Sediment Transport Mechanism and Grain Size Distributions in Stony Bed Rivers

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ABSTRACT

The riverbed elevation of stony-bed rivers is controlled by boulders and cobbles. The authors have determined the mechanism of riverbed variation, characteristic grain size groups, and riverbed stability in stony-bed rivers from the results of field experiments on straight channels conducted in the Joganji River .

In this study, we analyzed the results of field experiments using a meandering channel of the Joganji River. We examined characteristic grain-size distribution in meandering rivers with boulders and cobble and effects of meander and bank revetment on riverbed elevation and grain size distribution. Furthermore, we determined dimensionless physical parameter governing the forming of stable cross-sections in stony-bed rivers.

1. Introduction

To implement effective and efficient countermeasures to bed scouring and bank erosion in a stony-bed river, it is first necessary to understand how boulders and cobbles give effects the river's bed elevation and grain size distribution. In 2004 and 2005, we carried out large-scale field experiments using straight channels dug into a sandbar on a typical Japanese stony river, the Joganji, determining the bed variation mechanism and characteristic grain size distributions at various discharges, as well as the mechanism of bed stabilization brought by boulders and cobbles (Kuroda et al. 2005, Fukuoka et al. 2007).

A stony-bed river ordinarily has a complex planform, the result of repeated divergence and rejoining of the main water route. In such rivers, bank revetments are often built to prevent bed scouring and bank erosion where the water route is close to the bank. To minimize damage in and near rapidly flowing sections of stony-bed rivers, it is critical to develop the capability to predict bank erosion and local scouring by clarifying the mechanism of water route formation and the effect of revetment bank on bed elevation and bed grain size distribution.

In this paper, the authors first use data from field experiments conducted in the Joganji River in 2006 to consider differences in bed elevation and characteristic grain size distribution in a meandering stony-bed river where revetment bank is in

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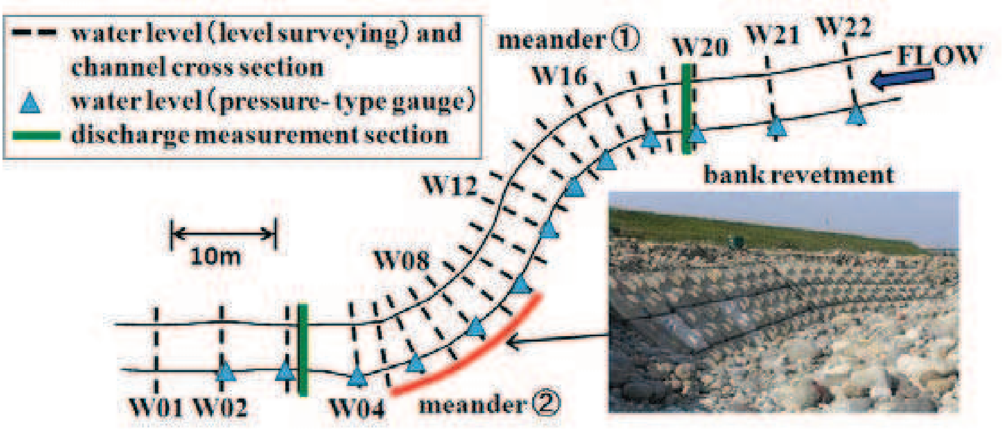


Figure1. Plan view of the test channel

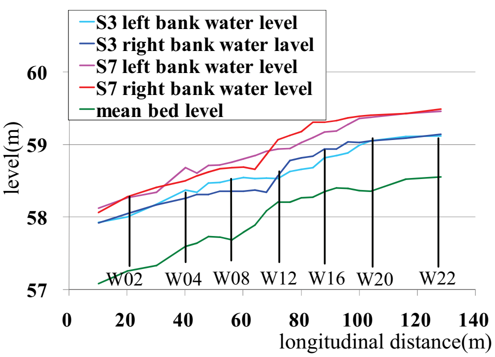


Figure2. Longitudinal distribution of water level and mean bed level

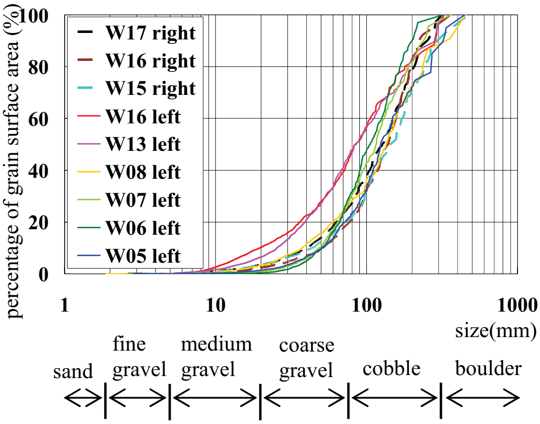


Figure3. Bed material grain size distribution by the surface image analysis

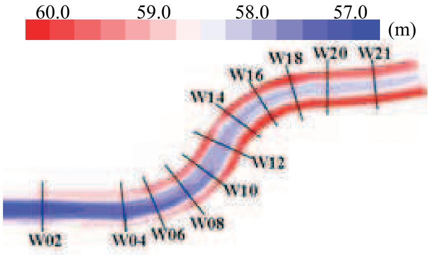
place versus those without revetments. Next, we examine the results of all previous Joganji river field experiments to consider the stable cross-section of stony-bed rivers.

2. Field Experiments in the Joganji River

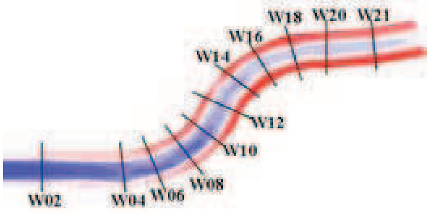
Figure 1 is a top view of the meandering waterway. This waterway contained two meanders and was dug into a sandbar at the 11.1 km point in the Joganji River. Meander 1 contained natural riverbanks, while revetments were built along the outer bank of meander 2. We measured water level, discharge, bed cross-section, and bed grain size distribution, the last of which was measured with surface image analysis and sieve analysis. As the experimental waterway was made of actual bed material, we released a discharge with a unit width discharge equivalent to the annual mean discharge of the Joganji river, and measured longitudinal distribution of water levels and discharge at the point where the channel achieved stability at that discharge. After

Table 1. observed discharge

case	S1	S2	S3	S4	S5	S6	S7
Observed discharge at the upstream (m^3/s)	4.0	6.3	10.9	3.9	9.9	15.3	15.4
Observed discharge at the downstream (m^3/s)	2.8	5.7	10.1	3.1	10.7	15.0	16.3



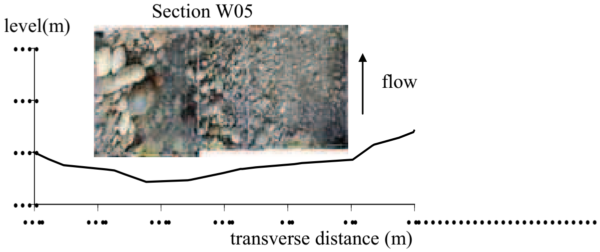
after flow S3 experiment



after flow S7 experiment

Figure 4. Bed elevation contour

Section W05



Section W16••

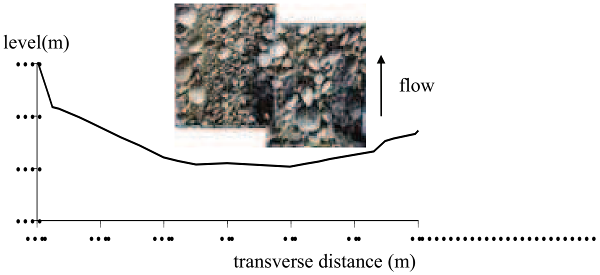


Figure5. Bed cross-section and bed surface photograph

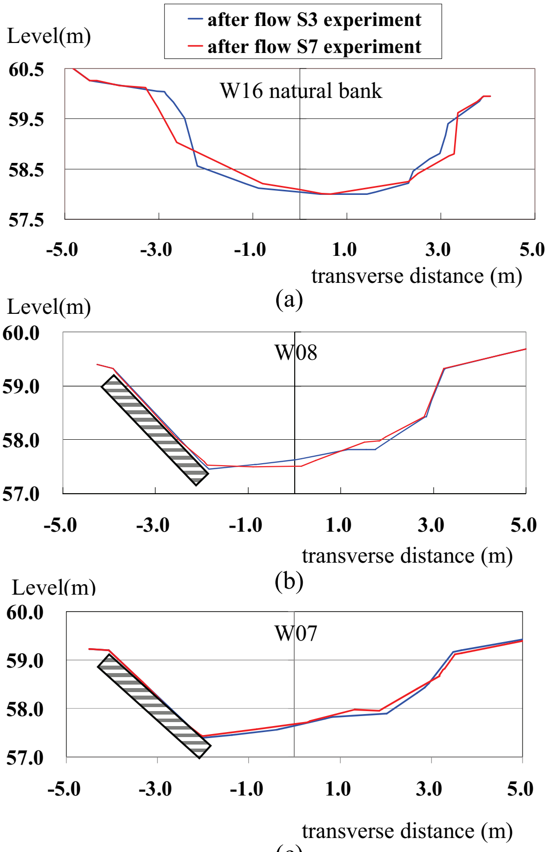
flow experiment S3 (discharge approx. 10 m^3/s) and after the experiment S7, at which maximum discharge was approximately 15.5 m^3/s, we drained the waterway by sealing off the waterway's upstream end, then performed bed cross-sectional surveying.

Figure 2 shows the longitudinal distribution of water level and mean bed elevation. The bed slope was 1:90 overall and increased at the transition points in meanders 1 and 2. As shown in Table 1 (observed discharge), discharge at the upstream discharge observation cross-section was 10.9 m^3/s for flow S3 and peaked at 15.4 m^3/s for flow S7. In Figure 3—the distribution of bed material grain sizes in the meanders as calculated with surface image analysis—we see that grain size varied from small gravel 2 mm in diameter to large stones 50 cm in diameter. Because of the differences in bed profile and bed materials between the inner and outer banks of the meanders, grain size distribution was calculated separately for the left and right banks, taking bed transverse slope into account. As seen in Figure 4—bed elevation contour after flow S3, flow S7,—we see that during flow S3, a characteristic channel shape of a meander flow formed. Particularly in meander 2, which contained revetments, localized scouring occurred on the revetment face, with sediment accumulation along the inner bank. It is also apparent that in meander 1, which is formed by natural banks, more bank erosion was caused by flow S7 than by flow S3. It also shows that along natural bank, sediment caused by bank erosion accumulated at the locations of localized scouring. Figure 5 shows the bed cross-section and a bed surface photograph for locations W05 and W16. These show that the large-diameter bed materials are all aligned in the downstream direction (i.e., in a flattened state). This is because the force from the flow causes the stones to align in the same orientation as the flow, making it smaller for resistance to act on them. Large-diameter materials were predominant at the outer banks of the meanders, smaller-diameter materials at the inner banks. Along the left bank at location W05, the revetment prevented bank erosion, although bed elevation dropped at the base of the revetments. Along the left bank at W16, the natural bank was eroded, and sediment was deposited on the bed, resulting in a bed smoothly sloping in the transverse direction from the outer bank. This demonstrates that in a sufficiently wide river with sufficiently large bed materials, the relationship between bed shape and bed materials clearly reflects the flow conditions.

3. Mechanism of Channel Formation in Stony-Bed Rivers

(1) Characteristic Grain Size Distribution in Meandering Stony-Bed Rivers

Using the results of field experiments, this section discusses the effects that channel alignment and revetments have on the bed profile and bed grain size distribution of a stony-bed river. From grain size distribution in the meander reach (Fig. 3), we see that along an outer natural bank, grain size is large overall, with little fine-grained material, while large amounts of fine-grained sediment accumulated along the inner bank due to secondary flow. We also see that along a revetment, in contrast, grain size was smaller overall compared to that observed along natural outer banks. In addition, the bed material at W08 and W05 differed from that of other revetment locations in that it exhibited a distribution shape approximating that of a natural bank. Figure 6 shows the channel cross-sectional shape at W07 and W08—where revetments were built—and at W16—the site of natural banks. At meander 1 (natural bank), the friction velocity was 0.5 m/s, indicating stronger friction force at work than in the straight section upstream. Along a natural bank, the earth that falls into the waterway due to bank erosion caused by this large fluid force results in a less steep transverse slope [Fig. 6(a)]. Repetition of this process at various discharges ultimately results in a stable channel like that shown in Fig. 7(a). When earth containing cobbles and boulders are deposited into the waterway from the banks in this state, static equilibrium results, and the bed comes to exhibit a broad grain size distribution. Static equilibrium is a state in which even small-diameter bed materials remain in place; this is due to the absorption of the tractive force by large-diameter materials capable of withstanding it and which are exposed on the bed surface by bed and bank scouring. In meander 2 (revetment bank), the friction velocity along the revetment was a high 0.7 m/s, and the main flow velocity line ran close to the revetment. Despite local scouring [Fig. 6(c)] at the revetment face due to

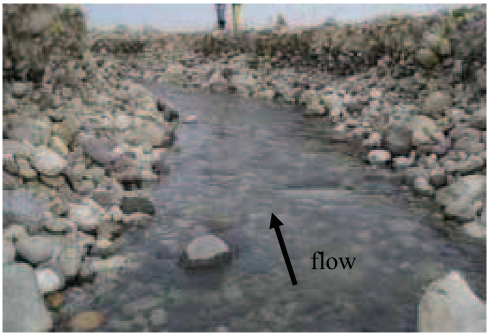


(a)

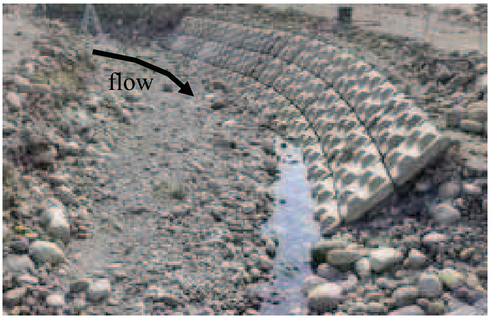
(b)

(c)

Figure 6. Channel cross-sectional



(a) natural bank



(b) revetment bank••

Figure 7. Stable-state channel

concentration of the flow there, exposure of large-diameter bed materials caused scouring to stop, resulting in a stable state like that shown in Figure 7(b). In this case, because the revetment prevents the transport of earth and rock away from the bank, the bed contains smaller-diameter material than along a natural bank, to which sediment is continuously transported from upstream.

At point W05—the boundary between the revetment banks and natural banks—the proximity of the fast flow to the outer bank due to the revetment [Fig. 7(b)] caused significant erosion to the natural bank just downstream from the transition point, indicating the severe erosion occurring there—as is well known to occur at the boundary between a hard revetment and a soft natural bank. In this case, the grain size distribution widened and a stable bank resulted due to the deposition onto the bed of large rocks along with other material freed up by bank erosion.

Thus, the channel shape of a stony-bed river is determined by large rocks on the bank and the bed. In addition, differences in the mechanism of sediment transport arising from channel alignment and the presence of revetments also affect bed shape and the grain size distribution of bed materials.

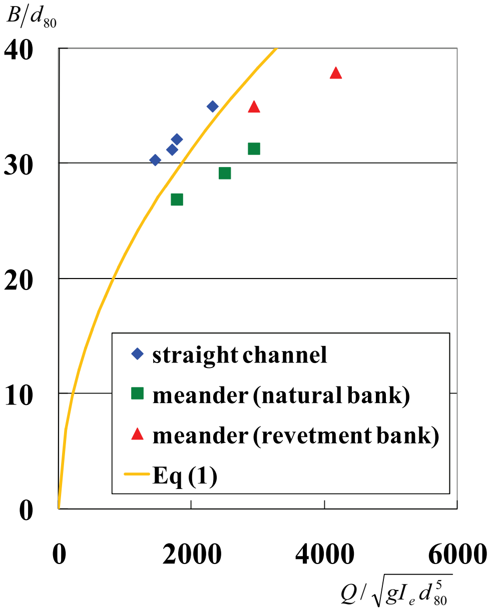


Figure 8. Relationship between the discharge and surface width of stony-bed river

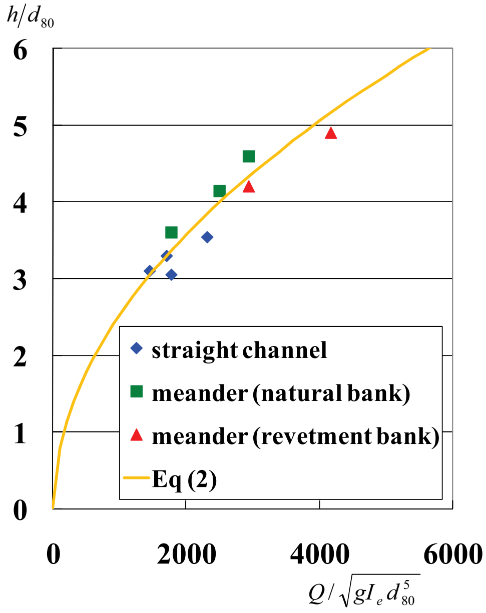


Figure 9. Relationship between the discharge and depth of stony-bed river

(2) The Stable Channel Cross-Section of a Stony-Bed River

In general, the cross-sectional form of rivers is determined largely by dynamic relation of discharge Q, slope I, and bed material d. This section considers the mechanism by which the cross-section of stony-bed rivers is determined. Ikeda et al. (1986) have investigated the stable cross-sectional shape of gravel-bed rivers.

Dimensionless consideration of the above dynamic relation leads to Eq(1) and Eq(2) for the width B and depth h respectively:

$$B/d_{80} = 0.7\left(Q/\sqrt{gI_e d_{80}^5}\right)^{0.5} \tag{1}$$

$$h/d_{80} = 0.08\left(Q/\sqrt{gI_e d_{80}^5}\right)^{0.5} \tag{2}$$

Figure 8 shows the relationship between the dimensionless discharge and dimensionless width of a stony-bed river. Also shown in the figure are the results of experiments conducted in straight stony waterways. The horizontal axis shows dimensionless discharge based on discharge Q, representative grain diameter d_{80}, and energy gradient I_e; the vertical axis shows dimensionless width based on d_{80}. As the representative grain diameter, d_{80} is used because the bed of a stony-bed river is stabilized by the presence of stones and other large-diameter bed material (Kuroda et

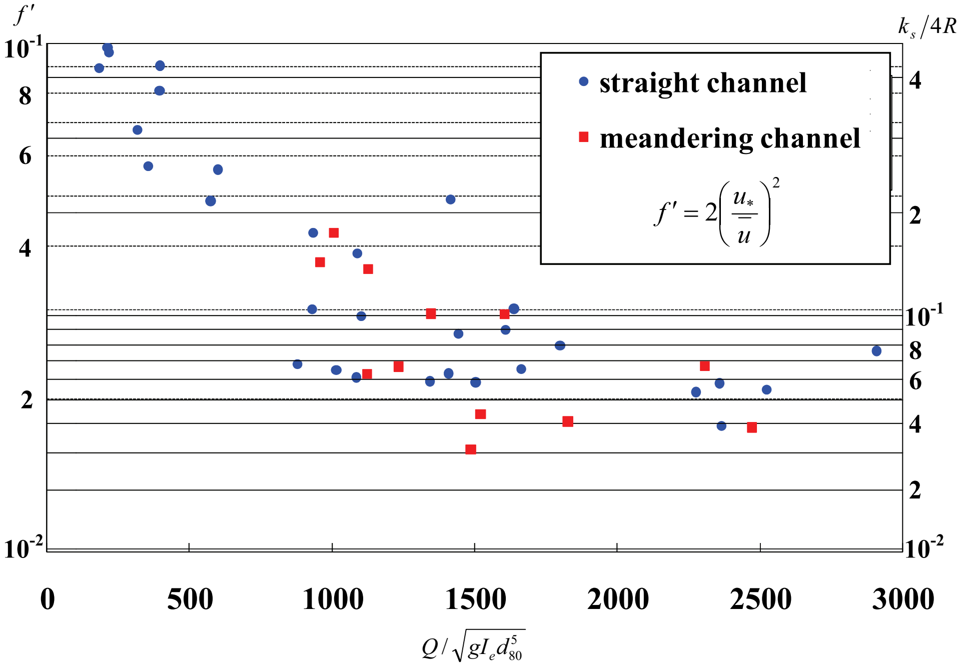


Figure 10. Resistance diagram of the flow in stony-bed river

al. 2005, Fukuoka et al. 2007, 2008) . Although d_{90} is preferable, we chose d_{80} because of the poor precision of calculation that would result from d_{90} due to its low percentage of the total. Trends are seen nearly same between straight natural-bank channels and meandering natural-bank channels. A little difference is believed to be due to the larger grain sizes found in meandering natural-bank channels owing to the large stones deposited there by bank erosion. In addition, we obtained larger values for dimensionless discharge and dimensionless width for meander sections with revetment banks than for straight sections without revetment banks. This difference is because revetments prevent the supply large stone-containing earth from the banks, resulting in relatively smaller bed material grain sizes compared to natural banks. Figure 9, which like Figure 8 plots dimensionless discharge on the horizontal axis and bed material–derived dimensionless depth on the vertical axis, shows that in both straight and meandering sections, dimensionless depth increases with dimensionless discharge. These values correspond to the region where the resistance coefficient f’ remains constant on the resistance graph for stony-bed rivers as shown Fig.10. This is thought to reflect that with the exposure of rocks effecting static bed stability, it is the resistance of stones that primarily determines the depth of flow.

To summarize the mechanism of channel formation in stony-bed rivers as discussed above: As discharge increases, small-diameter bed material is moved by the flow’s tractive force, resulting in bed scouring, which eventually exposes large stones, creating large bed irregularities. By absorbing the flow’s tractive force, the large stones help create static equilibrium and a broad grain size distribution. When discharge increases further, the river attempts to achieve stability by increasing its cross-sectional area through bank erosion rather than bed scouring owing to the near stability of the bed due to the large stones. As more and more stone-containing earth falls into the river due to bank erosion, the bank side slope becomes less steep. The large rocks supplied by bank erosion also help achieve static equilibrium and stability at the bank side, as well. Particularly in a meander, where fluid force is stronger than in a straight section, bed scouring is severe, and more sediment is also deposited onto the bed, resulting in larger grain sizes than in a straight section. At this stage, a static, stable cross-sectional shape in which both bed and bank are unchanging takes form. If revetments are in place, the flow will cause bed scouring in front of them, but the exposure of large stones will eventually stop scouring so that stability is achieved. Because revetments prevent the supply of large stone-containing earth from the banks, bed materials have a smaller grain size distribution compared to sections with natural banks. When discharge is even greater, the same series of processes is repeated, widening the river and eventually achieving a stable water channel.

5. Conclusions

The stones and other large-diameter materials in a stony-bed river create static equilibrium, and differences in sediment transport—particularly in a meander or along revetment banks—have been shown to effect both bed shape and bed material grain size distribution. In addition, we derived the relation of dimensionless width and dimensionless depth versus dimensionless discharge which is related to discharge, slope and representative bed material sizes of stable-bed rivers.

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