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Experimental investigation on inversion of ADVP measurement for suspended sediment concentration, a case study

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Abstract. To obtain vertical velocity profile and related suspended sediment concentration (SSC) simultaneously with little interference as far as possible is always of hydraulic researchers' interest. For this purpose, the experiments with suspended sediment of silica sand were carried out in water vessel in order to investigate the inversion of acoustic backscatter intensity for SSC distribution in acoustic Doppler velocimeter measurement. A Nortek Vectrino Profiler (ADVP) was used in the experiments. The influences of the sediment diameter, the average concentration and the instrument parameter setting on acoustic backscatter signal (AMP) were tested. The results show that AMP values of middle layer are larger than those of the other layers and they have similar logarithmic relationship with SSC as in ADV measurement inversion. The relationship was found to depend on the particle sizes and the sampling cell configuration. The more layered in a same sampling section, the weaker the backscattered intensity and the larger the intensity difference between the middle layer and the other layers. When certain amendment is given to the AMP values on each layer, the ADVP measurements can still be transferred into SSC by using the simple logarithmic relationship. Through the experiments, the acoustic inversion approaches are suggested and the involved formula for sediment concentration profile for the case is established.

1. Introduction

For a long time, measurement of suspended sediment concentration (SSC) without affecting the ambient turbulence has been a key issue in sediment transport research. Acoustic equipment has great potential to measure the small-scale sediment processes without interference but with high spatial and temporal resolution, which has been gradually accepted by sediment researchers in past 30 years [1]. For example, there is a good correlation between the time-averaged back-scattered signal intensity and the time-averaged sediment concentration when measuring the velocity by ADV (Acoustic Doppler Velocimeter). This correlation can be used to invert the backscatter signal strength to specific particle information such as time-dependent SSC by applying the functional relationship between them, so as to solve the difficulty of sediment measurement. A number of scholars have proposed such methods and procedures for suspended particle concentration inversion by means of ADV[2-7].

However, these studies had to focus on the particle concentration at a certain point owing to the instrument measuring system of ADV, while in the actual situations, SSC changes over the time and



space. ADVP, an upgrade of ADV with the same acoustic theory, can measure a 3 cm thick section of velocity profile as in Figure 1a and give the acoustic backscatter signal information of each layer on the profile as well. Therefore, in terms of theory, ADVP can be also used for inversion of SSC. Unfortunately the existing studies didn't provide us adequate proven results for their application in this field, whether the instrument parameter settings or the data performances are not clear. In order to improve simultaneous measurement of SSC and velocity without extra devices in flow field, this paper aims to investigate the effect of concentration, particle size, sound frequency and layer partition on the backscattering signal of ADVP through experiment by a case study. We will analyze the measured signal value AMP to test the applicability of ADVP in inversion of fine particle sediment concentration. After that we try to establish the inversion formula for our instrument to provide a practical computing tool for the local SSC and give some beneficial references for similar applications in SSC measurement. Some conclusion remarks are given in the end part.

2. Material and method

2.1. Experiment set-up

The experiments were conducted in a 25 cm high vessel where the turbid water was well stirred artificially right before the measuring as shown in Figure 1b. To avoid flocculation, we used commercial silica sand for sediment in the experiments. There are 8 sand groups of different size with the mean particle sizes ranged from 12.03 μm to 28.42 μm . The sand sample from each group was considered as uniform approximately.

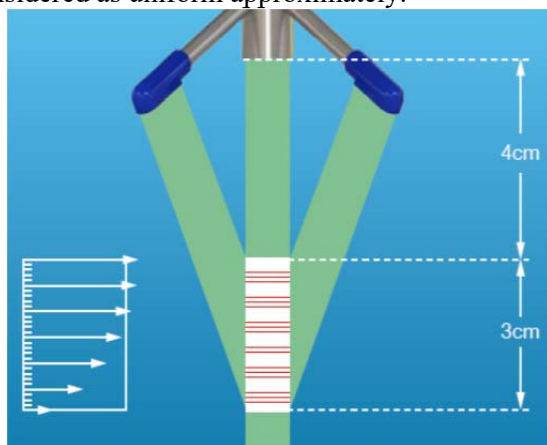


Figure 1a. Sketch of the ADVP probe and its largest sampling range in vertical.

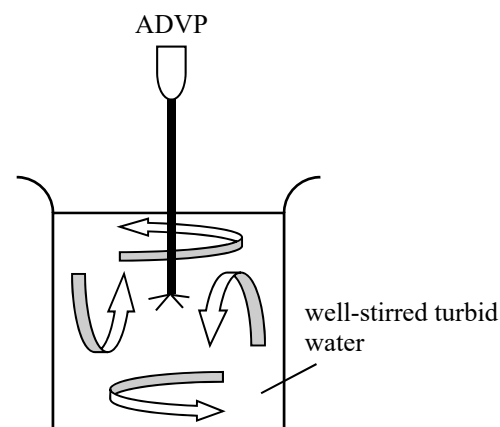


Figure 1b. Sketch of the measurement in the experiments.

The velocimeter we used was the Nortek Vectrino Profiler of 10 MHz, one of the latest versions of ADVP from Nortek company. The equipment parameters are shown in Table 1.

Table 1. Parameters of the Nortek ADVP in the experiments.

Sampling frequency (Hz)	Distance from probe (cm)	Cell height (mm)	Acoustic frequency (MHz)	Probe numbers /
1-200	4-7	1-4	10	4

2.2. Measuring approaches and data processing

The ADVP was configured in advance. It was installed on a stable frame and had been set to work without record operation. We could monitor on the screen if everything was alright. For each experiment run, 2000 ml turbid fresh water was prepared in the glass vessel with the sand of a certain size according to the designed concentration. We blended it with a stirring rod till it got fully mixed

just before the measurement started. Then we stopped stirring and the cup was put to the right place under the ADV immediately to let the probe submerge. In the same time the ADV started to record to the data files.

With the water speed decreasing, the suspended sediment began to deposit. But SSC in the water did not decrease totally at once except that near the top, because the depositing rate and sediment flux at any place were close to be equal for the initial uniform concentration in short time of the beginning. In the experiments, it was found that the SSC was generally unchanged only in the first 10 s. So we deleted those invalid data due to the initial manual operations which could be recognized from the value coherence, and just take the normal data of the first 10 s of each run into our analysis. Meantime the actually SSC were considered equal to the pre-determined values.

For the recorded data, the time series of Velocities, Correlation and SNR were used for process judgment and those having unstable relation or weak signals were discarded. The Amplitudes (AMP) indicated the back-scattered signal intensity. The collected AMP values from every probe were smoothed and denoised respectively before they were averaged by 4 probes. Then they were averaged again in 10 s before they were used in later analyzing.

2.3. The influences of the instrument configurations

2.3.1. Sampling frequency. It was found that high sampling frequency resulted in wild fluctuation of original AMP values. Thus we chose lower frequencies in the experiments. The sampling frequencies of 10 Hz, 20 Hz and 30 Hz were tested respectively with the sand of $19.08\ \mu\text{m}$ and the concentration of $0.5\ \text{g/L}$. The layer thickness was set to 3 mm. The results of the averaged AMP are shown in Figure 2, where the cases of 10 Hz and 20 Hz have little differences while the 30 Hz has some small fluctuations. In general the lines have good coherence which indicates little effects of lower frequency on AMP data. We adopted 20 Hz in all runs in the following.

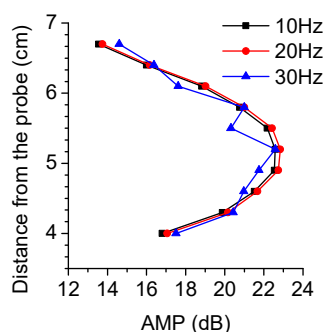


Figure 2. Influence of the sampling frequencies on signal intensity.

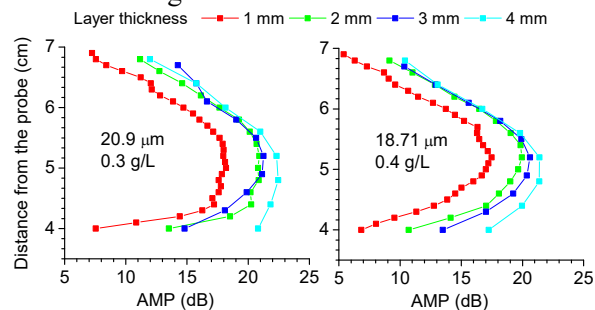


Figure 3. Effects of layer thickness on signal strength.

2.3.2. Thickness of sampling cell. When thickness of the cell layer was set to 1 mm, 2 mm, 3 mm and 4 mm respectively, the number of layers on the sampling section were thus 30, 15, 10 and 8 correspondingly. It can be seen from Figure 3 that on the same distances from the probe, the smaller the layer thickness, the smaller the AMP value and the larger the AMP difference between middle layer and the two end layers. These signify that the back-scattered signals were weaker in smaller thickness setting. In other words, thinner layers were more affected by the adjacent layers and resulted in evident decline of signal intensity. Hence moderate layering was selected in the experiments.

3. Results and discussions

The instrument parameters were finally set as follows: sampling frequency of 20 Hz, measuring profile length of 3 cm on 10 layers with each layer of 3 mm thick. According to the references for ADV inversion [8], the relationship between SSC and AMP will deviate from one-to-one function when SSC gets to a higher value. So we kept the SSC lower than $0.5\ \text{g/L}$ for all runs.

The measured AMP on different layers varied with SSC in logarithm as in Figure 4. In spite of the different particle sizes and the layer locations, the values of signal intensity increased approximately linearly as the concentration increased. That means logarithm relationship in general between their values and the line can be expressed as follows

$$AMP = k \lg SSC + b \quad (1)$$

where AMP denotes the measured AMP value in dB, SSC the SSC value in g/L, k the line slope and b the related intercept. Such relationship was broadly reported in the references for ADV. Therefore ADV had the same inversion rules as ADV on each layer.

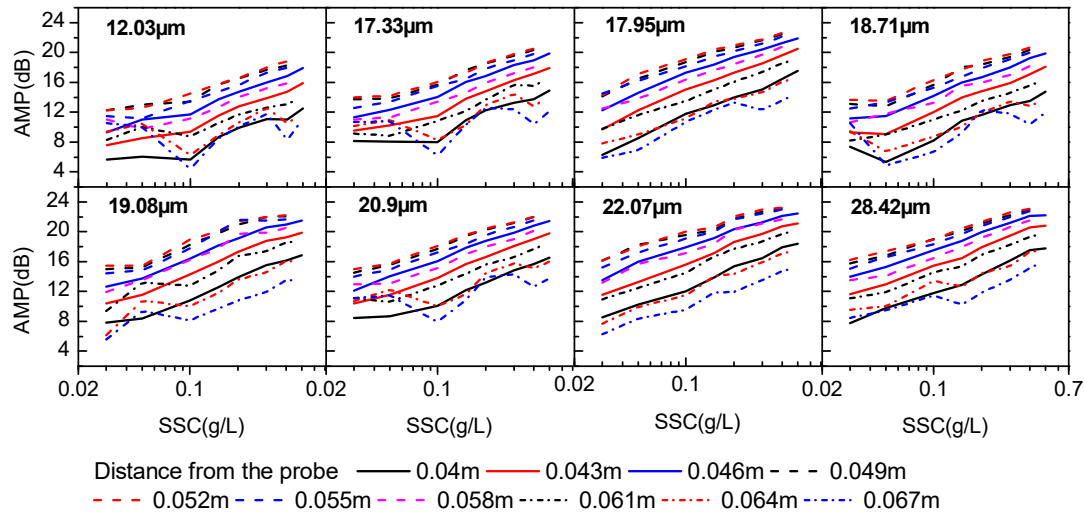


Figure 4. Dependence of the layered AMP on the SSC for different particle sizes.

Seen from Figure 4, for different particle sizes as well as different layers k values show little changes but b values vary clearly with the distances from the probe. The closer to the middle, the larger b value the layer has. We considered that the three layers in middle i.e. at 0.049 m, 0.052 m and 0.055 m from the probe, had the strongest signal intensity and took their average for k and b values by fitting the data with equation (1). The results are shown in Figure 5 where k values are almost constant in overall and b values gradually grow with the particle size. For simplicity, we took the average value of 6.58 as the k value and a parabolic fitting function in calculation of the b values as the following.

$$b = -0.025D^2 + 1.3D + 8.58 \quad (2)$$

where D denotes the particle size in μm .

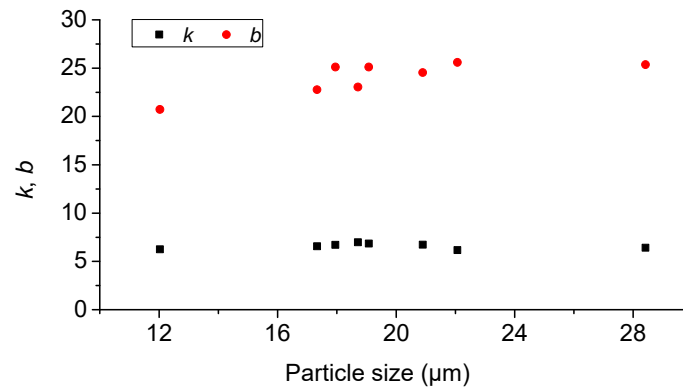


Figure 5. k and b values for the middle layer in equation (1).

The equation (2) was evidently applicable to the intermediate layer. For a specific particle size, on the rest of the layers the measured AMP were smaller than those of the middle layer. The AMP value

differences between the measured by ADVP and the computed by equation (2) on each layer for the sand group of 19.08 μm as an example are shown as in Figure 6. The value differences varied with the layer distance from the probe but were dependent little on SSC. Also as in Figure 7 the differences showed little dependence on the particle size but the data point series for different sand groups were consistent to each other. Therefore, a modifying compensation m_i merely on layer location was needed to each of the layers other than the middle one. For mathematical reason, we took a polynomial fit to the average as follows with the adjustment R-square of 0.998 and it is graphed by the solid line in Figure 7.

$$m_i = -0.8783d^4 + 17.584d^3 - 125.82d^2 + 376.98d - 388.51 \quad (3)$$

where d denotes the distance from the probe in cm. Thus the 10 layers in the experiments had corresponding value of m_i in Table 2 where the sequence number i differentiates the layers.

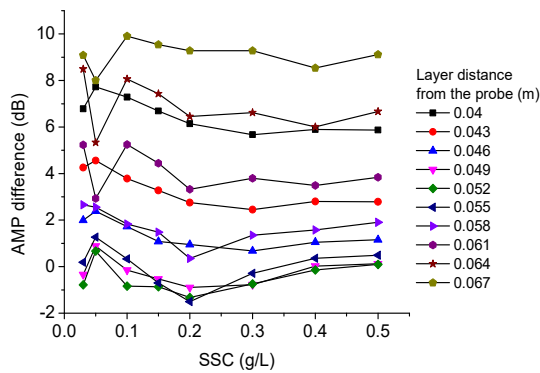


Figure 6. AMP differences of each layer from the computed value for the middle layer of the sand group of 19.08 μm .

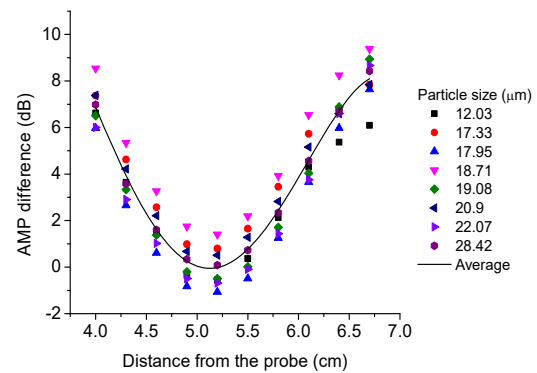


Figure 7. The AMP differences averaged on the sediment concentrations for the experiment sand groups. The solid line is the average for the total particle sizes.

Table 2. m_i value for each layer.

i	1	2	3	4	5	6	7	8	9	10
The distance from the probe (cm)	4	4.3	4.6	4.9	5.2	5.5	5.8	6.1	6.4	6.7
m_i	6.82	3.87	1.55	0.17	-0.11	0.66	2.31	4.46	6.57	7.94

By far, the SSC value in g/L on the layer numbered by i , which is denoted by $\text{SSC}_{(i)}$, is able to be obtained by following expression with the AMP on the corresponding layer which is denoted by $\text{AMP}_{(i)}$.

$$\text{SSC}_{(i)} = 10^{\frac{(\text{AMP}_{(i)} + m_i) - b}{k}} \quad (4)$$

The effects of instrument, particle size and layer location on the observed signal are represented by k , b and m_i respectively.

Figure 8 shows the inversion results for the sand group of 22.07 μm in well mixed turbid water. It was more satisfying for the concentration smaller than 0.3 g/L in spite of some fluctuations. When we stopped stirring, the sand particles deposited gradually and after a while the distinctly un-uniform concentrations along the depth formed. Figure 9 shows the results in such depositing case as the pre-determined concentration was 0.2 g/L with the sand group of 12.03 μm and the waiting time after the stop was 2 min. The inversed vertical SSC profile could reveal the sediment aggregation to the bottom

but the inversion was challenged near the boundary due to the solid wall as well as the particle sorting. Their effects on back-scattered acoustic signal strength were so complicated that they had not been investigated in this paper.

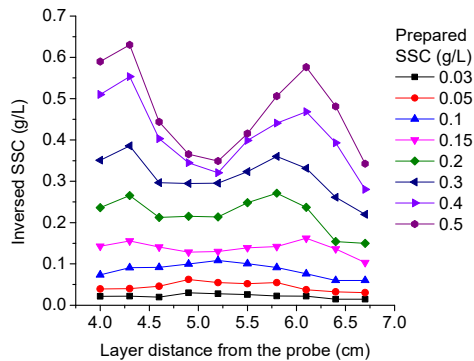


Figure 8. The inversed SSC for the uniform turbid water.

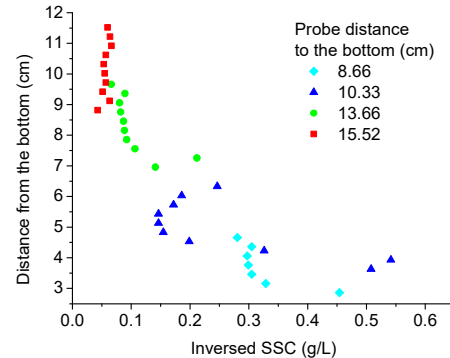


Figure 9. The inversed SSC for the non-uniform turbid water.

4. Conclusions

The procedure of inversion of ADVP measurement for SSC has been studied through the turbid water experiments in lab vessel to investigate possibility of simultaneous SSC profile measurement by means of acoustic velocity profiler device. The effects of instrument configurations, different concentrations, particle sizes and sampling cell locations were tested and analyzed. The results show some conclusions as following.

1) For a certain sound frequency, the sampling frequency has little effects on the back-scattered signal intensity while the distance between sampling cells has some influences. The denser the cell spacing is, the weaker the AMP values are. Hence many or few layers on sampling section in configuration should be avoided if it is possible.

2) The logarithmic relationship between the values of AMP and SSC are still satisfied for low sediment concentration as in equation (1) for ADVP measurement as in the similar inversion of ADV measurement. But the strongest signals would appear in the intermediate cells while the other cells have weaker signals as they get further from the middle. When 2 or 3 middle cells are taken as the normal layers owing to their great signal strength, the AMP values on the other cells should be given some corrections before they are used in the inversion.

3) In equation (1) of the middle layers in inversion, the slope k has little variation while the intercept b increases slowly with the particle sizes. For the other layers the correction given to the measured AMP values, m_i , depends on the layer distance from the probe. The values of b and m_i can be evaluated by the polynomial fitting method. With the determined values of k , b and m_i the inversion equation for SSC is available.

4) In the experiments, the inversions for the uniform and non-uniform concentrations showed that the procedure was workable to some extent. But it was challenged in situation of large concentration, sediment sorting and near-wall zone, which expects further explorations in the future.

Acknowledgement

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