E-proceedings of the 38th IAHR World Congress
September 1-6, 2019, Panama City, Panama
doi:10.3850/38WC092019-1559

VERTICAL STRUCTURE OF VELOCITY DISTRIBUTIONS MEASURED IN A THERMALLY STRATIFIED RESERVOIR

MAKOTO UMEDA[1] & BUNYU KOBORI[2]

[1] Tohoku University, Sendai, Japan
e-mail makoto.umeda.c6@tohoku.ac.jp

[2] Civil Engineering and Eco-Technology Consultants, Tokyo, Japan,
e-mail kobori@kensetsukankyo.co.jp

ABSTRACT

In this study, field measurement was carried out in Isawa Dam Reservoir, located in the Kitakami River system in the northern area of Japan, on the flow structure under a thermally stratified condition. The administrator and the local people of the reservoir have concerns about prolonged discharge of higher turbidity water into the downstream, and it is necessary to find solutions to prevention of higher turbidity discharge from the dam. For that purpose, this study made analysis on flow structure in the reservoir that influences on behavior of fine suspended sediment. From the observation results, layered structures of flow velocity were found in the both components of horizontal and vertical velocity. However, the respective components showed different structures and behaviors with each other. We defined “velocline”, which corresponds to a depth at which vertical distribution of the velocity component exhibits apparently large changes. The depth of the velocline of horizontal velocity was close to the thermocline, but vertical displacement was large and frequent. On the other hand, there were two veloclines whose depths were several meters above and below the thermocline, and movement of the veloclines were much smaller than that of horizontal component. In the latter half of the measurement period, scattered velocity variations were observed in the epilimnion, which were presumably caused by the turnover mixing initiated by surface water cooling.

Keywords: reservoir, stratified flow, velocity distribution

1 INTRODUCTION

Dam reservoirs are important water resources for tap water in Japan. Therefore, water quality management in the reservoir is essential. Besides, the global warming, which is becoming more and more apparent in recent years, seems to cause several kinds of water quality problems in the water resources reservoirs: water bloom from excess growth of phytoplankton and high turbidity caused by heavy rainfall sometimes affect the water purification process of tap water.

The off-flavor taste of tap water caused by phytoplankton and extreme turbidity may cause stoppage of water supply. Therefore, fine suspended particles, including phytoplankton, needs to be considered for water quality management. However, behavior of such fine particles in a density stratified water body in the environment has not been sufficiently clarified. Based on this motivation, we analyzed the flow structure in a lake water body with temperature stratification in Isawa Dam Reservoir in this study.

Hydrodynamic investigations in density stratified reservoirs have been conducted in many previous studies due to the water environmental issues in river environments. Yokoyama and Shintani (2006) analyzed the relation between the internal seiche behavior and the lake basin shape according to the stratification conditions in Shichikashuku Dam Reservoir. Umeda et al. (2006) examined the behavior of flood intrusion into the stratified reservoir in the same Shichikashuku Reservoir from field measurement and numerical analysis..

As mentioned above, environmental hydraulics research has been frequently conducted to solve various water quality and environmental problems in dam reservoirs, and many findings have already been obtained. Consequently, various methods for analyzing the behavior of turbid water and fine sediment in stratified reservoir water body have been proposed. For example, Umeda et al. (2004) developed a vertical 2-dimensional hydrodynamic simulator combined with a new modeling idea of computing behavior of settling fine sediment in stratified water. However, the detailed mechanism of movement of suspended fine particles in density stratified water is still unclear.

2 METHODS OF THE STUDY

2.1 Study area

Isawa Dam Reservoir constructed in the Kitakami River system in Northeast region of Japan was the study site of this study. Ishibuch Dam was previously in operation before the construction of Isawa Dam as an redevelopment project of Ishibuchi Dam. Isawa Dam was costructed about 2km downstream of Ishibuchi Dam, which is now sunk in the bigger Isawa Reservoir. Isawa Reservoir has a basin area of 180.5 km2 and a total storage capacity of 1.43 × 108 m3. Figure 1 shows the plan shape of the Isawa Reservoir. The annual average turnover rate of the lake water of Isawa Reservoir is as small as about three, since the capacity of the reservoir large relative to its basin area. The maximum reservoir water level of Isawa Reservoir is 345.6m above sea level, the top edge of Ishibuchi Dam is 324m, and the deepest level of the lake bottom is about 253 m.

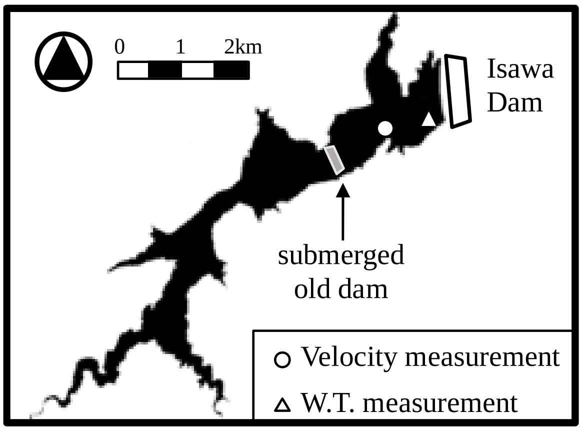

Figure 1. Plan view of Isawa Dam Reservoir with locations of measuring points (velocity and water temperature).

2.2 Observation

The flow measurement in the reservoir was performed by installing an ADCP (Teledyne RDI ADCP, 600 kHz, measurement accuracy ± 3 mm/s) at a point shown by a circle in the downstream area of the reservoir in Figure. 1. The observation period was one month from August 27, 2016 to September 27, 2016. The ADCP was installed at the elevation of about 300m near the bottom of the lake at the location. The measurements were made at intervals of 20 minutes with a layer thickness of 1 m from near the bottom where the device was installed to the water surface. However, data near the water surface were removed from the results because large noise was included in the data. The water temperature conditions in the lake were measured by the dam management office using an automatic observation device installed near the dam (the triangle in Figure. 1). The measurement was conducted twice at 9 am and 9 pm every day.

2.3 Data analysis

The measurement results of the flow velocity were aligned with the longitudinal direction of the reservoir from the original components of east-west and the north-south. The angle of the reservoir was 30 degrees from the north. Since the raw velocity data had some variations, five data moving averages were applied to the measured data with regard to time for the same elevation.

Spatiotemporal structures were found in the distribution of the flow velocity from plotted diagram, and data processing was performed to capture the structure more clearly. The horizontal velocity is higher in the epilimnion and lower in the hypolimnion as is generally known. Such layered structure of velocity was also observed in the results of this study. In order to show the layered structure of the velocity distribution, the division depth of the horizontal velocity was defined by a simple method as shown in Figure. 2. This diagram shows an example velocity data measured at 3 pm on September 21, when the velocity condition was relatively stable.

The straight line is the fitting result to absolute values (circles) of the observed velocity distribution.(thin solid line). In this processing, the data from the lowest measuring point to that of 30m from the bottom were considered for the regression for convenience of batch process to all data without considering the water level variation during the period. For this regression line, the depth at which the flow velocity is 5 mm/s was extracted as the division depth between upper and lower velocity layers (hc in Figure. 2). The velocity of 5 mm/s was determined from trials and errors. This demarcation depth of velocity layer is hereafter called as the "velocline" in this study. The velocity difference between the upper and lower layer was small in some cases depending on the distribution of the velocity, and it was not possible to detect the depth of 5 mm/s in such velocity condition. Those cases were treated as no velociline.

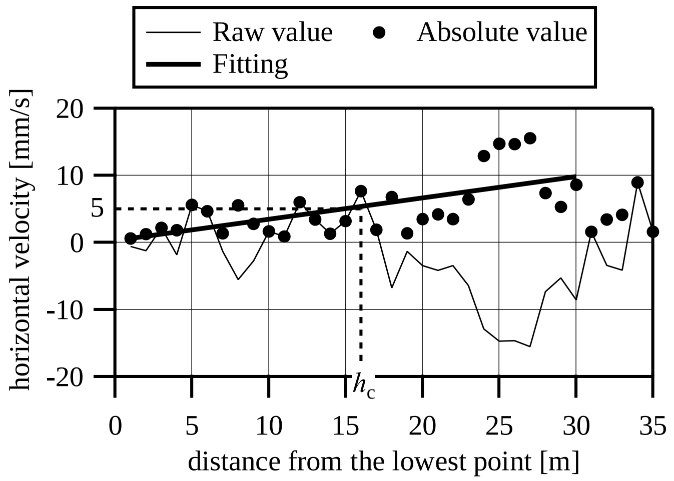

Figure 2. An example data set for analysis of horizontal velocity distribution.

Unlike the horizontal velocity, the vertical velocity component in the observation result of this study had a three-layered structure. Most of the observation results of vertical velocity had a distribution form with peaks and valleys as shown in Figure. 3. This is a typical distribution of vertical velocity, obtained at 1:00 pm on August 29. For this distribution pattern, sinusoidal function fitting was performed, and the depths at which the phase is π and 2π (hd and hu in Figure. 3) were defined as demarcation depth of velocity layers. Data from the bottom measuring point to 28 m were used for the fitting with the same reason as horizontal component processing. Depending on the flow conditions, however, clear distribution as shown in Figure. 3 was not distinguished, and those cases were treated as no veloclines. Since the time variations of the depths of velocline had large fluctuation, 10 data moving average was applied to smooth the line for the result diagrams of both horizontal and vertical components.

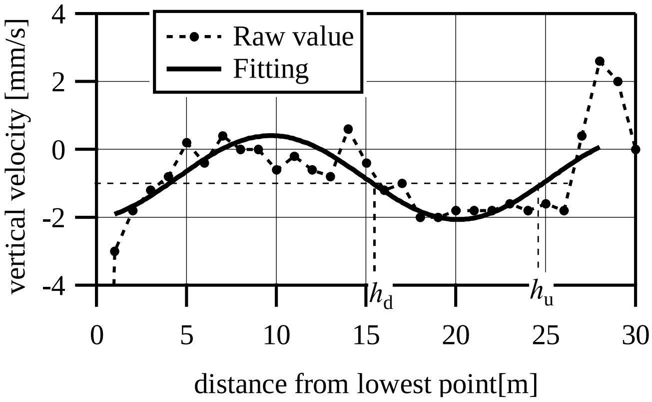

Figure 3. An example data set for analysis of vertical velocity distribution.

3 RESULTS AND DISCUSSION

Figure 5 shows the observation results of water temperature and flow velocity. The horizontal axis indicates time (date), and the vertical axis indicates elevation. The bottom elevation of 300m corresponds to the lowest depth of the measurement by ADCP. However, there is a more deeper area in the reservoir on the cross section of the reservoir around the installation of the ADCP. As a general condition during this period (Figure. 4), there were a flood by a typhoon on August 29 and a flood due to a low pressure weather condition on September 8. However, the discharge during those floods were at most several hundred m3/s, which are small scale runoff for this reservoir. Therefore, most of the inflow discharge was stored in the reservoir. The water level rose about 7 m during this period. As for the weather conditions, the temperature began to fall on the low pressure passage on September 8, and air temperature drop was observed around September 18 due to stagnation of the autumn rain front. Figure. 5 shows the results of hydraulic conditions in the reservoir: water temperature, horizontal velocity, and vertical velocity. The black solid lines in the middle and bottom panels indicate the velocline, the demarcation depth of flow velocity layers. The thermocline exists at about 315m above sea level during the observation. The depth of thermocline appeared to decline gradually, but the change in depth is rather small. Fluctuations of thermocline and water temperature distribution are observable , especially during floods, from the data, although measurement twice a day is not enough to distinguish subtle changes.

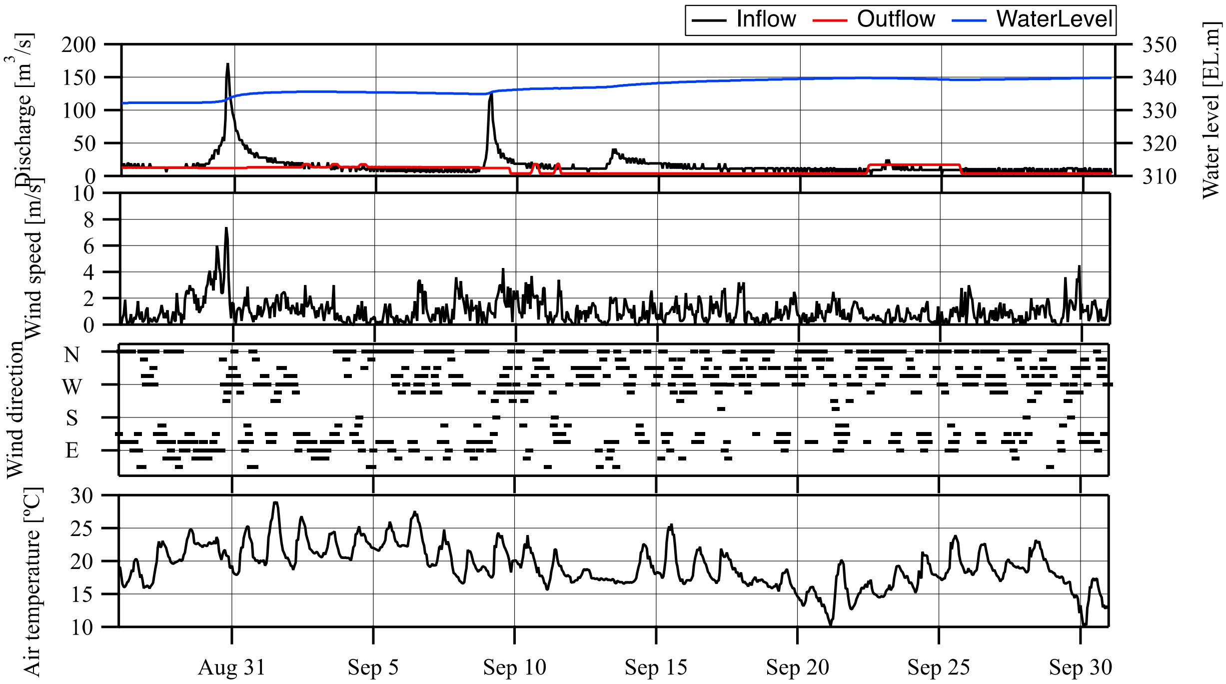

Figure 4. Reservoir operation conditions and meteorological conditions during the measurement in this study.

The horizontal velocity, as shown in the middle panel of Figure. 5, is rather small with a maximum value of about 20 mm/s Observations conducted by Yokoyama and Shintani 3) in Shichikashuku Reservoir, which is another large reservoir in the same northeast region of Japan, showed flow velocities of up to about 100 mm/s to 50 mm/s depending on the season. Compared with their study, the velocity range of this study is smaller but acceptable, as there were only small external forces for lake current during the measurement with small floods and wind above lake generally slower than 5 m/s. A flow pattern expressed by stripes of red and blue bands in the Figure. 5 suggests occurrence of periodical both way current along the longitudinal direction of the reservoir. This current is more remarkable in the first half of the measurement period. The cause of this flow is estimated from a numerical study by Umeda et al. (2018) that the periodical flow is basically generated with seiche initiated by wind driven current. As main cause of those current is wind blowing upon the water surface, magnitude of velocity is larger in the epilimnion than in the hypolimnion. However, in the middle panel of Figure. 5, relatively large fluctuation is observed in the depth which divide the upper layer with higher velocity and the lower layer with slower velocity. The black solid line in the diagram shows the depth of the boundary of flow characteristics, which is defined as “velocline” obtained from the method shown in Chapter 2. Although the result of the velocline depth is sometimes slightly different from the visual impression, the line obtained by our method successfully express the boundary depth of the layers that have different flow tendency. The velocline is located around the elevation of 320m, which almost corresponds to that of thermocline. However, amplitude of the depth fluctuation is as large as about 20m.

The range of the vertical velocity shown in the bottom panel of Figure. 5 is 2 mm/s or less, which is one order of magnitude smaller than the horizontal velocity. There is a three-layered structure found in the diagram

: a layer with an upward flow (red) near the surface, a layer with a downward flow (blue) in the middle, and an almost neutral flow (white) layer in the hypolimnion. This flow pattern with stably upward flow in the surface layer, and stably downward flow in the middle layer suggests a three-dimensional flow structure in the reservoir. Such current distribution can be generated not only the water surface wind and resulted seiche but also the water intake. The daily water intake for water supply is carried out with the intake facility installed at the same point as the water temperature monitoring device in the lake (triangle in Figure. 1), and the reservoir water is normally taken from around the water surface. Besides, the reservoir bathymetry, which is not at all symmetric, can also influence spatial distribution of flow. The veloclines in the vertical velocity profile are shown with black solid lines in the figure, which was extracted by the method of this study assuming a sinusoidal distribution in the vertical velocity profiles. Movement of the boundary lines in vertical velocity distribution is smaller than that of horizontal velocity. However, the veloclines gradually decline with time. In those general conditions, a sharp drop of about 5 m in the middle layer can be identified around September 15. After this event, both of horizontal and vertical velocity began to show random fluctuations around 330 m (about 10 m depth). This period corresponds to the time when the air temperature showed remarkable decrease presumably caused by the stagnation of the autumn rain front. This drop of air temperature induced circulation and mixing from the water surface due to cooling of surface water temperature.

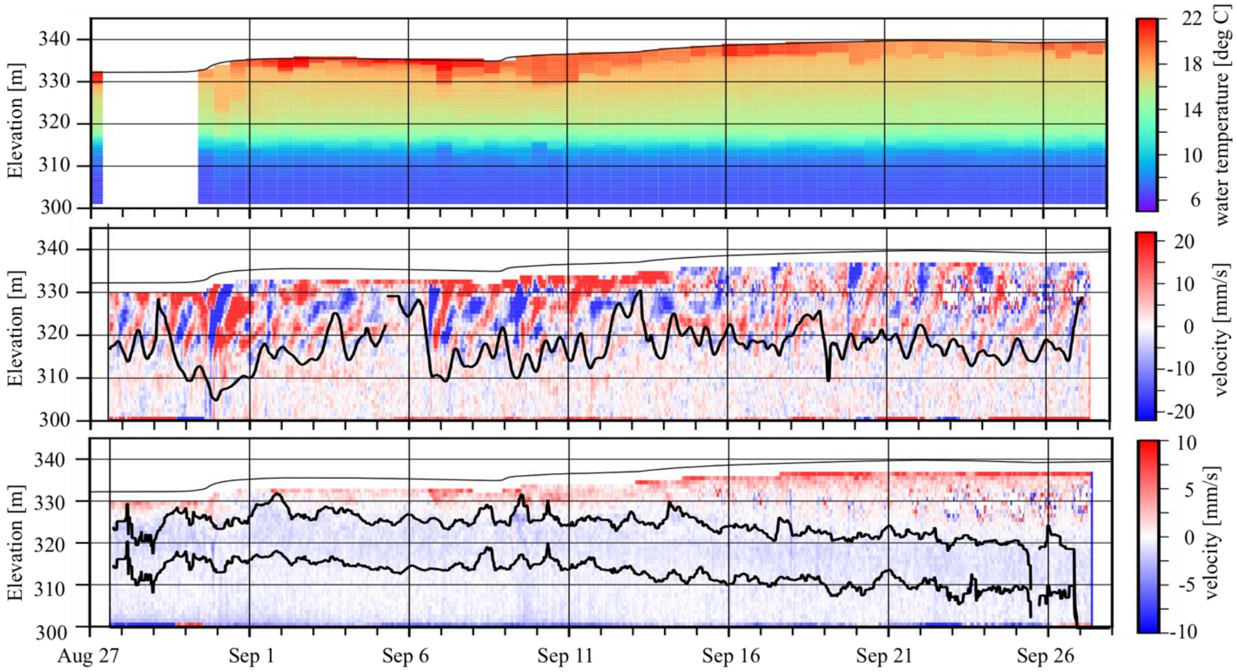

Figure 5. Results of measurement: Time series of profiles of water temperature (top), horizontal velocity (middle), and vertical velocity (bottom) .

4 CONCLUSIONS

In this study, spatiotemporal structure of flow in a stratified lake water was analyzed based on field measurement conducted in Isawa Reservoir in Japan. Main conclusions of the study are as follow:

1) Methodology of extracting boundaries of flow layer was invented. The method was applied to the observation results measured with ADCP in Isawa Reservoir. The extracted boundary of flow layer is named as “velocline” in this study.

2) The spatiotemporal distribution of horizontal velocity exhibited a flow pattern that the epilimnion had faster flow because of wind driven current, and the hypolimnion had slower flow. This tendency corresponds to those generally known in most of deep lakes. Change of elevation of velocline was larger than that of thermocline.

3) A three-layered structure was extracted in the vertical velocity distribution. Fluctuation of veloclines are relatively small and appeared to correspond movement of thermocline, which is a different tendency compared with horizontal velocity.

ACKNOWLEDGEMENTS

The authors were supported by the Social Implementation Program on Climate Change Adaptation Technology (SI-CAT), MEXT, Japan.

REFERENCES

Shintani, T. (2014). Performance of GLS turbulence closure model implemented in 3D unstructured hydrodynamic simulator. *Journal of Japan Society of Civil Engineers, Ser. B1*, 72 (4), I_667-I_672.

Shintani T., and Nakayama, K. (2009). Development and verification of object-oriented environmental hydrodynamic model. *Annual Journal of Hydraulic Engineering, JSCE*, 53, 1267-1272.

Umeda, M., Yokoyama, K. and Ishikawa, T. (2006). Observation and Simulation of Floodwater Intrusion and Sedimentation in the Shichikashuku Reservoir, Journal of Hydraulic Engineering, 132 (9), 881–891.

Umeda, M., Ikegami, J., Ishikawa, T., and Tomioka, S. (2004). Numerical modeling of flood water intrusion and fine suspended sediment behavior in a stratified reservoir, *Annual Journal of Hydraulic Engineering, JSCE,* 48, 1363-1369.

Yokoyama, K. and Shintani, T. (2006). A study on internal seiche and steady oscillating current in a reservoir. *Annual Journal of Hydraulic Engineering, JSCE*, 50, 1273-1279.