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EXPERIMENT OF CHANNELIZATION DUE TO SEEPAGE EROSION

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ABSTRACT: We have investigated channelization due to seepage erosion using two sizes of coarse sand (d_{50} = 0.86 and 0.56 mm), two chamber slopes (S = 0 and 3%) and three upstream water depths (H = 15, 17 and 19 cm). Water was fed at the far upstream end of a sand layer, and a small incipient channel was made at the center of the downstream scarp. Thus, groundwater flow converged into the central channel, promoted erosion and caused the development in both width and length. At the beginning, the retreat rates of channel heads were rapid but decreased after a while. A higher H induced a faster retreat and a larger size of the center channel. In the experiments with S = 0%, channel head bifurcation was always observed for d_{50} = 0.86 mm but not d_{50} = 0.56 mm. Thus, not only the characteristics of groundwater flow field soil properties but the sediment properties also affect the shapes of evolving channels. For S = 3%, however, bifurcation was only found in the experiment with d_{50} = 0.86 mm and H = 15 cm. It implies that H also controls bifurcation. In addition, new channels were initiated at the downstream scarp when S = 3%. An increase in the streamwise discharge due to a steeper slope may weaken the convergence of the groundwater flow into the center channel. Using the concept of network circularity, we can divide the channel development of our experiments into the initiation and extension phases.

Keywords: Channelization, Seepage erosion, Network circularity, Experiment

1. INTRODUCTION

Water flow as a main driving force that erodes landscape can be classified as surface and subsurface flows. For subsurface flow, seepage induces soil piping at scarps in which groundwater emerges, causes the instability of scarps and finally triggers mass failures. Erosion at the scarp can continue if seepage is strong enough to remove sediment out of the scarps [1]. As a result, soil layers are incised by channels (channelization). As channels evolve, their heads sometimes split into two parts, and each part turns into a sub-channel migrating in a different direction. This phenomenon is called bifurcation. The repeated process causes a complex pattern of channel networks. Because of the distinct geometrical features of channel networks, a large number of studies have been conducted in the fields of geomorphology and geophysics. However, it is also important from an engineering point of view because a large quantity of sediment is produced in the process of channelization. Therefore, understanding the developing process of channels provides important information on sediment yield [2].

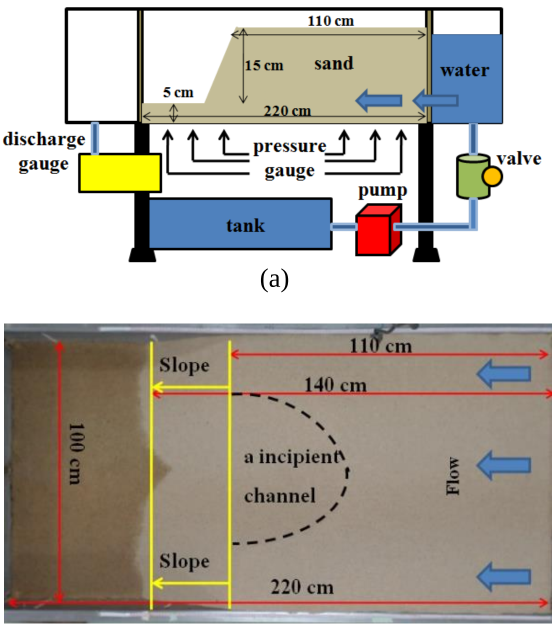
Recently, the processes of channelization and bifurcation by seepage erosion has been an interesting topic. The experiments conducted by [3] show that under the constant water discharges, a steeper chamber slope causes a shallower groundwater depth and results in an increase in the number of incisions at scarps. As the sediment layer depth increases, the channel width also increased. Also, they have performed a linear stability analysis to study the incipient channelization. They have found that groundwater flow tries to cause channel incision and channelization, while mass failures acting as a diffusive function to smoothen the scarp from the incision. Thus, the competition between two processes provides the channelization with the characteristic spacing. More experiments have been done by [4], and they found that channel bifurcation location is farther from a scarp when the chamber slope becomes steeper.

In [3] and [4], water fed to the experimental chambers at the far upstream end. Channel bifurcation by uniform rain on the sediment surface has been studied by [5]. They show that the groundwater flow field is governed by the Laplace equation if water fed from the upstream end. And it causes the channels to elongate upstream with a constant width. However, the flow field is described by the Poisson equation (the Laplace equation with source term) when it is rain feed. Water is approximately uniform in the radial direction of the channel head, and, thus, channel head is bifurcated. The concept of the effect of groundwater flow field on channel bifurcation has been extended by [6] & [7]. They have applied the Dupuit-Forchheimer equation to compute the groundwater flow field in the vicinity of a channel head. They found the characteristic angle between two bifurcated subchannels of $2\pi/5$. This angle agrees with the field observation of a channel network generated by seepage erosion.

In this study, we have extended the experiments by [3] & [4]. In their experiments, there were no initial channels at the downstream scarp. Thus, incised channels randomly appeared along the scarp. If an incised channel is initiated at the side of the chamber, it develops slower than that at the center due to less flow convergence toward its head. Thus, it cannot explain the evolution of a specific channel very well. This limitation was eliminated in this study by initiating a small initial channel at the center. Thus, the effects of sediment size, chamber slope and water depth on the development of a center channel can be investigated.

2. EXPERIMENT SETUP

We have performed the experiments in a 1.00 x 2.20 x 0.225 m^3 chamber. At the setup stage, the 5-cm thick base layer was filled with dry sand for adjusting bed slope, and then a 15-cm thick of the sand layer was built on top of the base by a wall. This special wall has a box with a dimension of 20 x 20 cm^2 to block the sand filled at the downstream center to create an initial channel. When the wall removes, it creates the sediment layer with a center channel as shown in Fig.1.



(a)

(b)

Fig.1 Experiment setup where (a) is side view and (b) is top view.

The far upstream water level was controlled by a valve and a standing drain pipe. Water flowed through the sand layer and emerged at the scarp. Thus, seepage erosion generated the development of a center channel. While the channel evolution was captured by a camera installed above the chamber, the discharge was measured by a weir under the chamber. Two different sizes of coarse sand, d_{50} = 0.86 and 0.56 mm, were used. The chamber slope (S) were adjusted to flat or 3%. The upstream water level (H) was set to 15, 17 and 19 cm. Thus, there are totally 12 experiments.

3. RESULTS AND DISCUSSION

3.1 Experimental Results

The general physical characteristics and sequences of seepage erosion phenomena in our experiments can be explained as follows. After a while from the beginning, water emerged at the scarp in the vicinity of the center channel head first because the center channel is the nearest outlet of groundwater. The discharge at the channel head is also higher than other places due to flow convergence. At the face of the scarp, three process zones proposed by [1] can be seen. The lower face or the toe of the scarp, where water was saturated and emerged as seepage, is called "sapping zone." The strong seepage in this zone caused sediment particle removal from the face and destabilized the scarp. The upper face of the scarp, called "undermining zone," collapsed due to slope instability. At the channel head, seepage was found to be sufficiently strong that the failed sediment material can be transported away from the face by fluvial processes, called "fluvial zone." These processes continued and generated the development of the center channel toward upstream end.

The photos of the final stage of channel evolution from the top camera for some experiments were shown in Fig.2. It is found that all channels had amphitheater-shaped heads with steep sidewalls. This is usually for channelization by seepage erosion because the process of mass failure induces steep collapse of the sediment layer. Figure 2a for the case of d_{50} = 0.86 mm, S = 0%, H = 19 cm shows channel bifurcation before it reached the upstream end. Since a capillary force is stronger as a sediment size becomes smaller, wetter areas on the sand surfaces in Fig.2c and d for d_{50} = 0.86 mm can be seen. In addition, a larger scale of mass failures is observed for a smaller sediment. This is possibly due to a stronger cohesive force.

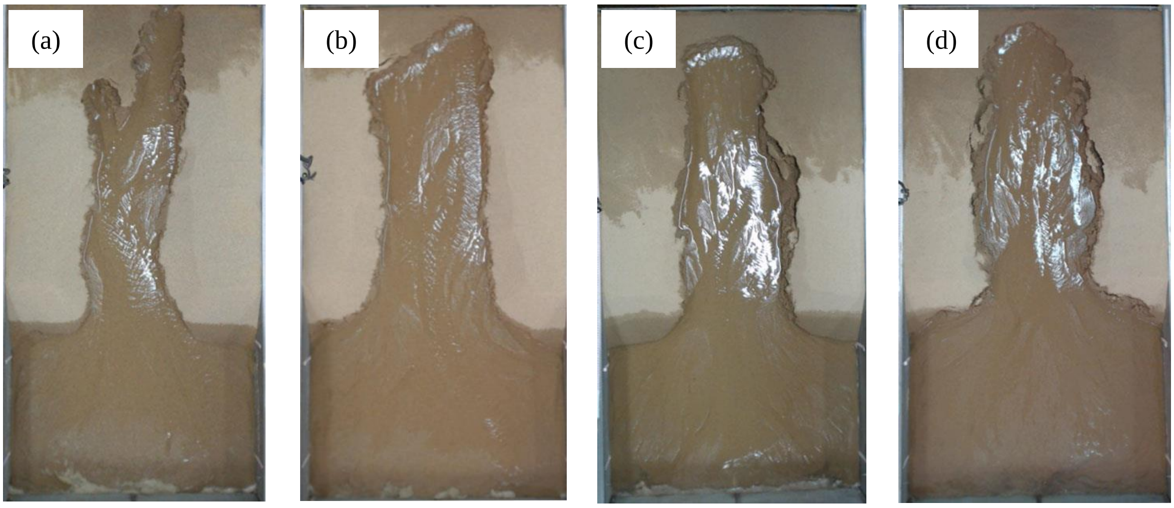


Fig.2 Plan views of channels where flow is from top to bottom, and
(a) is d_{50} = 0.86 mm, S = 0%, H = 19 cm, (b) is d_{50} = 0.86 mm, S = 3%, H = 19 cm,
(c) is d_{50} = 0.56 mm, S = 0%, H = 19 cm and (d) is d_{50} = 0.56 mm, S = 3%, H = 19 cm.

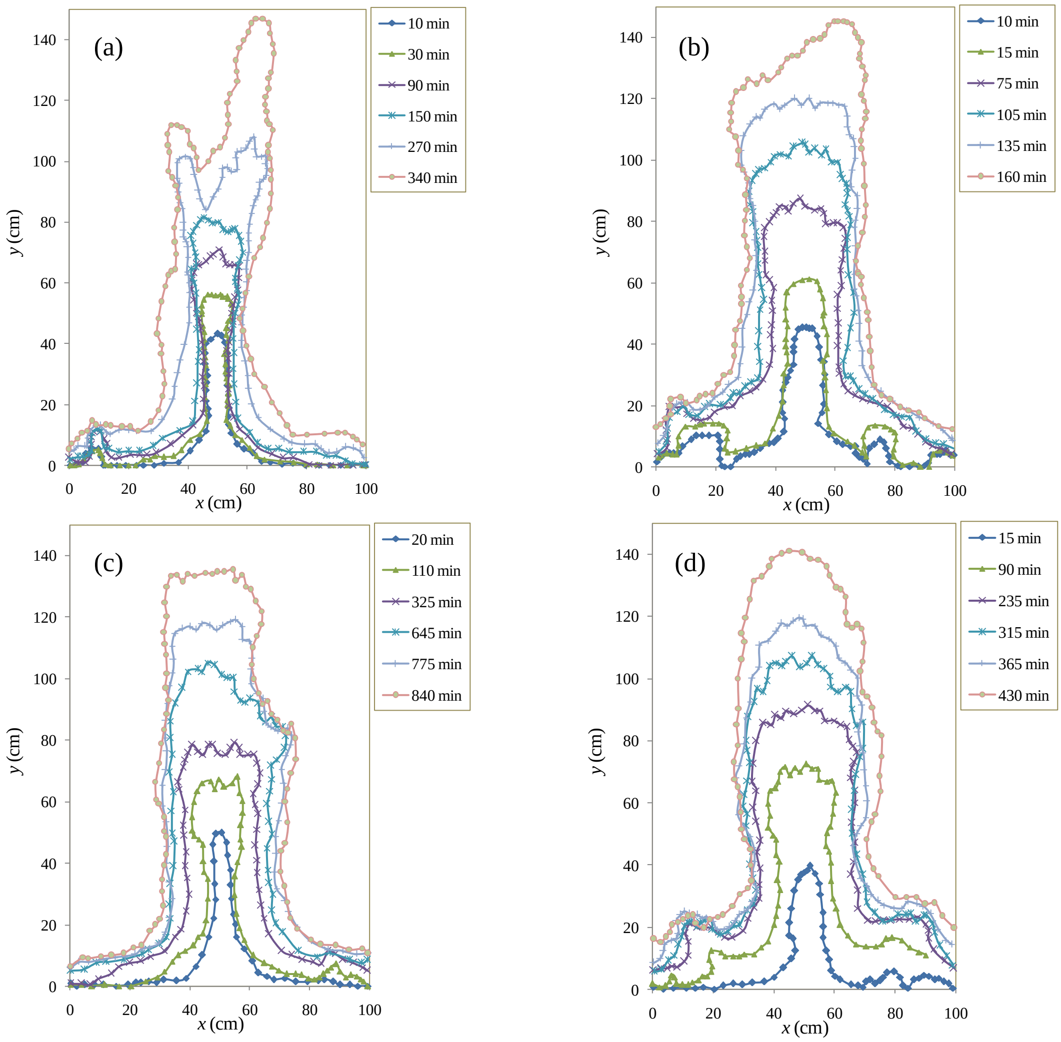


Fig.3 Temporal evolution of channels corresponding to Fig.2 where
(a) is d_{50} = 0.86 mm, S = 0%, H = 19 cm, (b) is d_{50} = 0.86 mm, S = 3%, H = 19 cm,
(c) is d_{50} = 0.56 mm, S = 0%, H = 19 cm and (d) is d_{50} = 0.56 mm, S = 3%, H = 19 cm.

Table 1 Summary of the experimental results

d_{50} (mm)	S (%)	H (cm)	Q (l/s)	Z (cm)	Bifurcation	New channels
0.86	0	15	0.275	7.04	Yes	No
0.86	0	17	0.325	9.30	Yes	No
0.86	0	19	0.350	9.50	Yes	Yes
0.86	3	15	0.370	9.33	Yes	Yes
0.86	3	17	0.375	9.37	No	Yes
0.86	3	19	>0.40	9.58	No	Yes
0.56	0	15	0.125	6.50*	No	No
0.56	0	17	0.170	9.10	No	No
0.56	0	19	0.190	9.40	No	No
0.56	3	15	0.165	9.05	No	Yes
0.56	3	17	0.205	9.12	No	Yes
0.56	3	19	0.210	9.52	No	Yes

Remark: *the erosion stopped before the channel head could reach the upstream end.

Figure 3 shows the examples of the temporal evolution of channel by digitizing the photos corresponding to Fig.2. We can see that initial channels widened and elongated upstream. From the observation, the widening at the sides of channels was generated by the fluvial process within the channels similar to bank erosion, but the widening at the channel heads was generated by seepage erosion. In addition, at the intermediate stage, new channels were initiated at other locations on the downstream scarp before most of them were disappeared by the widening of the center channels. The retreats of whole scarps are stronger when the slopes are steeper. It is also found that channels migrated faster with a large sediment size with a higher slope (Figure 3b). This is possible due to that a higher discharge induces a higher rate of erosion.

3.2 Characteristics of Channel Evolution

Table 1 summarizes the final discharges (*Q*), the final incision depths (*Z*) at the scarp, and the occurrences of bifurcation and new channels in our experiments. It is found that *Q* for the cases of d_{50} = 0.86 mm is higher than the ones of d_{50} = 0.56 mm. Also, *Q* increases with a steeper slope. This is because a larger sand size has a higher permeability and a steep slope provide a higher energy slope. The values of *Z* are almost constant for all cases except the case of d_{50} = 0.56 mm, *S* = 0% and *H* = 15 cm because the erosion stopped before the channel head could reach the upstream end. However, for the same d_{50}, a larger *Q* gives a slightly deeper *Z*. It is found that channels were bifurcated when the sediment size is large and the slope is small. Our results that a milder slope induces bifurcation confirms the results of [4]. Nevertheless, the reason that we can see bifurcation for a smaller d_{50} of 0.56 mm is not clearly understood. We hypothesize that a large scale of mass failure may be a factor that stabilizes a channel head from bifurcation. New channels were always initiated when *S* = 3%. According to [3], the channel spacing is related to groundwater depth. If the depth is shallower, the spacing is shorter. The concept is confirmed by our results because shallower depths happened for a steep *S* of 3%.

3.3 Network Circularity

According to [8], channel network development can be divided into three phases by a parameter named network circularity (N_c), written as

$$N_c = \frac{A}{A_c} = \frac{A}{\pi (P/2\pi)^2} \tag{1}$$

where *A* and *P* are the eroded area and perimeter of channel network, respectively, and A_c is the circle area computed using *P*. N_c has a value between 0 and 1, where N_c = 1 means that the shape of the channel network is perfectly circular.

Figure 4 shows the concept of channel network development by [8] for three phases. The first phase is called "Initiation" of which the main channels elongate upstream rapidly (N_c decreases with the fastest rate). The second phase is "Extension" where the channel heads expand laterally and bifurcate into tributary channels (N_c decreases with a slower rate). And the last phase "Abstraction" is that the channel heads continue widening and cause divide decay (N_c increases slightly).

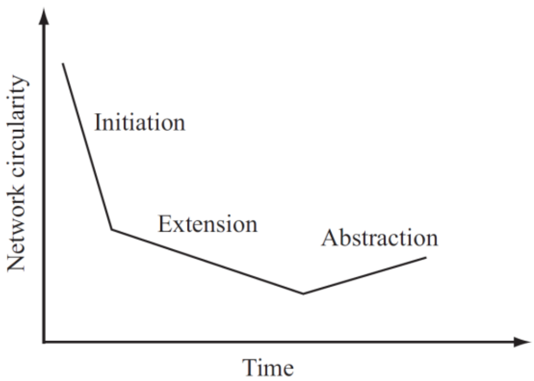


Fig.4 Concept of channel network development by network circularity (N_c) [8].

From our experimental results, we have computed the change of N_c with time as shown in Fig.5. It is found that N_c was firstly about 0.8, but it decreases rapidly for a short period of the beginning of the channel evolution before the decay rate of N_c is smaller and quite a constant later. Thus, the channel evolution in our experiments was in the initiation and extension phases. This concept agrees with our observation that at the final stage of our experiment we could not see the process of channel divide decay. However, the case of d_{50} = 0.56 mm, S = 0% and H = 15 cm is an exception because N_c shows an increasing trend. It is due to that the channel head stopped migration but the fluvial process slowly eroded the banks and subsequently caused the shape more circular.

4. CONCLUSION

A three-dimensional laboratory experiment of channelization by seepage erosion has performed. From the results, channel width and length increased with time. The groundwater flow field is proved to be the main factor to control the shapes of channel networks and bifurcation. However, we show that the sediment size is also important. As the scale of mass failure is related to sediment size (larger failure when the size is smaller), we hypothesize that the larger scale stabilizes the scarp from channelization and bifurcation. This idea is similar to the previous theory of channelization [3] that the mass failure represents the diffusion-like function that tries to smoothen the perturbations along the scarps. Finally, we have introduced the concept of network circularity to investigate the development of channel network. It shows that this concept can be used to describe the phases of channel evolution (initiation and extension) in our experiment well.

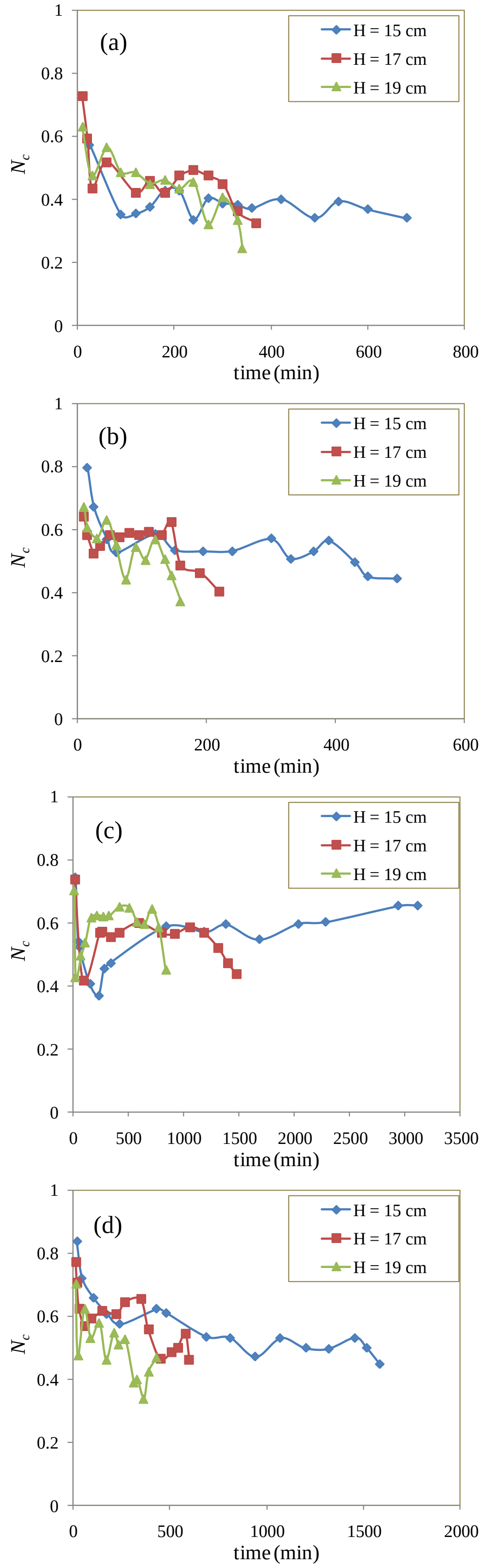


Fig.5 Temporal evolution of network circularity (N_c) where (a) is d_{50} = 0.86 mm, S = 0%, (b) is d_{50} = 0.86 mm, S = 3%, (c) is d_{50} = 0.56 mm, S = 0% and (d) is d_{50} = 0.56 mm, S = 3%.

5. ACKNOWLEDGEMENTS

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