodplain, which is small for lotus-root-shape channels. This is because in the straight channel, the floodplain current itself has a certain momentum. If there is no floodplain momentum exchange, the floodplain current cannot also flow.

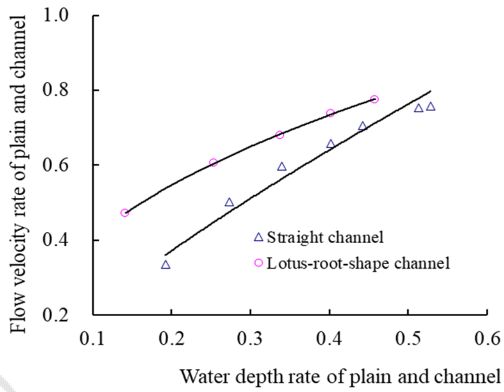

Figure 3: Relations between relative velocity and straight and lotus root - shape channels relative depth corresponding to plain and channel.

This momentum is provided by the gravity component of uniform water flow. The reason for the momentum exchange between the floodplains is mainly due to the certain difference in the flow velocity of the two channels, and such difference gradually decreases over water depth. However, in the lotus-root-shape channels, the floodplain water movement is different. Running in the transition section, because of the single channel, the flow speed is high. When the flow enters the diffusion section, the current with higher momentum is transmitted to floodplain. While before the momentum exchange of floodplain current is very small. On the one hand, the flow velocity of floodplain is very small; balanced on the other hand, by the high velocity flow just before entering the diffusion section. It is conceivable that when they meet, due to the large difference in velocity between the two channels, violent momentum exchange will inevitably occur. Therefore, the floodplain momentum exchange of lotus-root-shape channels is stronger than that of straight channels.

In addition, it can be seen from Figure 3 that when the relative water depth of floodplain is relatively small, the difference in the floodplain velocity of the two channels is large. In case of larger water depth of floodplain, the floodplain velocity ratio of the two channels has a small effect.

For a certain flowing cross-section, the momentum of the water body on cross-section is constant. The momentum of floodplain will increase, and the momentum of main channel will be reduced. The momentum exchange of lotus-root-shape channel floodplain is more intense than that of the straight channel. The momentum transferred from former main channel to floodplain will be large inevitably, so that the momentum of the main channel on lotus-root-shape channels decreases more, and the increase in amplitude of the momentum on floodplain is relatively larger. Therefore, the floodplain velocity ratio of lotus-root-shape channel is larger than that of the straight channel. When the water depth of floodplain is small, due to the larger floodplain resistance, a considerable part of the reduced momentum of the main channel is used to overcome the floodplain resistance, and the actual momentum obtained on the floodplain decreases. In the case of basically equal water depths of the two channels, the reduced momentum of main channel on lotus-root-shape channel is larger than that of the straight channel. It is shown that on the one hand, the main channel of the lotus-root-shape channel reduces the momentum more, and the floodplain indicates more increased momentum; On the other hand, when the momentum of the main channel of the straight channel is reduced, the momentum of floodplain is also less increased. Among the reduced momentum of the main channel of the straight channel, the momentum used to increase the velocity of floodplain is less weighted relative to the remaining momentum of the main channel. However, in the reduced momentum of the main channel in the lotus-root-shape channels, the momentum used to increase the flow velocity of floodplain has a greater weight in the remaining momentum of the main channel. When the water depth of floodplain is relatively small, the weight of the two channel types differs greatly, which is expressed in the flow velocity ratio of floodplain, i.e., the difference in floodplain velocity of lotus-root-shape channels is greater than that of the straight channel. With the increase of water depth on floodplain, the difference in weight between the two channels gradually decreases, and the difference in floodplain velocity ratio also gradually decreases.

3.3 Vertical Velocity

There are some differences between the vertical velocity distribution of lotus-root-shape compound channel and the straight channel, which is mainly manifested near the interface of floodplain. The vertical velocity distribution of the straight channel is large in the middle and small at two ends, while that of lotus-root-shape channel basically shows the characteristics of larger on the top while small at the bottom, but the distribution is relatively uniform. According to preliminary analysis, the momentum exchange of floodplain in the straight channel is only concentrated in a certain depth below the water surface, which reaches the maximum at the water surface and gradually weakens downward. This exchange method determines that the vertical velocity distribution is large in the middle, while small on surface and bottom. However, in the lotus-root-shape channels, almost the entire vertical line from water surface to the bottom participates in the floodplain momentum exchange, which is mainly due to the strong momentum exchange of floodplain in lotus-root-shape channels. The momentum exchange process ensures that the main water body channel with larger momentum entrains the floodplain water body with less momentum into the main channel water body. In addition, the main water body channel with larger momentum in equivalent volume enters the floodplain water body, which leads to the increase of floodplain water body momentum. According to the principle of conservation of momentum, it can be shown that the momentum of main channel water body will decrease. Due to the large difference in the flow velocity of floodplain water body (especially when it starts to diffuse), for the entrainment of main water body channel on floodplain water body, almost the entire vertical water body above the floodplain bed surface participates in such exchange. It can be seen from the rapid increase of floodplain flow velocity that such exchange of massive water body causes a sharp decrease in the momentum of the upper water body of the main channel. The momentum difference between the lower and upper water bodies of the main channel becomes large sharply, so that the upper and lower water bodies will inevitably generate momentum exchange. This results in most of the water bodies on the vertical line of the main channel participating in the momentum exchange. The result of this momentum exchange is the redistribution of the momentum throughout the entire vertical line of the main channel. In the vertical distribution, the velocity is relatively uniform with small gradient, and the distribution still shows the characteristics of larger on the top and lower at the bottom, but the velocity value of the entire vertical line decreases. It should be noted that although there is also momentum exchange in the vertical direction of water body of the straight channel, the momentum exchange in the floodplain is smaller than lotus-root-shape channel. Meanwhile, momentum exchange is also gradual in the vertical direction, i.e., gradually increasing from the momentum exchange occurrence area to water surface, and there is no sharp change between the upper and lower water bodies in the area where the momentum exchange occurs.

3.4 Average Velocity of Vertical Line Distributed along the Lateral Direction

The vertical average velocity of lotus-root-shape compound channel is basically similar to that of the straight channel in the lateral distribution. The vertical average velocity gradually decreases from the central area of the main channel to both sides of the floodplain, as shown in Figure 4. However, there are some differences between the two channels. First, the difference between the maximum and minimum velocity of the floodplain is different. The variation in flow velocity of the lotus-root-shape channel is smaller than that of the straight channel. Secondly, the decreasing rate of vertical average velocity of lotus-root-shape channel is smaller than that of the straight channel. Lastly, the vertical average velocity of the two kinds of compound channels differs greatly in the main channel, while less in the floodplain.

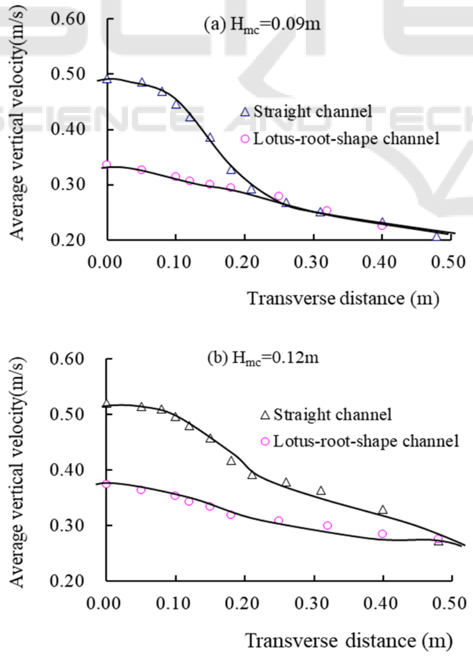

Figure 4: Transverse distributions of the depth - averaged velocity.

From the previous analysis, it can be known that the movement status of floodplain flow of the lotus-root-shape and straight channels before momentum exchange of floodplain is different. For the main channel, on the one hand, the difference in the flow capacity of the two channels determines whether the main channel of lotus-root-shape channel has less momentum than the straight channel. On the other hand, the momentum exchange of main channel flow of the lotus-root-shape channel has larger weight than the straight channel. Determined by the combined effect of these two aspects, the vertical average velocity of the main channel of the lotus-root-shape channel is relatively smaller than that of the straight channel. For the floodplain, on the one hand, the momentum of the main channel water body in the lotus-root-shape channel used for the momentum exchange of floodplain has a larger weight. The unit water body on the floodplain of the lotus-root-shape channel gains more momentum than the straight channel. On the other hand, before momentum exchange, the floodplain water body of the straight channel already has a certain momentum, while the momentum of floodplain flow of the lotus-root-shape channel is very small. Therefore, the combined effect of these two aspects determines that the flow velocity of the floodplain of the straight channel is larger than the lotus-root-shape channel, but the difference between the two channels is relatively smaller than that of the main channel.

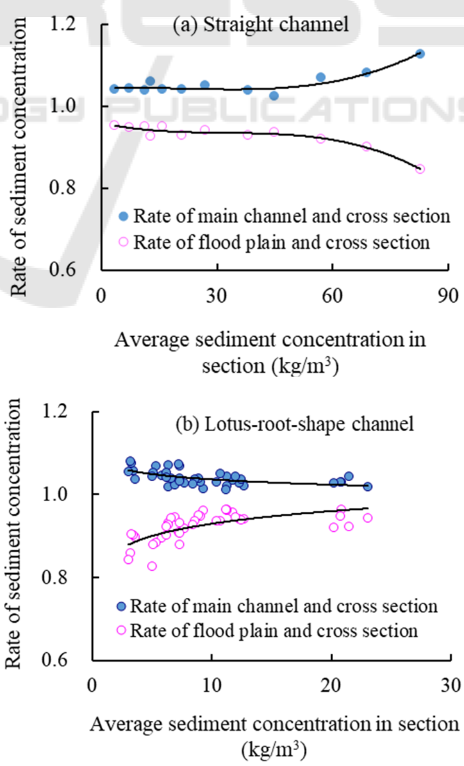

Figure 5: Relations among sediment concentration corresponding to main channel, floodplain and cross section.

4 COMPARATIVE ANALYSIS ON SEDIMENT CONCENTRATION DISTRIBUTION CHARACTERISTICS OF TWO TYPES OF COMPOUND CHANNELS

4.1 Average Sediment Concentration of Floodplain

The distribution of the average sediment concentration in the floodplain of the lotus-root-shape compound channel has certain similarities to that of the straight channel. In general, the average sediment concentration of floodplain is less than that of the main channel. However, the average sediment concentration ratio of the floodplain cross section of lotus-root-shape channels varies contrarily with the change of the sediment inflow and the straightness of the channel. As shown in Figure 5, the reason for this difference may be due to the different boundary characteristics of the two channels.

In the straight channel, the boundary is straight, the flow of floodplain and main channel has a certain capacity, and the momentum exchange occurs due to the different velocity of the two channels. Because the boundary is constant along the way, when the water body runs a distance, the water body between floodplain will reach a dynamic balance, the same is true of the movement of sediment in the water body of floodplain. In the straight channel, the water body of floodplain has a certain ability to independently carry sediment. Although the sediment in the water body of main channel will enter floodplain partially through the momentum exchange of floodplain, the sediment of floodplain also enters the main channel through the exchanges of water body. The average sediment concentration of floodplain is less than that of the main channel thus, the net transport of sediment in the main channel to floodplain occurs. Before the sediment concentration in the water body of floodplain reaches saturation, the average sediment concentration of floodplain is relatively small. Therefore, the sediment transported to floodplain from main channel is smaller compared to the sediment carried by the floodplain itself, which is negligible. In this case, since there is no obvious siltation in the water body of floodplain, the average sediment concentration of the floodplain changes little. Therefore, the ratio of the average sediment concentration of floodplain to the average sediment concentration of cross section changes little with sediment inflow. After the average sediment concentration of floodplain reaches saturation, as sediment inflow increases, the average sediment concentration of the main channel also rises, but that of floodplain cannot reach a significant increase due to saturation. Therefore, the ratio of average sediment concentration of floodplain to the average sediment concentration of cross section (reflecting sediment inflow) decreases as sediment inflow increases, and the ratio of average sediment concentration of the main channel to that of cross section increases as sediment inflow increases. As the sediment inflow increases, the siltation on floodplain increases, and the net sediment transported to the floodplain from the main channel increases. This also suppresses the increase in the average sediment concentration of the main channel and cross section to a certain extent. In the lotus-root-shape channels, the channel boundary is curved, and the flow cross-section of floodplain varies greatly. The boundary characteristics of the lotus-root-shape compound channel determine that the momentum required for the movement of floodplain is mainly provided by water body of main channel. Similarly, the sediment carried by water body of floodplain is also provided by the sediment in the water body of the main channel. This means that with the exchange of water body of floodplain and the main channel will transport the net sediment to the floodplain. Such net sediment transport volume is the same order of magnitude as that in the water body of floodplain. Meanwhile, with the increase of sediment inflow, the net sediment transport from the main channel to the floodplain gradually increases. It can be seen that in the lotus-root-shape compound channels, part of the sediment in water body of main channel will be transported to the floodplain, and the sediment concentration of the main channel itself will also decrease, which is reflected in the ratio of average sediment concentration of the floodplain to that of the cross section, i.e., the ratio of the average sediment concentration of the floodplain to that of the cross section increases as the sediment inflow increases. The ratio of the average sediment concentration of the main channel to that of the cross section decreases as the sediment inflow increases. Before the sediment in the water body of floodplain is saturated, the average sediment concentration of the floodplain and that of the cross section vary greatly. After the sediment in the water body of floodplain reaches saturation, the sediment in the water body of floodplain will become silted. As the sediment inflow increases, the siltation on the floodplain gradually increases, which further suppresses the increase in the average sediment concentration of the main channel and the cross section, resulting in a decrease in the ratio of the average sediment concentration of the floodplain to that of cross section.

Figure 6 shows the relationship between the relative sediment concentration of the straight channel and the lotus-root-shape channel, the relative water depth and the relative flow velocity of floodplain. It can be seen from the figure that the average sediment concentration ratios of the straight channel and the lotus-root-shape channel both increase with the increase in the relative water depth of floodplain. However, the average sediment concentration ratio of the floodplain along straight channel increases faster with the relative water depth of the floodplain, while the width of the lotus-root-shape channel increases relatively slowly; the average sediment concentration ratio of the floodplain of straight channel and lotus-root-shape channel increases with the rise in relative flow velocity of the floodplain, while the amplitudes of the two channels vary little with the relative flow velocity of the floodplain.

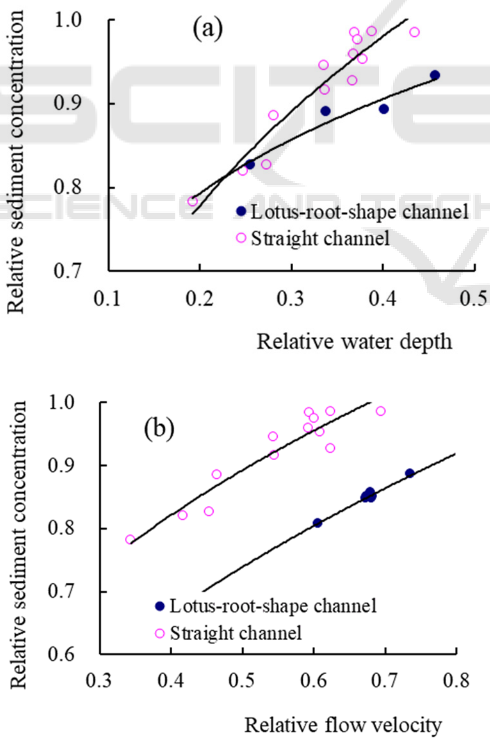

Figure 6: Relations among relative velocity, sediment concentration and depth for floodplain and main channel.

4.2 Distribution of Vertical Sediment Concentration

It can be seen from Table 1 that the vertical gradient of the sediment concentration of the lotus-root-shape compound channels is smaller than that of the straight compound channels. For the same river type, regardless of the straight channels or lotus-root-shape channels, the vertical average gradient of the average sediment concentration of floodplain is always significantly greater than that of the average sediment concentration of the main channel, and that of sediment concentration gradually increases from the vicinity of floodplain interface to both sides of the floodplain. It is shown that the vertical unevenness of the sediment concentration of the floodplain is rather larger than that of the main channel. Near the interface of the floodplain, this unevenness reaches a minimum value and gradually increases toward both sides.

Table 1: Transverse gradient changes of vertical average sediment concentration (kg/ m3.m).

Transverse distance (m)	0.00	0.08	0.12	0.15	0.25	0.35	0.45
Straight channel	22.12	19.79	19.42	70.08	96.15	100.65	121.81
Louts-root-shape channel	16.47	15.86	15.62	64.13	77.34	80.51	99.21
Ddifference between the two	5.66	3.93	3.80	5.95	18.82	20.14	22.61

5 CONCLUSION

By comparing the flow capacity of three types of channels, i.e., single channel, straight compound channel and lotus-root-shape compound channel, it is known that the single channel has the largest flow capacity, followed by the straight channel, and that of the lotus-root-shape channel is the smallest.

The velocity ratio and discharge ratio of straight channel and lotus-root-shape channel increase with the increase of the relative water depth of plain and channel, and the ratio of lotus-root-shape channel is greater than that of straight channel.

The distribution of sediment concentration in the floodplain of the lotus-root-shape compound channel is similar to that of the straight compound channel. However, the sediment concentration ratios of floodplain cross section of the two types show contrary change laws with sediment inflow.

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