Electromagnetic Wave Surface Velocimetry

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Abstract: Electromagnetic wave surface velocimeters (ESVs) measure the Doppler shift in electromagnetic waves reflected from the water surface. They provide nonintrusive water surface velocity measurements from bridges and river banks. Comparisons with laboratory and field tests show very good agreement over a wide range of elevation and planview angles. Laboratory testing shows comparable results between ESV and other measurement techniques when $0.4 < V < 1.6$ m/s and $15 < \theta < 45°$. Field testing at three different locations shows that the optimal operation conditions are at an elevation angle $\theta \approx 30°$, planview angle $\varphi < 13°$, and $0.30 < V < 2.00$ m/s. The ratio of cross-section-averaged velocity to mean free surface velocity is approximately $CF_{DAV} \approx 0.88$ for high flow velocities during floods. The standard deviation of the field measurement for these three streams was less than 15% of the mean value.

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Introduction

Hydraulic engineers need velocity and discharge measurements during river floods. Flow velocity is normally measured by submerged velocimeters (SVs) located at various depths to determine a vertical velocity profile. This intrusive method has been traditionally used to calculate discharge, but it is very difficult for real-time applications during floods. Rating curves are often extrapolated from measurements at lower flow conditions.

Measurements of discharge and depth-averaged velocities in open channels using two-dimensional (2D) laser Doppler anemometers have been studied by Nezu and Rodi (1986), Nezu et al. (1997), and Kırkgöz and Ardıçıoğlu (1997) among others. Chiu (1989) derived equations for velocity profiles from channel bed to water surface in open channels. Chiu and Murray (1992) and Chiu and Tung (2002) derived equations for velocity profiles and maximum velocity for nonuniform flow in open channels, respectively. Gordon (1989) measured water discharge using acoustic Doppler velocimeters (ADVs) in rivers. Also, Carollo et al. (2002) and Chen and Chiew (2003) measured flow velocity using an ADV in vegetated channels and open-channel flows, respectively. It is sometimes difficult to set up intrusive flow meters during large floods with floating debris and likely equipment breakdown.

Hydraulic engineers are currently trying to estimate flow velocity and water discharge during floods from surface velocity using nonsubmerged velocimeters (NSVs). Lee and Lee (2002) developed a method to measure surface velocity using an electromagnetic wave surface velocimeter (ESV). The discharge measuring method of the ESV relates the surface velocity to the Doppler frequency shift between the emitted and received electromagnetic waves (Lee et al. 2001). However, there are differences in velocity measurements between the ESV and the propeller type (PV), the 1D micropropeller (M1DV), the 2D magnetic sensor type (M2DV), and the 3D acoustic Doppler velocimeter (Lemmin and Rolland 1997; Song and Chiew 2001). These differences can be corrected by introducing a correction factor for the depth-averaged velocity (CF_{DAV}). The CF_{DAV} is defined as the ratio of the depth-averaged velocity v_{DAV} measured by the SV to the surface velocity v_{WSV} measured by the ESV. As a substitute to depth-averaged velocity measurements with the SV, the CF_{DAV} could be combined with ESV measurements to estimate the water discharge during floods. It is also important to consider that surface flow velocity measurements would be useful to determine the impact force of floating woody debris during floods (Haehnel and Daly 2004).

This study describes the electromagnetic wave surface velocimeter and provides comparisons of laboratory and field measurements. It is also the objective of this paper to define the optimal operation conditions and the CF_{DAV} values for field applications during floods.

Electromagnetic Wave Surface Velocimeter

Flow discharge in open channels can be measured by SV and NSV methods. Typical discharge measurement methods require the product of the cross-section-averaged velocity and the cross-section area. The SV method requires submerged velocity and depth measurements from a bridge or a boat. In contrast the ESV method is nonintrusive as shown in Fig. 1.

The ESV determines the surface velocity from the Doppler shift in frequency between emitted and returned electromagnetic wave from the following equation:

$$f_{dw} = \frac{2v_{WSV}}{\lambda} \cos\theta \cos\varphi \qquad (1)$$

where f_{dw}=Doppler frequency shift equal to the difference $(f_{gw} - f_{rw})$ between reflected frequency f_{rw} and emitted frequency

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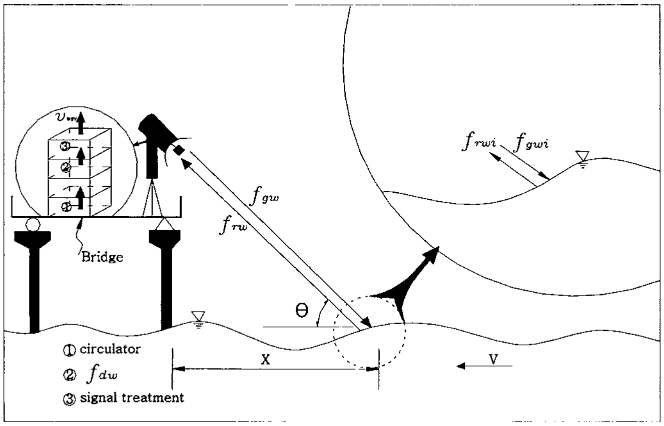

Fig. 1. Sketch of water surface measurement by ESV

of the electromagnetic wave f_{gw}; v_{WSV}=velocity at water surface; λ=electromagnetic wavelength; θ=angle between water surface plane and electromagnetic wave beam; and φ=planview angle between beam and flow direction.

In practice, the surface flow velocity is linearly proportional to the Doppler frequency shift and is determined most accurately where the angles θ and φ are not too large, such that the surface velocity becomes

$$v_{WSV} = \frac{f_{dw}\lambda}{2\cos\theta\cos\varphi} \tag{2}$$

The equipment required to measure the surface velocity by Eq. (2) is shown in Table 1 and Fig. 2. It consists of primary elements with parts for the signal treatment including a 10 GHz oscillator and power divider, an antenna, a goniometer, and a tripod.

The Cf_{DAVi} is introduced in order to define the ratio between the depth-averaged velocity and the surface velocity measured by the ESV, or

$$Cf_{DAVi} = \frac{v_{DAVi}}{v_{WSVi}} \tag{3}$$

where v_{DAV} and v_{WSV}=, respectively, the depth-averaged velocity and surface velocity at a point i along the vertical. This factor will be obtained through field tests under various conditions.

Table 1. ESV Equipment Characteristics

Element	Characteristic
Oscillator	Generates electromagnetic wave of X-band (10 GHz) frequency from converting dc to ac power
Power splitter	Separates the signal from oscillator
Circulator	Controls the emitted electronic wave, the reflected wave, and the signal direction angle
Antenna	Emits the electromagnetic wave; it also receives the electromagnetic wave reflected at water surface
Mixer	Determines the Doppler frequency shift between the returned signal and the frequency of the oscillator
Goniometer	Measures the angle between the flow velocity direction and the electromagnetic wave
Tripod	Supports the antenna
Signal treatment	Saves and displays the converted velocity from the frequency analysis by Fourier transforms. It also amplifies the faint received Doppler signal reflected at the water surface

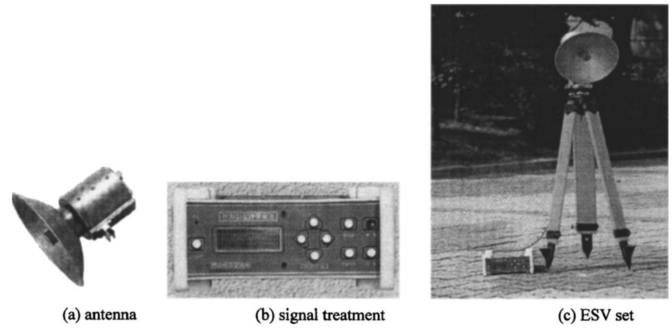

Fig. 2. ESV equipment

The flow discharge can be estimated from bridges or other high locations on the river bank. Discharge measurements of the ESV can be calculated from the following equation:

$$Q = \sum_{i=1}^{n} v_{DAVi}a_i = \sum_{i=1}^{n} (Cf_{DAV}v_{WSV})_i a_i \equiv CF_{DAV}\sum_{i=1}^{n} v_{WSVi}a_i \tag{4}$$

where Cf_{DAVi} $(=v_{DAVi}/v_{WSVi})$=local ratio of depth-averaged to surface velocity; v_{DAVi}, v_{WSVi} and a_i=depth-averaged velocity, surface velocity, and area in subsection i, respectively; and CF_{DAV}=coefficient for the entire cross-section area.

Laboratory Tests

Laboratory and field tests were designed to determine the mechanical capacity and performance of the ESV, in comparison with other measurement techniques.

Laboratory tests proceeded to determine the range of operational application of the ESV in terms of flow velocity, flow depth, and elevation angle. It was used for open-channel experiments in a small flume 30 cm wide, 40 cm high, and 10.5 m long; and a larger flume 77 cm wide, 85 cm high, and 17.8 m long, respectively. Those tests compared ESV measurements with the velocity of surface floats (5 cm×5 cm polystyrene piece) and also with depth-averaged velocities under a range of flow velocity conditions measured with a M1DV in both flumes.

Laboratory tests with mid-channel flow velocities were compared with flow velocities of 0.40, 1.00, and 1.60 m/s measured by surface float and M1DV. The discharge was adjusted with a gate valve and the antenna was set at an elevation angle of θ=30°. Table 2 and Fig. 3 show the comparison between surface velocity measurements using the ESV and the depth-averaged velocity measured by M1DV and mid-channel velocities measured with surface floats.

Table 2. Flow Velocity Measurements (m/s) from Laboratory Tests

Velocity range	ESV (elevation angle θ=30°)	M1DV	Surface float
Low velocity (0.40 m/s)	0.29	0.45	0.44
Intermediate velocity (1.00 m/s)	0.99	0.92	1.08
High velocity (1.60 m/s)	1.59	1.61	1.67

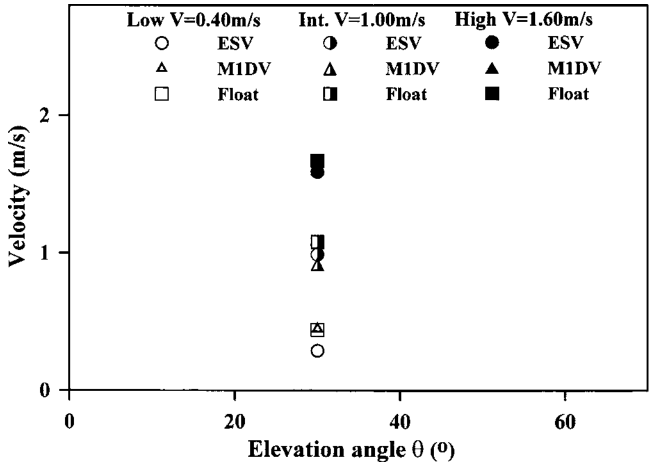

Fig. 3. Comparisons of laboratory tests for three flow velocities

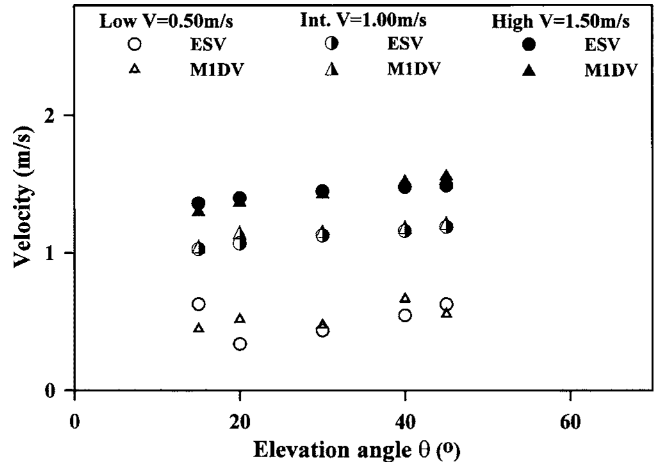

Fig. 5. Comparisons of laboratory tests at various elevation angles and flow velocities

Laboratory tests in the large flume at flow depths of 33.3, 43.8, and 62.6 cm, respectively, were compared with surface velocity measurements by surface float and depth-averaged velocities measured by M1DV. The results are shown as in Fig. 4.

Laboratory tests with different elevation angles and flow velocities compare measurements between surface velocity by surface float, and depth-averaged velocity by M1DV for low flow velocity of 0.50, intermediate of 1.10, and high of 1.50 m/s at elevation angles of $\theta = 15$, 20, 30, 40, and 45°. The results are shown in Fig. 5.

The results of the laboratory tests shown in Figs. 3–5 depend on flow velocity, flow depth, and elevation angle, respectively. In the case of flow velocity $0.4 < V < 1.6$ m/s, the ESV shown in Fig. 3 is close to M1DV and float measurements. In Fig. 4, the ESV measurements compare well with the M1DV and float measurements at a range of flow depth of 33–63 cm and flow velocities of $0.5 < V < 1.5$ m/s. In Fig. 5, comparable measurements are obtained at elevation angles θ ranging from 15 to 45°.

In summary, the performance of the ESV has been tested in the laboratory for a range of flow velocities $0.4 < V < 1.6$ m/s. The ESV measurements compare well with other measurement techniques at an elevation angle $15 < \theta < 45°$.

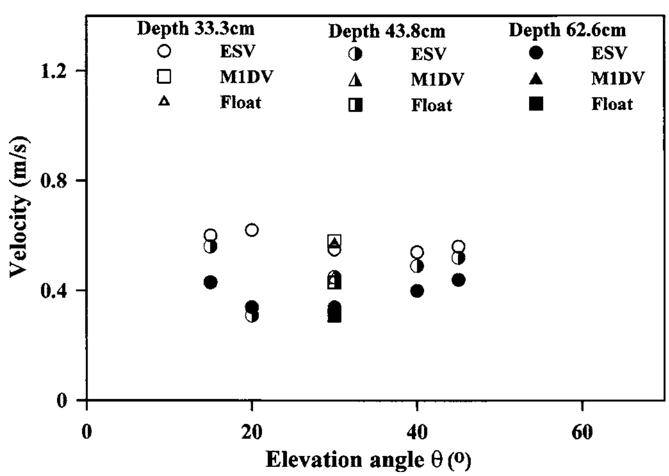

Fig. 4. Comparisons of laboratory tests for three flow depths

Field Tests

Field tests for the CF_{DAV} determined the ratio between depth-averaged velocity measurements by the SV and surface velocity by the ESV under different flow and bed material conditions. The depth-averaged velocity was measured with the SV by arithmetical or weight averaging of two- or several-point velocity measurements using the M1DV (Vanoni 1941; Dawdy 1961; Colby 1964), M2DV (McCutcheon 1981; Julien 1998), and ADV (Lee 2001; Julien 2002).

Field tests to determine the optimal operation conditions and the CF_{DAV} values were carried out at a low $V = 0.30-0.50$, intermediate $V = 0.50-1.30$, and high flow velocity $V = 1.30-2.00$ m/s with bed material conditions ranging from clay to gravel. Three field locations were selected to include class 1 and class 2 rivers of the national river classification system in Korea. Field tests were conducted at three stations with different bed material conditions and channel slopes of 1/500–1/800. Three different measuring stations were selected: (1) lower velocities of $0.30 \leqslant V < 0.50$ m/s at the Anyung Bridge site, a tributary of the Gum River at Daejon; (2) intermediate velocities of $0.50 \leqslant V < 1.30$ m/s at the Nonsan site, a canal of Topjung Reservoir; and (3) higher velocities of $1.30 \leqslant V \leqslant 2.00$ m/s at the Chungsung site, in the upper basin of the Gum River. After selecting the streams, the exact sampling location was determined from site investigations. At a given measuring position, the ESV was set up on a bridge, or river bank, and the exact velocity measuring points were determined. In order to find the limitations and optical/mechanical operation conditions of the equipment, field conditions are summarized in Table 3. The velocity measurement positions are determined as a function of horizontal distance X and diagonal distance l corresponding to the elevation angle θ and planview angle φ, respectively. Depth-averaged velocities were measured by the SV methods (PV, M2DV, and ADV, respectively).

Anyung Bridge Field Site

As shown in Fig. 6(a), this station is located on the bridge. The river width is about 100 m with flow depth 30–40 cm and mean velocity of about $V = 0.5$ m/s during low flow periods. As shown in Fig. 6(b), the measuring method checked the 7 m height difference between the water surface and the antenna center. After

Table 3. Velocity Measurement Positions with Distance and Angle Conditions at Field Tests

Conditions	Measurement number	Figure number	Anyung Bridge site Angle (degrees) θ	φ	Distance (m) X	l	Nonsan site Angle (degrees) θ	φ	Distance (m) X	l	Chungsung site Angle (degrees) θ	φ	Distance (m) X	l
Horizontal distance X at elevation angle θ	1	①	50		7.1		50		1.72		50		2.94	
	2	②	40		10.1		40		2.45		40		4.17	
	3	③	30		14.7		30		3.56		30		6.06	
	4	④	20		23.4		20		5.65		20		9.62	
	5	⑤	10		48.2		10		11.65		10		11.85	
Planview angle φ at diagonal distance l	1	a		10		14.9		12.8		11.95		10		6.15
	2	b		20		15.6		25.1		6.24		20		6.45
	3	c		30		17.0		36.7		4.44		30		7.00
	4	d		40		19.2		47.2		3.61		40		7.91
	5	e		50		22.9		57.0		3.16		50		9.43

setting up the ESV on the bridge, the selected points measurements were located at elevation angle (from ⑤ to ①) of θ=10, 20, 30, 40, and 50°. This corresponds to horizontal distances X of 48.2, 23.4, 14.7, 10.1, and 7.1 m, respectively. The planview angles (from a to e) are, respectively, φ=10, 20, 30, 40, and 50° with an elevation angle θ=30°. The corresponding diagonal distances l from the ESV are 14.9, 15.6, 17.0, 19.2, and 22.9 m, respectively. The surface velocity is measured at reflected points by the ESV, and compared with depth-averaged velocity measured at the same point by PV and M2DV. The depth-averaged velocity v_{DAV} was determined from PV and M2DV measurements using the one-, two-, or three-point method.

Nonsan Field Site

Nonsan station, as shown in Fig. 7(a), is located on a wooden bridge 100 m below the control gate of Topjung Reservoir and supplies water for irrigation. The surveyed channel has a width 8 m, flow depth 70–100 cm, and velocity V=0.5–0.8 m/s during the irrigation period. The measuring method shown in Fig. 7(b) is like the previous description in Fig. 6(b) except that measurements are taken at 2.65 and 5.29 m from the right bank. The ESV is set up on the wooden bridge at an elevation of 2.05 m above the water surface to measure the surface velocity at elevation angles θ of 10, 20, 30, 40, and 50° (from ⑤ to ①) for the corresponding horizontal distances X of 11.65, 5.65, 3.56, 2.45, and 1.72 m. In case of the second line, the planview angles (from a to e) have values φ of 12.8, 25.1, 36.7, 47.2, and 57.0°. The corresponding diagonal distances l from the ESV are 11.95, 6.24, 4.44, 3.61, and 3.16 m, respectively. The surface velocity v_{WSV} is measured at reflected points by the ESV, and compared with the depth-averaged velocity v_{DAV} measured at the same point by PV and ADV. The depth-averaged velocity was determined from PV and ADV measurements using the one-, two-, or three-point method.

Chungsung Field Site

The Chunsung station shown in Fig. 8(a) is located on a small bridge over the fast flowing Gum River. The measuring method shown in Fig. 8(b) is like that previously described in Fig. 6(b) and differs from part of marked to measure point for reflected point of electromagnetic wave at elevation angles θ of 10, 20, 30, 40, and 50° (from ⑤ to ①) for the corresponding horizontal dis-

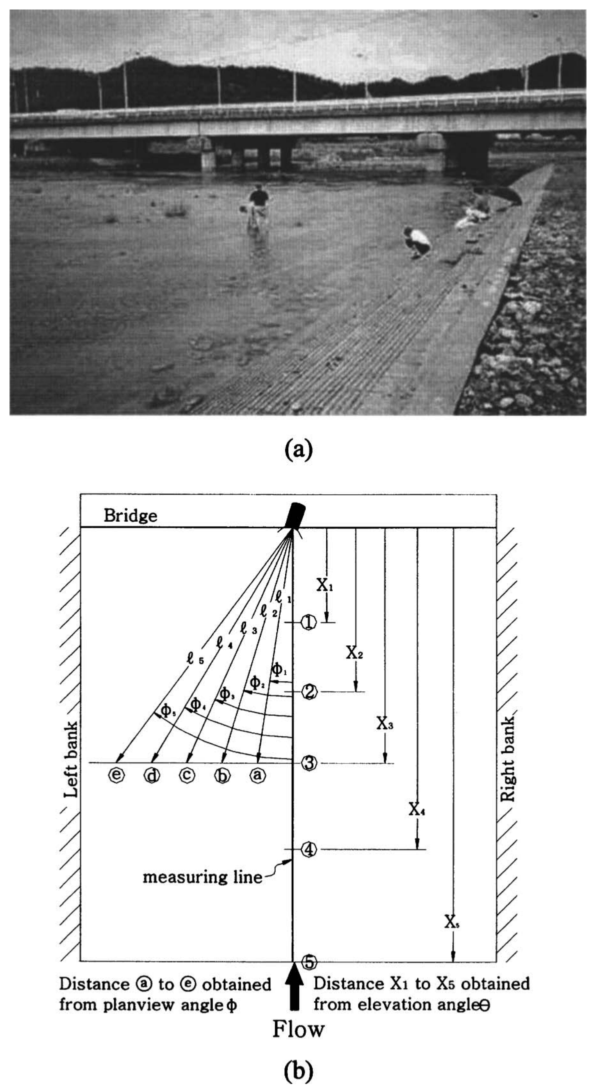

Fig. 6. Anyung Bridge site and flow velocity measurement method

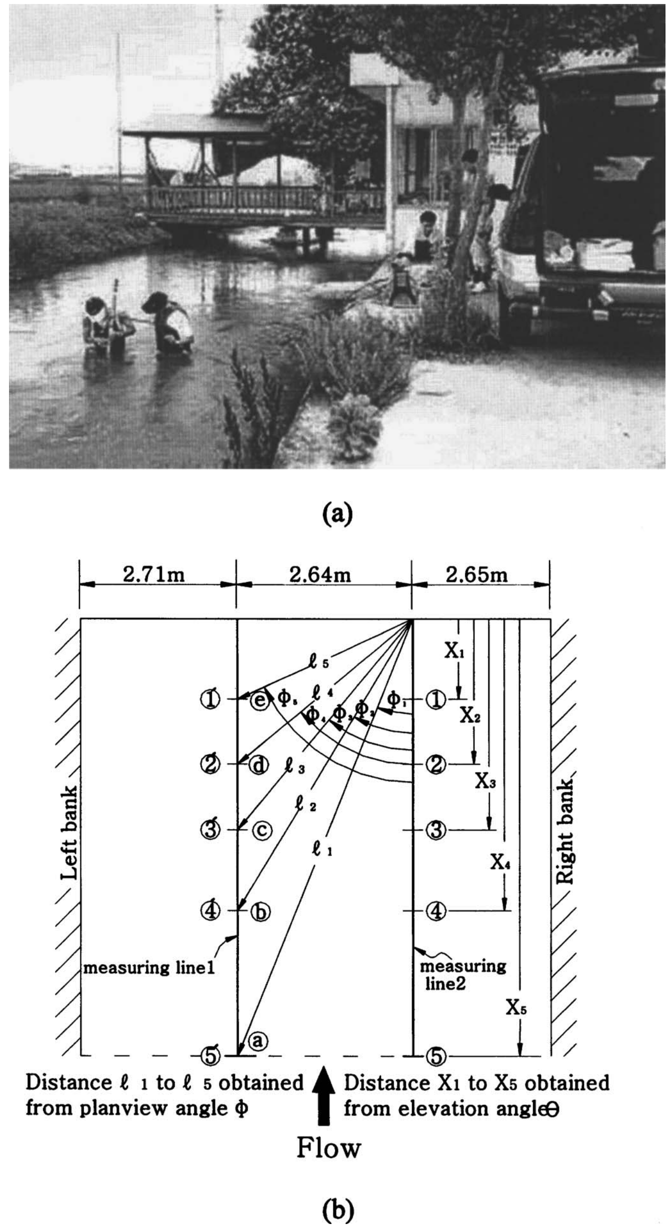

Fig. 7. Nonsan site and flow velocity measurement method

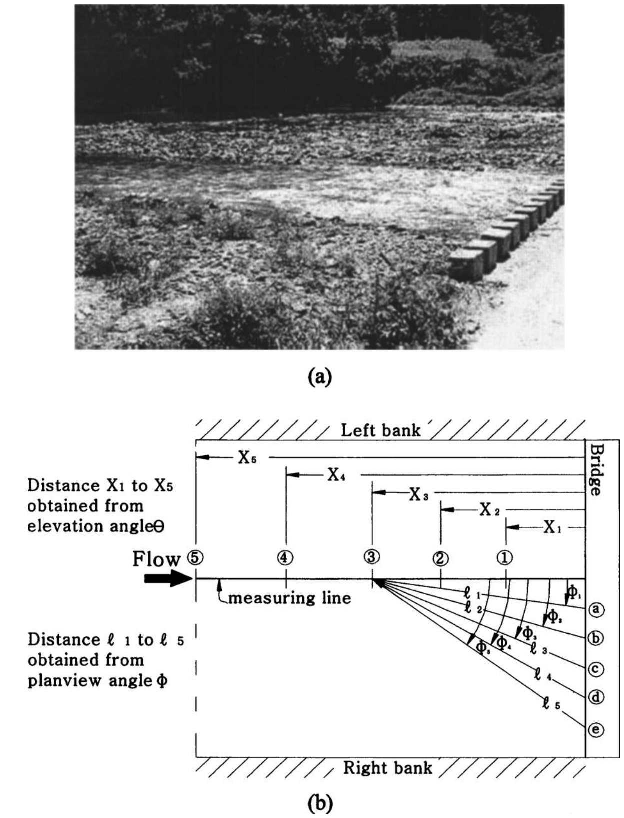

Fig. 8. Chungsung site and flow velocity measurement method

tances X of 11.85, 9.62, 6.06, 4.17, and 2.94 m at the ESV. The planview angles (from a to e) have values φ of 10, 20, 30, 40, and 50° with an elevation angle $\theta = 30°$. The corresponding diagonal distances l from the ESV are 6.15, 6.45, 7.00, 7.91, and 9.43 m, respectively. The surface velocity v_{WSV} is measured at reflected points by the ESV, and compared with depth-averaged velocity v_{DAV} measured at the same point by PV and ADV. The depth-averaged velocity was determined from PV and ADV measurements using the one-, two-, or three-point method.

Comparison between Electromagnetic Wave Surface Velocimeter and Field Measurements

Velocity measurements from the ESV are compared with the field measurements at low $0.30 \leqslant V < 0.50$ m/s at the Anyung Bridge site, intermediate $0.50 \leqslant V < 1.30$ m/s at Nonsan site, and high velocity $1.30 \leqslant V \leqslant 2.00$ m/s at the Chungsung site, respectively. The results in Figs. 9 and 10 show, respectively, comparisons by the dimensionless ratio Cf_{DAV} between depth-averaged velocity and surface velocity at different elevation angles θ or downstream distance X, planview angle φ or diagonal distance l, using the ESV and SV methods. Figs. 9(a) and 10(a) show values of CF_{DAV} from the ESV and depth-averaged velocity using the PV and M2DV at the Anyung Bridge site. Figs. 9(b and c), and 10(b and c) show similar comparisons between ESV surface velocity and depth-averaged velocity using the PV and ADV at the Nonsan and Chungsung sites, respectively.

Fig. 9 shows a comparison between the ESV and the PV and M2DV with downstream distance X or elevation angle θ. The least error is obtained at $\theta_3 = 30°$ or $X_3 = 14.7$ m. The results of comparisons between ESV and PV and ADV in Figs. 9(b and c) show the least error at $\theta_3 = 30°$ or $X_3 = 3.56$ and 6.06 m, respectively. Those averaged values show the least error $\theta \approx 30°$ in comparison with measured values between ESV and PV, M2DV, and ADV at downstream distance with elevation angles.

In Fig. 10(a), research results with diagonal distance l or planview angle φ, the best agreement between the ESV and the PV and M2DV occurs when $\varphi_1 = 10°$ or $l_1 = 14.9$ m. Also, the comparisons between the ESV and the PV and ADV in Figs. 10(b and c) show the least error at $\varphi_1 = 12.8°$ or $l_1 = 11.95$ m, and $\varphi_1 = 10°$ or $l_1 = 6.15$ m, respectively.

In summary, the least error between ESV and PV, M2DV, ADV is obtained when $\varphi \approx 10-13°$. Also, the optimal ranges of operation conditions for the ESV are $\theta \approx 30°$, $0.30 < V < 2.00$ m/s, and $\varphi < 13°$.

Verification of CF_{DAV}

From the field measurements, the ratio CF_{DAV} of the depth-averaged flow velocity to the ESV surface velocity is shown in

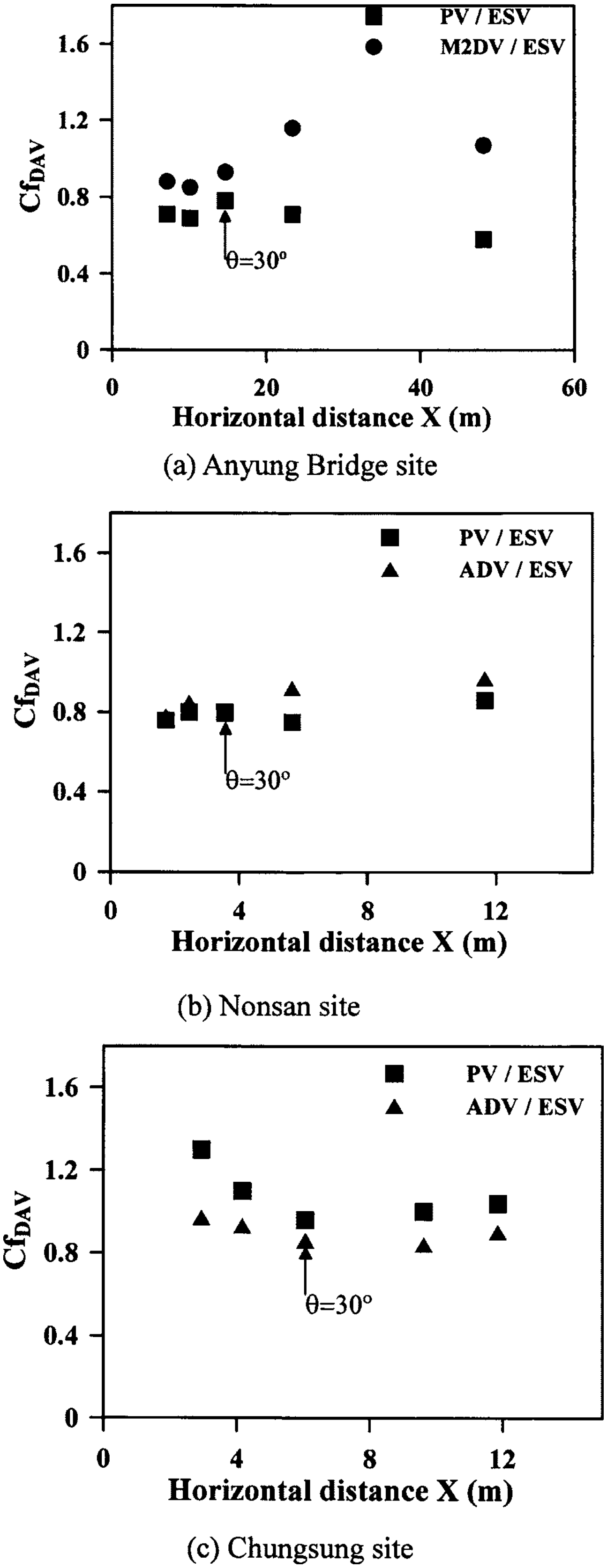

Fig. 9. Velocity comparisons with downstream distance

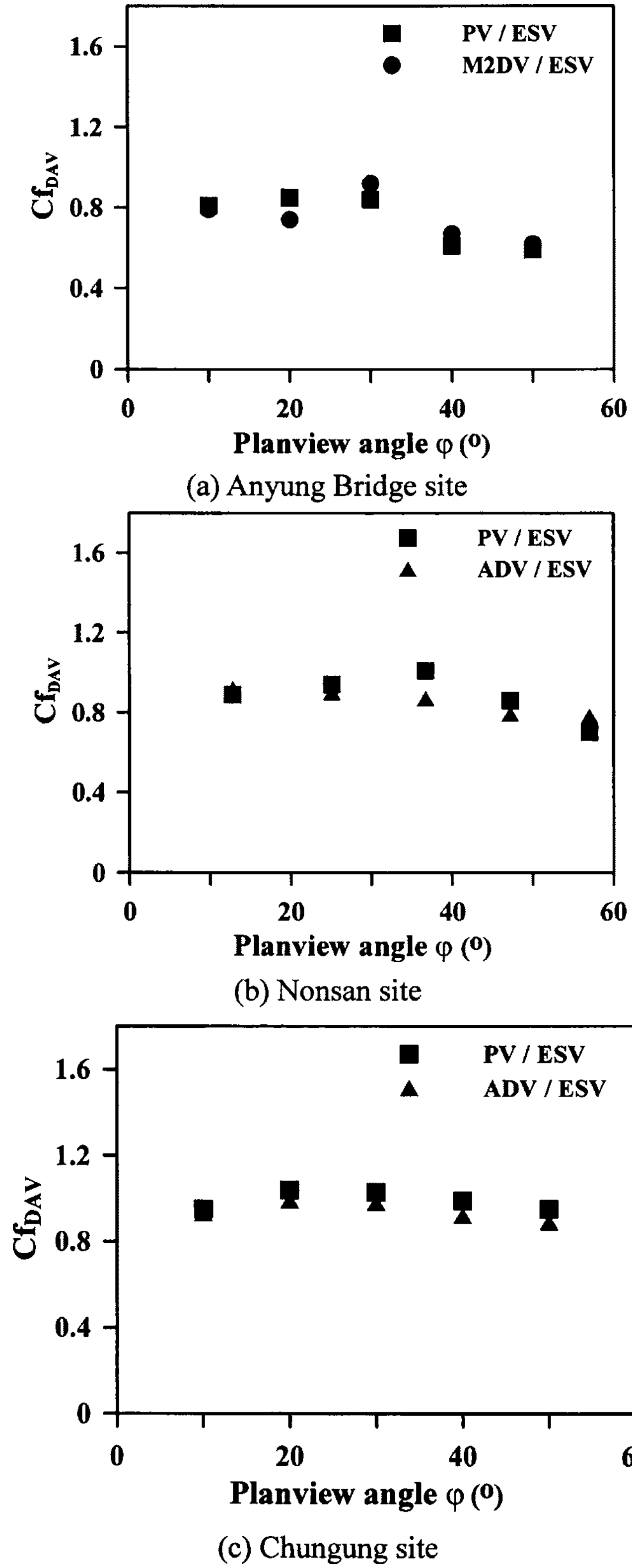

Fig. 10. Velocity comparisons with planview angle

Fig. 11 at the Anyung Bridge site [Fig. 11(a)] for 35 measurements, the Nonsan site [Fig. 11(b)] for 45 measurements, and the Chungsung site [Fig. 11(c)] for 28 measurements.

The values of CF_{DAV} are, respectively, (1) in the range 0.42–0.77, averaging 0.61 with standard deviation 0.094, at low flow velocity in the gravel bed Anyung River as shown in Fig. 11(a);

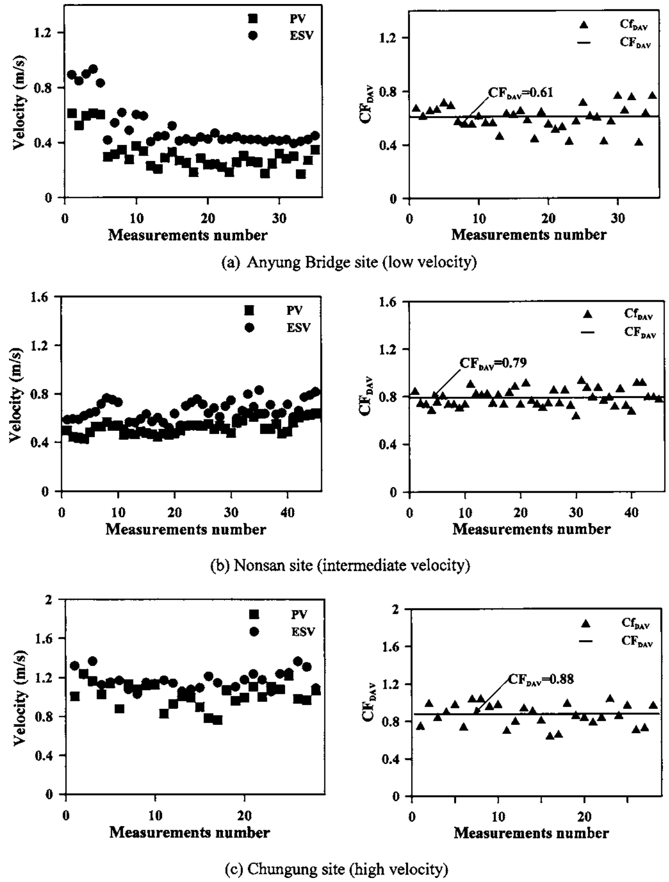

Fig. 11. Values of CF_{DAV} at three field sites

(2) in the range 0.68–0.94, averaging 0.79 with standard deviation 0.073, at intermediate flow velocity in a clay bed irrigation canal as shown in Fig. 11(b); and (3) in the range 0.65–1.05, averaging 0.88 with standard deviation 0.12, at high flow velocity in the gravel bed Chungsung River as shown in Fig. 11(c).

Thus, the CF_{DAV} values in this study can be recommended for hydraulic field applications of the ESV with $CF_{DAV} \approx 0.88$ for high flow velocities during floods. Once calibrated at specific sites the ESV can provide real-time surface velocity measurements and discharge estimates. The standard deviation of the measurements ranges from 9 to 15% of the mean value of CF_{DAV}.

Conclusions

This study defines the practical range of applicability of electromagnetic wave surface velocimeters from a set of field and laboratory tests. The ESV measurements show very good agreement with surface velocity measured with floats and microvelocimeters.

The ESV efficiency is very good in comparison with the SV for a reasonable range of elevation and planview angles as well as in convenience of the measurement method from bridges and river banks. From those ranges of elevation and planview angle conditions, the optimal operation conditions for $0.3 < V < 2.0$ m/s are $\varphi < 13°$ and elevation angle $\theta = 30°$.

The CF_{DAV} is introduced in order to correct for the velocity difference between depth-averaged velocity with the SV and surface velocity with the ESV and the NSV. The CF_{DAV} results are in the range 0.42–0.77 averaging 0.61 for low velocity in the gravel bed Anyung River, 0.68–0.94 averaging 0.79 for medium velocity in a clay bed irrigation canal, and 0.65–1.05 averaging 0.88 for high velocity in the gravel bed Chungsung River. The CF_{DAV} values in this study can be recommended for hydraulic field applications of the ESV with $CF_{DAV} \approx 0.88$ for high flow velocities during floods. The standard deviation of the measurements is less than 15% of the mean value for the three streams considered.

Notation

The following symbols are used in this paper:

a = flow subsection area;
CF_{DAV} = correction factor for entire cross-section area from Eq. (4);
Cf_{DAV} = correction factor of depth-averaged velocity at local subsection area ($Cf_{DAV} = v_{DAV}/v_{WSV}$);
f_{dw} = Doppler frequency shift between reflected and emitted electromagnetic wave ($f_{dw} = f_{gw} - f_{rw}$);
f_{gw} = frequency of emitted electromagnetic wave;
f_{rw} = frequency of reflected emitted electromagnetic wave;
i = number of subsection;
l = diagonal distance in planview;
Q = water discharge
V = average velocity for entire cross-section area;
v = point velocity in flow subsection area;
v_{DAV} = depth-averaged velocity in flow subsection area;
v_{WSV} = surface velocity in flow subsection area;
X = horizontal or downstream distance;
θ = elevation angle of antenna (electromagnetic wave);
λ = wavelength of electromagnetic wave; and
φ = planview angle of antenna.

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