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DEVELOPMENT OF A DISCHARGE MEASUREMENT TECHNIQUE COMBINED WITH MEASUREMENT OF MEAN FLOW VELOCITY AND NUMERICAL SIMULATION OF CROSS-SECTIONAL VELOCITY DISTRIBUTION; FIELD VERIFICATION IN A LARGE RIVER

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SYNOPSIS

River discharge is a principal, and a significant hydrological quantity for river planning, management, and environmental conservation. To obtain precise measurements of discharge, techniques were developed for determining cross-sectional mean flow velocity by hydroacoustical measurement of local velocity in conjunction with numerical simulation of velocity distribution. This new discharge measurement system "*ATENAS*" was installed in the Tone River, and its measurement performance for a river 500m wide verified. The accuracy obtained is comparable to or better than that of the commonly used velocity profiler. Reverse flow discharge to 4,000m^3/s was continuously and stably measured by ATENAS, whereas estimated discharge obtained by floats was unstable during flooding. In the case of a high volume of discharge, the velocity profiler underestimated flow velocity. This was thought to be due to bed load motion.

INTRODUCTION

The primary objective of river planning is to prevent floods. River channels are designed so that water volume flows securely up to the design flood discharge. Maintaining adequate flow at normal times is also an objective for proper utilization, maintenance of normal river function, and environmental conservation.

In making a river plan, the river's discharge is calculated from a runoff analysis based on past rainfall, water level, water demand, etc. To verify the runoff analysis, improve its accuracy, or both, it is necessary to measure time-series variation in the actual discharge in order to relate river flow to rainfall observations. Measuring river discharge, therefore, is essential to various aspects of riverine management such as disaster prevention, water utilization, and environmental conservation.

River discharge is usually estimated from water level data by means of a discharge rating curve determined from a number of discrete measurements obtained by floats and propeller meters (1). It has been pointed out that this procedure has various technical problems, and improved accuracy in measuring discharge is required (2). Some recently proposed measuring techniques have not proved to show sufficient reliability and accuracy to serve as alternative procedures for making stable measurements in large rivers.

Consequently, in spite of its importance in river management, no valid technique for measuring river discharge is considered to have been established.

We developed a new technique for continuously measuring flow in large rivers that has a high accuracy even under flooding conditions and high turbidity. This technique combines the numerical simulation of flow velocity distribution with measurement of mean flow velocity along a measurement path across the river.

A discharge measurement system named ATENAS (Advanced TEchnology of Numerical simulation of velocity distribution and hydroAcousticS), which implements this new technique was installed in the lower reaches of the Tone River to verify its measurement performance in a large river.

This discharge measurement system continuously measures river discharge from low-water flow to flooding with the same or higher level of accuracy as do precise flow evaluations made by commonly used velocity profilers.

PROBLEMS OF EXISTING PROCEDURES AND FEATURES OF THE NEWLY DEVELOPED TECHNIQUES FOR FLOW MEASUREMENT

Existing flow measurement procedures and their problems

a) Flow measurement obtained with a discharge rating curve

A discharge rating curve is based on the assumption that flow volume is uniquely related to a certain water level value. In fact, discharge often cannot be expressed as the monotonic function of water level due to tidal effects, effects of a low-gradient river bed, weir operation, vegetation in the river channel, and other related factors.

b) Discrete flow measurement problems

In the usual discrete flow measurements, local flow velocity, V_i, is measured then multiplied by a calibration factor, k_i, yielding the cross-sectional mean flow velocity. This velocity is then multiplied by the local area, A_i, giving the local discharge. Lastly, the total discharge, Q, is obtained as the summation of local discharges;

$$Q = \sum_i k_i V_i A_i \qquad . \qquad (1)$$

Floats commonly are used to measure flow velocity during flooding. Since in down river flow, floats are affected by flow disturbances caused by piers, a local stream that produces a cellular secondary currents, and other factors, the accuracy and reliability of such measurements is not very high (2).

Measuring surface flow velocity by means of radio waves, ultrasound, or a video-camera has been proposed as alternatives to using floats. These techniques, however, have two drawbacks: (i) they are difficult to apply during periods of strong wind, heavy rain or snow, and of heavy fog. (ii) in principle they have difficulty in measuring low flow velocity.

Furthermore, with these techniques, such as with floats, a calibration factor is required to evaluate discharge, but the values of such factors are tentative, and so have not been determined properly at present (1). The calibration factor should vary with the distribution of flow velocity at each measurement site, but the tentative values are classified only by water depth. It is also difficult to determine the calibration factor from actual measurements of infrequent situations such as a large flood.

Fig.1 shows discharge measured by floats at measurement sites along the lower reaches of the Tone River where hydraulically complex flow occurs due to tidal effects and the locally-asymmetric river bed.

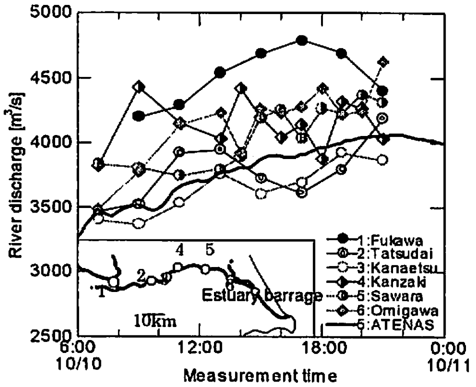

Fig. 1 Discharge measured by floats along the Tone River's lower reaches during flooding by typhoon no.22, 2004..

The peak values of discharge differ greatly, up to about 1,000m^3/s, and the discharge trend at each site is not smooth but fluctuates.

When flow is measured based on the Doppler effect by towing a velocity profiler, it is unnecessary to determine the optimum calibration factor because flow velocity is measured precisely across the overall cross section of the river. This technique is restricted to relatively low flow velocity. In practice, it is also hard to continuously monitor the discharge.

A horizontal velocity profiler has been used for flow measurement (3), but there are technical problems with velocity estimation in non-measurable areas, limitation of river width, and measurement possibility under high turbidity.

c) Summary of technical objectives in measuring river discharge

Current objectives are

(i) to measure local flow velocity continuously with a high level of accuracy independent of surrounding circumstances,

(ii) to obtain the optimum calibration factor that reflects the velocity distribution at individual measurement sites.

A combination of techniques to achieve these objectives can facilitate making highly accurate and continuous discharge measurement in rivers.

Features of the new techniques in the ATENAS discharge measurement system

To achieve the above objectives, we developed a technique to continuously measure flow velocity with high accuracy, even in large rivers, which does not depend on surrounding circumstances, and one based on a numerical simulation to determine the optimum calibration factor.

a) Flow velocity measurement in large rivers

Averaging local flow velocity measurements over a wide area usually effectively suppresses fluctuation caused by local disturbances. The ultrasonic transit time method (1), (4) was adapted to measure flow velocity. By this method, the mean flow velocity across the river can be calculated from the difference in the transit times of ultrasonic pulses traveling diagonally across the flow in the downstream and upstream directions.

The advantage of this method is that essentially the velocity measured is not affected by water temperature or salinity which changes the speed of sound in water.

Although the method has been in the practical use since the 1970s, measurement often has failed in times of flood, of high turbidity, and in large rivers more than 100m wide (5).

Absorption and scattering losses caused by suspended solids are the principal factors of ultrasonic attenuation in water. These losses decrease as the ultrasonic frequency is lowered. A 28kHz ultrasonic transducer with high output was, therefore, adopted instead of a conventional 100 to 200 kHz one. Absorption of this low frequency ultrasound in water is negligible for a distance of up to 1,000m. Moreover, the scattering attenuation coefficient of 28kHz ultrasound, produced by suspended solids, is one-third that of 200kHz if the suspended solid size is approximated to 20 μ m (7).

In contrast, this lower frequency ultrasound has a longer wavelength than the conventional ultrasound that is used. A larger error in flow velocity then occurs if the transit time obtained has an error corresponding to one wavelength.

This means that the simple, conventional determining procedures based on a signal amplitude threshold cannot be used to measure flow velocity with lower ultrasonic transducers. A new digital signal processing algorithm was, therefore, developed to measure transit time correctly by tracing peak positions in the ultrasonic signal.

b) Determination of the optimum calibration factor

Although it is desirable to select the calibration factor by considering the flow velocity distribution, it is difficult to obtain by actual measurements for any flow regime. Instead, a numerical simulation, by which the velocity distribution is calculated for every considerable flow, was introduced to obtain this factor. In this work, this technique is referred to as the SIMK calibration method (8).

In this method, the velocity distribution in the cross-section at the measurement site is simulated by solving the Reynolds equation for an incompressible fluid in a proper numerical model. The solution method, using the Finite Element Method, is suitable for modeling river channels because of its flexibility for generating calculation meshes.

Fig.2 shows an example of simulated velocity distribution in the cross section of the Tone River. From this distribution, the calibration factor is calculated as the ratio of the overall mean flow velocity to the mean flow velocity along the acoustic path across a river.

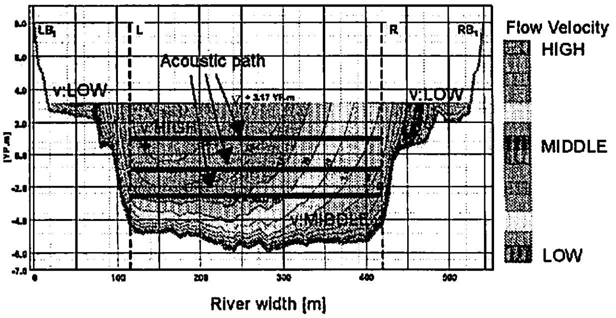

Fig. 2 Example of distribution of flow velocity in the cross section of the Tone River estimated by the SIMK calibration method

Based on many previous analyses (9), we confirmed that the calibration factor is determined by the SIMK calibration method with an accuracy of +/- 3% even if the simulated value of the flow velocity is not exactly equal to the actual value at a certain water level. In other words, the use of the relative distribution of flow velocity rather than the magnitude of that velocity is the main feature of the SIMK calibration method.

The relative height of the acoustic path varies with changes in the water level associated with discharge, and the calibration factor also changes. The calibration factor, therefore, must be given as a function of the water level, w , and height of the acoustic path d ; $k(d, w)$, by simulating the flow regime at various water levels.

Thus a reliable calibration factor can be obtained for any flow regime by the SIMK calibration method without measuring the flow velocity distribution. Furthermore, it is not necessary to adjust the measurement system to correspond to other discharge measurements, and discharge can be obtained just after installation.

FIELD VERIFICATION OF DISCHARGE MEASUREMENT ACCURACY IN A LARGE RIVER

Overview of the verified system

To verify the measurement performance of our newly developed techniques under flow conditions from low-flow to large flooding, we installed an ATENAS discharge measurement system at Sawara along the lower reaches of the Tone River in its estuary basin 41km from the river mouth.

Ultrasonic transducers were set on mounts held by PHC piles placed near both river banks. The acoustic path length was 381m. The acoustic path layout is shown in Fig.3 (Y.P. refers to the Yedogawa Peil standard geographic height).

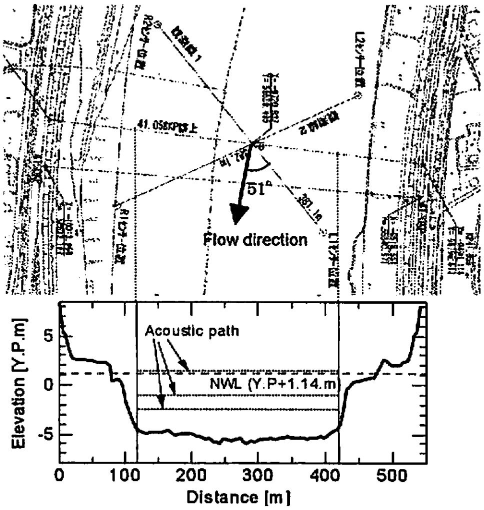

Fig. 3 Horizontal and vertical layouts of acoustic paths at Sawara

The relationship between the water level and the cross section was determined from the surveyed riverbed profile. The cross section was calculated from the water level by the relationship in ATENAS. The flow velocity was measured at 10-second intervals, and the discharge was exported to the river office at 5-minute intervals after obtaining the moving average.

The calibration factor was a function of water level as determined by the SIMK calibration method before installation, in which flow velocity was simulated in detail within an area 1km downstream and 2km upstream from the measurement site. The roughness coefficient of the riverbed and the high water channel were chosen based on U.S. Geological Survey reference values (10).

Several observations by towing the velocity profiler were conducted from September 2004 to January 2005 to obtain the measured mean flow velocity along the acoustic path and the calibration factor. Velocity profiler specifications are shown in Table 1. Only the relative flow velocity to the velocity profiler itself was measured in the towing observations. The flow velocity magnitude was then corrected by towing speed as evaluated by bottom-tracking on the assumption that the riverbed was stationary.

Table 1 Velocity profiler specifications

Item	Specification	
Type	WorkHorse (RD Instruments)	RioGrande (RD Instruments)
Frequency	1200kHz	
Cell width	50cm	20cm
Correction of ship speed	Bottom-tracking	
Software	WinRiver	
Range of flow velocity	low - middle	high

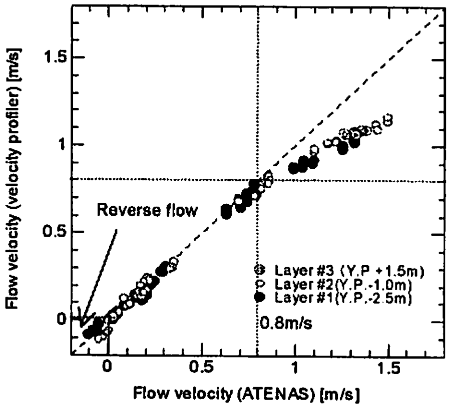

Fig. 4 Comparison between ATENAS and the velocity profiler of flow velocity at each measurement height

Mean flow velocity along the acoustic path across the river

a) Comparison with the velocity profiler

Fig.4 shows comparisons of mean flow velocity across the river at measurement heights for ATENAS and the velocity profiler at each measurement point. The values agree well within the measurement range from -0.1 (reverse flow) to 0.8m/s. The evaluation differences for ATENAS and the velocity profiler are

-0.01 +/- 0.02m/s in Y.P.-2.5m (Layer #1)
0.00 +/- 0.03m/s in Y.P.-1.0m (Layer #2)

where error is defined as a standard deviation.

This magnitude of error is equivalent to the measurement uncertainty of the towed velocity profiler. Therefore, ATENAS which adopts low frequency ultrasound and signal processing for long wavelength signals can measure flow velocity with the same as or a higher level of accuracy than velocity profiler towing observations.

The velocity profiler, however, underestimates the flow velocity in ranges above 0.8m/s. Kimizu, et al. (11) also reported velocity profiler underestimation in a high flow velocity range. The underestimations are thought to be caused by wrong bottom-tracking correction due to bed load motion (12).

b) Consideration of velocity profiler underestimation

To verify the cause of underestimation, the moving speed of the bed load is evaluated by means of measured velocity profiler data.

The ship velocity component in the direction opposite to flow is assumed to correspond to the moving speed of the bed load. The mean moving speed of the bed load is estimated by averaging the ship velocity component along the towing path. Estimated bed load speed values are compared with the mean flow speed, U_s, inside the bed load layer as calculated by the equation given by Egashira (13);

$$\frac{U_s}{U_*} = \frac{4}{15}\frac{K_1 K_2}{\sqrt{f_d + f_f}}\tau_* \tag{2}$$

where U_* = friction velocity; τ_* = dimensionless tractive force. The other variables in eq.(2) are

$$K_1 = \frac{1}{\cos\theta}\frac{1}{\tan\phi - \tan\theta}; \quad K_2 = \frac{1}{\overline{c_s}}\left(1 - \frac{h_s}{w}\right)^{1/2}$$

$$f_d = k_d\left(1 - e^2\right)\left(\sigma/\rho\right)\overline{c_s}^{1/3}; \quad f_f = k_f\left(1 - \overline{c_s}\right)^{5/3}\overline{c_s}^{-2/3}$$

$$\frac{h_s}{w} = \frac{1}{\left(\sigma/\rho - 1\right)\overline{c_s}}\frac{\tan\theta}{\tan\phi - \tan\theta}; \overline{c_s} = \frac{c_*}{2}$$

where θ = riverbed gradient; w = water depth. Values of parameters in these expressions were ϕ=34°, c_*=0.52, e=0.85, k_d=0.0828, k_f=0.16, σ/ρ=2.65, as reported by Egashira. The bed load diameter at Sawara was 0.21mm according to field survey results. The riverbed gradient was 1/10,000. The water level was substituted for the hydraulic radius. A logarithmic profile is assumed in the relationship between the mean flow and friction velocities because the water depth is thought to be sufficiently greater than the layer thickness of the bed load. The equivalent roughness coefficient selected was 48mm to adjust the calculated to estimated values.

The estimated and calculated results for bed load moving speed are plotted against mean flow velocity in Fig.5. Estimations obtained from towing observations are consistent with calculations made by eq. (2), providing evidence that the bed load was transported at a flow velocity of more than 0.8m/s at Sawara on the Tone River. This finding shows that in the case of high flow speed discharge measurements obtained by towing a velocity profiler often are affected by bed load motion. Such measurement error can be avoided; e.g., by using a differential GPS rather than bottom-tracking to correct the ship velocity (14).

As, in principle, ATENAS is unaffected by bed load motion, the deviation in flow velocity in Fig. 4 is considered to show the affect on velocity profiler towing observations produced by bed load motion. The mean moving speed of the bed load is easily estimated if ATENAS is combined with a velocity profiler with bottom-tracking.

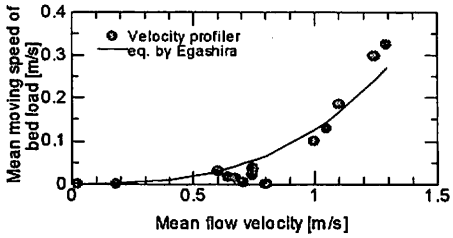

Fig. 5 Bed load moving speeds estimated by the velocity profiler

Calibration factor

To check the validity of the calibration factor determined, some velocity profiles of simulated and actual measurements are compared. Based on the calibration factor definition, the vertical profile of flow velocity, $V(d)$, is evaluated by

$$V(d)=\frac{Q}{k(d,w)\cdot A} \tag{3}$$

where $k(d,w)$ = the vertical distribution of the calibration factor determined by the SIMK calibration method; Q = the discharge measured by ATENAS; and A = the channel cross section.

The vertical profiles of the flow velocity evaluated by eq. (3) for various discharge values are compared with those obtained by the velocity profiler. Fig.6 shows that the evaluated velocity profiles agree well with the actual measured profiles for discharges from –150 to 1,400m³/s, in which the velocity profiler was not affected by bed load motion. The SIMK calibration method therefore was found to simulate the distribution of flow velocity in a river channel with sufficient accuracy. Consequently, the calibration factor is determined by this method under any flow condition.

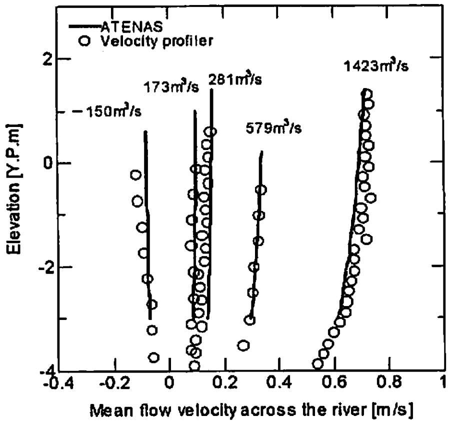

Fig. 6 Vertical profiles of mean flow velocity across the Tone River

Discharge

As reported in the previous sections, the mean flow velocity at the measurement height is measured accurately by ATENAS, and the optimum calibration factor can be determined by the SIMK calibration method. In this section, discharge is examined to verify the overall measurement performances of these techniques.

In measurements obtained by velocity profiler towing, flow velocities in unmeasurable areas near the water's surface, the riverbed, and both river banks were estimated by extrapolation.

A comparison of discharges obtained by ATENAS and the towed velocity profiler is shown in Fig.7. There is obvious underestimation by the velocity profiler due to bed load motion at more than 2,000m³/s. In contrast, for discharges below 2,000 m³/s, ATENAS yields almost the same accuracy as the towed velocity profiler, independent of flow direction.

Consequently, by combining low frequency ultrasound, signal processing suitable for the long wavelength signal, and numerical simulation to obtain the flow velocity distribution, river discharge can be measured continuously with a high level of accuracy, even in large rivers.

The estimated discharge measurement error for ATENAS is as follows. The relative measurement error for flow velocity is +/-0.6% based on sampling error in digitizing the received ultrasonic signal. The relative uncertainty in the calibration factor determination is about +/-3% based on past SIMK calibration method results (9). The relative uncertainty in calculating the channel cross section is about +/-1% based on the river survey's accuracy.

Consequently, the relative uncertainty of river discharge obtained by eq. (1) is +/-3.2%. This uncertainty is reduced by averaging the measured values. For instance, if five measured values are averaged, we expect the uncertainty of measurement to be $3.2\%/\sqrt{5} = 1.4\%$.

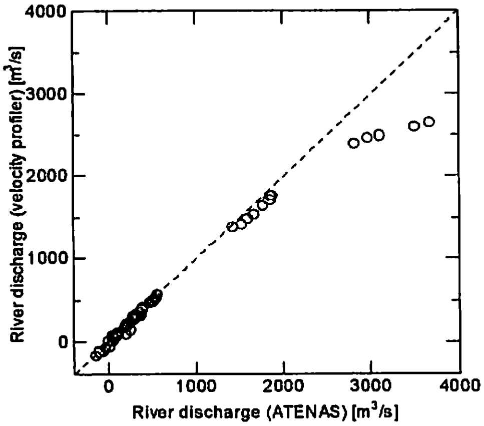

Fig. 7 Comparison of river discharge between ATENAS and the velocity profiler

DISCHARGE MEASUREMENT DURING FLOODING

On October 6th, 2004, immediately after the installation of ATENAS at Sawara on the Tone River, the Kanto region received torrential rainfall followed by the brunt of typhoon no.22.

Representative results of continuous unmanned discharge measurements by ATENAS during this period are shown in Fig.8. ATENAS clearly continuously measured the discharge from almost 0 to more than 4,000m³/s without measurement failure.

The figure below also shows the discrete discharge measurements made by floats and a towed velocity profiler. From October 6th to 7th, the three kinds of measured values were almost the same, but the discharge values obtained by the floats were relatively large. From October 10th to 11th, the peak discharge values with the towed velocity profiler were underestimated by about 30% as stated previously. Float measurements, however, still overestimated the discharge as compared to ATENAS. Furthermore, discharge as measured by ATENAS increased and decreased smoothly (Fig.1), whereas that measured by floats fluctuated greatly, except at Fukawa where there is a narrow segment.

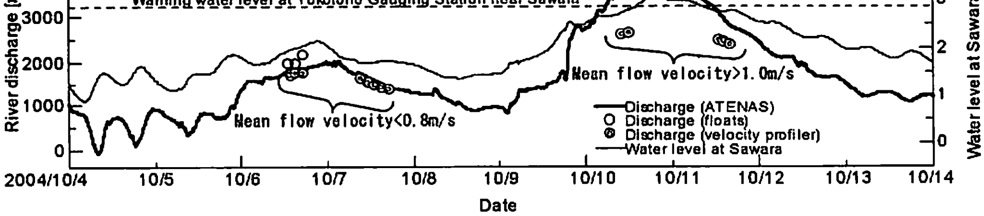

Fig. 8 Measured discharge and water level obtained by ATENAS installed at Sawara on the Tone River under torrential rain and typhoon no.22 in October 2004

As for the relationship between water level and discharge, from October 4th to 5th periodic changes in water levels caused by the tide were observed; moreover, discharge with the water level changed, having a phase lag. The tide's effect on the water level and discharge remained during the decline in flooding after October 11th. Discharge clearly was affected by the tide. The relationship between river discharges and water levels definitely can be measured by continuous observations like those of the ATENAS discharge measurement system.

In addition, typhoon no.23, which passed over the Kanto area later in October, caused a similar flood in which the peak discharge rose to 4,000m^3/s. At that time, ATENAS could measure the discharge continuously.

CONCLUSIONS

An understanding actual river discharge is very important for examining and improving runoff analysis accuracy in river design. Stable measurement of flow velocity, regardless of surrounding circumstances, and determination of the optimum calibration factor that reflects the flow velocity distribution under the flow conditions is essential to the measurement of river discharge. We combined a numerical simulation of the flow velocity distribution and flow velocity measurement using low frequency ultrasound and developed the ATENAS discharge measurement system, which incorporates the new techniques, to continuously obtain the discharge with a high level of accuracy. Discharge values measured by ATENAS installed at Sawara on the Tone River were compared with those obtained by the use of floats and a towed velocity profiler in order to verify measurement performance. Our conclusions are as follows:

(1) The adoption of low frequency ultrasound in the ultrasonic transit time method improved transmitting performance in large turbid rivers, and development of the additional signal processing algorithm for long wavelength ultrasound improved the accuracy of transit time measurements. As a result, flow velocity can be measured continuously with the same or a higher level of accuracy than by towing a velocity profiler.

(2) The distribution of flow velocity in a river channel was found to be estimated correctly by the SIMK calibration method based on numerical simulation. The calibration factor, defined as the ratio of the cross-sectional mean flow velocity to the local flow velocity, therefore can be obtained with sufficient accuracy for practical uses.

(3) The combination of the ATENAS discharge measurement system, which measures flow velocity by the low frequency ultrasonic transit time method and estimates the flow velocity distribution by means of numerical simulation, without failure measures river discharge from reverse flow to flooding at 4,000m^3/s in a large river about 500m wide. The measurement accuracy was found to be the same or higher than that of other existing discharge measurement techniques.

(4) If the bed load moves during high flow discharge, towing measurement by a velocity profiler often underestimates the flow velocity and flow discharge due to incorrect evaluation of the ship speed by bottom-tracking. In principle, the ATENAS discharge measurement system is not affected by such bed load motion.

(5) The mean moving speed of a bed load can be obtained by towing measurement with a bottom-tracking velocity profiler in combination with ATENAS.

As described above, the measurement performance of ATENAS was tested in an actual large river under flooding and normal flow. An examination of measurement performance under high turbidity and measurement of the discharge of a partial flow due to intrusion of a salt-wedge are subjects for future study.

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APPENDIX - NOTATION

The following symbols are used in this paper:

A = river channel cross section;
A_i = local measurement area;
c_* = volume concentration in a moving bed load layer
d = vertical distance from the water surface to acoustic path;
$k(d,w)$ = calibration factor as a function of d and the water level;
k_i = calibration factor in the local measurement area;
Q = river discharge;
U_s = flow velocity inside the bed load layer;
U_* = friction velocity;
$V(d)$ = vertical profile of flow velocity;

V_t = flow velocity in the local measurement area;
w = water depth;
θ = riverbed gradient;
ρ = bed load density;
σ = water density;
τ_* = dimensionless tractive force; and
ϕ = internal friction angle.

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