# Effect of Fluctuation of a Moving Boat Equipped with ADCP on Velocity-Profiles and Water-Depth Measurements

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## ABSTRACT

To have a better understanding of ADCP instruments and develop a system for the highly accurate measurement related to water discharge, velocity profiles and bathymetries, authors focus attention on a build-in inclination sensor in ADCP, which is a traditional liquid-surface-detection type. The field measurement with a floating vessel in Japan involves high velocity and vibration of water surface, which might induce the major sources of error related to a vessel fluctuation. Therefore, in this paper, authors quantitatively evaluate the influence of vessel fluctuation on ADCP measurement with 1) developing a measurement system with employing an MEMS inclination sensor, 2) conducting experiments in an experimental pool with the system, and 3) conducting the field measurement. The authors find out characteristics of the build-in inclination sensor of ADCP, apply the knowledge to actual discharge measurements, evaluate the systematical measurement error, and introduce the possible solution for eliminating missing values.

## INTRODUCTION

Researchers and engineers in Japan have recently started using Acoustic Doppler Current Profilers (ADCP) in field measurements during flooding, recognizing that they are useful, effective field-observational tools for velocity distribution measurements along boat tracks. However, error indexes need to be standardized in order to determine the reliability of observed data by coping with numerous error-producing factors involved in this type of measurement, such as supplemental devices, commands, operations, and river-bed conditions. Actually, United States Geological Surveys (USGS) determined data quality assurance guidelines about discharge measurements (Oberg et al. 2005). In the guideline, a threshold value as deflection of 5% from mean value of 4 times discharge measurements (2 times back-and-forth measurement) was employed. Also, Muller (2007) suggests measurement and correction methods when river beds moves as well. On the other hand, in Japan, not only discharge measurements across high energy flows but also flow-field measurements around river structures or trees in floodplains have been actively conducted; therefore, indexes for both river-discharge and flow-field measurements are needed to be established.

The authors' research group has been promoting the standardization of ADCP-associated techniques in terms of measurement, data processing, and data verification. One of the challenges has been how to obtain constant indexes based on non-uniform grid size. From the field engineer's view, it is impossible to maintain the uniform boat velocity, since it is affected by differences in flow fields across a section. Consequently, it becomes impossible to keep the grids the same size, since they are the multiplication of the boat speed and the interval of each ensemble. Therefore, the authors proposed a set of indexes which are the functions of velocity, of the standard deviation of a velocity error in a single ensemble, and of the distance of each ensemble (Okada et al. 2008).

In Japan, flow conditions during flooding often pose serious danger to observers, because of high velocity and vibration of water surface. In particular, the fluctuation of a floating vessel equipped with ADCP can be a major source of errors in the measurement of velocity distribution, water depth, and also possibly in bottom tracking, since the inclination sensor built into ADCP is a traditional liquid-surface-detection type, which is far inferior in measurement capability to a highly industrialized Micromachined Sensor. Similarly, Rennie (2003) also mentioned some influence of the vessel fluctuation to an observational error; however, he also suggested the error is smaller than instrumental noises from his field measurement.

Based on the background explained in the previous paragraphs, the authors conducted two experiments such as 1) in the experimental pool which provides purely still water to understand the characteristic of ADCP, 2) in high energy flow whose Froude number is almost one. For the purposes of conducting highly accurate observations, the authors used MEMS (Micro Electro Mechanical Systems) inclination sensor in the measurement, evaluated the influence of oscillation on measured velocity and water depth, and developed a data-correction method.

## CHARACTERISTICS OF ADCP FOR INCLINATION MEASUREMENT

To identify the characteristics of the built-in-liquid internal inclination sensor in ADCP, the authors first conducted an experimental study in an experimental pool (25 m width x 25m length x 5m depth). As shown in Figure1, the authors mounted ADCP and

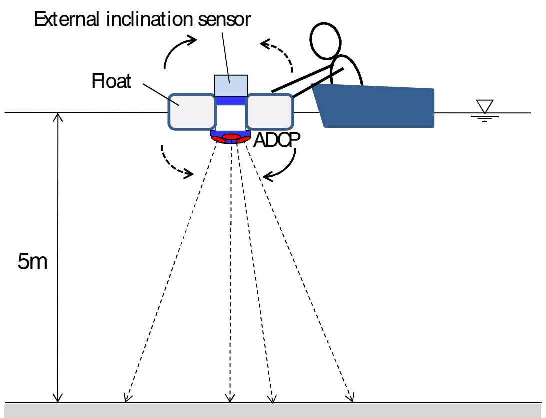



Fig.1 Measurement of inclination angle and depth using ADCP and external inclination sensor

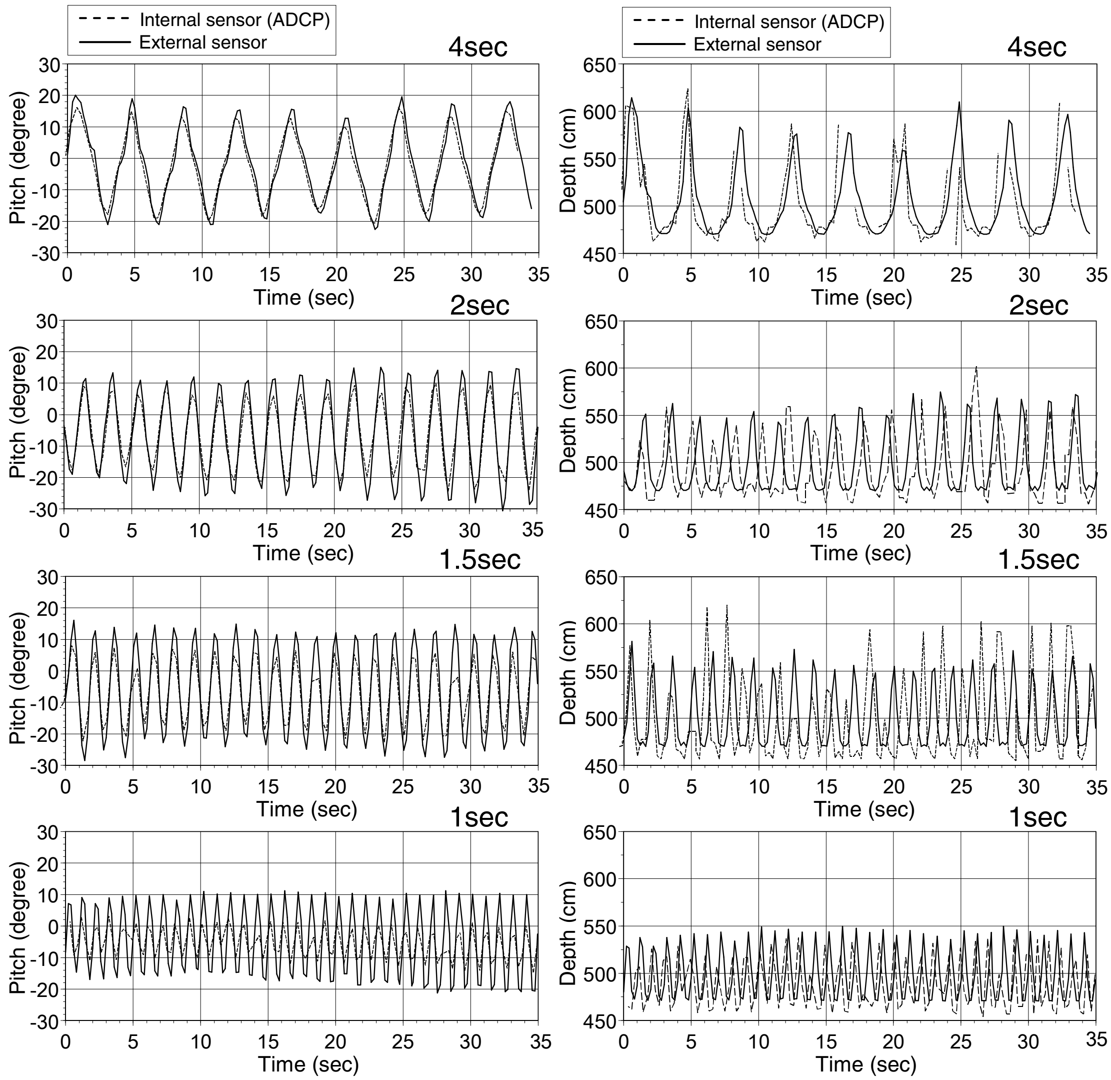
Table.1 Measurement setup of ADCP

| Workhorse ADCP 600kHz | |
|---|---|
| Measurement mode | WM1 |
| Depth cell size | 0.50m |
| Number of depth cell | 30 |
| Ensemble time | 0.32sec |
| Number of water ping | 1 |
| Bottom track command | On |
| Standard deviation | 13.62cm/s |
| Measurement command | EX01111 |
| Oscillation period | 1, 1.5, 2, 4 sec |

MEMS inclination sensors (NAV440 produced by Crossbow Technology, Inc) on a float, swung it by hand, and observed pitch and roll angles with both internal and external MEMS inclination sensors. Water depths were also measured with four different ADCP beams. The oscillation periods for this experiment were set to be 4, 2, 1.5, and 1 seconds from the authors' professional observation made during filed measurements (e.g., Okada 2008). Thereafter, 16 sets of experiment were conducted with 4 different commands and 4 frequencies. Also, other measurement setups of ADCP are listed in Table 1.

Fig.2 (a) and Tab.2 show the experimental results of the time-series pitch angles, and a summary of the experimental results. They indicate that the internal sensor observes a lesser angle for a shorter oscillation period than the external sensor. From the comparison of the averaged maximum amplitudes, a 13.1 % difference (in about 19 degree) can be recognized with the time period of 4 seconds, while 56.6 % (in about 14 degree) with the period of 1 second. Fig.2 (b) shows the time series of water depth obtained by the third beam. The solid curves show the calculation results using the pitch and roll angles measured by the external sensor, while the dotted curves show the results with those by the internal sensor. Similar with Fig.2 (a), a 6.3 % difference as maximum can be recognized with the time period of 4 seconds, while 10 % differences as maximum with the period of 1 second. In addition, phase lags can be recognized as well. Overall, the ADCP has characteristics of a precision associated with the inclination sensor, including the pitch and roll angles, was the largest at the oscillation period of 1 second, which subsequently caused the error in the water depth measurement.

In other words, it can be inferred that the internal liquid sensor is less capable of measuring amplitudes and phases, when the oscillation period is relatively shorter. In addition, regardless of the characteristics of the inclination sensor, about 10% error might be expected, since water depth measurement as one of the function of ADCP employs an averages of water depth observed from four different beams, which is independent from the inclination sensor.




(a) Time series of boat pitch on each time cycle

(b) Time series of measured depth and calculated depth

Fig.2 Comparison of measurement characteristics between ADCP internal inclination sensor and external inclination sensor on each time cycle

Table.2 Averaged maximum angles by each sensor and calculated velocity differences

| Period | Angles by external sensor, degree | Angles by internal sensor, degree | Differences, degree (%) | Expected velocity difference (%) |
|---|---|---|---|---|
| 4 | 18.46 | 16.04 | 2.42 (13.1) | 1.7 |
| 2 | 19.04 | 14.12 | 4.92 (25.8) | 2.5 |
| 1.5 | 18.83 | 12.72 | 6.11 (32.5) | 3.0 |
| 1 | 13.54 | 5.88 | 7.66 (56.6) | 2.3 |

## FIELD OBSERVATION AT TONE RIVER

Based on the knowledge from the experimental result in previous chapter, the authors conducted field observations at Tone River. Fig.3 shows a top view the observational site. Flow condition here has a maximum velocity of more than 4 m/s, and a highly fluctuated water surface even during normal stage. At this observational site, the authors conducted an ADCP measurement mounted on the River Boat with stretching a wire across the section. The measurement was conducted with a remote-controlled measurement system, developed by the authors, using a remote controller (Remo-ADCP manufactured by Hydro Systems Development, Inc.), the Work Horse ADCP with 1200 kHz, the MEMS inclination sensor (AMU manufactured by Silicon Sensing Systems Japan Ltd.), and RTK-GPS. Table.3 shows the measurement configuration setup of ADCP.

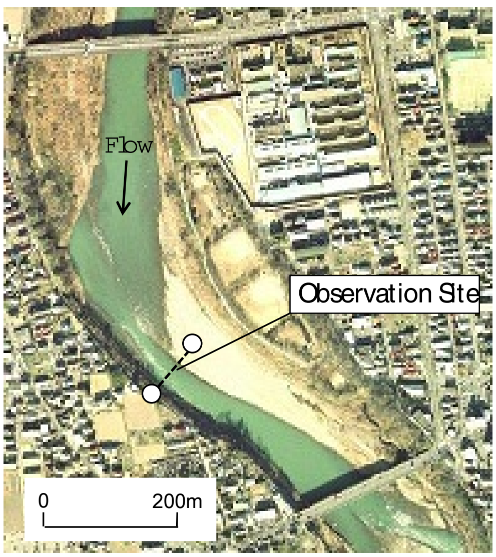


Fig.3 Plan view of observation site at Tone River

Table.3 Measurement setup of ADCP at Tone River

| Workhorse ADCP 1200kHz | |
|---|---|
| Measurement mode | WM1 |
| Depth cell size | 0.20m |
| Number of depth cell | 15 |
| Ensemble time | 0.25sec |
| Number of water ping | 1 |
| Bottom track command | On |
| Standard deviation | 26.38cm/s |
| Coordination | EX00000 |

Fig.4 shows time series of velocity at 0.5m from transducers, pitch and roll angles obtained by ADCP internal and MEMS inclination sensor. Since the observation was conducted from left to right bank, data number at 0 indicates the results around the left bank, while data number around 160 indicates the results around the right bank. During observation in a low velocity zone (assume velocity less than 200 cm/s), the angles with both sensors and differences are lesser compared with those in a high velocity zone (assume, velocity more than 200 cm/s). In the high velocity zone, as characteristics of results, phase differences as a wave are recognized between ADCP pitch and MEMS pitch. The pitch angles have periods from 2 to 3 seconds, while roll angles have periods from 1 to 2 seconds. In addition, the phase differences exaggerate angle differences; then the angle differences sometime reached to 10 degrees. Regarding

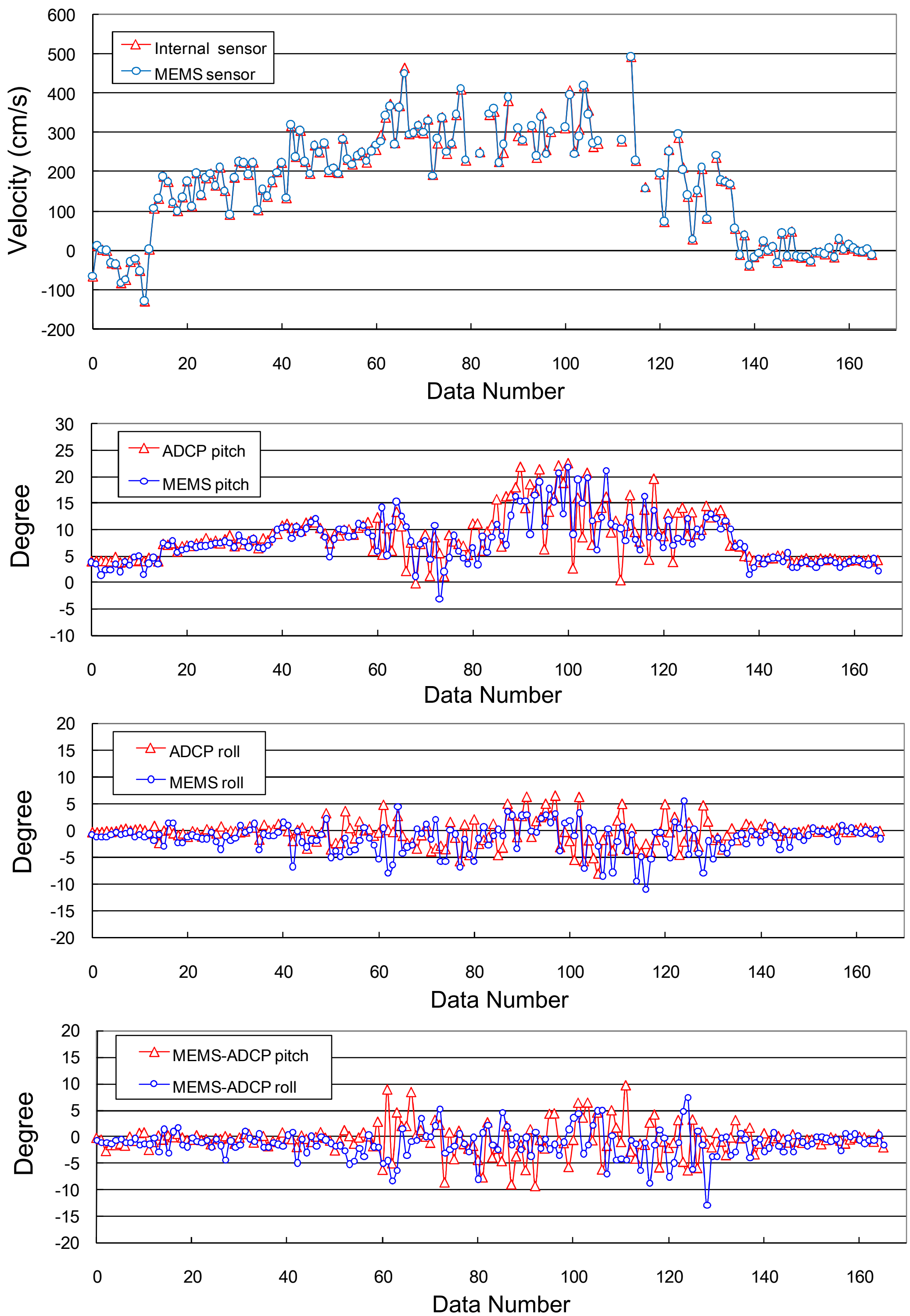



Fig.4 Time series of velocity and tilt angle measured by internal and MEMS sensor

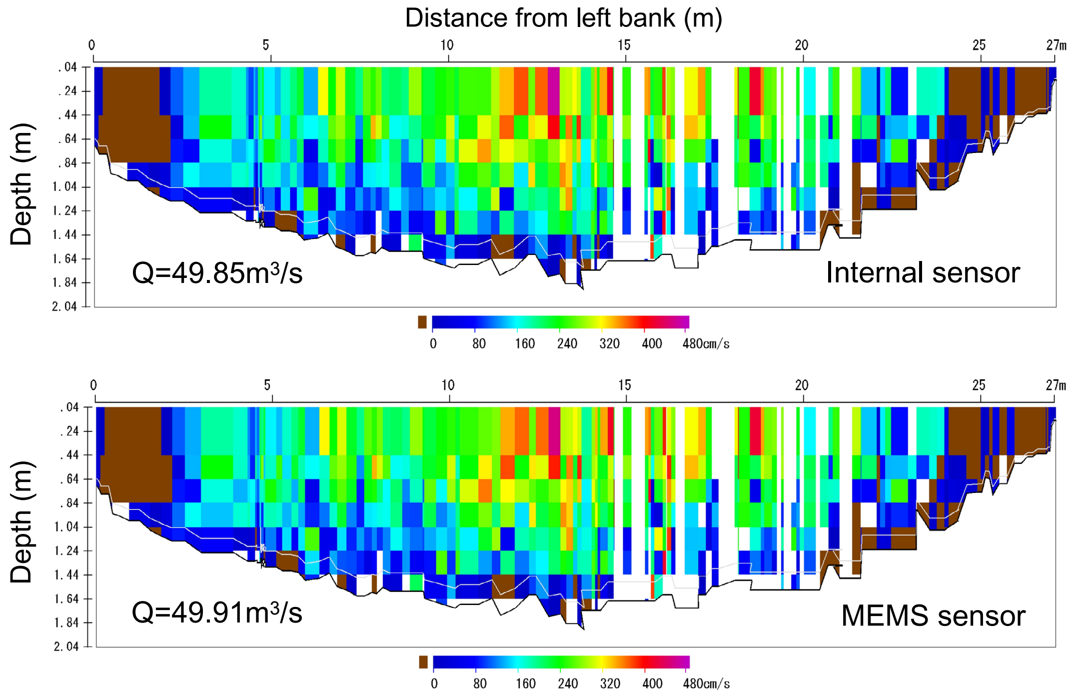



Fig.5 Comparison of velocity distribution corrected by ADCP and MEMS sensor data

about the limitation of ADCP measurement, missing values are mostly recognized when either pitch or roll angles exceeds 15 degree (as ADCP manual says), and when periods of the angles oscillation are relatively shorter.

Fig.5 shows contour curves of velocity distributions perpendicular to the cross section. Above figure is the velocity distribution calculated by the ADCP's internal sensor, while other figure is that calculated by the MEMS sensor. Without any interpolation at the location of the missing values, total discharges amounted about 50 $m^3/s$ for both cases. Regardless of the experimental results as discussed in the previous chapter, it is surprising that there is not much difference between the two discharges, even though the authors hesitate to conclude. In this case, positive and negative adjustments with the MEMS inclination sensor might be canceled each other with the processes of summation to obtain the discharges. For the future uses, possibility of the measurement error as shown in the Tab.2 is still need to be carefully considered with the discharge measurement at the different flow field.

With regard to the water depth measurement, portion of missing values are considerably large amounts, which consequently results the less reliable discharge measurements. Actually, successful measured ensembles with 4 beams are 84 out of 165 (50.9%), while those with 3 beams are 44 out of 165 (26.7 %). Others (about 25%) of ensembles become missing values with unknown reasons with either high velocity nor inclination angles.

## CONCLUSION

1. The internal liquid sensor is less capable of measuring amplitudes and phases, when the oscillation period is relatively shorter, such as more than 50% less angles when period of oscillation is 1 second. Consequently, velocity and water depth measurements need to expect about 2 to 3%, and about 10% error, respectively.
2. Regardless of the experimental results as shown in Table 2, it is surprising that there is not much difference of discharge between before and after adjustment with MEMS sensor, even though the authors hesitate to conclude. In this case, positive and negative adjustments with the sensor might be canceled each other with the processes of summation to obtain the discharges.
3. Missing values are mostly recognized when either pitch or roll angles exceeds 15 degree (as ADCP manual says), and when periods of the angles oscillation are relatively shorter. Therefore, designing of the boat, which does not exceed the angle of 15 degrees, and which has less oscillation.
4. Regarding to the water depth measurement in the high energy flow, portion of missing values are considerably large amounts (in this case about 49%). For more reliable and accurate discharge measurement, employment of an echo sounder with lower frequency, and adjustment with the MEMS sensor to the echo sounder is desirable.

## ACKNOWLEDGEMENT

Authors would like to express our gratitude to River division of National Institute for Land and Infrastructure Management, Ministry of Land, Infrastructure, Transport and Tourism Japan, who provide us valuable data related to the field measurement in Tone River.

## REFERENCES

Kevin A. Oberg, Scott E. Morlock and William S. Caldwell (2005). "Quality-Assurance Plan for Discharge Measurement Using Acoustic Doppler Current Profilers" U. S. Geological Survey, Scientific Investigation Report 2005-5183

David S. Mueller and Chad R. Wngner (2007). "Correcting Acoustic Doppler Current Profiler Discharge Measurements Bised by Sediment Transport", J. Hydraul. Eng., 132(12), 1329-1336

Shoji Okada, Takashi Kitsuda, Seiro Moromoto and Minoru Masuda (2008). "Flood flow observation in Shimanto River Gudo Point using unmanned boat equipped with ADCP " Annual Journal of Hydraulic Engineering, JSCE(CD-ROM)

Colin D. Rennie, Robert G. Millar and Michael A. Church (2003). "Closure to "Measurement of Bed Load Velocity Using an Acoustic Doppler Current Profiler" by Colin D. Rennie, Robert G. Millar and Michael A. Church", J. Hydraul. Eng., DECEMBER 2003, 1020-1021