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EFFECTS OF VEGETATION ROOT AND LEAF ON SLOPE EROSION CAUSED BY A HEAVY RAINFALL

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SYNOPSIS

The purpose of this study was to evaluate the effects of vegetation root and leaf on surface erosion which was caused by an artificial rainfall on a model slope. Experiments were conducted by means of Pachysandra which has many leaves to defuse raindrop impact, and a slope partially covered with many units of such vegetation. In half of the experiments, a stem and a leaf were cut off, and only a root remained underneath the slope surface. Erosion experiments of a bare slope were also conducted as a reference. As a result, it was confirmed that sediment yield from the slope with Pachysandra was considerably smaller than that from the bare slope. This indicates that the surface erosion due to raindrop impact was clearly reduced by the leaf system. We also found that the extension of eroded channel network and the amount of eroded sediment were affected by the vegetation arrangement.

INTRODUCTION

The erosion of the hillside slope or the soil roaming from farmland has recently become an important topic of research from the view point of environmental conservation and disaster prevention (1). Such erosion events become more and more serious in case of a torrential rain with much higher intensity. The first author (2) tried to conduct various fundamental experiments to understand this erosion process more precisely and to develop a technique to predict it numerically. In a series of experimental studies, Sekine and Ohmae (3) conducted slope erosion experiments with vegetation known as "Avena sativa" at the first stage. The effects of vegetation on the erosion of the slope were evaluated experimentally to a certain extent though the vegetation was obviously different from the actual one which was used as a ground cover on a hillside. In view of this matter, the vegetation known as Pachysandra was used in this study. Pachysandra can be found throughout East Asia including Japan, and functions as a ground cover of the slope surface. The purpose of this study is to investigate quantitatively the effects of the root and leaf system on the erosive process of slope which is caused by a heavy rainfall. Under the same conditions of artificial rainfall, several sets of erosion experiments were conducted under conditions where a slope was (1) just a bare one, (2) a slope partially covered with a root system only or (3) a slope with whole vegetation including a root and a leaf. By comparing the results of these two conditions among the above three, the effects of root or leaf can be evaluated separately. Another set of experiments was also carried out to investigate the effects of vegetation arrangement under the same condition of rainfall intensity and the covering ratio which is defined as the area covered with vegetation divided by the total area of slope.

As far as the authors know, no research has yet been carried out to investigate the effects of vegetation on slope erosion, although some papers (4) have dealt with the effects on a flow and sediment transport in rivers.

SUMMARY OF EXPERIMENT

Experimental apparatus and model slope

Experiments were conducted to investigate the erosion process of a model slope whose length and width are 160cm and 100cm, respectively. The slope has an inclination S_x of 0.05 in down-slope direction which corresponds to x axis. In the lateral direction y, which is perpendicular to x, the slope takes a cross section of "open-book" type, and it inclines symmetrically about a central valley line by $S_y = 0.05$. The slope was composed of silica sand No. 7 whose average grain size was 0.105mm. The thickness of sand was 7.5 cm along this center line in the initial condition. An illustration of the experimental apparatus is shown in the photograph of Figure 1 (a). One can see an exit mouth or the opening of slit at the downstream end of the flume, whose width is 4 cm. Its location is along a valley line of the slope. Both eroded sediment and rain water can discharge only from this exit mouth. Also, a fixed weir was set up horizontally at the downstream end underneath the initial slope. The erosion depth in this cross section was regulated to be less than 4 cm. This means that the maximum erosion depth was 4 cm in this experiment. In the state of initial slope condition, it was saturated with the infiltration water.

Artificial rainfall

Artificial rainfall was supplied from a hydraulic nozzle system which was set above the slope at the ceiling

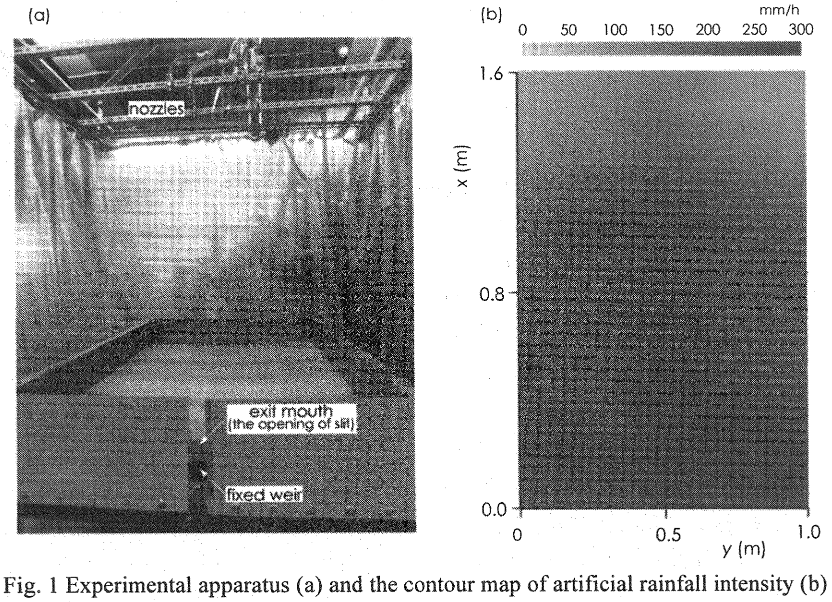

Fig. 1 Experimental apparatus (a) and the contour map of artificial rainfall intensity (b)

position of this apparatus, as is seen in Figure 1 (a). Average grain size of raindrop is about 0.66mm, and was large enough that the effect of raindrop impact on this erosion process was noticeable. The intensity of rainfall was controlled to maintain steady and uniform condition over the whole area of this slope. In order to verify this uniformity, a measurement of the intensity was made as follows: the whole area was divided into 420 sub-areas (28 divisions in downstream direction x 15 divisions in lateral direction), and the volume of rain per unit time at each sub-area was measured. Figure 1 (b) shows an example of the contour map of measured rainfall intensity which corresponds to Case A (explained later). Although the intensity in the region around both upstream edges of the slope was relatively smaller, one can see that the intensity was almost uniform. The averaged intensity was distributed between 143.1 and 151.7 mm/h in a series of experiments explained in this paper, and the difference between them can be neglected. The detail information is summarized in Table 1.

Table 1 Summary of experimental conditions

CASE	r (mm/h)	State of model slope and vegetaion				
		State of slope	Arrangement pattern	l_x (m)	l_y (m)	Covering ratio
A	147.0	Bare	-	-	-	0
B1	151.7	only with vegetation root	(a)	0.3	0.3	0
B2	143.1		(b)	0.2	0.2	0
C1	147.9	covered with vegetation (root and leaf)	(a)	0.3	0.3	0.245
C2	144.1		(b)	0.2	0.2	0.263
C3	146.0		(c)	0.3	0.3	0.259
C4	144.5		(d)	0.2	0.3	0.258

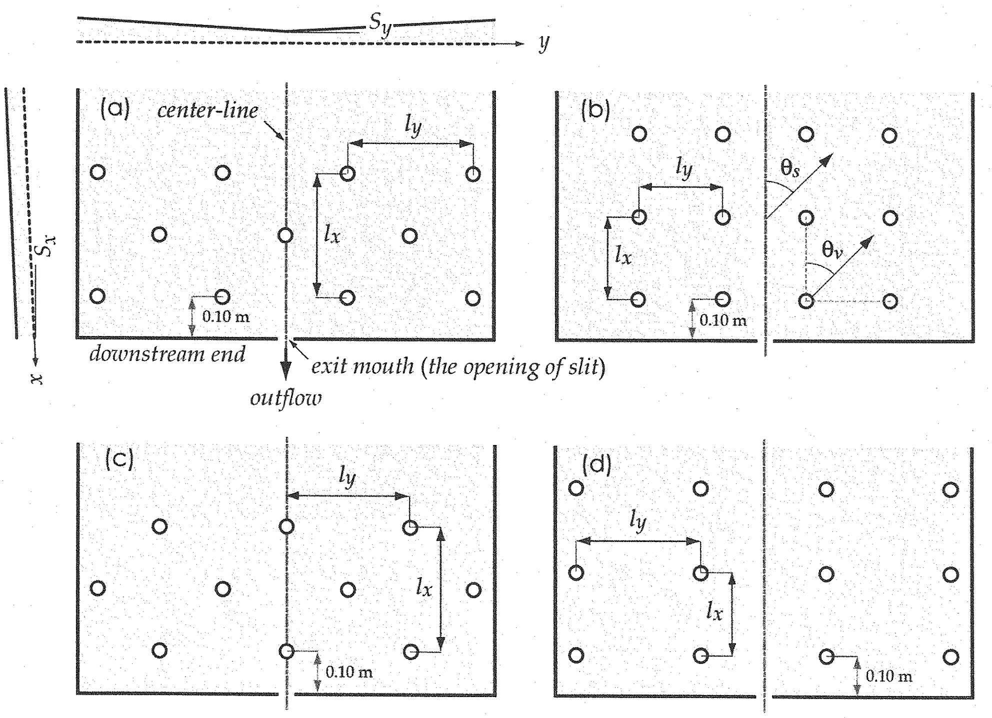

Fig. 2 Arrangement patterns of vegetation on model slope

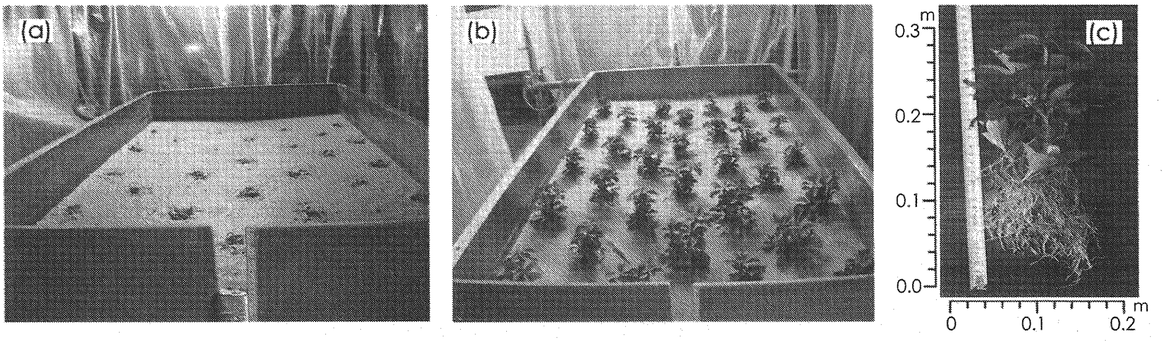

Photo 1 Summary of slope and arrangement of vegetation: (a) and (b) were taken just before the experiment in Case B1 and C1, and (c) the state of vegetation root just after the experiment in Case C1

Vegetation

In this study, vegetation known as Pachysandra was used as a ground cover on a model slope. This vegetation is an evergreen dicotyledonous under-shrub belonging to the Buxaceae. Its root is composed of the taproot and the lateral root, and its leaf is forest green, and has several serrated pairs in its superior margin.

Before conducting an erosion experiment, the following preparations were made in order to create the best conditions for this vegetation to fully grow; (1) three saplings whose height are about 5cm are planted in the column type cup which has 8.5cm in diameter and 7.5cm in height, (2) they were made to grow naturally with black soil for about 29 weeks, (3) when the height of stalk of their saplings exceeded 10cm and their roots grew enough, they were taken out of the cup, and the black soil was removed from the roots, (4) the slope composed of sand was dug down at several points, and the concave portions were made, (5) after bundling their roots, the grown vegetation unit was planted in each concave portion, (6) it had been taken care under this environment for one week, and then an erosion experiment was conducted. Photograph 1 shows the state of slope with vegetation and its grown root. The left and middle photographs of (a) and (b) were taken before the erosion experiment in Case B1 and C1 which will be explained later. In these cases, the vegetation unit was arranged at a cross-stitch position, and the number of vegetation units planted on the slope was 32. Another series of experiments was also conducted under the condition of different arrangement of vegetation. In these cases, individual vegetation unit was planted at orthogonal latticed position. The height of stem, the length of root and the scale of overall leaf system of individual vegetation were measured. In Case C1, for example, the height of stem was 10.5～16.7 cm (the average was 13.2cm) from slope surface, and the length of root is 6.0～9.5cm (the average is 7.5 cm). From the right photograph of Photo 1(c) which was taken just after the erosion experiment, one can see how the root of vegetation unit had grown considerably. According to the direct measurements after the experiment, the length of root was much larger than the maximum erosion depth 4 cm. It was also confirmed from this series of erosion experiments that the vegetation could not be pulled out of the slope due to a hydrodynamic force on it. This suggests that the root had grown sufficiently to affect the process of slope erosion.

Based on some information including the above, we inferred that the vegetation attained the state of fully growth and it is possible to make clear the effect of vegetation qualitatively in this experiment. However, strictly speaking, we were not sure whether the vegetation at that time showed its own potential strength against the erosion. This may be another problem which can be investigated in the future.

Experimental conditions and measurement

Experimental conditions are summarized in Table 1. The results of seven cases of experiments are shown in later pages, and their details are explained in this table. It should be noted that they are the representative cases, and we actually conducted more than twenty cases of experiments in this study. The experiments can be classified into following three categories:

(1) Model slope is not covered with vegetation at all. This means that it is a bare slope. In this paper, it is referred to "Series A".

(2) The slope was partially covered with group of vegetation unit, arrangement patterns of which are illustrated in Figure 2. As a result of this series of experiments, the effects of all roots and leaves of vegetation can be quantified. It is referred to "Series C".

(3) The arrangement of vegetation unit is the same as Series C, but the stem and leaves of the vegetation were cut off and the root only remained beneath the surface of the slope. Only the effect of the roots can be evaluated. It is referred to "Series B".

Vegetation unit was placed uniformly in the entire range of the slope. In patterns (a) and (b) in Figure 2, it was planted at the cross-stitch position. In patterns (c) and (d), on the other hand, it was at the orthogonal-latticed position. The characteristic lengths of such arrangement l_x and l_y are defined in Figure 2, and the values of them are summarized in Table 1. The number of vegetation units planted on the slope is 32 except for Case C3 in which the number was 31. The covering ratio, which is defined as the area covered with vegetation divided by the total area of slope, was about 0.25. The area covered with vegetation was estimated by means of digital photographic data which was taken from the air in the normal direction of slope surface. The name of each case in Table 1 is defined as follows: (1) the first character "A"," B" or "C" means the name of Series explained above, (2) the second character (or number) means the pattern of arrangement, and 1, 2, 3 or 4 corresponds to the above pattern (a), (b), (c) or (d). Case B1, for example, belongs to Series B and the arrangements are pattern (a). The arrangement pattern of Case B2 and C2 are same and are pattern (b). Case A is the base experiment, and is independent of the pattern. The variables θ_v in Figure 2 is defined as the characteristic angle between a line which links two diagonal points of vegetation units and the line which is parallel to the x axis. In the same figure, the arrow with the angle θ_s denotes the steepest uphill direction in the initial condition. In this study, the value of θ_s is equal to 45 degrees.

The first purpose of this study is to understand quantitatively the effects of vegetation root and leaves on the process of surface erosion of slope and the sediment yield. Case A, B1 and C1 are the first series of experiments to be compared in this study. A direct comparison was made among them in order to evaluate the effects of vegetation root and leaves. The difference between Case B1 and C1 in the eroded channel network or sediment yield from the slope was caused by the effects of vegetation leaves. And the difference between Case A and B1 corresponds to the effect of root. Another set of experiments was those of Case A, B2 and C2, and comparison was also made in this paper.

The second purpose is to clarify the influence of vegetation arrangement on them. As was explained above, Case C1, C2, C3 and C4 correspond to patterns (a), (b), (c) and (d). A comparison was made among the experimental results of these four cases.

In this experiment, a series of photographs and the video image for totally 30 minutes from the beginning of artificial rainfall were recorded in order to understand the process of surface erosion of slope. Before and after the rainfall, the surface elevation of the slope was measured digitally by means of a laser displacement sensor. Traverse lines of measurement were set in a longitudinal direction of the slope at an interval of 1cm in transverse direction. And the displacement sensor was made to run along each traverse line, and recorded about 150 digital data of the slope elevation. The number of traverse lines was 99, and the total number of measuring points was about 14850 (= 150 points x 99 lines) on the surface in the entire range of the slope. The pattern of eroded channel network as well as the local erosion depth itself could be obtained as a result of these measurements. Sediment discharge and water discharge from the exit mouth at the downstream end were also measured every minute. In addition, the water content of the slope was measured before and after the experiment.

RESULTS OF EXPERIMENTS AND DISCUSSION

Effects of vegetation root and leaf on slope erosion

Data obtained from a video image analysis and actual observation yielded information about the erosion process. They are summarized as follows: (1) flow resistance around vegetation units increases locally and the velocity of sheet flow there becomes relatively smaller, (2) surface erosion caused by the action of sheet flow is affected by a change of flow velocity field, (3) a raindrop impact on a water surface affects the process of sediment pick-up from the slope surface, and thus erosion becomes more active, (4) a vegetation leaf intercepts a raindrop, (5) a root system of vegetation makes the slope be less erodible, and a slope collapse or bank erosion does not occur so frequently compared with the case of bare slope. Overhang cross-section of channel was often observed as a typical pattern of erosion.

In Figure 3, experimental results of Case A, B1 and C1 are illustrated. In the left row of the figure, one can see a photograph of eroded slope surface at 30 minutes from the beginning of rainfall. At this instant, artificial rainfall stopped and this experiment was completed. The central row of figure indicates a contour map of erosion depth. The depth was evaluated as a difference between a local elevation of the slope surface at the beginning and the one which was measured at 30 minutes from it. While comparing the elevation between these two moments, deposition was not observed. This means that the value does not take a minus value. Dark colored portion in this contour map corresponds to the area where the erosion depth was larger. The white colored spotted area surrounded by an eroded portion with a dark color corresponds to the one which is occupied by vegetation unit. And in the right row of the Figure 3, a pattern of channel network eroded on the slope is shown. The different grade segment in gray scale corresponds to the newly eroded channel which was extended in upstream direction during each period. For example, the segment which corresponds to the period between 5 and 10 minutes in legend denotes the channel reach which formed for the interval of 5 minutes. The circle in this figure shows the latest position of migrating front of each channel in each period. This pattern was obtained by measuring the coordinates of the front on the video image taken at every minute. The upper, middle and lower photograph or figure in Figure 3 illustrates the result of Case A, B1 and C1, respectively. In addition to these, another set of experimental results of Case B2 and C2 are illustrated in Figure 4. In these cases, the vegetation units were arranged at the orthogonal-latticed pattern of (b) in Figure 2. The results of Case A shown in the upper figures in Figure 3 is common, and the results of Case B2 and C2 were also compared with it. The details of the experimental conditions are referred to in Table 1.

It can be seen from Figures 3 and 4 that the channel started to form at an exit mouth at the downstream end of flume, and the front of it migrates upstream. After that, the channel bifurcation occurs frequently, and the channel network is gradually developed in upstream direction. By comparing the pattern of channel network eroded on the surface, one can understand that (1) the erosion observed in Series C (i.e. Case C1 or C2) is less remarkable than in Series B (Case B1 or B2) and Series A (Case A), (2) the depth of erosion in Series A is largest, and the one in Series C is much smaller than that in Series A, and (3) the channel network in Series B or C is more complicated than in Series A.

On the basis of experimental results including Figures 3 and 4, the erosion process and the channel network formation were confirmed and are summarized as follows: (1) the eroded channel tends to migrate in the steepest

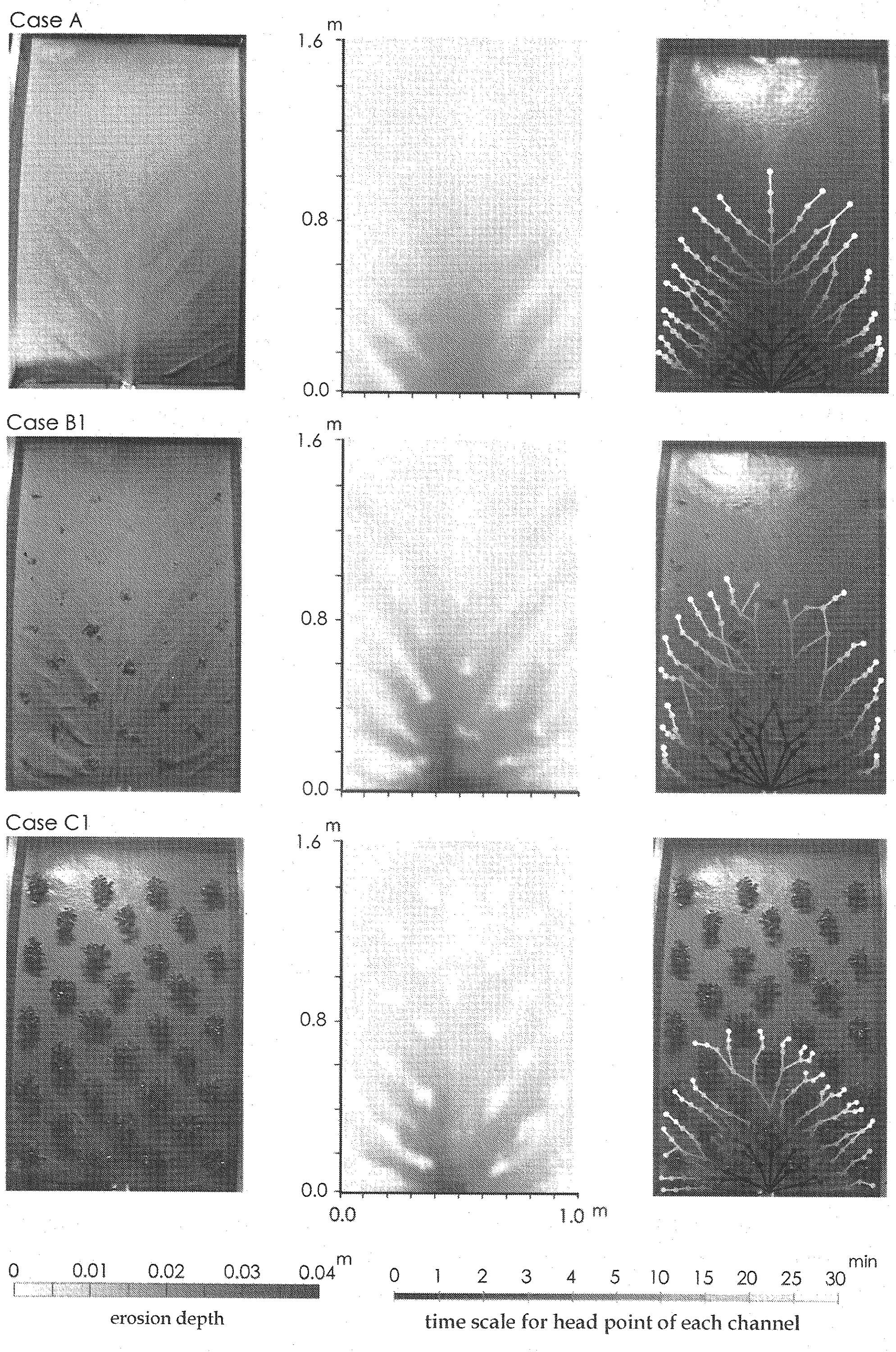

Fig. 3 Comparison of experimental results among Case A, B1 and C1: the left is the photograph taken just after the experiment, the center is the contour map of local erosion depth, and the right is illustration about the point of channel front migrating upstream at each instance.

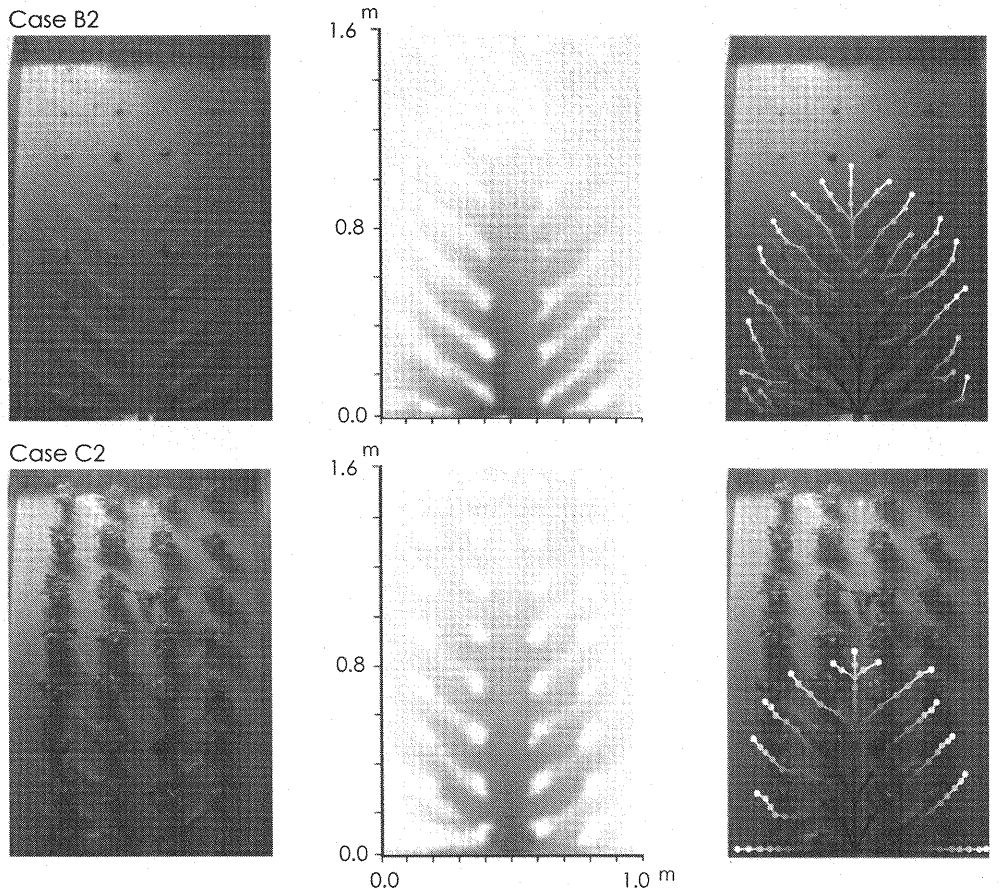

Fig. 4 Comparison of experimental results among Case B2 and C2: the legends are same as those in Figure 3.

direction of the slope, which corresponds to the direction of θ_s = 45 (degrees) in Figure 2, (2) the front of the channel advances with keeping out of the individual vegetation, (3) sediment deposition tends to occur temporally around or behind a root and stem of the vegetation unit, (4) the erosion depth takes a relatively smaller value in a zone diagonally behind the vegetation unit or in the upstream zones of vegetation, (5) a leaf of the vegetation cuts a raindrop off, and make the raindrop impact on a surface of sheet flow be moderate. As for the formation of channel network, the pattern in case of bare slope (Case A) is almost symmetrical along the centerline of the slope. As the pattern grows, on the other hand, the asymmetry becomes more complicated under a considerable influence of vegetation even though there is a root only (Series B and C). But the detailed pattern may depend upon the arrangement of vegetation unit. In case of B2 and C2, for example, the pattern seems not to be asymmetrical. In addition to the above, irregularly spotted erosion was observed around vegetation in Case C1 and C2. It may have caused by the action of raindrop from a leaf onto a slope surface. Sediment yield from this slope can be also reduced by the effect of vegetation. The details concerning this matter will be discussed in the next section.

Effects of vegetation arrangement on slope erosion

Experimental results of Case C1, C2, C3 and C4 are compared and discussed herein. Among these cases, arrangement patterns of vegetation unit are different (see in Table 1). The covering ratios of vegetation are almost same. The results in Case C3 and C4 are illustrated in Figure 5. By comparing the results of Case C3 and C4 in

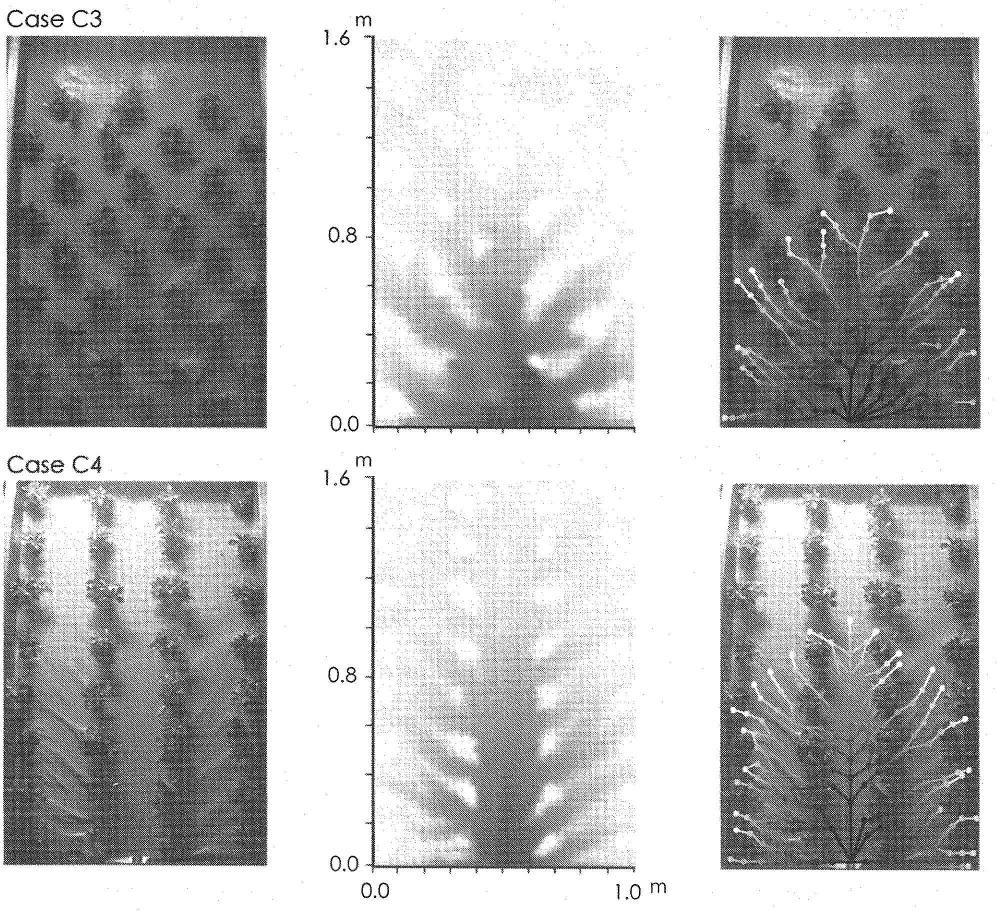

Fig. 5 Comparison of experimental results among Case C3 and C4: the legends are same as those in Figure 3.

addition to Case C1, C2, it is possible to examine the effects of vegetation arrangement on slope erosion. The following two important matters should be considered; (1) whether the angle θ_v defined in Figure 2 is equal to the angle θ_s or not, (2) whether one of the vegetation unit exists at a position just upstream of the exit mouth or not. As for the first matter, these two angles take the same value of 45 degrees in Case C1, C2 and C3. But in Case C4, on the other hand, the value of θ_v is greater than that of θ_s. As for the second matter, Case C3 is different from the other three cases. In this case, one vegetation unit located in front of the exit mouth at the downstream end, and plays a role just as a block or obstacle. Keeping these things in mind, a comparison was made among these results of experiments. The effects of vegetation arrangement on the surface erosion itself and the pattern of channel network can be summarized as follows:

(1) In case of a cross-stitch arrangement (Case C1 and C3), the channel formation in the steepest direction of the slope is dominant. A comparison of the results between Case C1 and C3 reveals that the pattern of the channel network in Case C3 becomes more complicated than in Case C1. The difference between them is whether or not one vegetation unit is located just upstream of the exit mouth as was explained above. In Case C3, it was observed that the rain water flows around the vegetation unit there and the erosion is more active in the vicinity of it. This results in the larger erosion in the area around the exit mouth. The eroded volume of sediment in Case C3, therefore, is much larger than that in Case C1, which corresponds to a complicated pattern of channel network.

(2) In case of orthogonal latticed arrangement (Case C2 and C4), on the other hand, the straight and relatively wide

channel is dominant and it extends directly from the exit mouth along a center line of slope. The channel reaches the area far from the exit, but the eroded area is restricted in a lateral direction. The width of the channel depends upon the spacing between neighboring units of vegetation l_y, and it is larger in Case C4 than in Case C2. The eroded volume of sediment in Case C4, therefore, is much larger than that in Case C2.

(3) A comparison of these four cases shows that the volume of eroded sediment is largest in Case C4, and is smallest in Case C1. The order of magnitude is Case C4, C3, C2 and C1.

Effect of vegetation on sediment yield

Sediment yield from an eroded slope through the exit mouth is discussed herein. In Figure 6, temporal variations of water and sediment discharge are illustrated. In the left figure, a comparison was made among Case A, B1 and C1, and comparison among A, B2 and C2 we made in the right figure. Another comparison was made among Case A, C3 and C4 in Figure 7. The vertical axis at the bottom of each figure denotes a relative sediment discharge R_{sd}. This means that a line shown as "Case C1 / Case A", for example, denotes a temporal variation of R_{sd} which is defined as Q_{c1} / Q_A. Q_{c1} or Q_A is the sediment discharge at any given time in Case C1 or Case A, and the variation of each value is shown in the middle figure.

In the upper figure, one can observe that there are no obvious differences in water discharge from the exit mouth among these cases. This result is consistent with the fact that the rainfall intensity was almost constant. Also one can see that a flow discharge attains a constant value at about 4 minutes from the beginning of rainfall, and after that the amount of discharge is almost the same as that of the volume of supplied water per unit time on the slope as an

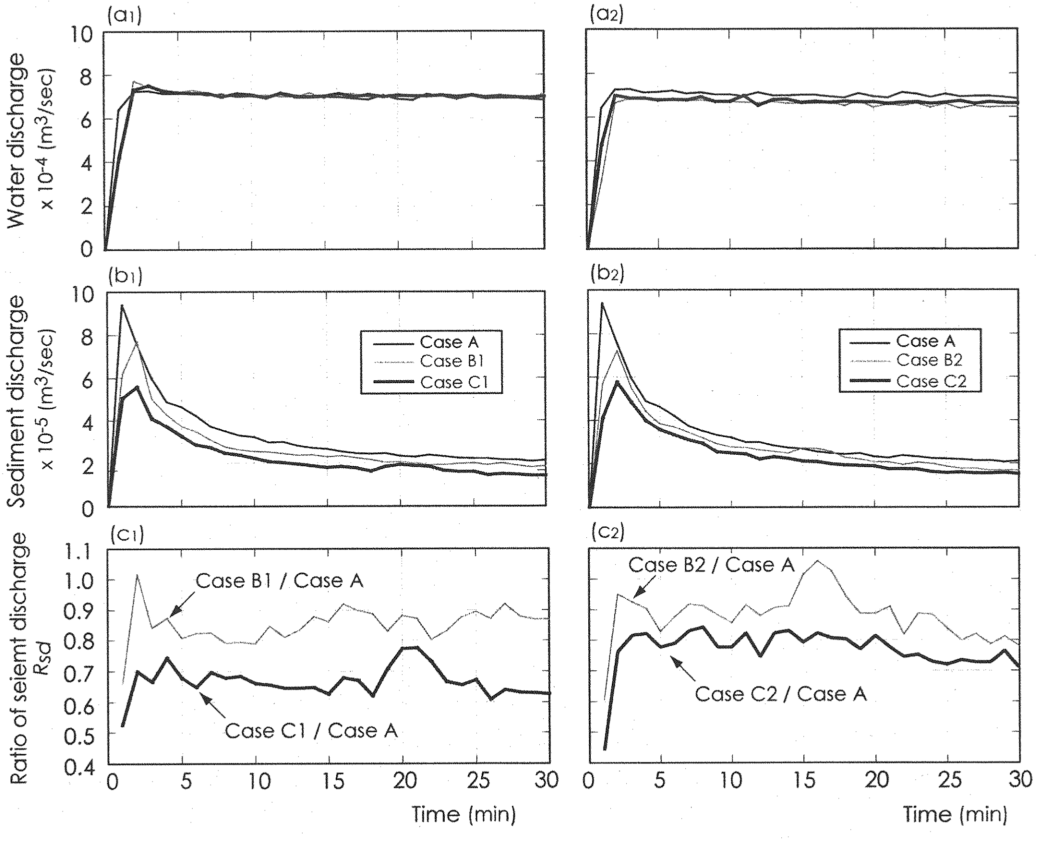

Fig. 6 Temporal variation of water and sediment discharge from the exit mouth along a downstream end

artificial rainfall. The value is about 7 x 10^{-4} m^3/s, and is equal to the product of the slope area and the rainfall intensity.

The difference in sediment discharge between Case B1 and Case A, for example, corresponds to the effect of vegetation root, and the one between Case C1 and B1 corresponds to the effect of the leaf and stem of vegetation. Followings are the conclusions from the results of a series of experiments:

(1) Sediment yield from an opening of the downstream end in Case A is the largest, and the value in Case B1 or B2 is the second in comparison with Case C1 or C2, as is seen from Figure 6 (b_1) or (b_2). This result can be easily expected qualitatively.

(2) It can be observed in Figure 6(c_1) that the sediment discharge in Case B1 keeps almost constant value of 85% of that in Case A. The discharge in Case C1, on the other hand, keeps about 70% of that in Case A. This means that the erosion was reduced by 15% due to the effect of vegetation root, and it was also reduced by 15% due to the effect of leaf and stem. In the arrangement of pattern (a) in Figure 2, the results suggest that the effect of root is almost same as that of leaves and stem. However, it was also found that the result depends upon the vegetation arrangement. More investigations will be needed.

(3) The effect of the vegetation arrangement was examined by comparing the results in Figures 6 and 7. There is a definite difference in sediment yield by the arrangement of vegetation even if vegetation density or a covering ratio is equal. The difference corresponds to the variation in the process of erosion or the channel formation, which has been explained in the previous section. Sediment discharge takes the highest value in Case C4, and the lowest value in Case C1.

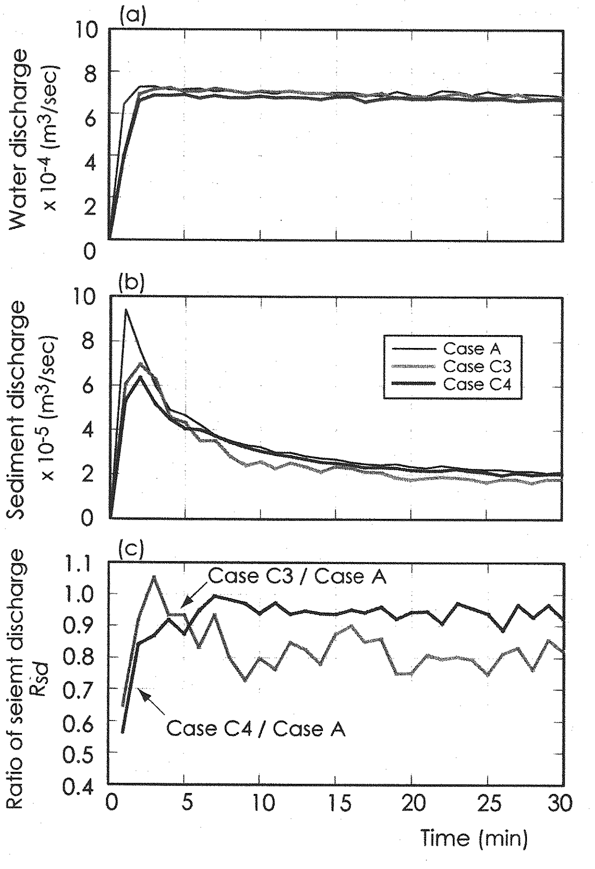

Fig. 7 Temporal variation of water and sediment discharge from the exit mouth at the downstream end

(4) Temporal variation of the sediment discharge took a peek or a maximum value, which was recorded at a few minutes from the beginning of artificial rainfall. Slope collapse occurred on the slope around the exit mouth for a while just after the sudden opening of the gate. It can be inferred that the above variation was caused by such a collapse.

CONCLUSION

In this study, the process of surface erosion caused by artificial rainfall was investigated experimentally. The effects of natural vegetation known as Pachysandra on both the process itself and the sediment yield from the slope were evaluated. We tried to evaluate the effect of vegetation root and that of leaf and stem separately in a series of experiments. Findings clearly show how the surface erosion can be reduced by the action of vegetation. The influence of the vegetation arrangement on this erosion was also investigated. Results of this research reveal that the arrangement affects the amount of erosion and the pattern of channel network formed on the slope considerably.

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