HEADCUT EROSION AFFECTED BY DOWNSTREAM DEPOSITION

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Headcut erosion has been a major concern recently, as it causes the gully erosion and the formation of incised channels. Flume experiments have been conducted to investigate the headcut erosion process in homogeneous soil. The effects of hydraulic and geometric condition on its migration speed in coarse and find sand have been analyzed. Color spray applied on the top surface resists the surface erosion as well as ensures the headcut development. The experimental result shows the plunge pool morphology remained unchanged with time for a given flow discharge. The migration speed depends on downstream bed slope and obviously on overland flow discharge. Downstream sediment transport capacity controls the migration speed. A conceptual model is introduced to explain details of the headcut migration process. The result of conceptual model reasonably agrees with the experimental data.

Key Words : *Headcut, migration speed, homogeneous soil, plunge pool erosion, conceptual model, sediment transport, downstream bed slope*

1. INTRODUCTION

Recently, headcut erosion has been a major concern because it drastically alters environmental conditions and produces sediment that causes further problems at downstream region. Headcut is the sudden change in bed elevation where intense, localized erosion takes place. Headcut erosion usually occurs when the surface layer is protected either by cohesive layer or by grass covering or by armoring action. Concentration of overland flow mainly causes the headcut erosion. Dissipation of energy at the drop causes excessive erosion and results in headcut upward migration. Once the erosion has commenced, it is unlikely that erosion will cease naturally until the threshold condition has appeared. Investigations on erosion due to headcut migration have both practical and environmental importance, as it is responsible for gully development and failure of earthen emergency spillways.

Several studies on headcut erosion have been done based on field observations[1),2),3)]. Because most field observations are made during low- or no-flow condition, understanding of the physical process governing the formation propagation, and degradation of headcuts as they migrates is very limited. Mechanics of jet scour immediately downstream of headcut also studied by some researchers[4),5),6),7)]. Experimental study for headcut migration through cohesive soil has been done by some researchers[8),9),10)]. In spite of above studies, little information exists on the processes of headcut migration, variation of scour hole morphology, mechanics of headcut erosion and the effect of both flow discharge and headcut height.

Headcut migration speeds in very fine soils with high bed slopes, where the downstream deposition of detached sediment from the headcut erosion process is not significant, are usually a function of flow discharge and the headcut height[3),8)]. But the migration process in medium or coarse particle with low bed slopes is rather complicated. The sediment detached from the erosion process is usually higher than the downstream transport capacity, and that leads a gradual deposition process at downstream reach as well as affects the headcut migration process. In such a situation, the conventional headcut migration concept may leads a wrong prediction in overall erosion process. However, the main objective of the present study is to improve general understanding of headcut erosion process in a wider range. Flume experiments have been conducted for different hydraulic and soil conditions

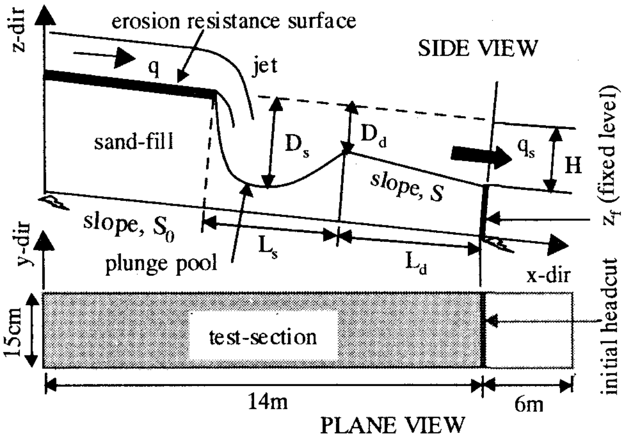


Fig.1 Schematic diagram of experimental set up

to investigate the effect of flow discharge, headcut height and downstream bed slope on headcut migration in non-cohesive homogeneous soil.

2. EXPERIMENTAL INVESTIGATION

(1) Set-Up and Procedure

All experiments were conducted in a 20m long and 15cm wide laboratory flume. The glass-made side-wall of the flume provided us an opportunity to observe the detail scouring process in a plunge pool, and its downstream conditions as well. Flow discharge was controlled by an adjustable inlet valve and monitored through a digital display-meter. Water was fed initially into an inlet tank, which acted as a reservoir for damping turbulence and controlling the flow discharge into the test section. The flume bed in the test section was filled by sand, which was connected with a wooden false bed at its upstream. A movable point-gauge was used to measure the water surface and bed elevation with time during experimental runs. The inclination of flume bed was 1:500 for all experiments. **Figure 1** shows the schematic diagram of the experimental set-up. Headcut position was monitored with time and the shape of plunge pool was recorded through photographs. Water surface and downstream bed profiles were measured at regular intervals. Results of 14 tests are reported in this paper.

(2) Sand Bed Preparation

The test section of the flume was filled by placing loose sand. Sand was filled and packed incrementally in several layers. A gentle compaction was applied to assure a uniform density. Firstly, the section was made flooded to remove all air-void. A vertical initial headcut was set at the downstream end of the test section. Adhesive color spray (4 x 10^{-4} m^3/m^2) was applied on the fill surface to make it erosion resistant and to ensure the development of headcut. About 24hr was allowed before experimental run to dry the surface layer completely. The different experimental conditions are tabulated in **Table-1**.

Table 1 Experimental conditions

expt. no.	fill material	initial headcut H (m)	unit discharge q (m^2/s)
R-1	coarse sand (d=0.88mm)	0.02	0.0069
R-2			0.0117
R-3		0.05	0.0031
R-4			0.0069
R-5			0.0117
R-6		0.10	0.0031
R-7			0.0069
R-8			0.0117
R-9	fine sand (d=0.25mm)	0.05	0.0031
R-10			0.0069
R-11			0.0117
R-12		0.10	0.0031
R-13			0.0069
R-14			0.0117

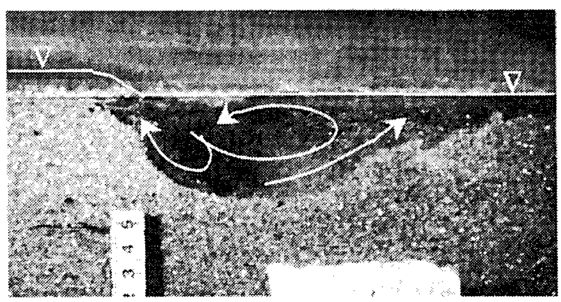


Fig.2 Photograph of the plunge pool shape (H=5 cm and q=0.0069 m^2/s)

3. RESULTS AND DISCUSSIONS

(1) Plunge Pool Erosion

Photograph of a typical case, which was taken during experimental run, is shown in **Fig.2** to provide a real imagination of the plunge pool shape. **Figure 3** shows the time variation of plunge pool shape for different flow discharges. It is observed that for a given flow-condition the shape of the plunge pool remained unchanged while the shape gradually increases with the flow discharge. **Figure 4** shows the fluctuations in L_s, D_s and D_d for different experimental runs.

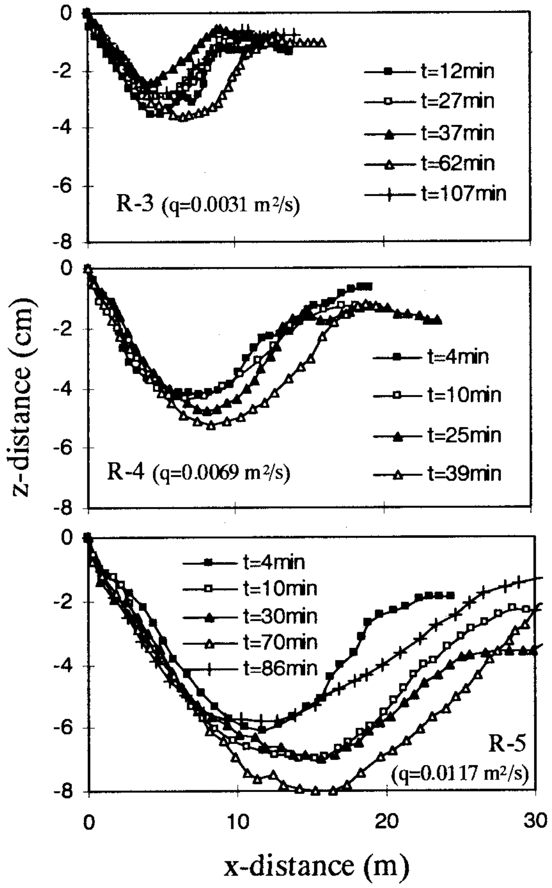


Fig.3 The time variation of plunge pool shape

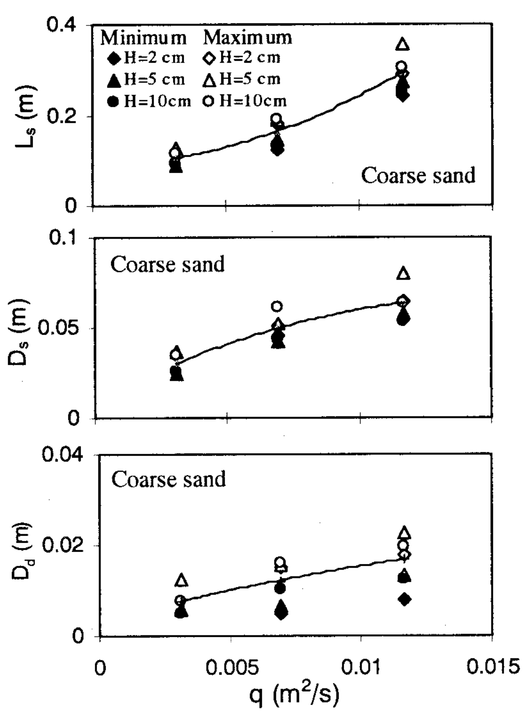


Fig.4 Fluctuation in plunge pool length (L_s), depth (D_s) and D_d

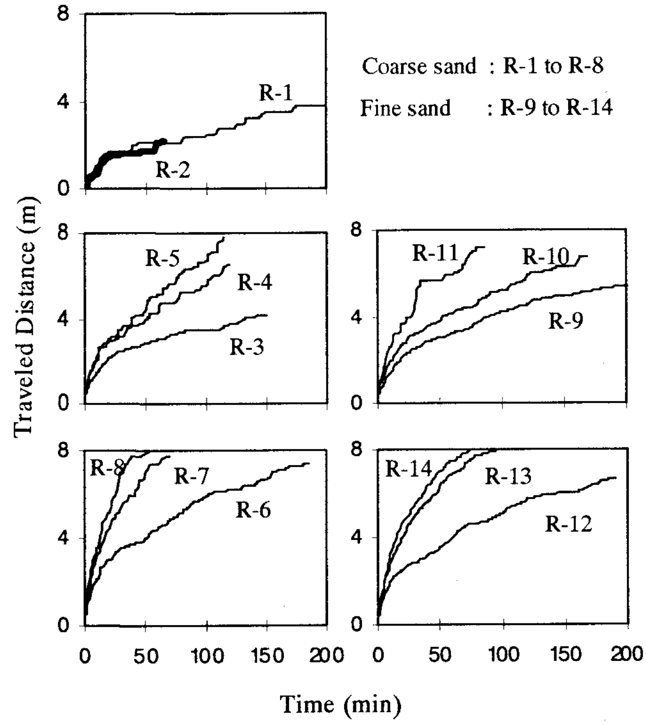


Fig.5 Position of headcut with time

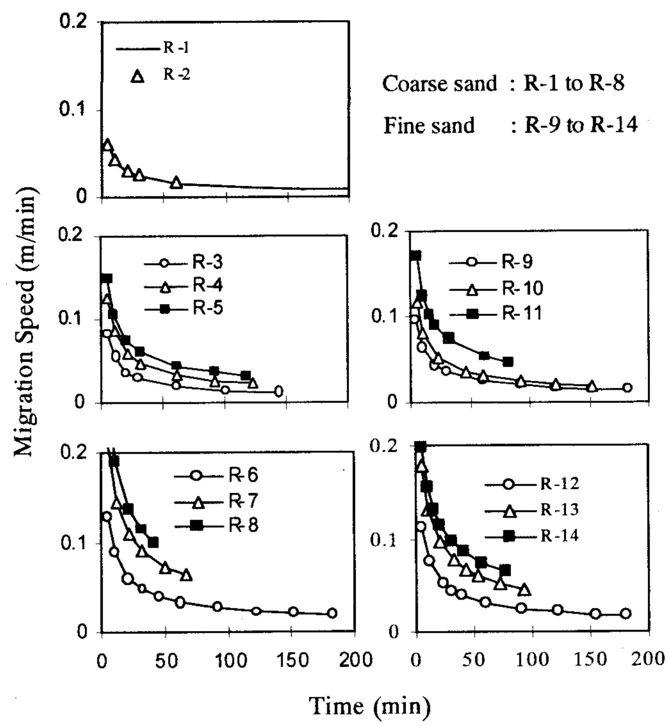


Fig.6 Headcut migration speed with time

(2) Headcut Migration and Bed Condition

Headcut migrates faster initially and then decreases with time for all of the experimental cases. **Figures 5 and 6** show the headcut migration with time. Detached sediment from the plunge pool erosion is transported downstream, which changes

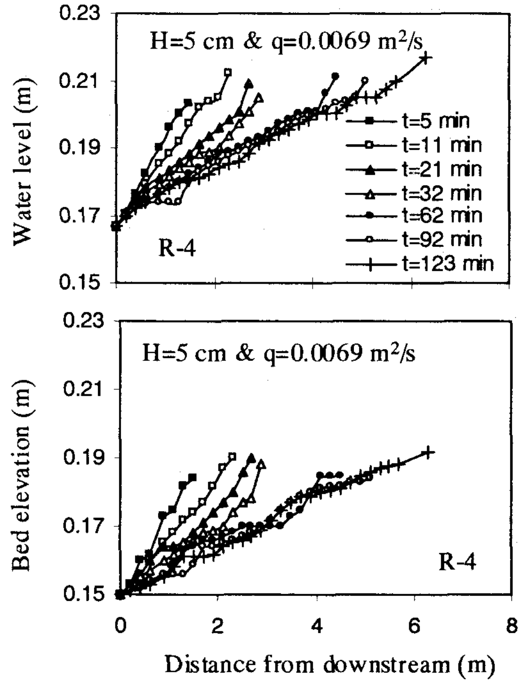


Fig.7 Temporal changes in downstream bed and water surface profiles

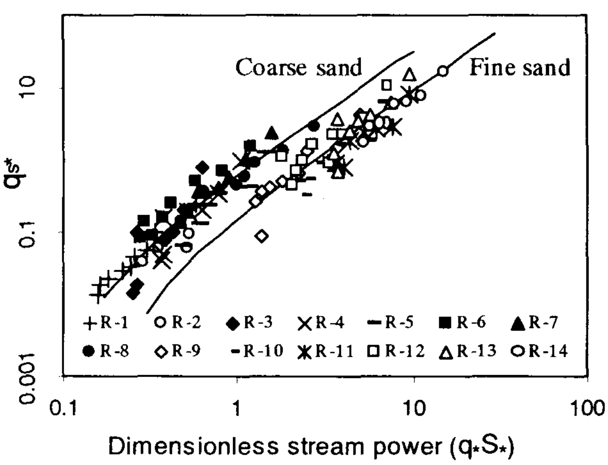


Fig.8 Downstream sediment transport with stream power

the downstream bed condition accordingly. **Figure 7** shows the temporal changes in downstream bed elevation and water level. The downstream bed slope changes gradually with time. The sediment transport capacity in downstream region controls the downstream bed slope and accordingly the headcut migration speed. The sediment discharge against the stream power is plotted in **Fig.8**, where the stream power is defined as the product of flow discharge and downstream bed slope. Best-fit dimensionless sediment transport formulae for both coarse and fine sand are introduced to express the downstream sediment transport capacity by using the experimental data:

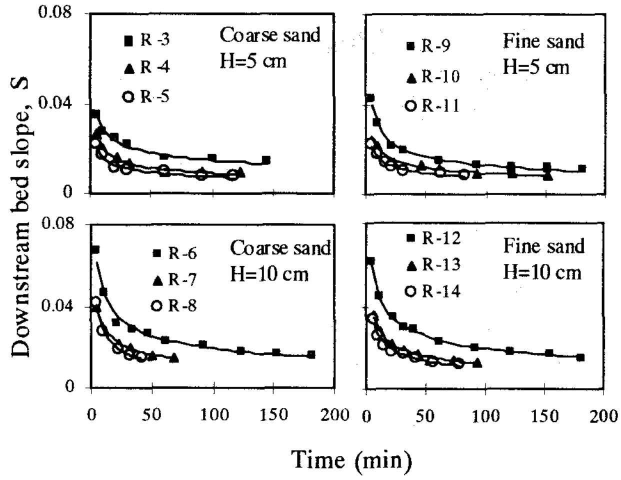


Fig.9 Changes in bed slope with time

For coarse sand,

$$q_{s*} = 0.7\{q_* S_* - (q_* S_*)_c\}^{5/3} \quad (1)$$

For fine sand,

$$q_{s*} = 0.2\{q_* S_* - (q_* S_*)_c\}^{5/3} \quad (2)$$

where q_{s*}, q_* and S_* are the dimensionless sediment discharge, flow discharge and downstream bed slope, respectively. The above mentioned terms were made dimensionless by using the following relationships:

$$q_{s*} = \frac{q_s}{\sqrt{(\sigma/\rho - 1)gd^3}} \quad (3)$$

$$q_* = \frac{q}{\sqrt{(\sigma/\rho - 1)gd^3}} \quad (4)$$

$$S_* = \frac{S}{(\sigma/\rho - 1)} \quad (5)$$

where g=acceleration due to gravity; d=sand diameter; σ/ρ = specific weight of sand. $(q_* S_*)_c$ =value of $q_* S_*$ corresponding to the critical tractive forces, which can be expressed as follows[11]:

$$(q_* S_*)_c = \tau_{*c}^{3/2} \frac{U}{u_*} \quad (6)$$

where τ_{*c}=dimensionless critical bed shear stress; U=mean velocity; u_*=shear velocity. τ_{*c} and U/u_* are determined by using the Shield diagram and the log-law, respectively, which lead the value of $(q_* S_*)_c$ equal to 0.0823 and 0.159 for the coarse and fine sand, respectively.

(3) Bed Slope and Migration Speed

The downstream sediment transport capacity depends on the downstream bed slope, which changes as the headcut position proceeds upstream. The changes in bed slope with time are shown in **Fig.9**. The average bed slope (S) decreases gradually with time and is found as an important

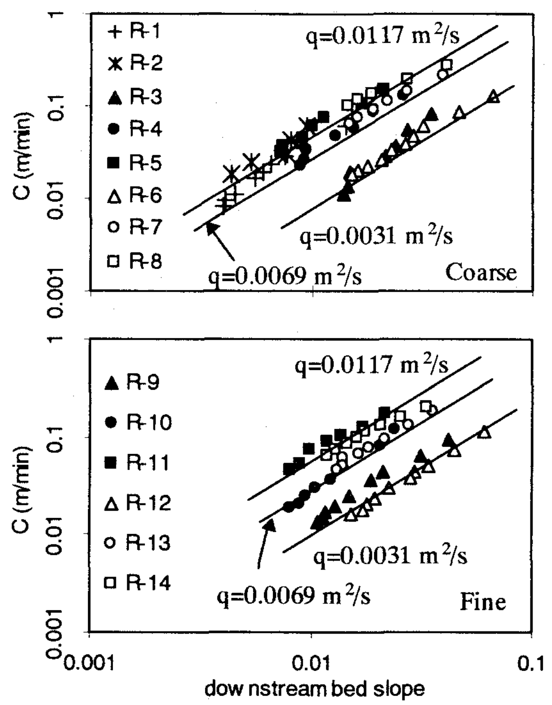


Fig.10 Migration speed with downstream bed slope

parameter to control the migration speed. Initially the high bed slope results the high sediment transport as well as the high migration speed. Migration speed decreases as the downstream bed slope decreases (**Fig.10**). When the sediment supplied by the erosion process will be the same as downstream transport capacity, then the downstream bed slope will remain unchanged with time. Once the slope becomes constant, the migration speed corresponding to that slope will be constant or equilibrium.

4. CONCEPTUAL MODEL

The downstream sediment transport capacity, the bed slope and the migration speed are interrelated each other. To establish a general relationship among all the parameters, a conceptual model is introduced in which it is assumed that D_s, L_s and D_d are constant with time. Downstream sediment budget shows (**Fig.11**),

$$(q_s)dt = (1-\rho_0)\left[\frac{H+D_d}{2}(L_d + dL_d) - \frac{H+D_d}{2}(L_d)\right] \quad (7)$$

where q_s=sediment output per unit width; dt=time interval; ρ_0=porosity of sand; L_d=downstream length. If the migration speed (C) is expressed by dL_d/dt, then we can write

$$C = \frac{2q_s}{(1-\rho_0)(H+D_d)} \quad (8)$$

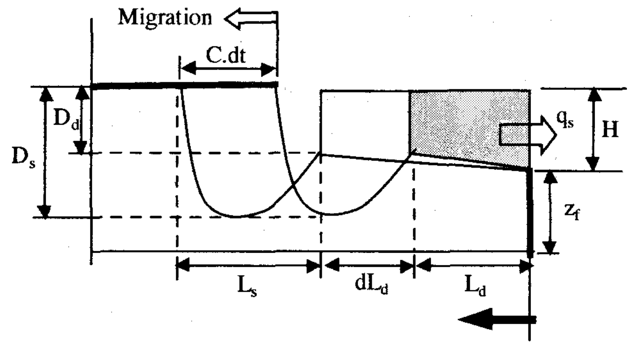
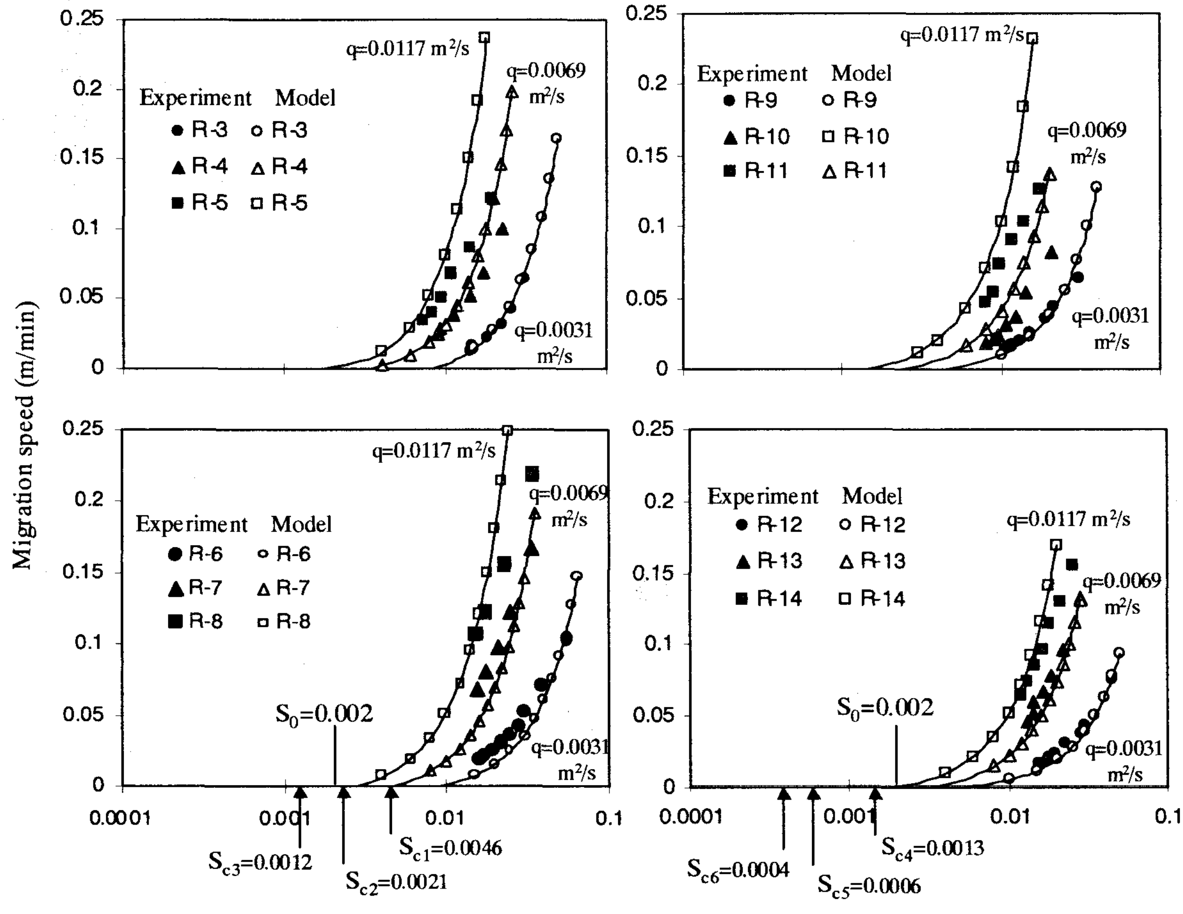


Fig.11 Conceptual sketch of migration process

The values of q_s (for a given slope) in Eq.(8) can be known from Eq.(1) or Eq.(2). Time averaged D_d, which is related to jet scour process, is known from experimental data (**Fig.4**). **Figure 12** shows a comparison between the conceptual model result and the experimental data. A close agreement between them ensures that the proposed conceptual model is good enough to predict the headcut migration speed. The downstream bed slope decreases as the headcut proceeds upstream. The slope will reach at its minimum value, which is obviously not less than the original bed slope (S_0), after a certain time. The migration speed corresponding to S_0 will be the constant or equilibrium migration speed. However, once the critical slope (S_c) corresponding to zero sediment transport appears earlier than S_0, the migration process will then stop virtually, as the downstream bed is unable to transport any more sediment further.

5. CONCLUSION

Headcut migration process in homogeneous non-cohesive soil and the effects of flow discharge and downstream deposition on migration speed were investigated through laboratory experiments. When the supplied sediment from the headcut erosion process is higher than the downstream sediment transport capacity, then the headcut migration speed is not only governed by the impact of flow jet but also by the downstream bed morphology. The present study ensures that the bed slope, which controls the downstream sediment transport capacity (q_s), is an important factor to describe the headcut migration speed (C). The C-S relationship shows that C is higher for higher S and gradually decreases as S decreases. This relation is also reproduced through the proposed conceptual model. The equilibrium migration speed can be obtained corresponding to minimum bed slope.



Note : S_{c1}, S_{c2} and S_{c3} are the critical slopes corresponding to unit discharges 0.0031, 0.0069 and 0.0117 m2/s, respectively, for the coarse sand case and S_{c4}, S_{c5} and S_{c6} are the same for fine sand case.

Fig.12 Comparison between experimental and conceptual model result

REFERENCES

1) Blong, R. J. : The development of continuous gullies in a pumice catchment, *American Journal of Science*, No. 268, pp. 369-383, 1970.
2) Piest, R. F., Bradford, J. M. and Wyatt, G. M. : Soil erosion and sediment transport from gullies, *Journal of Hydraulic Division*, ASCE, Vol. 101, pp. 65-80, 1975.
3) Temple, D. M. : Estimating flood damage to vegetated deep soil spillways, *Applied Engineering in Agriculture*, 8(2), pp. 237-242, 1992.
4) Stein, O. R. and Julien, P. Y. : Criterion delineating the mode of headcut migration, Journal of Hydraulic Engineering, Vol. 199, pp. 37-50, 1993.
5) Stein, O. R., Julien, P. Y. and Alonso, C. V. : Headward advancement of incised channels, *Proceedings of the Conference on Management of Landscapes Disturbed by Channel Incision*, edited by S. S. Y. Wang, E. J. Lamgemdoen and F. D. Shields, Jr., pp. 497-502, 1997.
6) Jia, Y., Kitamura, T. and Wang, S. S. Y. : A model for simulating scour processes in a plunging pool of loose bed-material, *submitted to Journal of Hydraulic Engineering*, ASCE, 1999.
7) Kitamura, T., Jia, Y., Wang, S. S. Y. and Tsujimoto, T. : A model for bed-scour induced head-cut, *Annual Journal of Hydraulic Engineering*, JSCE, pp.611-616, 1999 (in Japanese).
8) Hanson, G. J., Robinson, K. M. and Cook, K. R. : Experimental flume study of headcut migration, *Proceedings of the Conference on Management of Landscapes Disturbed by Channel Incision*, edited by S. S. Y. Wang, E. J. Lamgemdoen and F. D. Shields, Jr., pp. 503-509, 1997.
9) Robinson, K. M. : Gully erosion and headcut advance, *Ph.D Thesis*, Oklahoma State University, 1996.
10) Bennett, S. J., Alonso, C. V., Prasad, S. N. and Romkens, M.J.M. : Experiments on headcut growth and migration in concentrated flows typical of upland area, *Water Resources Research*, Vol. 36, No. 7, pp. 1911-1922, 2000.
11) Nakagawa, H. and Tsujmoto, T. : Lag behavior of unsteady flow with sand dunes, *Proc. 2nd International Symposium on River Sedimentation*, Nanjing, China, pp.173-186, 1983.

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