A Method for Calculating the Flow and Sediment Distributions in the Interactive Regions between the Channels and Plains of Compound Channels

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Abstract: In the present study, on the basis of the generalized experimental data of compound channels, and the regional characteristics of flow and sediment movements, four regions were proposed according to the compound sections of channels and plains. These included the undisturbed regions in the main channels; interactive regions between the channels and the plains; undisturbed regions in the floodplains; and the boundary regions. The interactive regions between the channels and plains, which were characterized by the most complicated water flow regimes, were further divided into logarithmic flow velocity zones (inner zones) and non-logarithmic flow velocity zones (outer zones). Then, by introducing an S-shaped curve, a method for determining the boundary between the inner zones and outer zones was proposed. The water-sediment exchange intensity in the interactive region is higher than that in other areas, so it is a key point in the study of compound channel.

1 INTRODUCTION

Compound channels, which have obvious flood plains and main channels in their sectional morphology, are the most common pattern of manifestation of alluvial rivers. In China, the lower reaches of the Yellow River have the characteristics of a typical compound channel. The main stream is approximately 880 km in length and begins in Mengjin County. The channel is mainly composed of flood plains and a main channel. The flood plain area is approximately 3,500 km^2 and accounts for 84% of the total channel area (Hu et al., 2012). Under natural conditions, due to the alluvial characteristics of the channel, it has been observed that although the compound channel maintains the pattern of channel and plains areas in the section morphology, the location of its main channel often moves. These movements are often shown as swings of the channel onto the plains. This type of swinging action not only directly threatens the safety of the channel's regulation works, such as flood control dykes, but also brings adverse effects to such industrial and agricultural production processes as intake and drainage utilities, flood plain utilization processes, and so on (Zhang, 2017).

It has been accepted that the determination of the laws of flow and sediment movements in compound channels are very important problems in current engineering practices. Also, the results of such studies would be of great value in the theoretical development of river dynamics. The theoretical studies of flood plain flow structures can potentially promote the development of river dynamics and lay foundations for the study of the laws of flow and sediment movements in compound channels. At the present time, there are abundant research results available regarding the characteristics of clear water flow in channel-plain compound channels. These studies have mainly included the flow capacities of compound channels and the resistance characteristics of channels and plains (Hang, 2016; Rhodes & Knight, 1994), as well as the flow structures and turbulence intensities of channels and plains (Shiono & Knight, 1991; Tominaga & Nezu, 1991), flow velocities, distribution characteristics of flood plains (Tominaga & Nezu, 1991; Hu et al., 2010), and so on. Previously, many research achievements were made in the study of muddy water flow, which have mainly included the

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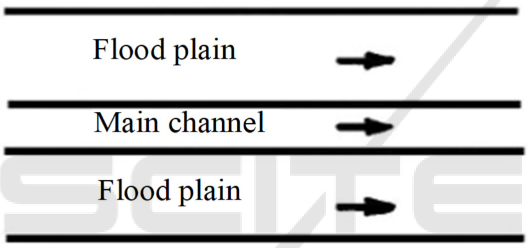
sediment concentrations and distribution characteristics of channels and plains (Hu et al., 2010; Edmonds et al., 2017; Armugha et al., 2018), and the sediment accumulations and distributions in channels and plains of natural channels (Liu et al., 2016; Chen et al., 1996; Ji et al., 2019). However, it was found that in the existing study results, there have been only a few studies conducted regarding the regional characteristics of the sediment and water distributions in the channels and plains of compound channels. Therefore, based on the experimental data and existing research results (Walling et al., 2015; Min et al., 2017), this study focused on the interactive regions of channels and plains, and proposed a method of determining the boundaries between the inner and outer zones, which would provide technical support and theoretical guidance for the planning and management of the plain areas of compound channels.

(a) Straight channel



(b) Compound cross-section

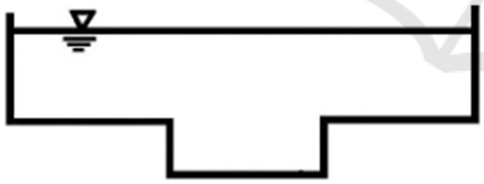


Figure 1: Structural form of the compound channel.

2 BASIC SITUATION OF THE EXPERIMENTAL AREA

In a previous related study, the author performed a large number of experiments regarding the distributions of flow and sediment in the channel and plain areas within a 30 m long self-circulating channel (Hu et al., 2010; Ji et al., 2019). The self-circulating plain consisted of a straight channel and wide-narrow alternating channels, and its sections were mainly rectangular sections. The beds of the channel and plain areas had a height difference of 0.06, and the bed and side wall of the channel were cement surfaces. The channel structure is shown in Figure 1. In the experiment, sections were compound rectangular sections, with the same widths as the main channel and height differences from the channel and plain areas.

During the experiment, the experimental water depths had ranged between 0.03 and 0.13 m, and the sediment concentrations had ranged from 4 to 83 kg/m^3. Fly ash was used in the experiment as the experimental model sand. The median particle sizes of the experimental model sand ranged between 0.014 and 0.056 mm; the specific gravity was 2,100 kg/m^3; and the non-uniformity coefficient was between 1.73 and 2.12.

3 REGIONAL HARACTERISTICS OF COMPOUND CHANNEL

Due to the height differences in the beds of the different channels and plains of the compound channel, the momentum transfers among the channel and plain flows tended to be obvious. The flow energy losses at the boundary areas of the channels and plains were found to be larger, and the flow capacities of compound channels had become obviously smaller than those of single rectangular channels of the same scale. According to the existing research results, the distributions of the flow and sediment in channels and plains had the following characteristics:

(1) From the average flow velocities of the channel and plain sections, it could be seen that the average velocities of the main channels and the entire sections of the compound channels first increased, then decreased, and then increased once again with the increases in the water depths. Meanwhile, the average velocities of the plain areas tended to increase monotonously with the increases in the water depths. The average sediment concentrations of the plain areas were less than the average sediment concentrations of the main channels. The ratios of the average sediment concentrations of the channel and plain areas had increased with the increases in the relative water depths of the channels and plains (Hu et al., 2010).

(2) It could be seen from the average velocities in the vertical direction that the lateral variations of the velocity gradients near the boundaries between the channels and the plains in compound channels tended to be large. Also, water flow exchanges characterized by strong momentum were observed between the main channels and the plains. The peak values of the

momentum exchanges between the channels and the plains had generally appeared near the boundaries between the channels and the plains, and then had gradually decreased toward both sides (Shiono et al., 1991). It was found that when the channel and plain areas were sufficiently wide, areas had existed where the lateral velocity gradients tended to remain constant in both the main channels and the plains. In those areas, the flow had basically not been affected by the momentum exchanges between the channels and the plains. Moreover, interactive zones of the channel and plain areas were evident between the two regions, in which the lateral gradients of the flow velocities had changed greatly, and the flow movements had strong three-dimensional characteristics. Correspondingly, the vertical mean gradients of the sediment concentrations had tended to gradually increase from the vicinities of the boundaries between the channels and plains to both sides of the channels and plains. The vertical heterogeneity of the sediment concentrations in the plain areas was found to be much greater than that of the main channels, which had been observed to reach minimal values near the boundaries of the channels and plains, and then gradually increase toward both sides of the channels and plains (Hu et al., 2010; Chen et al., 1996).

(3) From the perspective of the vertical distributions, the vertical velocity distributions of the water flow far away from the boundaries of the channels and plains and the boundary wall areas were less deformed. However, in the areas near the boundaries of the channels and plains, the vertical velocity distributions tended to be more deformed. The maximum velocities of the vertical velocity distributions on one side of the main channel were observed to be no longer at the surface of the water, but at certain depth levels below the water surface. On one side of the plain, the water velocities had gradually increased from the bottom to the surface, with the maximum velocities still observed on the water surface. In addition, the vertical velocities at certain depths from the bed surfaces had still obeyed the logarithmic distributions. However, outside of those ranges, the vertical velocities had tended to deviate from the logarithmic distributions, and the measured values on one side of main channel was consistently smaller than the calculated value of logarithmic formula. Also, the measured values on the plain side was consistently larger than the calculated value of formula. However, in the transverse direction, the differences between the measured values and calculated values of the flow velocities had reached the maximums at the boundaries of the channels and plains, and those differences had then gradually decreased toward one side of the main channel or plain. In the vertical direction, the difference between the measured values and the calculated values was zero at a certain water depth from the bed surface and had gradually increased in an upward direction to reach the maximum near the water surface (Hu et al., 2010).

Therefore, from the aforementioned research results regarding the flow and sediment movements in a compound channel, it could be ascertained that obvious regional characteristics had existed in the sectional distributions.

4 DETERMINATIONS OF THE INTERACTIVE ZONES IN COMPOUND CHANNEL

4.1 Zoning of the Compound Sections in Compound Channel

In the current study, in accordance with the movement characteristics of the flow in the channels and plains of a compound channel, a cross-section of the flow of the compound channel was divided into four regions as follows: 1. An undisturbed region of the main channel (Region I); interactive region between the channels and plains (Region II); undisturbed region in the floodplains (Region III); and a boundary region (Region IV), as detailed in Figure 2. Moreover, the formula (Hu et al., 2010) which was used for calculating the width of each region is also presented in Figure 2. In the formula, h_d represents the bed height differences of the channels and plains; b_{mo} is the width at one side of main channel in the interactive zone of the channels and plains; b_{fo} is the width at one side of plain in the interactive zone of the channels and plains; $Z_{I\text{-}II}$ indicates the transverse coordinates of the boundary of the undisturbed region in the main channel and the interactive region between the channels and plains; $Z_{II\text{-}III}$ is the transverse coordinates of the boundary of the interactive region between the channel and plain areas and the undisturbed region in the flood plain; and $Z_{III\text{-}IV}$ indicates the transverse coordinates at the boundary between the undisturbed region in the flood plain and the boundary region.

In view of the regional characteristics of the flow and sediment distributions in compound channels, especially in the most critical interactive zones between the channels and plains (Walling et al., 2015), the interactive zone between the channels and plains was further divided into a logarithmic velocity zone (inner zone) and a non-logarithmic velocity zone (outer zone). The boundary of those zones is indicated by αH in Figure 3.

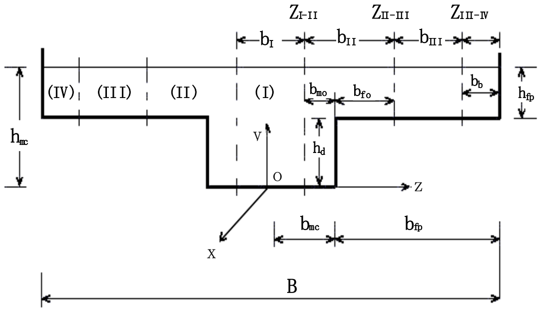


Figure 2: Schematic diagram for the sectional zoning of a compound channel.

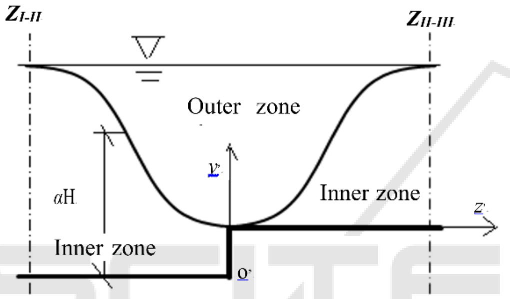


Figure 3: Schematic diagram for the velocity zoning in the interactive zone between the channels and the plains of a compound channel.

4.2 Determination of the Boundary between the Inner and Outer Zones in the Interactive Regions

In the present study, from the characteristics of the vertical velocity distributions of the water flow, it could be seen that the boundary between the inner and outer zones of the channel-plain interaction zone was basically an "S" type distribution (Walling et al., 2015) in the main channel and plain areas. For that reason, an S-type curve was introduced for the purpose of demonstrating the boundary between the inner and outer zones of the channel-plain interaction zone (Hu et al., 2010; Liu et al., 2016; Chen et al., 1996; Ji et al., 2019). The formula (Wang & Guo, 1979) was as follows:

$$y = \mathrm{M}/(1+\mathrm{N}\exp(-\mathrm{C}z)) \tag{1}$$

Where M, N, and C are the undetermined coefficients larger than 0, when z = 0 and y = M/(1+N); and when it tends to be ∞, y = M. In order to facilitate the analysis process, the coordinate system was required to be appropriately transformed. The origin of the coordinate system was shifted from the middle position O of the main channel bed (Figure 2) to the peak O' of the boundary of the channel and plain areas (Figure 3). The coordinate variables were then accordingly transformed from y and z to y' and z'. After the coordinate system transformation was completed, the curve fitting was carried out according to the measured data of the main channel and plains, respectively. Then, for any three observational values (z1, y1), (z2, y2), and (z3, y3), the simultaneous equations were obtained by substituting Formula (1), respectively, and the following formula was obtained by setting z2 = (z1+z3)/2:

$$M = \left(y_2^2(y_1+y_3)-2y_1y_2y_3\right)\Big/\left(y_2^2-y_1y_3\right) \tag{2}$$

After the estimated value of M was obtained, Formula (1) was transposed and the following formula was obtained after taking the natural logarithm:

$$\ln\left(\left(M-y\right)/y\right) = \ln N - Cz \tag{3}$$

Then, if was set, Formula (3) could be transformed to a linear formula as follows:

$$\bar{y} = \ln N - Cz \tag{4}$$

Therefore, the conformity of y and z to the logistical equation (Zwillinger, 1997) can be obtained by the correlation coefficient of and z:

$$\gamma_{\bar{y}z} = SP_{\bar{y}z}\Big/\sqrt{SS_{\bar{y}}\cdot SS_z} \tag{5}$$

The regression statistics N and C can then be calculated using the following formula:

$$\begin{gathered} -C = SP_{\bar{y}x}/SS_x \\ N = \exp(\bar{y}+C\bar{x}) \end{gathered} \tag{6}$$

Then, according to the above-mentioned linear processing method, the data at the turning point of one side of main channel at the boundary of Z_{I-II} and O', as well as at the boundary between the inner zone and outer zone; or the data at the turning point at one side of plain at the boundary O' and Z_{II-III}, as well as the boundary between the inner zone and outer zone, respectively, which could be substituted into

Formulas (2) and (6), for the purpose of fitting and calculating the M, N and C values. Therefore, the formula for the calculation of the boundary between the inner and outer zones of the interactive region of the channel and plain areas could be successfully obtained as follows:
For the main channel:

$$y'/H_{fp} = 1.0046/\left(1+99.4571\exp\left(9.9877z'/b_{mo}\right)\right) \quad (7)$$
$$-b_{mo} \le z' \le 0$$

For the plain areas:

$$y'/H_{fp} = 1.0104/\left(1+100.04171\exp\left(-9.1699z'/b_{fo}\right)\right) \quad (8)$$
$$0 \le z' \le b_{fo}$$

Where b_{mo} and bmo represent the widths at one side of main channel and plain in the interactive zone of the channels and plains, respectively; H_{fp} is the water depths of the plain areas; and y' and z' are the vertical and lateral coordinates with the boundary between the channels and plains as the center of the circle. The fitting results of boundary of the interactive zone between the main channels and plains in the interactive zone of the channel and plain areas are shown in Figure 4.

In combination with the results detailed in Figures 2 and 3, it could be seen that αH represented the distance from the boundary between the inner and outer zones of the channel and plain areas interactive zone to the bed surface of the channel. As detailed in the figures, one side of the main channel was represented by $\alpha H = h_d + y'$, and so on. The sizes of the boundary values of the inner and outer zones could then be expressed using the following formula:

$$\alpha_{mc} = \left(y' + h_d\right)/H_{mc} \quad (9)$$
$$-b_{mo} \le z' \le 0$$

Where H_{mc} indicates the water depth in the main channel and is y' in the calculation results of Formula (7). For the plain areas, the sizes of the values of boundary between the inner and outer zones could be calculated using the following formula:

$$\alpha_{fp} = y'/H_{fp} \quad (10)$$
$$0 \le z' \le b_{fo}$$

Where y' is calculated according to Formula (8).

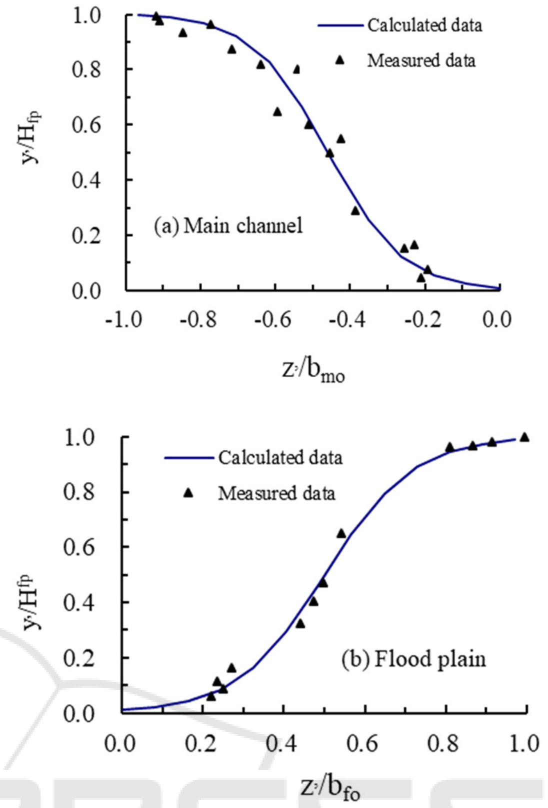


Figure 4: Comparisons between the calculated and measured values of the boundary between the inner and outer zones of the interactive zone of the channel and plain areas.

5 CONCLUSIONS

The flow and sediment movements of the channels and plains in the examined compound channel had displayed obvious regional characteristics. Therefore, in accordance with those observed characteristics, the compound sections of the channels and plains could be divided into the following: An undisturbed region in the main channel; interactive region of the channels and plains; undisturbed region in the flood plain; and the boundary wall region. The interactive region of the channels and plains which had best reflected the flow and sediment distribution characteristics of the channels and plains included the logarithmic velocity zone (inner zone) and the non-logarithmic velocity zone (outer zone). It was found that the vertical distributions of the water flow in the inner zone had followed the logarithmic velocity formula. Also, the velocity of water flow on the side of the main channel in the outer zone was observed to be lower than the calculation results of the logarithmic formula, while that on the side of the plain area was found to be larger than the calculation results of the logarithmic formula. Therefore, based on these findings, the boundary between the inner zone and the outer zone had been successfully determined in this study. Then, by introducing an S-shaped curve, the calculation formula of the boundary was deduced, which provided a clear basis for the control and management of the channel and plain areas.

This study's analysis results of the different zones indicated that the interactive zone of the channels and plains should be considered as the key point for the regulation and management of a compound channel.

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