地理学报(英文版) 2001年第11卷第3期

Relationship between energy dissipation rate and channel morphology in the development of the model braided channel

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Abstract: A certain pattern of channel is the product of its self-adjustment under given boundary, discharge and sediment conditions. Based upon the principle of process-response model, an experimental study with 18 runs is carried out in LESRC. This paper is focused on the variation of the energy dissipation versus the channel morphology during and after the bedmaking process of braided channel. The results show that there exists a good empirical relationship between the energy dissipation rate and channel morphology. According to this relationship and the theory of minimum rate of energy dissipation, the authors explain the metamorphosis of the model channel with the development of the braided river.

Relationship between energy dissipation rate and channel morphology in the development of the model braided channel ZHANG Ou-yang, JIN De-sheng, CHEN Hao, GUO Qing-wu (Institute of Geographic Sciences and Natural Resources Research, CAS, Beijing 100101, China) 1 Introduction A certain pattern of channel is the product of its self-adjustment under given boundary, discharge and sediment conditions[1]. A lot of experiments have been performed in flumes, usually with an initially-regulated straight channel being constructed in the flume, to determine the impact of these conditions on channel morphologies and patterns[2-6]. Schumm´s experiments[3] demonstrated that when the bed-load channels transport only sand at constant discharge, channels develop from straight, in turn, to meandering-thalweg, alternate bar, chute cutoff, and then to braided channels as slope and sediment load increased. Further, Ni Jinren[4] generalized that under any boundary conditions and any initial slope, an initially-regulated straight channel always develops, sooner or later, without exception through meandering-thalweg channel to meandering channel with alternate bar. And then whether it keeps meandering or develops to braided channel is largely dependent on its boundary conditions. Our experiments also showed the same results[6]. But a proper explanation of why the initially straight model channel in the flume will develop in this way is still needed. Based on the experiment data, this paper tries to answer this question following the theory of minimum rate of energy dissipation[7]. 2 Outline of the experiment The experiments were carried out in the Lab of Experiment and Simulation in River and Coast (LESRC). The approach of process-response model which made river channel by controlling boundary conditions, valley slope, water discharge and coming sediment load[5] was adopted to design the experiment. There were three groups of the experiments altogether. The first group, the bedmaking experiments, had seven runs (I-1-I-7) beginning with an initially made straight channel and with constant discharge-bankful discharge, sand feed and median diameter of 1.5 L/s, 0.6 g/s and 0.142 mm in each run respectively. It took 80 hours for the model channel to develop from the originally straight channel to the braided channel[6]. The discharges in the second group (II-1-II-4) were larger than the bankful discharge, and the ones in the third group (III-1-III-7) were smaller than the bankful discharge. The experiment conditions are listed in Table 1. Table 1 The water and sediment feed conditions of the experiment 3 Results 3.1 The variation of the energy dissipation rate The unit stream power[8] has been simplified as follows[1]: where E is the unit stream power, U is the mean velocity, and J is the channel gradient. The unit stream power (E) is used as the index of the energy dissipation rate and plotted in Figure 1. From Figure 1 the variation process of the energy dissipation rate in the experiment can be seen. Given the constant bankful discharge of 1.5 L/s, the channel has the highest energy dissipation rate when it still keeps straightt, then the energy dissipation rate begins to decrease when the width, sinuosity of the channel increase and the slope decreases, and the energy dissipation rate attains its minimum value when the sinuosity reaches its maximum value a t the point of 28 hours. After that, when a threshold is encountered, the energy dissipation rate begins to increase with the channel widening and braiding. Eighty hours later, the feed water and sediment discharge are increased, and accordingly, the energy dissipation rate increases quickly. And 100 hours later, when the discharge is decreased to that smaller than the bankful discharge, the energy dissipation rate decreases accordingly. After run III-3, the discharge is nearly a constant, but the energy dissipation rate still decreases gradually and tends to a minimum value. The variation of the energy dissipation rate is the result of the adjustment of the channel morphology, which is the response to the particular water and sediment discharge and certain boundary conditions of the channel. 3.2 The relationship between the energy dissipation rate and the channel adjustment The energy dissipation rate can be figured out with simultaneous equations of the Maning and the flow continuum as follows: where n is the roughness, B is the channel width, and Q is the discharge. Following the way of equation (2), the experiment data from I-1 to III-4 can be expressed as the following empirical equation: The equation (3) preferably reveals the relationship between energy dissipation rate and channel morphology adjustment (Figure 2). The theoretical equation (2) and the empirical equation (3) have the same mode, and their exponents of the independent variables are the same except that the exponent of J has minor discrepancy. These two equations show that the results of the experiment are in accordance with the theoretical analysis. From Figure 3a we can see that the energy dissipation rate increases, accordingly, with the increasing discharge except run I-1 at which the energy dissipation rate is apparently higher than ordinary values because of the influence of the straight, steep, deep and the narrow initial channel. The variation of the energy dissipation rate is mainly decided by the variation of the velocity according to equation (1). And the velocity is influenced mainly by the roughness. The relationship of the energy dissipation rate versus the roughness (n) can be expressed as follows: Equation (4) means that with the increasing of the roughness, the energy dissipation rate decreases exponentially (Figure 3b). The relationship between the energy dissipation rate and the variation of width is somewhat complex. At constant bankful discharges, the energy dissipation rate decreases with the channel widening first, then it increases with the increasing width after a minimum threshold being encountered. When the discharges increase, the energy dissipation rate increases with the increasing channel width (Figure 3c). There exist similar relationships between energy dissipation rate and the channel cross-section morphology index and the channel gradient (Figure 3d, e, f). The relationship between energy dissipation rate and the sinuosity (p) is that there exists a tendency of the energy dissipation rate decreasing with the increasing sinuosity. And this tendency is more apparent under constant discharge. The relationships stated above reveal that the relationship between energy dissipation rate and the single morphological variable is not always simply the increasing and decreasing relationships, but may be the nonlinear relationships. The adjustments of the channel morphological variables usually interact and inter-constrain on each other. They become complicated through the feedback and time lag processes. The channel morphological variables in Figure 3 usually interact on each other synthetically and they all have impacts on the variation of the energy dissipation rate. Figure 3 Relationship between the energy dissipation rate and the channel morphology 4 Mechanism of channel metamorphosis along with the energy dissipation rate According to the theory of minimum rate of energy dissipation, there exists a self-adjustment of the channel to transport water and sediment with a tendency of minimum rate of energy dissipation under given constraint conditions. From equation (2) or (3) one can find out that under given water and sediment discharges, the channel can attain this minimum value by three ways: (1) Increasing channel resistance; (2) decreasing channel slope; and (3) increasing channel width. If the channel adjusts dominantly by increasing channel length, decreasing slope to reduce its energy dissipation rate, the channel will develop meandering; if it adjusts mainly by increasing width, the channel will develop braided[1]. The channel will develop to what pattern is mainly dependent on the channel boundary conditions. The mechanism of the channel developing from the initially straight to meandering and then to braided will be explained with the experiment data based on the theory of minimum rate of energy dissipation. An unbraided channel flowing from the inlet to the outlet may follow one of the three courses: straight, zigzag, or meandering. But the only possible way is a sinuous one according to the theory of minimum rate of energy dissipation[9]. From run I-1 to I-4 in the experiment, the developing of the model channel from straight to meandering-thalweg is the result of the decreasing of the energy dissipation rate. The sinuosity reaches its maximum value when the energy dissipation rate decreases to its minimum value. At this point, the channel decreases its energy dissipation rate by the ways of increasing channel width and decreasing channel gradient, from which the latter is the dominant way (Figure 3d, c). The decreasing of the channel gradient is fulfilled by increasing channel length, and as a result, increases the sinuosity (Figure 3f). At the same time, the channel also adjusts its morphologies, such as increasing width-depth ratio (Figure 3e) and increasing channel resistance by forming alternate bars, to decrease its energy dissipation rate. Figure 1 shows that under the same boundary constraint conditions, the energy dissipation rate in sinuous state is the lowest. The river in meandering state is the embodiment of equilibrium[10]. Thus, to meet the minimized energy dissipation rate and to reach a quasi-equilibrium state, the model channel in the experiment developing from straight to the meandering-thalweg one. The boundary conditions of the model channel in the experiment are somewhat loose, so that the bank can be easily eroded and thus produces too much sediment. When the channel couldn´t carry the sediment load, it would aggredate with excessive sediment[6]. Therefore, this quasi-equilibrium in the experiment is temporary and unstable. When the width increases to a critical point, a further increase will result in a decrease in depth. This will lead to a decrease in flow velocity so that the stream is unable to carry the necessary sediment load. As small streams in general have steeper slopes and shallower depths than large streams, they should have a larger rate of potential energy loss per unit water along their courses of flow. So, at this point the channel will divide into smaller but steeper channels and will thereby keep a balance between sediment inflow and outflow. That is, channel braiding is likely to occur where the channel width exceeds that necessary to carry the given discharges[11]. According to this theory, in order to increase the sediment carrying capacity and tend to a new equilibrium, from I-4 to I-7 in the experiment, the model channel increases its rate of energy dissipation (Figure 1). The increasing of the energy dissipation rate is fulfilled by change channel morphological variables. At this point, the channel increases its width and width-depth ratio (Figure 3c, e) and thus provides the conditions for braiding. When the width increases to exceed a critical point, the channel braided. The braiding of the channel increases the channel slope and decreases the stream sinuosity. Thus, the channel increases its rate of energy dissipation successfully by adjusting its channel morphology to carry the necessary sediment load. Because the anti-erodisity of the bank and the point bar is lower, they can be easily eroded and change their morphological variables. As a result, the alternate bar that is necessary for the meandering river couldn´t keep for long. Under new conditions of braiding, the channel also has a tendency of minimizing its rate of energy dissipation. In order to decrease its rate of energy dissipation effectively, the channel increases mainly its width (Figure 3c) and forms midbar to increase channel roughness. Thus, the braided channel formed. 5 Conclusions This paper showed the variation of the energy dissipation rate in the channel development process and gave an explanation to the channel developing initially straight to meandering and then to braided channel. The formations of the meandering and braided channel patterns are the results of the channel to carry 456+necessary sediment load with minimizing rate of energy dissipation. Many experiment models especially the process-response model[5] often construct model channels to meet the prototype beginning with initially straight channels and then controlling the feeding water and sediment discharges to let the channels develop to the target channel patterns under the prepared given boundary conditions. Previously, the water discharge and sand at the entrance was often determined by trial and error[2]. The relationship between the rate of energy dissipation and the channel metamorphosis in this paper can serve as a theoretical basis for debugging the feeding sediment and water discharges and constructing target model channel in the experiment. The experiment results also confirm the theory of minimum energy dissipation rate [9,11] that there exists a minimizing tendency of energy dissipation rate in the evolution of the alluvial channel. This explanation of the formation of braided channel is also in agreement with the theory analysis[12]. References

关键词： energy dissipation rate; channel morphology; braided channel development; experimental study