Hydraulic Structure and Material Transport in an Irrigation Channel with a Side-Cavity for Aquatic Habitat

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Abstract

Due to the growing concern for natural environment conservation in Japan, agricultural channels have recently been required to provide structures for an aquatic habitat. Following such request, an irrigation channel running in To-on, Ehime, was reconstructed for aiming to create the aquatic habitat by widening a part of the channel. This paper deals with the flow and material transport in the channel with a side-cavity, by means of field observation and numerical experiment. The field observation revealed a clock-wise eddy in the cavity. The average velocity in the cavity was less than 10 cm/s and flow in the cavity was always calm, not so depend on the discharge in the channel. To simulate the flow and then investigate the material transport in the channel, a horizontally 2-D shallow water flow model combined with quadrree numerical grids was used. The materials were modeled to be transported horizontally with the same speed as water flow. At the same time, however, they settle down following the Stokes law of resistance. The computed result showed that the material having small settling velocity is easy to be transported into inner part of the cavity.

Key words: Eco-friendly channel, Field observation, Numerical simulation, Finite volume method, Quadrree grids, Settling velocity

1. INTRODUCTION

Due to the growing concern for natural environment conservation, Food, Agriculture and Rural Areas Basic Act came into force in Japan in 1999. Following the act, Land Improvement Act was revised in 2001 and Law for the Promotion of Nature Restoration was enforced in 2003. Based on these acts, all the land improvement projects should be in harmony with nature or take conservation/restoration of ecosystem into consideration.

It is becoming widely known that several aquatic species and freshwater fishes enter agricultural channels and even reach paddy fields for feeding, spawning and so on (Saito et al., 1988). A “paddy field fishway”, which is made for helping fish to ascend from a drainage channel to a paddy field, is the one good example for environment measures to maintain rich fish fauna in agricultural channels (Hata, 1999; Suzuki et al., 2000).

Hata (1998) classified the agricultural channels into 4 levels according to channel materials, aquatic plant growth, etc., from the view point of habitat maintaining rich biota. Hirota (2007) summarized environment measures employed in upgrading paddy projects under preserving the ecosystem. These measures used in water channel works included making riffle-pool system, installing fishways/fish-nest blocks, and setting stones/wooden-poles producing wide range of velocity distribution in channels. A cobble pavement instead of concrete lining on the bottom and sides of channels has been often employed in channel works, since spaces between cobbles would provide refuges and nursery grounds for aquatic juveniles.

To conserve rare species, a side-cavity was constructed in an agricultural drain canal and has created suitable flow and environmental conditions for aquatics (Hirose et al., 2009). Flow in a side-cavity is largely affected by its shape, especially by its aspect ratio (= streamwise length/spanwise length of the cavity). Nakagawa et al. (1995) demonstrated that one big eddy was formed when the aspect ratio was 1 and a small eddy induced by the big eddy was also observed when the aspect ratio was 3. Kimura et al. (1998) conducted laboratory and numerical tests of the side-cavity with two aspect ratios, which were 1.5 and 2, and classified properties of the sediment deposition affected by the eddies in the cavity into 4 patterns. Nezu et al. (2001) measured instantaneous velocity in the cavities, whose aspect ratios were 3, 5 and 10, by using PIV technique and found out the followings. In the case of aspect ratio 3, the horizontal eddy exists stably. In contrast, in the case of the aspect ratio 5 and 10, eddies continuously generated by the shear instability increase the instability in the flow in the cavity.

All above studies targeted the flow in rectangular cavities of laboratory model. Flow in the cavity of other shapes in fields has not been investigated. An irrigation
channel running in To-on, Ehime, Japan was reconstructed for aiming to create an aquatic habitat by widening a part of the channel with half egg shaped in 2004 (Fig.1). The channel originates from an artificial spring and then water flows for about 3 km long in the channel throughout the year. Existence of water all year round, not only in irrigation period, is the most essential for creating an aquatic habitat in an irrigation channel.

This study aims to reveal the area, where the velocity is enough small for aquatics, especially for those who have not enough swimming ability to survive in the channel, e.g. Medaka *Oryzias latipes*, and material transport in egg shaped cavity by field observation and numerical simulation. In this paper, results of field observation are described and then using results of numerical flow simulation validated by field observations, material transport in the channel is numerically estimated. Lastly the function of side-cavity is discussed based on the estimated material transport.

2. FIELD OBSERVATION

Field observations were conducted on Aug. 12 (irrigation period) and Sep. 27 (non-irrigation period), 2004. The observation on Aug. 12 and that on Sep. 27 will be called Case 1 and Case 2, respectively, hereafter. Length of observation area along the channel, including the side-cavity, is 30 m. The channel width is around 1.5 m and maximum width at widened area is 8 m. The bottom gradient along the channel is 1/725.

Water depths and velocities were measured at every 1 to 2 m interval longitudinally, depending on the location in the channel and at every 0.5 to 1 m interval transversally in the side-cavity. And velocities were measured at 60% of water depth by a 3-D electromagnetic current meter. Observation points then amounted to 126 and 119 in Case 1 and Case 2, respectively. Since the flow was turbulent in the channel, average velocities were obtained from the velocities measured for 30 to 60 seconds in 1 second interval.

2.1 Discharge
Discharge measurements were made in the channel by simultaneous velocity and cross-sectional-area measurements. The velocity was measured every 0.25 m interval across the channel. The resultant discharges in Case 1 and Case 2 were 0.41 m³/s and 0.10 m³/s, respectively. The discharge of Case 1 was roughly 4 times of that of Case 2.

2.2 Water depth
Measured water depths are visualized in Fig.2(a) and (b). From the figure, you can easily find that the inner part of cavity is deeper than the area along the channel. The depth in the cavity was about 10 cm deeper than that in the channel. Bottom of the cavity is originally constructed 15 cm below that of channel. Average water depths in the cavity at Case 1 and Case 2 were around 35 cm and 20 cm, respectively.

![Fig.2 Water depth contours (unit: m)](image)

2.3 Flow
Fig.3(a) and (b) show the observed velocity vectors for Case 1 and Case 2, respectively. A clock-wise eddies were formed in the side-cavity in both cases. The aspect ratio of this cavity is calculated as about 3 (=streamwise length/maximum width of the cavity). Since there is no corner in the cavity, only one big eddy exists stably. This is a different point from the results of model experiment in which the rectangular cavity has the aspect ratio 3 (Nakagawa et al., 1995).

Average velocities in the channel and cavity in Case 1 were 76 cm/s and 9 cm/s and those in Case 2 were 56 cm/s and 9 cm/s, respectively. The average velocity in the cavity does not seem to depend on that in the channel.

The distribution of current magnitude in the cavity is tabulated in Table 1. Around 70% of the cavity area have the velocity less than 10 cm/s in both observation cases. The area having the velocity over 30 cm/s is less than 10% of the cavity. Hata et al. (2001) confirmed that Medaka *Oryzias latipes* can swim freely in the
Though the velocity difference in the channel between two cases was about 20 cm/s, the difference in the cavity was almost negligible. This shows the velocity fluctuation in the cavity, due to the change of discharge, is rather small compared to that in the channel.

3. NUMERICAL SIMULATION

The numerical model used in this study consists of grid generation model and flow solver. Quadree grid is used for computational grid and horizontally two-dimensional shallow water equations are used as governing equations in the flow solver. Godunov-type scheme is employed in discretization of convective term of governing equation and central difference approximation for other terms. Fourth order Runge-Kutta scheme is used for temporal integration. Smagorinsky model is used for evaluating kinematic eddy viscosity. The governing equations are as follows (Rogers et al., 2001):

\[
\frac{\partial \xi}{\partial t} + \frac{\partial UH}{\partial x} + \frac{\partial VH}{\partial y} = 0
\]

\[
\frac{\partial (UH)}{\partial t} + \frac{\partial}{\partial x} \left( U^2 H + \frac{1}{2} g (\xi^2 + 2 h \xi) \right) + \frac{\partial (U VH)}{\partial y} = g \xi \frac{\partial h}{\partial x} - \tau_x
\]

\[
\frac{\partial (VH)}{\partial t} + \frac{\partial (U VH)}{\partial x} + \frac{\partial}{\partial y} \left( V^2 H + \frac{1}{2} g (\xi^2 + 2 h \xi) \right) + \frac{\partial (V VH)}{\partial y} = g \xi \frac{\partial h}{\partial y} - \tau_y
\]

\[
\nu = (c \cdot h \Delta t) \left[ \left( \frac{\partial U}{\partial x} \right)^2 + \left( \frac{\partial U}{\partial y} \right)^2 + \left( \frac{\partial V}{\partial x} \right)^2 + \left( \frac{\partial V}{\partial y} \right)^2 \right]^{3/2}
\]

where \( \tau_x \) is the time, \( x \) the coordinate along longitudinal direction of the channel, \( y \) the coordinate in transversal direction, \( \zeta \) the free surface elevation above the still water level, \( h \) the water depth below the still water level, \( H = \zeta + h \) the total water depth, \( U \) and \( V \) the depth-averaged velocities in the \( x \) and \( y \) directions respectively, \( g \) the acceleration due to gravity, \( \rho \) the density of water, \( \tau_x \) and \( \tau_y \) the bed shear stresses in the \( x \) and \( y \) directions respectively, \( \nu \) the horizontal kinematic eddy viscosity coefficient, \( c \) the Smagorinsky constant (\( = 0.1 \)), and \( \Delta \) the length of numerical grid. The bed shear stress terms are evaluated as

\[
\tau_x = \frac{\rho g n^3 U \sqrt{U^2 + V^2}}{H^{1/2}}
\]

\[
\tau_y = \frac{\rho g n^3 V \sqrt{U^2 + V^2}}{H^{1/2}}
\]
locities in the cavity are 5 cm/s greater than observed ones. This may be explained by the underestimate of bottom friction around the cobble-paved bank of the side-cavity. Due to the restriction of the numerical model, the sloping bank of the cavity was modeled as a vertical wall. Then the modeled water depth along the bank of the cavity is about 10 cm deeper than observed ones. This could generate the underestimate of bottom stress in computations.

4. MATERIAL TRANSPORT ESTIMATION

Since the velocity in the cavity is much lower compared to that in the channel, materials drifting in the channel would be trapped and accumulated in the cavity. Using the computed flow field, the accumulation of drifting material in the cavity is numerically estimated. Sand particle is chosen as a drifting material in this study. This experiment focuses on the accumulation pattern of sand particles of varying diameters. Sand particles are modeled to be transported horizontally with the same speed as water flow. However, at the same time, they settle down following Stokes law of resistance.

Over fourteen hundreds sand particles, of different diameters \(D = 0.04 - 0.1\) mm, are released at the upstream \(x = 3.0\) m and \(y = 8.3 - 9.8\) m uniformly, ref. Fig.7 of the channel. The flow condition used is same as the computed results of Case 1. The initial positions of particles are 15 cm high above the bottom, which is half of the water depth in the channel. Settling velocity \(V_s\) is calculated by Eq.(7) (Rouse, 1950),

\[
V_s = \frac{D^2 g \left( \frac{\rho_l - \rho}{\rho} \right)}{18 \nu}
\]  

where \(V_s\) is the settling velocity, \(\rho_l\) (2.56 g/cm\(^3\)) the density of sand, \(\rho\) (1.00 g/cm\(^3\)) the density of water and \(\nu\) (0.01 cm\(^2\)/s) the kinematic viscosity coefficient.

Sinking at the speed calculated by Eq.(7) and at the same time being transported horizontally at the speed of water flow, the particles finally settled to the bottom. Table 2 shows the sinking velocity and the drifting time until settling to the bottom according to the diameters. For example, the sand particle of diameter 0.1 mm takes less than 20 seconds to the bottom and the sand particle of diameter 0.04 mm takes around 2 minutes.

The computed locations where the sand particles settle are depicted in Fig.7. The results showed most of the sand particles of larger diameter are settled on the bottom of the channel and those of smaller diameter tend to be settled in the cavity. 12.8% of the particles whose diameter is between 0.04 mm and 0.06 mm are trapped in the cavity. 8.0% of particles whose diameters
Table 2: Settling velocity and drifting time according to the diameter of particle

<table>
<thead>
<tr>
<th>Diameter (mm)</th>
<th>Sinking velocity (cm/s)</th>
<th>Drifting time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.04</td>
<td>0.136</td>
<td>110.4</td>
</tr>
<tr>
<td>0.05</td>
<td>0.212</td>
<td>70.6</td>
</tr>
<tr>
<td>0.06</td>
<td>0.306</td>
<td>49.1</td>
</tr>
<tr>
<td>0.07</td>
<td>0.416</td>
<td>36.0</td>
</tr>
<tr>
<td>0.08</td>
<td>0.544</td>
<td>27.6</td>
</tr>
<tr>
<td>0.09</td>
<td>0.688</td>
<td>21.8</td>
</tr>
<tr>
<td>0.10</td>
<td>0.849</td>
<td>17.7</td>
</tr>
</tbody>
</table>

are between 0.06 mm and 0.08 mm and 0.7% of particles whose diameters are between 0.08 mm and 0.10 mm are trapped in the cavity, respectively.

From the calculated bed shear stress by Eq.(5) and (6), the average friction velocities are estimated 4.3 cm/s in the channel and 0.5 cm/s in the cavity. On the other hand, the critical friction velocity \( u^*_{cr} \) is estimated 1.3 cm/s for the sand particle with diameter 0.1 mm and 0.9 cm/s for the sand particle with diameter 0.04 mm by Eq. (8) proposed by Iwagaki (1956).

\[
\begin{align*}
\bar{u}^*_w &= \left(0.123\left(\frac{\rho_s}{\rho} - 1\right)\right) \sqrt{\frac{2}{f_n}} \frac{3}{\sqrt{2}} \left(\frac{R}{\rho_s - 1}\right)^{1/2} \frac{d^{3/2}}{g} \quad 2.14 \leq R_e < 54.2 \quad (8) \\
\bar{u}^*_w &= 0.14 \left(\frac{\rho_s}{\rho} - 1\right)gd \quad R_e < 2.14
\end{align*}
\]

where

\[
R_e = \left[\left(\frac{\rho_s}{\rho} - 1\right)g\right]^{1/2} \frac{d^{3/2}}{\nu}
\]

in which \( d \) is the diameter of sand particle in cm.

The particles settling on the bottom of the channel are then carried downstream due to the large bottom stress there, as suggested by the comparison between friction velocity and critical friction velocity in the channel. On the other hand, fine particles settle at the cavity part and remain there due to less bottom stress there. Moreover we can easily estimate from the numerical results that lighter materials, which have small settling velocity and long drifting time compared to sand, tend to be transported into the cavity.

Comparing the distribution of sand particle in Fig.7 and the water depth related to sediment in Fig.2(a), deeper area in Fig.2 corresponds to the one with no sediment in Fig.7. More sediment is found in downstream part in the cavity, especially the area along the channel in Fig.7. This area corresponds to the shallow part in the cavity in Fig.2(a). Above mentioned facts could partially validate the estimation method.

Based on the computational results of material transport, it can be said that those who have not enough swimming ability to survive in the channel, e.g. Medaka \textit{Oryzias latipes}, would be trapped in the cavity. There they could survive.

Moreover since the velocity in the cavity is very small compared to that in the channel, the cavity would also work as a refuge for those who have swimming ability to survive in the channel under normal condition, when the channel is flooding.

Creating the large area where the velocity is small (< 10 cm/s) and working as a trap, and at the same time as a refugee from the channel, make the side-cavity indispensable for supporting aquatic diversity in the channel.

5. CONCLUSION

Hydraulic structure and material transport in the cavity, which was constructed for an aquatic habitat, in the irrigation channel was investigated by field observations and numerical experiments. Field observations revealed that the large low-velocity region (< 10 cm/s) was formed in the cavity, though the velocity in the main channel was over 70 cm/s during the irrigation period. And numerical experiments demonstrated the cavity can trap the materials drifting in the channel. Both the results of field observations and numerical experiments demonstrate the side-cavity indispensable for support aquatic diversity in the channel.

REFERENCES

Hata, K. (1999): Field experiment on the migration of fishes to an idle
conservation Area on Aquatic Life in an Eco-friendly Drainage Canal,
and restoring biodiversity in rural area, J. Jpn Soc. Water Env.,
30(10), 7-11 (in Japanese).
Iwagaki, Y. (1956): Fundemental study on critical tractive force (I) Hy-
Kimura, I., Hosoda, T., and Maramoto, Y. (1998): Characteristics of sus-
pended sediment transport in open channel flows with a dead zone,
Annual J. Hydr. Eng., 42, 1057-1062 (in Japanese with English ab-
stract).
study on hydraulic characteristics of flows in embayments, An-
nual J. Hydr. Eng., 39, 595-600 (in Japanese with English ab-
stract).
Nezu, I., Onitsuka, K., and Iketani, K. (2001): Measurements of
open-channel flows with a horizontally dead zone by using PIV
 technique, Jour. JSCE, 677/II-55, 53-61 (in Japanese with English
abstract).
Rogers, B., Fujihara, M., and Borthwick, A.G.L. (2001): Adaptive q-
tree Godunov-type scheme for shallow water equations, Int. J.
Saito, K., Kato, O., and Koizumi, A. (1588): Movement and
spawning of several freshwater fishes in temporary waters around
abstract).
Suzuki, M., Mizutani, M., and Gotoh, A (2000): Development of
Small-scale fishway for preserving ecosystem in paddy fields,

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