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INFLUENCE OF BED MATERIAL, BANK HEIGHT AND BOUNDARY SHEAR STRESS ON VOLCANIC ASH SOIL BANK

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ABSTRACT

Volcanic ash soil is widely scattered in Hokkaido, and numerous river banks are formed by volcanic ash. Although volcanic ash is generally considered susceptible to erosion, there have been few studies on rivers with volcanic ash banks. As a result river channels with volocanic ash banks are maintained similarly to those with sand banks, which may result in poor safety and flood control. To study the mechanism of erosion in river channels with volcanic ash banks, a relation between the erosion process and the shear stress is investigated in a largescale straight flume,

INTRODUCTION

Increasingly, with a view toward preservation of natural river environments, attention is being paid to approaches, methods, etc., in river-related works projects, and, thus, to the reality of river-bank erosion. If bank erosion occurs during flooding, it can lead to various disasters, and studies on the prevention and control of river-bank erosion have been conducted. In actuality, however,what has been found from experimental efforts has not always corresponded to what occurs on actual rivers. The major differences between on-site and experimental phenomena are due to differences in scale. Some erosion-related phenomena simply cannot be understood from laboratory tests because of the small scale; yet few erosion tests using sufficiently large-scale watercourse models have been conducted. Now that the need to incorporate the natural environment into improvement works is greater than ever, tests with appropriate bed materials on an appropriate scale are required, in order to understand the true causes and mechanisms of erosion.

In this study erosion tests were undertaken using a large-scale, straight channel with different bank heights, bed materials and boundary shear stresses, in order to understand sediment transport in the erosion process that could not be fully reproduced in laboratory tests, and to understand the factors that affect the cross-sectional shape of river channels undergoing erosion. Comparisons focusing on differences in bank height, bed material and boundary shear stress are presented below.

TEST OF CONDITIONS

A series of tests were undertaken at a large-scale, straight, outdoor channel made of concrete, shown in Photo-1. The of the course was about 4 meters, and length was about 40 meters. The flow capacity of the facility was slightly over the maximum discharge of 1.0m3/s; in all cases, a discharge of 1.0m3/s was used. Water level was adjusted by using a gate installed at the downstream end of the channel to maintain the same flow conditions. Tablel shows initial conditions and bed materials for each case.

Shikotsu pyroclastic deposits (Spfl) collected from a mountain near the site of the experiment were used as bed materials in the tests. The same kind of material was used in case

1, case 2 and case 3. In case 4, material of smaller grain size was used with a maximum grain size of 25.4 millimeters. Bank height was the height from the edge of the water. The bank height was 10 centimeters in cases 1 and 2, and 30 centimeters in cases 3 and 4.

The water surface slope was 1/1500 in cases 1, 3 and 4, and 1/500 in case 2; thus, boundary shear stress was almost equal in cases 1, 3 and 4, and double in case 2.

In order to make the tamped condition of the experimental bed as close as possible to the natural condition of an actual river, porosity of the bed materials was assessed based on wet unit weight, as measured by an RI tester (a device to measure water content). There were slight differences in tamped condition (density and water content as percentage of dry weight) of the soils in the different cases, but, in general, actual river conditions were well reproduced. Table-1 also shows experimental soil conditions for each case, as well as data on soil near the place where the volcanic ash was collected, for reference.

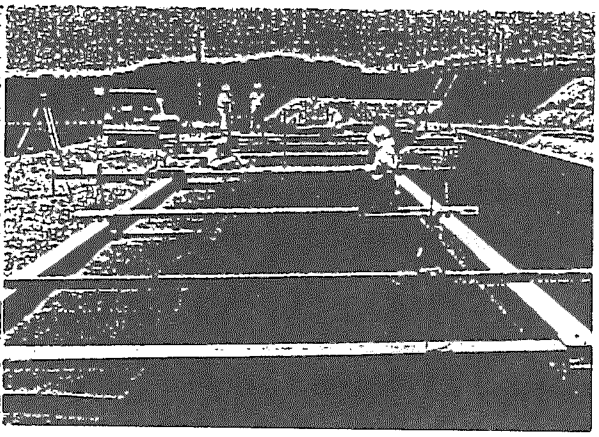


Photo-1 Experimental Watercourse (Water Flow)

Table-1 Initial Condition and Bed Materials in Each Case

Case	Q l/s	I	Bank height cm	Initial slope	Wet unit weight t/m^3	Water content (%)	Porosity (%)	d_m mm	d_{50} mm	d_{max} mm
case1	1.0	1/1500	10	34.7°	1.363	17.7	54.8	8.56	0.28	50.8
case2	1.0	1/500	10	35.2°	1.395	31.4	58.5	4.66	0.23	50.8
case3	1.0	1/1500	30	35.2°	1.500	30.4	55.1	6.98	0.14	50.8
case4	1.0	1/1500	30	35.2°	1.434	23.4	54.5	2.72	0.303	25.4
Actualsite	–	–	–	–	1.344	29.4	60.8	–	–	–

The width and water depth of the experimental channel were determined based on the method of Ikeda et al3).,and the bed materials were formed cross-sectionally into a trapezoidal shape. With the results of preliminary tests last year taken into account, such items as water surface slope, cross-sectional shape, watercourse width change, grading distribution, sediment volume and velocity of flow were measured during the water flow. Details at each survey station, time, etc., for each item are as follows.

(1) Surface slope: The level of water was measured every 50 minutes at five points, 4, 12, 20, 28 and 36 meters from the upstream end.

(2) Cross-sectional shape: In order to understand cross-sectional changes in the channel during the erosion process, as well as sediment volume and stable cross-sectional shape, the watercourse was observed at the 20-meter and 25-meter points from the upstream end, with measurements at 10-centimeter intervals laterally across the bed, after 50, 150, 300 and 500 minutes of water flow for cases 1, 3 and 4, and after 30, 70, 130 and 200 minutes of water flow for case 2. Water flow was suspended at the time of each measurement.

(3) Channel width change: In order to determine erosion speed, the watercourse was observed every five minutes at the 20-meter and 25-meter points from the upstream end, laterally across the channel.

(4) Grading distribution: In order to determine the mechanism of sediment movement, throughout the erosion process until a stable river-bed stage was reached, samples of bed material were collected 30 meters from the upstream end at six evenly spaced points across the channel. Each time the water flow was suspended for observation of the cross section. At the three points closer to the right bank, sample bed materials were collected at three different depths, i.e., at the surface and at 10 and 20 centimeters vertically below the surface. Each collected sample was screened and measured.

(5) Velocity of flow: In order to obtain contour diagrams of velocity and boundary shear stress, velocity at the 20-meter point from the upstream end, about halfway along the channel, was measured at points 3, 6, 9, 15, 25 and 40 centimeters above the river bed, at 30-centimeter intervals across the watercourse, using a 2-dimensional electro-magnetic current meter.

RESULTS AND DISCUSSION

The results of the experiments (cross-sectional shape, erosion speed and grading distribution) will be discussed, and the three factors influencing the erosion mechanism, i.e., bed material, bank height and boundary shear stress, will be compared. All comparisons are between cases with only one differing factor; that is, the other two factors were constant. The effect of differences in bed material is shown in a comparison between case 3 and case 4 (where the maximum grain size was less than in case 3). Differences in bank height, in a comparison between case 1 and case 3 (where bank height was 20-centimeters higher than in case 1), and differences in boundary shear stress, in a comparison between case 1 and case 2 (where the boundary shear stress was about twice that in case 1). Table-2 lists the combinations of cases and the relevant factors.

Table-2 Comparison between Cases

factors	compared cases
bed material	*case*3 and *case*4
bank height	*case*1 and *case*3
boundary shear streets	*case*1 and *case*2

Cross-Sectional Shape

Because the state of erosion at the edges of the water was found to be uniform throughout thewatercourse, cross- sectional shapes for each experimental case were compared at the 20-meter point from the upstream end, about the halfway point of the watercourse, as shown in Figure-1.

Little difference in cross-sectional shape was seen in cases 3 and 4, where the only difference was bed material. In cases 1 and 3, the only difference was bank height, and the

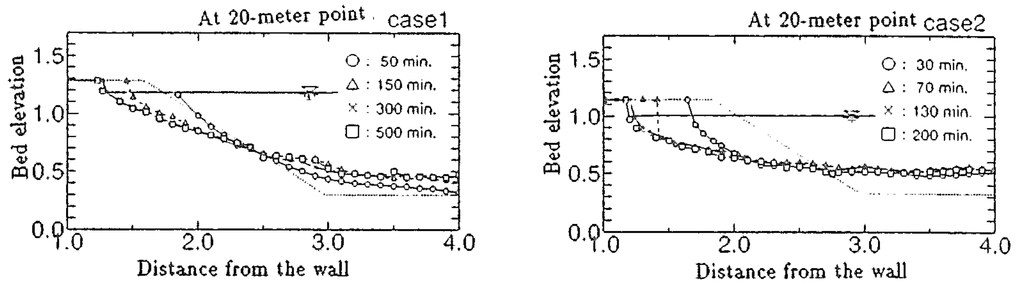


Figure-1 Cross-Sectional Change from Erosion

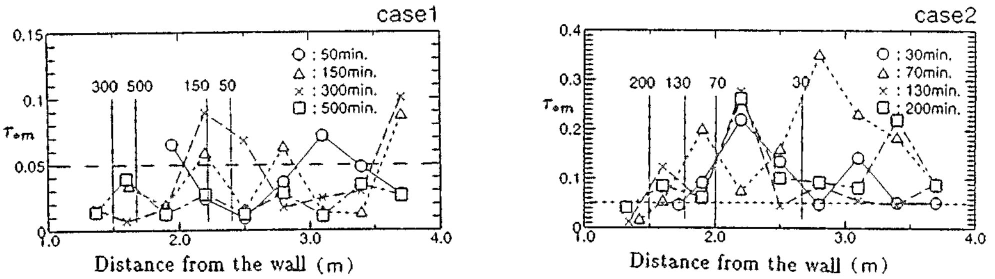


Figure-2 Boundary Shear Stress over Time

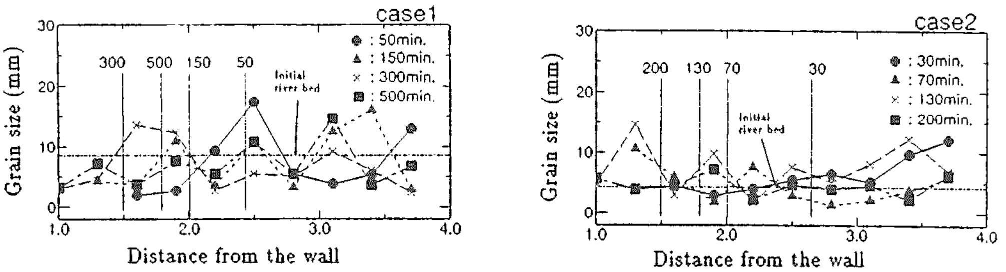


Figure-3 Average Grain Size of Surface Sediment cross-sectional boundary points dividing the eroded and sedimented areas changed similarly, but, in case 3, there was more sediment in the flat area because the bank height was 20 centimeters higher than in case 1. Figure-2 shows changes in boundary shear stress with the passage of time, for cases 1 and 2, where the only difference was boundary shear stress. From Figure-1 and 2, it can be seen that the cross-sectional shape in case 2, with the larger boundary shear stress, was already close to the stable cross section after 30 minutes of water flow, proving that erosion occurred quickly. Also, the shape of that stable cross section was rather flat, because sediment deposited to a remarkable extent on the flat river bed. On the other hand, the stable cross section in case 1 showed a rectilinear slope with constant inclination. It was clear that cross-sectional shape varied largely according to boundary shear stress. The arc-shaped cross section in case 2 was created because water depth was greater toward the bottom of the slope and, accordingly, boundary shear stress was greater toward the horizontal river bed, producing more sediment moving laterally. As a result, the supply of sediment from the upper part of the slope couldn't keep up with the volume of sediment moving laterally at the eroded area. This result was similar to results in conventional laboratory experiments. In laboratory-scale experiments, however, it was difficult to precisely reproduce the erosion phenomenon, and larger values of boundary shear stress were employed, which often resulted in arc-shaped cross sections.

From the above results, it can be understood that boundary shear stress has much to do with cross-sectional shape at eroded areas. In Figure-2, changes in dimensionless boundary shear stress at each lateral point along the cross section are shown. These boundary shear stresses were obtained by first drawing flow-velocity contour diagrams based on the measured values of flow velocity, then dividing the cross-sectional area of flowing water(the area between normal lines crossing the velocity contour lines at right angles) by wetted perimeter, and then making them dimensionless with an average grain size value at each location. From Figure-1, the values of the dimensionless boundary shear stresses were the same cross-sectionally at the stage of stability in cases 1,.2 and 3; also, all values were less than the limiting boundary shear stress except in case 4, where the value of the boundary shear stress was still 0.09 at the eroded area, which was above the limiting boundary shear stress, even after 300 minutes of water flow, suggesting that erosion would continue.

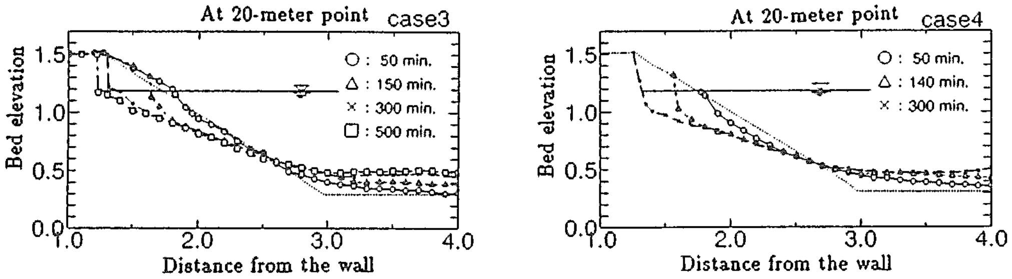


Figure-1 Cross-Sectional Change from Erosion

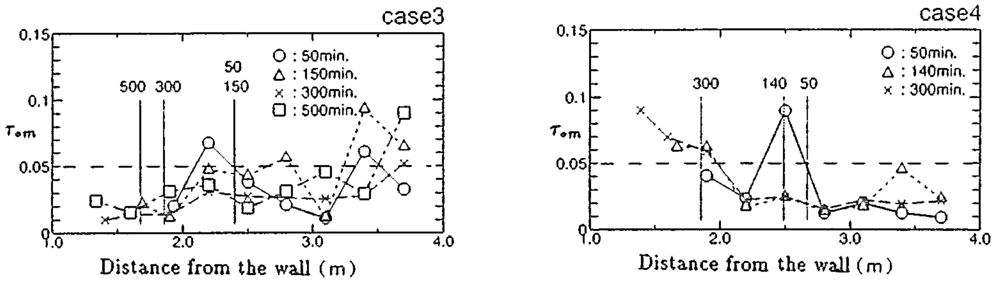


Figure-2 Boundary Shear Stress over Time

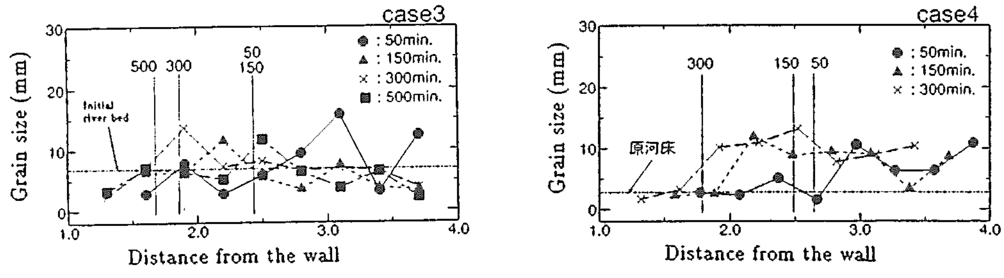


Figure-3 Average Grain Size of Surface Sediment

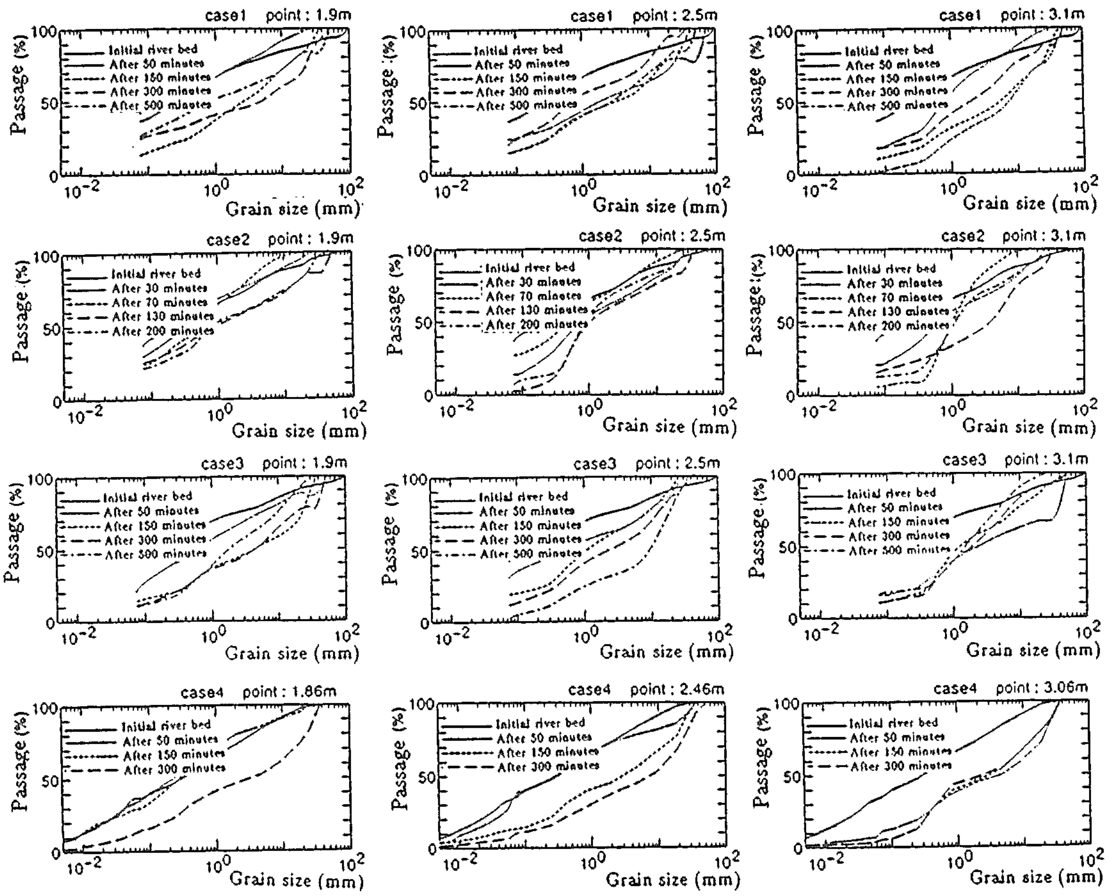
Changes in Surface-Sediment Grading

Figure-3 shows changes in the average grain size of surface sediment with the passage of time. In the figure, grain size is on the vertical axis, and distance from the left bank is on the horizontal axis. The boundaries between erosion (a cross-sectional area less than the previous stage) and sedimentation (a cross-sectional area more than the previous stage) in the course of the erosion process are shown by the dotted vertical lines. To the left of the dotted lines are the eroded areas, and to the right are the sedimented areas. Average grain size on the original river bed in each case is also given.

In Figure-4, the grain size accumulation curve of sediment collected from the surface of (a) eroded slopes, (b) graded slopes, and (c) flat river beds, are shown for all cases. Based on this index, and taking the movement of grains into consideration, the cases will be compared. Cases 1, 3 and 4 had the following phenomenon in common: After the initial flow of water, average grain size was larger at the flat river bed toward the right-bank concrete wall, showing clearly the tendency for large grains to be left at the flat river bed.

During the initial stage of erosion, fine grains were carried out and only coarse grains were left at the flat river bed, where the boundary shear stress was strong. At eroded areas along the edge of the water, fine grains on steep slopes were carried away, and only coarse grains remained. This effect appeared after a water flow of 150 minutes. At 300 minutes of water flow, the coarse grains on steep slopes had been covered with collapsing sediment from the banks. Then, at 500 minutes of water flow, the average grain size (the mixture of large and small grains) was found to be uniform cross-sectionally, having reached the stage of cross-sectional stability. In Figure-4 (c), characteristic grain-size accumulation curve with steps appeared in case 4, showing the tendency for sediment to stabilize with two grain sizes. In cases 3 and 4m a similar tendency, but not as distinct, was also seen.

In case 1 and case 3, the only difference was height. From Figure-4, the tendency for grain size to gradually become larger, until reaching the stable cross section, was confirmed for



(a) Eroded area (b) Graded area (c) Flat river bed

Figure-4 Grading Distribution over Time

case 1. There was, however, no distinct change in grain-size accumulation curve after a flow of water of 50 minutes, other than in case 1. Case 1 had a shorter bank than cases 3 and 4, and less lateral movement of sediment, from which it is concluded that there was an inhibitory effect on the classification of grains.

Since the boundary shear stress in case 2 was great, course grains were easily washed away, and , in comparison with other cases, areas with larger average grain size did not appear so distinctively. Especially in Figure-4 (b), a tendency for grain size to become uniform was clearly seen at the graded portions. First, fine grains were washed downstream instead of settling out, and, at the same time, coarse grains were left isolated because of the removal of the fine grains around them. Resistance against the flowing water became greater and even the coarse grains were washed downstream, because of which grain size tended to become more uniform at the sedimented area, compared with other cases. Case 2, with large boundary shear stress, was characterized by the tendency that, at the graded slope part shown in Figure-4(b), although more fine grains tended to be carried away than in other cases, the amount of grains with sizes ranging from 0.5mm to 10mm changed little because of the supply of sediment from the eroded part. In other respects, however, case 2 showed the following general tendencies similar to other cases: After a 30-minute flow of water, a larger number of coarse grains were seen at the flat river bed, and, as time passed, fine grains were also sedimented into the same area. At the edge of the water more coarse grains were found than fine grains, the fine grains having been carried away after 70 minutes of flow a similar tendency to that found in case 3 and case 4 after 150 minutes of water flow.

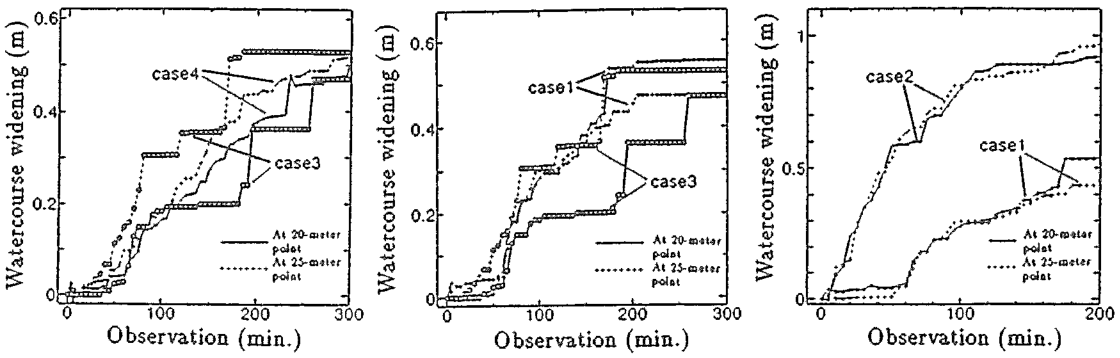
The following phenomena were found to occur similarly in all cases: During the early stage of water flow, erosion at areas lower than the edge of the water, especially at flat river beds where there was a large boundary shear stress, was distinctive; that is, fine grains were washed away and only coarse grains remained. Next, at the steep slopes in the eroded areas near the edge of the water, boundary shear stress was small, sufficient to carry only fine grains, resulting in coarse grains being left there. But, as time went on, erosion at the water edge progressed, and sediment was supplied from the collapsing bank crown to overcome the tendency to leave only coarse grains.

Then, at the flat river bed, fine grains that had been carried away would start to settle out, covering the coarse grains that had appeared at the earlier stage of erosion. As a result, average grain size returned to close to that of the original river bed, reaching a stable cross section with an even lateral distribution of fine and coarse grains.

Erosion Speed

Erosion speeds are compared in Figure-5(a), (b) and (c), where the vertical axes are the rate of width-increase of the watercourse at the 20-meter and 25-meter points from the upstream end, and the horizontal axes are time.

Figure-5(a) is a comparison of case 3 and case 4, where the only difference was bed material. From the figure, erosion in both cases progressed at almost the same rate. The width expansion in case 3, however, with larger maximum grain size than case 4, showed large steps, while the line of case 4, with smaller maximum grain size than case 3, did not show such stepped behavior because erosion there progressed rather steadily, bit by bit. Yet erosion in both cases progressed overall at the same rate because the bank heights were the same.



(a) (b) (c)

Figure-5 Width Change

A comparison of case 1 and case 3, with different bank heights, is shown in Figure-5(b). When comparing the average erosion speeds along lateral lines 20 meters and 25 meters from the upstream end, a larger amount of sediment was produced when the bank collapsed in case 3, which had a higher bank height, but it took a long time for the sediment to be carried away, resulting in a slower overall erosion rate than in case 1. The width-change progressed in a large-stepped pattern. Figure-5(c) shows a comparison of case 1 and case 2, with different boundary shear stresses. In case 2, where the boundary shear stress was about twice that of case 1, erosion started to widen the watercourse at the edges immediately after the flow of water began. In case 1, boundary shear stress was small and the fine grains were not removed very actively. As a result, although erosion progressed slowly, widening at the water edge didn't appear until 50 minutes after the beginning of water flow. The width changes of the watercourse after 200 minutes of water flow were about 1 meter in case 2, and about 0.5 meters in case 1. The rate of widening in case 2 was about twice that in case 1, showing that the erosion speed in case 2 was about twice that of case 1.

COMPREHENSIVE DISCUSSION

All cases will be comprehensively discussed with reference to Figure-6, where the vertical axis is the parameter of estimated volume of eroded sediment passing the eroded cross section, which was made dimensionless using average grain size (dm) at each location and angle of slope (θ); The horizontal axis is the boundary-shear-stress ratio (τ_{*m}/τ_{cm}), the ratio of dimensionless boundary shear stress to limiting boundary shear stress. In case 4, in comparison with case 3, values are generally concentrated at the upper area. This shows that, inspite of the fact that case 4 had almost the same boundary shear stress as case 3, sediment volume was much greater because maximum grain size was smaller than in case 3, and the screening effect of the coarse grains was smaller. Also, in case 3 and case 4, both of which had higher banks and more sediment than case 1, but similar boundary shear stress, the values are located higher in the figure than for case 1. In case 2, which had higher boundary shear stress and more sediment than casel, values are found in the upper area, which was a distinct difference from case 1. Figure-6 shows that there were slight effects depending on differences in bed material and bank height in this experiment. Actually, however, those effects were small in comparison with the distinct differences seen in the results of case 1 and case 2, with different boundary shear stresses. It can therefore be concluded that boundary shear stress is the major factor indetermining erosion.

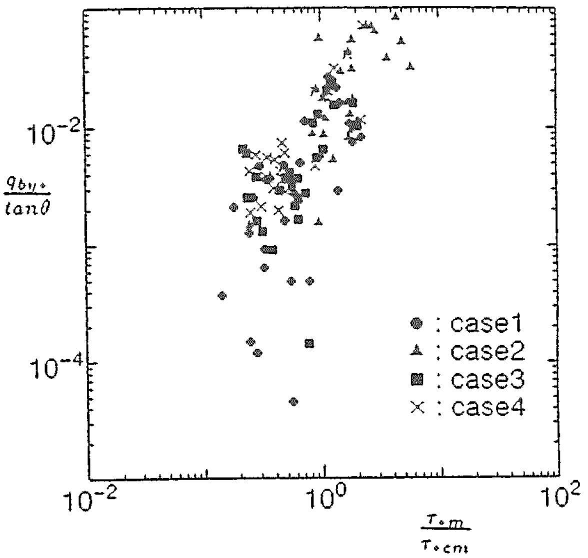


Figure-6 Sediment Volume and Boundary Shear Stress

CLOSING REMARKS

The erosion mechanism was investigated, focusing on three major factors - bed material, bank height, and boundary shear stress. Results made clear that differences in bank height did not affect erosion very much, and that, generally, tractive force was the major factor. Differences in boundary shear stress affected erosion of the cross section directly and distinctly. When the boundary shear stress was greater, cross-sectional erosion formed the channel into an arc shape, while, when boundary shear stress was near the limiting boundary shear stress, cross-sectional shape was rectilinear with constant slope. In this experiment, using a large-scale watercourse, when the limiting boundary shear was applied, it was possible to reproduce a rectilinear slope with constant grade, as had been seen in actual rivers, but had not been reproducible in laboratory-scale experiments.

As to the average grain size of bed materials with the passage of time, it was observed that, in the process of bank erosion, boundary shear stress and bed materials interact to the point where average grain size becomes close to that of the original river bed, and eventually average grain size becomes laterally uniform. Also, from the figure on dimensionless boundary shear stress, the same erosion process can be seen, in the sense that values become a certain uniform level below the limiting boundary shear stress, thus stabilizing the cross section. In the future, similar experiments will be conducted, taking the influence of vegetation, stratification and other factors into consideration, to clarify in more detail the mechanisms of sediment transport and the erosion phenomenon.

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