EXPERIMENTS ON CHANNEL INCEPTION BY SURFACE RUNOFF

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An experimental study of channel inception by surface runoff was conducted by the use of a wide and short rectangular flume as well as two types of sediment mainly composed of silica powder. The experiments were set up based on the concept of the "downstream-driven theory" of channel inception. Several combinations of discharge, soil and slope were selected in order to study the channel inception process in detail, and to test the theoretical findings obtained by Izumi and Parker[1)]. During the whole course of the experiments, four distinct types of channel inception processes were observed. Irregular shapes of channels and high tendency towards bifurcation were observed in high clay content soil whereas narrow and straight channels were observed in less clay content soil. In the case of mild slope (0.5%), the channel spacing increases with increasing surface flow discharge while, in the case of steep slope (5%), it decreases with increasing discharge.

Key Words*: *channel inception, channel spacing, soil erosion, dominant wavenumber and experiment.

1. Introduction

The channel network is one of the major geomorphological events, and is accountable for topographic features of certain localities. It is mentioned by many researchers that the channel formation is a self-organizing process, in which uniform channel spacing is often observed, as argued by considering maps of different areas as witnesses[1)-6)].

As it is known, our global environment comprises a variety of phenomena which are dynamically interactive as arranged in such a manner that one affects the other and vice versa. Therefore, without appropriate management, our global environment may fall in a vicious cycle, and cannot keep up its dynamism.

Of these phenomena, the channel formation can be considered as an important part, among other things, of the geomorphological evolution system. They are possibly created either due to erosion by overland or subsurface flow. In addition, slope instability at channel heads can generate destructive debris flow, resulting in the formation of gullies with heavy sediment transport[4)].

The process of channel formation by surface runoff has been considered as a water-land interaction, in which surface flow is determined by the shape of the Earth's surface while the shape of the Earth's surface is affected by the erosion due to the surface flow.

The extent of the channel evolution depends on both the nature of runoff, erosive power of runoff which is related to its discharge and speed, and the nature of the soil surface, its resistant capacity against erosion due to surface runoff. Among a variety of factors, there are important parameters that cannot be ignored, like velocity of water, gradient of the Earth's surface and nature of the land cover[1)-6)].

Of the different aspects of channel formation, one important issue is that channels are not arbitrarily formed or spaced rather they are organized to show patterns with somewhat uniform channel spacing. So far, there are few theoretical attempts to bring this issue on board[1-3]. The formation of channels initiated at the downstream end has been studied in terms of linear stability analysis, and it is called "downstream-driven theory"[1] of channel inception. There is also another approach to address the formation of channel, which is called "upstream-driven theory"[2]. Recently, there has been an attempt to improve the existing analyses by extending to more general cases of slopes with arbitrary shapes[3]. Although the assumption made in the analyses is different, all came up to a somewhat similar conclusion that the channel spacing is approximately ten times the Froude critical depth of the surface runoff divided by the surface friction coefficient.

The aim of this experimental study is to verify the practical validity of the theories proposed by Izumi and Parker[1], Izumi and Fujii[4], and Pornprommin et al.[3]. The main focuses of this study are the following: to test the theoretical findings experimentally, and to study the channel inception processes in detail.

2. EXPERIMENTAL SETUP

All the experiments were performed in the laboratory in Hokkaido University using the flume (sediment chamber) shown in Figure 1. Both discharge and slope are controllable so as to try a variety of combinations of discharges and slopes. The flume is 150 cm in width and 120 cm in length. The discharge can be controlled by the valve before going into the water tank located at the upstream end of the flume. We filled the flume with sediment to make a 5-cm-thick sediment layer. Water flows down on the surface of the sediment layer and incises channels. Water starts to flow when the water level in the water tank exceeds the height of the upstream end of the sediment placement chamber.

We conducted three series of experiments in order to elucidate the effects of the variation in soil types and slopes. In the first series, high clay content soil was used under mild slope conditions. In the second and third series, low clay content soil was used under mild and steep slope conditions, respectively.

In the experiments, we used two types of soil, high clay content soil and low clay content soil, composed of silica powder and clay (kaolinite). The high clay content soil is composed of 70.6% fine sand (70 μm), 17.6% silt (10 μm), and 11.8% kaolinite, modeled after fine sandy loam. The low clay content soil is composed of 16.5% coarse sand (600 μm), 58.6% fine sand (70 μm), 22.9% silt (10 μm), and 2% kaolinite, modeled after coarse sandy loam. The sediment was reused in a series of experiments.

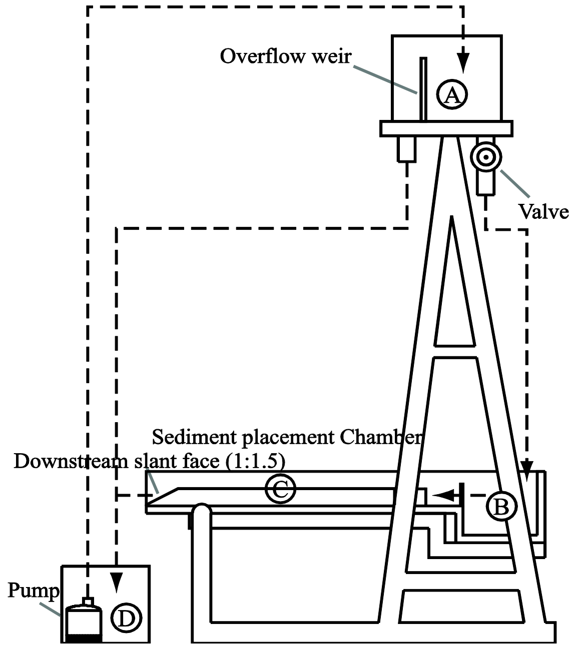


Fig.1 Experimental apparatus: the broken line indicates water flow path. A: discharge head regulator; B: water collector chamber; C: sediment placement chamber; D: reservoir

We prepared the soil so that it is relatively easily eroded but still have some cohesivity[7]. The scale of the model in the experiments was small as compared to the field. In order to reproduce realistic channel formation processes observed in the field, cohesivity of soil is important. In addition, in order to obtain channel spacing smaller than the flume width, we need to realize very shallow flow. For active erosion under very shallow flow, the sediment should be easily eroded.

The sediment was thoroughly mixed to homogenize the textures before placing in the flume. Bulk density and shear strength of the soil were measured in most of the experiments. A slant of 1:1.5 (V:H) was formed at the downstream end of the sediment layer. The lateral gradient was kept zero to assure that uniform flat overland sheet flow can be achieved[8]. We started each experiment after soaking the sediment mixtures for several days.

Erosion processes were recorded by using digital camera installed on the rear top of the flume. In addition, the shear strength of the soils was measured using the direct method with vanes. The soil moisture content and the bulk density were also measured with the use of the gravimetric method.

3. RESULTS AND DISCUSSION

(1) Observation on channel inception processes

Four types of channel inception processes were observed during the whole course of the experiments: channelization by undercutting and mass failure, channelization by undercut and mass failure preceded by erosion, channelization by localized erosion, and channelization by pure surface erosion.

a) Channelization by undercutting and mass failure

This type of channelization process was observed in the case of mild slopes. Channelization starts by scouring at the toe of the channel head. Overhanging “soil blocks” are formed by the scouring, and collapse successively. Soil aggregates and disintegrated soil particles are transported downstream by flow. The causes of channelization are mainly the scouring process and the mass failure. This process is associated with high cohesivity of the sediment (high clay content soil). The shear strength is relatively high as compared to the low clay content soil.

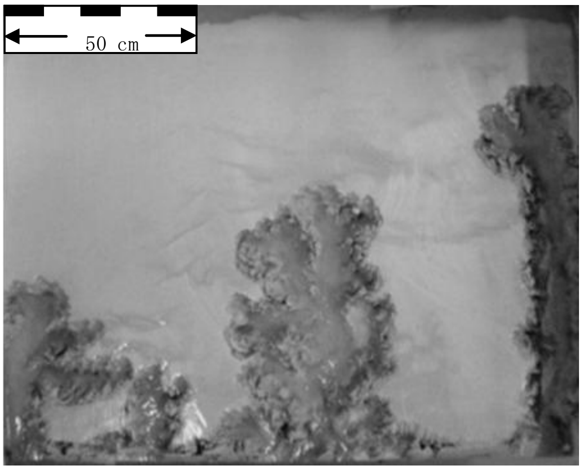


Fig. 2 Channelization process by undercutting and mass failure.

b) Channelization by undercut and mass failure preceded by erosion

This channelization process is similar to the preceding type except undercut and mass failure is preceded by shallow surface erosion in the upstream vicinity of each channel head. The shallow erosion is migrating upstream with the channel head. The formation of shallow surface erosion is assumed to be similar to that of hollows upstream of channel heads[5]. This type of channelization was observed in the case of soils with less shear strength as compared to the preceding type.

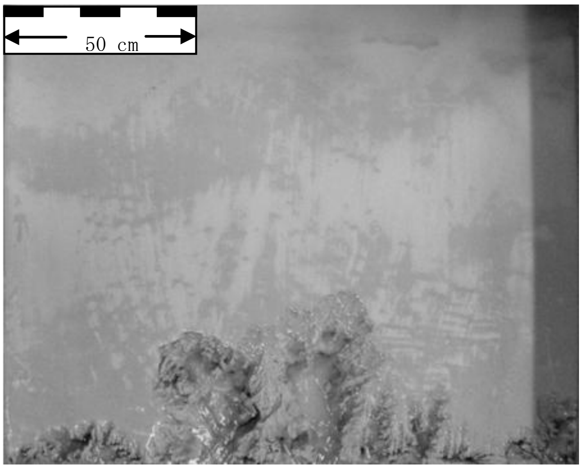


Fig. 3 Channelization by undercut and mass failure preceded by erosion.

c) Channelization by localized erosion

This type of channel inception process is mainly due to surface erosion that occurs on both the downstream and upstream vicinities of precipices. Neither mass failure nor the transport of soil aggregates is observed. The erosion rate is very high. This channelization was observed in the case of soils with low shear strength.

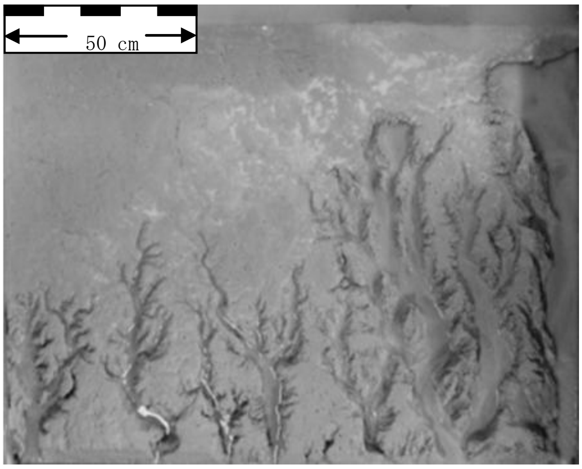


Fig. 4 Channelization process by localized erosion.

d) Channelization by pure surface erosion

In the case of steep slopes, the erosion process is not restricted in the vicinity of channel heads. The channel inception process is mainly caused by surface erosion upstream of channel heads as well as at precipices. The channel formation process is intensified by upstream channel head migration.

In addition, we observed that small channels were formed along the channel banks. The channel spacing of the small channels is rather uniform, ranging from 5 mm to 15 mm. The formation of the small channels is assumed to be caused by the drain of small amount of water from the outside to the inside of channels.

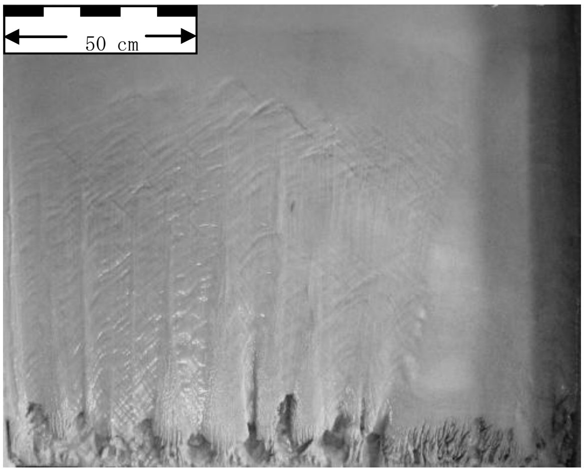


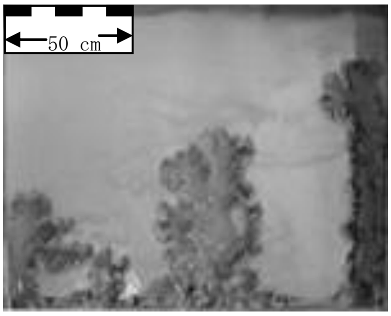
Fig. 5 Channelization process by pure surface erosion.

(2) Effects of cohesivity and slopes on channel formation processes

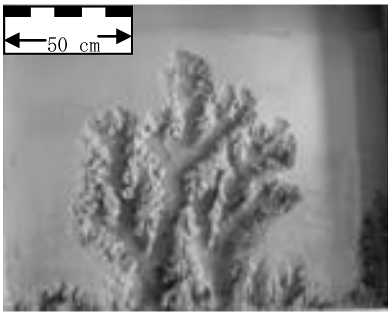
The photographs of the experiments are shown in Figure 6. Figures 6(a) and (b) are the channels observed in the first series of experiments, in which high clay content soil is used under the mild slope condition. Figures 6(c) and (d) show the channels observed in the second series, in which low clay content soil is used under the mild slope condition. Figures 6(e) and (f) correspond to the third series, in which low clay content soil is used under the steep slope condition.

Comparing Figures 6(a, b) and (c, d), we can study the effects of cohesivity on the channel formation processes. We observed irregular shapes of channels and high tendency towards bifurcation in Figures 6(a) and (b). Meanwhile, the channels in Figures 6(c) and (d) have clear straight shapes. The erosion rate in Figures 6(a) and (b) was very low while it is high in Figures 6(c) and (d). The channel spacing increases with increasing discharge in all the cases in Figures 6(a)-(d).

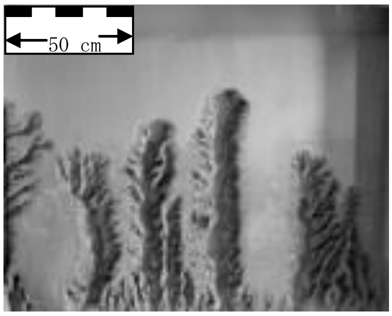
From the comparison between Figures 6(c, d) and (e, f), the effects of slopes on the channel inception processes can be elucidated. Figures 6(c) and (d) correspond to the case of mild slopes (0.5%, subcritical flow condition), and Figures 6(e) and (f) to the case of steep slopes (5%, supercritical flow conditions). It is found that the channel inception process in the case of steep slopes was different from that in the case of mild slopes in the following points. The erosion process was active everywhere on the sediment layer compared with the mild slope cases. Channels were clearly observed upstream of channel heads due to the flow concentration before



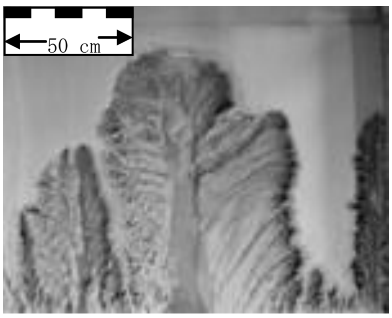
(a) Exp_1-3, discharge: 12.41 l/min, slope: 0.5%, soil: high clay content



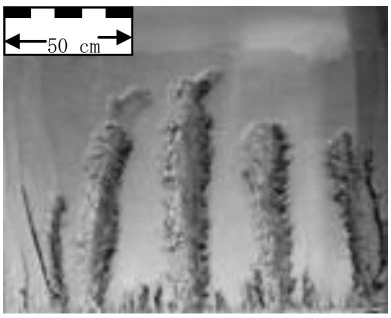
(b) Exp_1-6, discharge: 26.4 l/min, slope: 0.5%, soil: high clay content



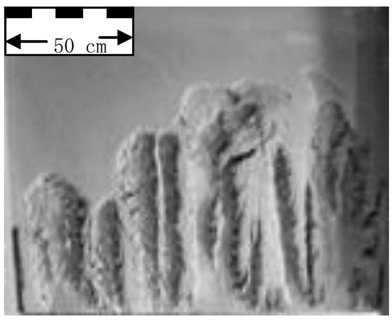
(c) Exp_2-2, discharge: 9.55 l/min, slope: 0.5%, soil: low clay content



(d) Exp_2-4 discharge: 24.22 l/min, slope: 0.5%, soil: low clay content



(e) Exp_3-1 discharge: 12.34 l/min, slope: 5%, Soil: low clay content



(f) Exp_3-3 discharge: 24.97 l/min, slope: 5%, soil: low clay content

Fig. 6 An over view of the experiments: (a) and (b) are experiments conducted with high clay content (first series); (c) and (d) are experimental pictures among soils with low clay content and mild slope (second series); and (e) and (f) are among experiments with less clay content but steep slope (third series).

the migration of channel heads farther upstream. The channels are straight and relatively narrow, and the channel formation process is accompanied with step formation in the upstream of channel head, which was observed migrating upstream as the main head of channel retreats upstream. This was also explained by Parker and Izumi[9]. The most imperative observation in this experiment was that the channel spacing increases as discharge increases, which is opposite to the channel formation in the mild slope.

(3) Comparison between the experiments and the theory

The experimental results are compared with the results of the theory of downstream-driven channel formation[1].

It was observed in the experiments that channels are initiated at the downstream end in the case of mild slopes. This is consistent with the assumption made in the analysis of the downstream-driven channelization theory. Meanwhile, the channelization process in the case of steep slopes turns out to be different from that in the case of mild slopes in the sense that active erosion takes place in the whole area of sediment layer.

The channel spacing λ in m versus the Froude critical depth D_c in m observed in the experiments is shown as symbols in Fig. 7. Keeping the theoretical results in mind, we assume that channel spacing is proportional to the Froude critical depth. In Fig. 7, linear regression lines of the observed data crossing the origin are also shown. The regression line corresponding to the case of low clay content soils is described by

$$\lambda = 189 D_c \quad (1)$$

Meanwhile, the regression line in the case of high clay content soils is

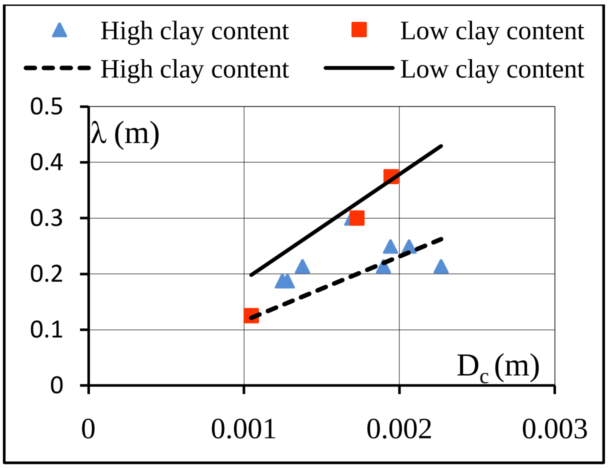


Fig. 7 Channel spacing versus Froude-critical depth for the experiments conducted in mild slope. The solid line represents regression equation for both sediment mixtures.

$$\lambda = 106 D_c \quad (2)$$

where λ is channel spacing (m) and D_c is the critical depth in the Froude sense (m).

Fig. 8 shows the results of the theoretical analysis[1]. The growth rate of perturbation ω is theoretically derived as a function of the wavenumber k, the normalized critical shear stress ψ, and the normalized upstream slope σ normalized by the friction coefficient C_f (upstream slope/friction coefficient). In the figure, the exponent of the erosion function γ is assumed to be 1.5 herein (erosion rate is assumed to be proportional to the bed shear stress to the 1.5 power). The figure shows that ω increases to the maximum positive value and decreases to negative value as the value of k increases in all the cases of ψ. It is assumed that the perturbation with the dominant wavenumber k_c associated with the maximum growth rate ω grows faster than any other perturbation, so that the dominant wavelength λ_c corresponds to the dominant channel spacing[1].

According to the theory of downstream-driven channel formation, the channel spacing can be related to the Froude critical depth by

$$\lambda_c = \frac{2\pi D_c}{k_c C_f} \quad (3)$$

where C_f is the surface roughness coefficient.

In the case of laminar flow such as shallow flow realized in our experiments, the surface roughness coefficient C_f can be theoretically obtained by the integration of the analytical laminar flow solution of two-dimensional Navier-Stokes equations. That is

$$C_f = \frac{3}{\mathrm{Re}} \quad (4)$$

where Re is the Reynolds number defined as UH/ν., where U is the velocity of the surface runoff, H is the flow depth, and ν is the kinematic viscosity. The average value of C_f in all the cases of experiments is 0.081. From Fig. 8, the characteristic

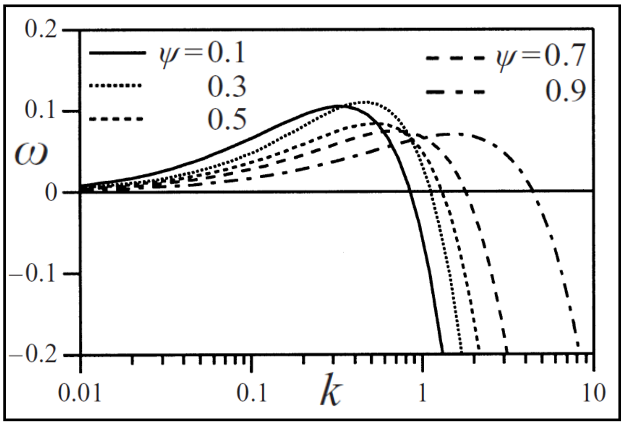


Fig. 8 Dependency of ω on ψ and k, for σ = 0 & γ = 1.5: adopted from Izumi and Parker[1].

wavenumber k_c associated with the maximum growth rate of perturbation ranges from 0.3 to 1.5 when ψ is from 0.1 to 0.9, respectively. With the use of the value of C_f and the dominant wavenumber k_c calculated in the above, the channel spacing predicted by the theory can be written as

$$\lambda = (51.4 - 257.1)D_c \quad (5)$$

It is found that Eqs. (1) and (2) are consistent to the above equation.

As observed in Fig. 7, the ratio of the channel spacing for the Froude critical depth is larger in the case of low clay content soil than that in the case of high clay content soil. Though we cannot make a firm conclusion, it may possibly be that this is explained by the difference of the critical bed shear stress between high and low clay content soils. In the case of low clay content soil, cohesivity is rather low, so that the critical bed shear stress can be assumed to be small. Meanwhile, high clay content soil is more cohesive so that the critical bed shear stress may be large. According to the theory, the dominant wavenumber k_c increases with the critical bed shear stress. If the high clay content soil has larger critical bed shear stress and vice versa, the experimental results are consistent with the theoretical results. If we make back calculation of the value of k_c from the experimental data, we find 0.41 and 0.72 for low and high clay content soils, respectively. The corresponding values of ψ are 0.1-0.3 and 0.5-0.7, respectively.

4. CONCLUSIONS

The main conclusions of this study are the following:

- four types of channel formation process were observed: channelization by undercutting and mass failure, channelization by undercut and mass failure preceded by erosion, channelization by localized erosion, and channelization by pure surface erosion,
- in the case of mild slopes, the channel spacing increases with increasing discharge while, in the case of steep slopes, the channel spacing decreases with increasing discharge,
- irregular channel shapes and high tendency towards bifurcation were observed in high clay content soil,
- channels formed in the less clay content soil have narrower widths and straight shapes compared with those formed in the high clay content soil,
- channels formed on steep slopes are straight and narrow compared with those on mild slopes,
- the processes of channelization in the experiments under mild slope are consistent with the assumption made in the theory of downstream-driven channel formation,
- the channel spacing observed in the experiments in the case of mild slopes can be consistently explained by the theory of downstream-driven channel formation, and
- the spacing of channels decreases with increasing soil shear strength.

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