Characteristics and Estimating Method of Travel Time Required for Flow in Water Management

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Introduction

In planning and designing irrigation canal systems in Japan, more efficient, adequate and labor-saving methods of water control and distribution than ever before are strongly demanded at present. Under such a situation, there are extensive discussions on how the water management should be carried out covering a whole irrigation canal system which mediates water demand and supply.

For planning effective water management systems, it should be important to know at first the travel time of flow to reach a certain point of water use, which is compared to the time required for transport of goods in marketing systems. At present, however, it is usual that how long it takes for the effect of changes (increase or decrease) given to water flow at an intake structure to reach a given diversion work or a check point (i.e. the flow travel time) can only be known by many years experience of canal tenders, namely by tests on the spot. But, needless to mention, it is necessary to know it beforehand for planning effective canal water management systems.

The travel time of flow can be considered as follows: Taking a canal system of a steady flow condition with a discharge, Q_i (m^3/s), decrease or increase in discharge by ΔQ (m^3/s) causes a final steady flow of $Q_i \pm \Delta Q$ (m^3/s). The duration, in which a transitional hydraulic phenomenon from the initial steady flow condition to the final steady one occurs, is the travel time of flow (or of water). To know this transitional hydraulic phenomenon, a numerical integration (mathematical model) of basic equations for unsteady flow is useful. In general, however, it is impossible practically to carry out a simulation of unsteady flow with every possible flow at a given canal system. On the contrary, if the travel time of flow could be estimated on the basis of information obtained by applying method of unsteady flow analysis to steady flow profiles before and after the transitional phenomenon, it seems to give a great benefit to planning and designing of water management system. Therefore, the result of the mathematical analysis of unsteady flow in a canal with a rectangular cross-section was examined, and it was made clear that the flow travel time can be gripped by paying attention to changes in volume of water stored between steady flow conditions in the canal before and after the changes of irrigation water supply. This finding will be presented in this paper.

Study by mathematical model of unsteady flow

1) *Outline of experimental model and experimental group*[1,2]

This mathematical experiment on unsteady flow was carried out for a canal of rectangular cross-section with canal width, $B=30$ m, and at the condition of space difference, $\Delta x=400$ m, and time finite difference, $\Delta t=5.0$ sec. The experiments can be divided into two groups. In the first group, bottom gradient of the canal and coefficient of roughness were kept constant, $i=1/4000$ and $n=0.015$ respectively, but canal length was altered to 2400, 4800, 7200 or 9600 m, with varying boundary conditions at the down-

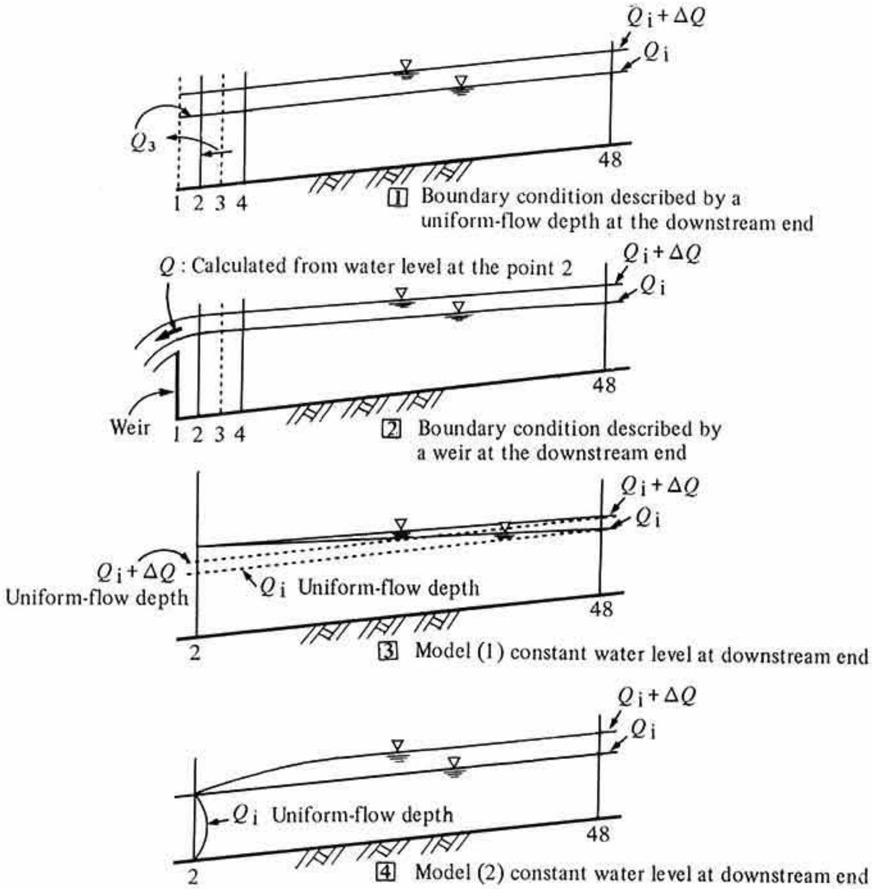

Fig. 1. Surface profiles of an initial and a final steady-flow

stream end. In this group, the discharge at the initial steady flow condition was set at 60 m^3/s, and it was increased or decreased, so that this group can examine effects of boundary conditions at the downstream end and the scale of canal.

The second group was to examine effects of different initial flow conditions, and was composed of several experiments dealing with differences in Froudes number, in uniform flow depth of the initial steady flow condition, or in longitudinal gradient of canal. In any group of experiments, an increase or decrease of discharge was given to the initial steady flow condition in a moment just like a sudden start and stop of operation of a pump.

As to the condition of downstream end of canal, 4 different patterns (Fig. 1) were adopted by taking into consideration changes or no changes of water level at the site of diversion work, and capacity of diversion work.

2) Characteristics of flow-arrival curve and dimensionless expression[4]

As the result of the mathematical model experiments shown above, curves showing the flow-arrival at the downstream were obtained. The curves were examined and summarized as follows. In Fig. 2, symbols of equations appearing

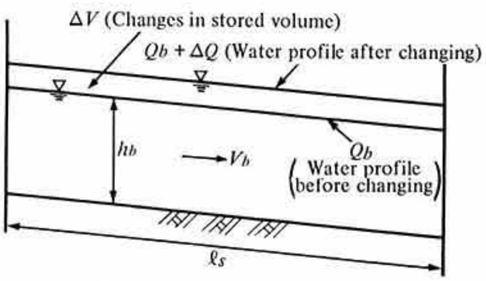

Fig. 2. Symbols used for uniform flow

below are shown conceptually.

(1) Under the condition of the above two groups of experiments, the time when the flow-arrival curve ascends is almost similar to the value of T_h, which depends on velocity of waves, calculated by the following equation based on information of the initial steady flow condition.

$$T_h = l_s/(v_b+\sqrt{gh_b}) \quad \cdots\cdots(1)$$

where, g: acceleration of gravity

l_s, v_b, h_b : shown in Fig. 2.

(2) Patterns of the flow-arrival can be divided into two, using the ratio of the T_h of the Equation (1) to T_v of the Equation (2) where T_v signifies the time calculated on the basis of changes in volume of stored water in the canal reach.

$$T_v = \Delta V/\Delta Q \quad \cdots\cdots(2)$$

The first one is the case of $T_h/T_v \geqq 1.0$. The flow-arrival curve ascends suddenly, at the time T_h, and then converges after considerable fluctuation. In this case, the time of flow-arrival depends on velocity of waves.

The second one is the case of $T_h/T_v < 1.0$, as shown below.

(3) Under the condition of $T_h/T_v < 1.0$, it was made clear that the flow-arrival curves can be expressed as a single dimentionless curve (Fig. 3), which is free from effects of boundary conditions of downstream end, length of canal, magnitude of increased or decreased discharge, and the initial flow conditions, when the former curves are made dimensionless as shown below.

The dimensionless values concerned are $(Q_t - Q_b)/\Delta Q$ for discharge on the ordinate and $t/\left(\frac{\Delta V}{\Delta Q}\right)$ i.e. t/T_v, for the time on the abscissa. This dimensionless curve passes a point (1.0, 2/3), because the coordinate of its point of ascent is $(T_h/T_v, 0.0)$, and ordinate value corresponding to 1.0 of abscissa is 2/3.

Method of estimating flow-arrival time[3)]

1) The estimating method

(1) From the information of flow regarding the non-uniform flow conditions before and after

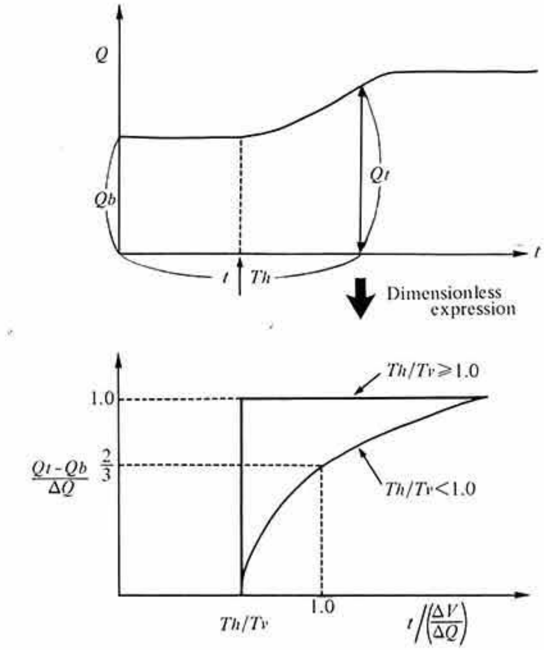

Fig. 3. Water travel condition

the change of discharge, h_b, V_b, ΔV, and ΔQ shown in Fig. 2, are known and based on them, T_h, T_v, and T_h/T_v are calculated.

(2) When $T_h/T_v \geqq 1.0$, calculation can be done in accordance with Fig. 3. Namely, the total quantity, ΔQ, simultaneously reaches at T_h/T_v.

(3) When $T_h/T_v < 1.0$, the dimensionless curve, showing the flow-arrival, is subjected to a linear approximation, and calculation is made by using approximate linear equations (Fig. 4).

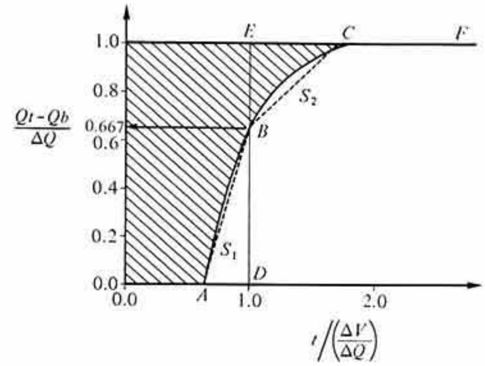

Fig. 4. Construction of prediction curves

The coordinate of the initial ascending point, A, of the flow-arrival curve is given as $(T_h/T_v, 0.0)$. The proportion of flow, which has already

Table 1. Conditions in mathematical simulations

Case No.	i	n	Q_b(m³/s)	ΔQ(m³/s)	v_b(m/s)	h_b(m)	Fr_1	Remarks
Q-1	1/2000	0.015	42.84	39.66	1.267	1.102	0.386	h=1.5 m fixed at downstream end
Q-1$\binom{(1)}{(2)}$	1/1500	0.015	49.47	17.02 −15.10	1.649	1.00	0.527	Downstream boundary condition of uniform flow

reached, to the total flow going to arrive, corresponding to $t/T_v=1.0$, is 2/3 in various cases, and it seems that 2/3 can be taken as more or less a constant. Therefore, the coordinate of point B in Fig. 4 is (1.0, 2/3). On the basis of points, A and B, the point(X) on abscissa corresponding to 1.0 of the ordinate (i.e. point C, indicating a total amount of the flow which has reached) is obtained as follows. In Fig. 4, the area of a square up to 1.0 of the abscissa is equal to the volume of change in stored water, ΔV, so that a principle that the area of ΔABD becomes equal to that of ΔBEC can be applied. As the coordinate of point C is (X, 1.0), the value of X can be obtained by the following equation:

$$X=3.0-2.0(T_h/T_v)$$

Then, using the linear equations connecting A, B, and C, the mode of flow-arrival can be calculated.

2) Verification of the estimating method

Applying the method proposed in the preceding section to the case shown in Table 1, estimates obtained by the estimating equation were compared with the result of mathematical experiment to verify the estimating method. Only

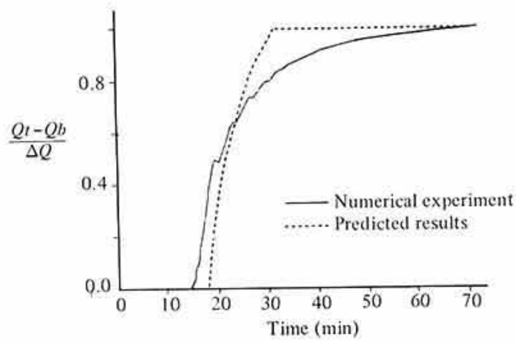

Fig. 5. Comparison between numerical experiment and predicted results (in Case Q-1)

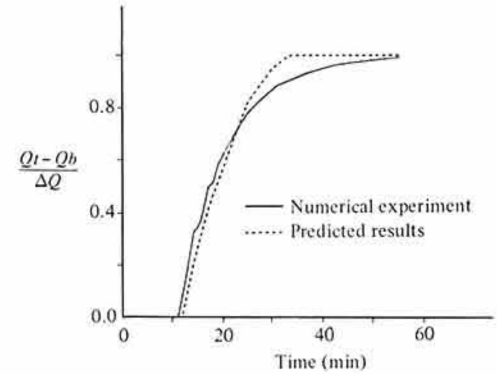

Fig. 6. Comparison between numerical experiment and predicted results (in Case Q-1 (1))

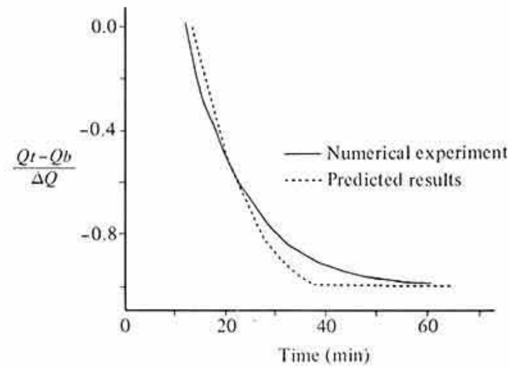

Fig. 7. Comparison between numerical experiment and predicted results (in Case Q-1 (2))

graphs of the results are shown here as Figs. 5, 6, and 7, which indicate fairly satisfactory agreements even for the case when the flow is affected by a weir or the case when an increase or decrease of uniform flow is made.

Conclusion

Mathematical model experiments were carried out to know the mode of flow-arrival and it was found that the mode of flow-arrival is divided into two groups using the ratio of Equation (1) to (2), as an indicator. When the value of T_h/T_v is greater than 1.0, the flow-arrival curve ascends suddenly with the time depending on velocity of waves. When T_h/T_v is less than 1.0, changes in water storage capacity of the reach is taken into consideration, and by using dimensionless expression, the flow-arrival can be obtained by an almost identical curve, to which an approximate linear equation is given.

Furthermore, the author found that in case when $h_1 \gg \Delta h$ and of uniform flow, the ascending point of curve is shown by Froude number of the initial steady flow condition, and the point where the total flow reaches is shown by the ratio of wave velocity to mean flow velocity. In addition, it was already confirmed that to the canal with a syphon, which is a fixed structure and exerts a great effect on the shape of flow profile, among structures set in the course of canal, the estimating method is applicable as effectively as to open channels. It was also confirmed that the similar estimating method can do for canals of trapezoidal or a standard horseshoe cross-section, besides a rectangular cross-section.

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