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# PERFORMANCE OF OPEN-CHANNEL ELECTROMAGNETIC FLOW METER IN CONCRETE-LINED AND NATURAL CHANNELS

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## SYNOPSIS

The performance of an open-channel electromagnetic flow meter in concrete-lined and natural channels was investigated. It was found that a good correlation between the induced potential and observed discharge can be derived for the concrete-lined channel, without considering the effect of electric conductivity in water (ECW). However, the effect of ECW is important in the natural river. To significantly improve the accuracy of measurement, a parameter functionally related to water stage was used. Pollution of the electrodes over a period of time seems to alter the system characteristics. Hence, a periodic calibration of the parameters is required to maintain a constant performance level.
Keywords: Hydrological observation, electromagnetic flow meter, open channel, non-insulated river, electric conductivity

## INTRODUCTION

While accurate assessment of the quantity of flow in rivers in indispensable for approprate river and water resources management, a discharge observation is rather difficult in actual rivers because of the large variation in the discharge itself and the large size of the measurement cross-sections. From a viewpoint of providing the technology which leads to real-time, automatic and continuous observation of the flow in rivers and improvements in the accuracy of observations, as well as to reduction of the labour involved in the observation work, this research started in 1983 and has been continuing for the development of an open-channel electromagnetic flow meter applying Faraday's law of electromagnetic induction to flow measurement on rivers. It has been confirmed that these flow meters have now reached a certain stage applicable to practical use at least on channels on the scale of indoor test channel 1), 2), 3).

After a brief explanation of the open-channel electromagnetic flow meter, discussions are made in this report on the results of the field observation carried out at the Okiura Dam and on the Ayase River after the publication of the previous reports. The water channel at the measuring point of the Okiura Dam was a rectangular concrete-lined channel and, in terms of the measurement characteristics, the channel bed can be regarded as insulated (insulated channel), while the measuring point on the Ayase River was on a natural riverbed and the channel can not be regarded as insulated (non-insulated channel). The measurement characteristics of the open-channel electromagnetic flow meter on insulated and non-insulated channels are extracted from the observation results and clarifications made on the observation performance and serviceability of the flow meter on actual rivers.

## OPEN-CHANNEL ELECTROMAGNETIC FLOW METER

### 2.1 Measurement Principles

The open-channel electromagnetic flow meter works on the principle of Faraday's law of electromagnetic induction. When a conductor (the flowing water in this case) moves through a magnetic field at a certain velocity, an induced potential difference is generated in the direction perpendicular to both the magnetic field and the movement of the conductor (along the width of the river if the magnetic field is vertical). The potential difference at the two ends of the conductor along its width will be proportional to the velocity of the conductor (flow velocity), the magnetic flux density and the width of the conductor (width of the river). The principle itself has already been applied widely to electromagnetic flow meters for use on pipe conduits and portable electromagnetic current meters. There are, however, a large number of problems regarding the application of the principle to open channels, such as the variation in the measurement cross-section with the rise and fall in the water level, the large size of the channels themselves, the limits to the precision in the installation of the electrodes and coils and the difficulty of cutting off the noise from sources outsides the water channels. Therefore, it is required to create a system on conditions quite different from those for the pipe conduit flow meters and portable current meters.

The potential difference E(V) measured on the left and right banks of the river in the simplest case with the water flowing uniformly at a velocity V(m/s) through a magnetic field with a uniform flux density B(T, tesla) in a channel with a rectangular cross-section, b(m) in width, and bounded by non-magnetic, insulating materials can be calculated from the following equation.

$$E_t = V \cdot B \cdot b \qquad (1)$$

The discharge Q(m/s) under these conditions will be,

$$Q = V \cdot b \cdot h \qquad (2)$$

Putting the two equations together,

$$Q = E_t \cdot h / B \qquad (3)$$

Since the flux density B is a value that can be adjusted artificially and is already known, the discharge Q can be obtained by measuring the potential difference E and the water depth h.

Because of the difficulty of making the flux density uniform within the measurement cross-section on normal rivers in practice, a magnetic field distribution correction function is required to correct this effect. Corrections need also to be made for the variation in the channel width because the cross-sections on normal rivers are not necessarily retangular. Since these two are generally both functions of the water depth, a single function, termed the magnetic field/channel width function $f_1$, will be used here. At the same time, the zero point on the flow meter may have shifted owing to errors in the installation of the electrodes and coils. The shift $E_0$ of the zero point needs to be subtracted from the measured potential difference. An approximate expression, therefore, for the potential difference actually measured in an insulated channel is provided by Eq. 4 and the discharge can be calculated using Eqs. 3 and 4.

$$E = f_1 \cdot E_t + E_0 \qquad (4)$$

System Composition

The open-channel electromagnetic flow meter can be divided into the artificial magnetic field generation device, dlectromotive force detection device and recording device.

The artificial magnetic field generation device consists of the frequency oscillator for generating low-frequency AC magnetisation wave forms, the magnetisation output amplifier for amplifying the signals into the magnetisation current sent through the coil and the magnetisation coil that actually generates a vertical artificial magnetic field in the water channel. Sinusoidal waves were used at first for the AC magnetisation wave forms in laboratory tests and for field observation with the electromagnetic flow meter on the Ayase Riber, but trapezoidal waves are used in all cases today to improve the stability of the zero point. In order to remove the induced noises from commercial power sources that are superimposed on the measured potential difference and to get the compatibility of the removal of low-frequency noise and speedy response, the magnetisation frequency has been 2.5 Hz or 1.25 Hz in the 50 Hz zones. For the magnetisation coils, "C-shaped" coils have been adopted for facility of installation and aesthetic effect (Figure 1). There is a natural magnetic field around the earth and the vertical component of this field in the Kanto Region is approximately 0.36 gauss (gauss = $10^{-4}$ T) (from the "Rika Nenpyo (Chronological Scientific Tables)"). The purpose of using an artificial AC magnetic field in preference to this natural magnetic field is to remove the effect of the polarisation between the electrodes and the flowing water and the effects of the stray currents.

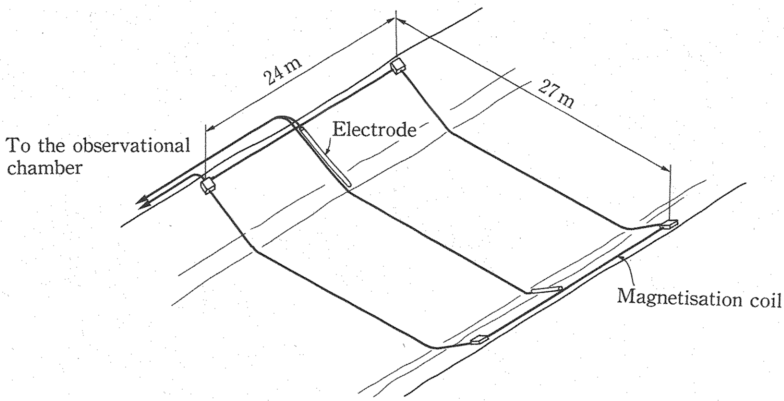


Fig. 1 Configuration of the magnetisation coil and electrodes of an open-channel electromagnetic flow meter (Ayase river)

The electromotive force detection device consists of the electrodes placed on the two banks of the channel for detecting the potential difference generated in the channel and the potential difference amplifier that amplifies the minute potential difference signals of the order of microvolts to the order of millivolts and detects the signals corresponding to the flow velocity in the parts where the effects of the differential noise are the smallest through phase detection.

Personal computers are used for the recording device at the two field observation facilities discussed below and the computation and recording of the discharge and flow velocity are carried out on site.

Characteristics of Open-Channel Electromagnetic Flow Meter

The principles and structure of the open-channel electromagnetic flow meter described above means that 1) it can also be used for measurement of backflow, 2) its installation does not alter the water level, 3) it does not obstruct the passage of boats and fish and 4) it does not mar the scenery. Its installation should be avoided, however, at locations where riverbed profile or velocity distribution vary rapidly. Because of the power limit of the magnetisation output amplifier, from which the magnetisation current is sent to the coil, the width of the channel for a open-channel electromagnetic flow meter should be less than around 30 m.

## OBSERVATION RESULTS AT THE OKIURA DAM

### System Outline

With the cooperation of the Aseishigawa Dam Construction Office of the Ministry of Construction's Tohoku Regional Construction Bureau and the Dam Engineering Centre, an open-channel electromagnetic flow meter was installed in March 1988 on the notch section of the crest of the Okiura Dam (Aseishi River, Iwaki River System, Aomori Prefecture), which was due to be submerged by the completion of the Aseishigawa Dam further downstream. The aim of the installation was completing the techniques involved in the practical application of open-channel electromagnetic flow meters to insulated channels and making accurate assessments of the inflow into dams, especially at times of droughts.

The notch section consisted of a large notch 53 m in width and 10 m in height and a smaller notch at its centre 10 m in width and 1 m in height. A pair of rod electrodes were installed on each notch for detection of the potential difference (Figure 2).

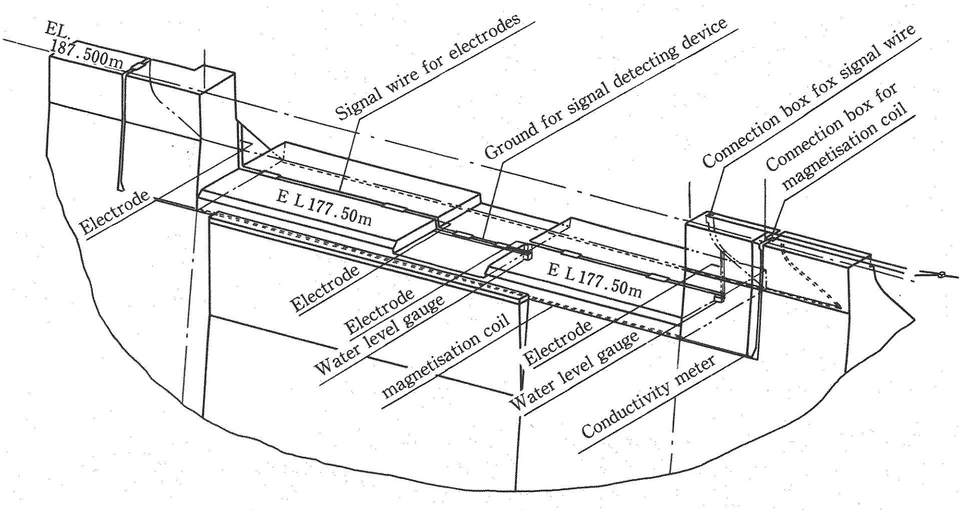


Fig. 2 Diagonal view of the open-channel electromagnetic flow meter at the Okiura dam

The size of the magnetisation coil, with 45 turns, was 70.4 m by 10.5 m in the vertical direction. Its installation along the dam body as shown in Figure 2 gave a configuration quite different from the ideal linear and point symmetry, resulting in a large differential noise due to the installation error of the coil and electrodes. Because the effect of the differential noise on the wave form as a whole resulted in a large shift in the measured potential difference with a magnetisation frequency of 2.5 Hz, the frequency was reduced to 1.25 Hz. The effect of the low-frequency noise becomes larger when the magnetisation frequency is halved again to 0.625 Hz. Taking into account the earlier observation results on the Ayase River, trapezoidal wave magnetisation was adopted from the start. The magnetisation current was ±7.0 A and the flux density was approximately 0.11 gauss on the small notch.

## Observation Results

The observation results are discussed below, focused mainly on the results of the tests conducted in 1988. In view of the difficulty of carrying out discharge observation by conventional methods on the large notch where fast currents are rarely observed, the system calibration was implemented on this occasion using only the data for when there were complete overflows over the small notch when accurate reference discharges could be obtained through conventional observation. The H-Q relation worked out from laboratory model tests was used as the overflow equation for the small notch. The validity of this equation has been confirmed through comparison with discharge observation using current meters on site.

Investigations were first conducted on whether the riverbed could be regarded as being insulated. The measured potential difference in a water channel of which riverbed cannot be regarded as being electrically insulated can generally be approximated by a simple equivalent circuit model expressed by the following equations.

$$E = f_1 \cdot f_2 \cdot E_t + E_0 \qquad (5)$$

$$f_2 = r_2/(r_1 + r_2)$$

$$r_1 = (1/\sigma_1) \cdot (b/h) \qquad (6)$$

In conventional methods, there was a definition for $r_2$ similar to that for $r_1$ and it was considered that $r_2 = 1/\sigma_2 = \text{constant}$ ($\sigma_2$: riverbed conductivity), but it was excluded from the equation here since it was discovered by the authors that the riverbed resistance was generally a function of the water level on non-insulated channels (see below). It sufficed to calculate $r_2$ backwards from Eqs. 5 and 6, since the purpose of the investigation here was to judge whether the riverbed at the installation cross-section could be regarded as being insulated for practical purposes from the point of view of the measurement characteristics of the open-channel electromagnetic flow meter. The relationship between the values for $1/r_2$ obtained through back calculation (inverse of apparent riverbed resistance) and the water level is shown in Figure 3. It can be seen that the values for $1/r_2$ are found dispersed between 0 and 1 μS/cm, confirming that there is not significant relationship between $1/r_2$ and the water level.

The zero point shift was then found to be 110 μV from a comparison between the measured potential difference and the cross-sectional average flow velocity obtained with the overflow equation using the complete overflow data for October and November after the system had become stable. The satisfactory results shown in Figure 4 (rms error = ±0.6 $m^3/s$) was obtained when the discharge calculated from the potential difference subjected to zero-point and magnetic field correction and the water level was compared with the discharge obtained with the overflow equation.

Because of a damage to some instruments by a lightening, the data for the periods when there was a complete overflow over the small notch that could be used for comparison were not available in 1989. The recording of the data resumed in 1990 after the instruments were repaired. When the Okiura Dam was completely submerged and the flow velocity over the small notch could be considered to have been zero, the flow velocity as displayed on the electromagnetic flow meter was also zero. It indicates that there had not been a shift in the zero point that was observed on the electromagnetic flow meter on the Ayase River as described below.

It may be concluded from the foregoing that the open-channel electromagentic flow meter has reached a stage where it can be applied to practical use on channels whose beds can be regarded as being insulated.

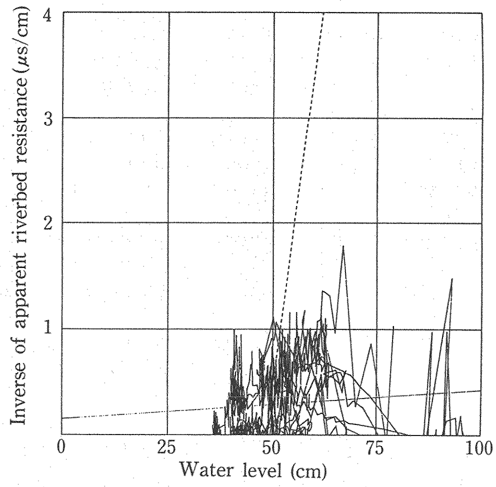


Fig. 3 Relationship between water level and inverse of apparent riverbed resistance (small notch of the crest of the Okiura dam)

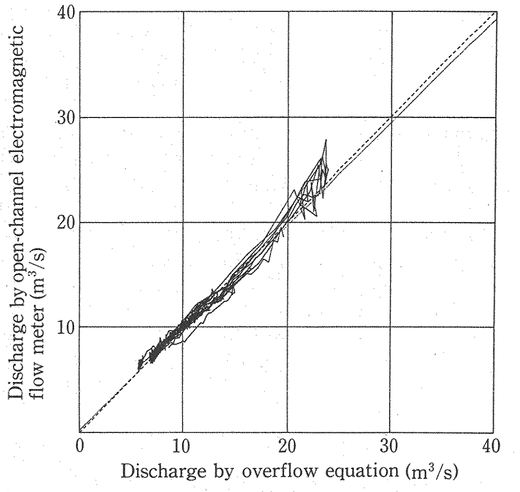


Fig. 4 Relationship between the discharge of open-channel electromagnetic flow meter and that of overflow equation

## OBSERVATION RESULTS ON THE AYASE RIVER

### System Outline

The facility on the Ayase River is the first for field observation open-channel electromagnetic flow meter in Japan. The flow meter was installed just above the Yakou Reference Point on Ayase River in February 1987 with the cooperation of the Edo River Works Office of the Kanto Regional Construction Bureau. The aim of the installation was assessing the problems that arise in application of the flow meter to actual rivers and making improvements on the instruments to give them an established form. A plan view of the flow meter facilities is given in Figure 5. The observation point lies in the tidal zone and backflow of water is observed at times. Although a part of the left-bank side of the cross-section on which the electrodes are placed in covered with concrete, the remainder of the riverbed is in natural conditions and not insulated. The width of the channel is around 20 m under normal conditions. The magnetisation coil has 105 turns and a near-square shape, 27.3 m by 24 m in the vertical direction. It was placed as an C-shaped coil along the riverbed. The magnetisation wave form is a 2.5 Hz trapezoidal wave form and the flux density approximately 0.13 gauss (when magnetisation current = ±2.5A) at the electrode cross-section. Cylindrical stainless steel tubes 7 m in length were used for the electrodes. Because of the difficulty of installing new electrode pits, they were covered with foaming ceramic for protection against waves and rubbish and were placed along the river banks. Sinusoidal waves were used at first for the magnetisation wave form on the electromagnetic flow meter on Ayase River, but rapid variations in the measurement signals thought to be due to the zero point shift were often observed and trapezoidal waves were selected in its place in view of the facility of removing differential noise with this wave form. Dramatic improvements have been observed in the stability of the measurement signals as a result.

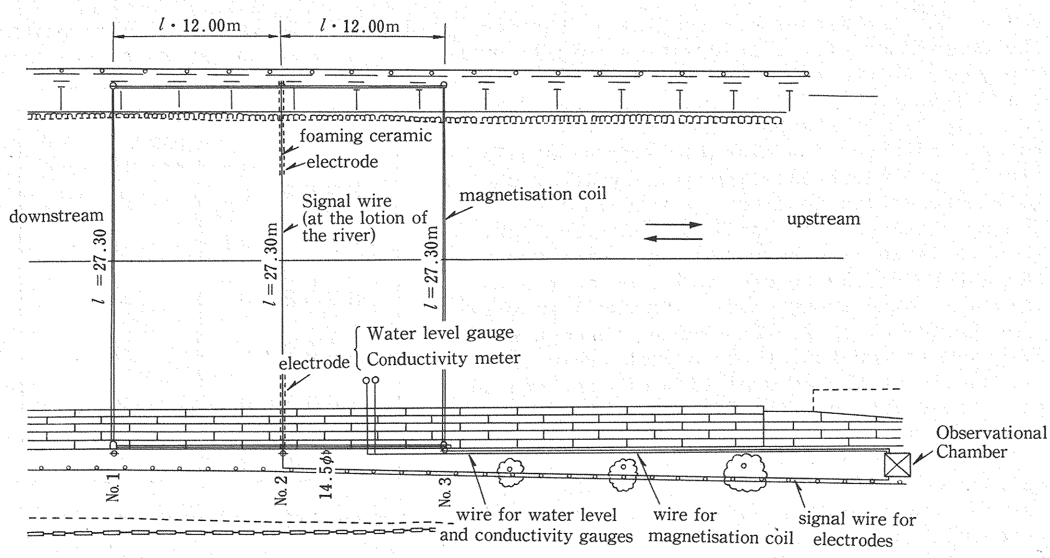


Fig. 5 Plain view of the Ayase-river electromagnetic flow meter

6 sets of the observation test for comparison of the measured potential difference and the results of continuous discharge observation over periods of 24 hours or so have been carried by July 1990 since trapezoidal wave magnetisation was adopted. The observation conditions for these tests are given in Table 1. In all cases, the discharge observation was by five direct-reading propeller current meters (one point in the depth direction) and was implemented at 20 minute intervals. The water in the Ayase River is heavily contaminated and, in addition to the accumulation of sludge around the electrodes and dirt on the foaming ceramic, damage to the ceramic was found to be resulting in the infiltration of the sludge into the electrodes. In view of this, cleaning work was carried out around the electrodes and the installation method for the electrodes was reviewed. It was decided that the electrodes covered with foaming ceramic should be fixed together with a wooden frame and the electrodes were reinstalled immediately after the test observation in February 1989.

Table 1. Observation cases in the Ayase river

| Case | Date and time | Number of data | Velocity range | Magnetisation current |
|---|---|---|---|---|
| 880926 | 88/9/26,13:40 ~9/27,14:00 | 74 | 87cm/s ~7cm/s | ±3.70A |
| 890206 | 89/2/6,11:20 ~2/7, 12:00 | 75 | 38cm/s ~-22cm/s | ±3.38A |
| 890308 | 89/3/8,12:00 ~3/9, 13:00 | 76 | 55cm/s ~-0cm/s | ±3.23A |
| 890918 | 89/9/18,14:00 ~9/19,16:00 | 79 | 38cm/s ~18cm/s | ±2.46A |
| 900709 | 90/7/9,14:40 ~7/10,16:00 | 71 | 58cm/s ~3cm/s | ±2.50A |
| 900723 | 90/7/23,12:40 ~7/24,16:00 | 83 | 61cm/s ~-0cm/s | ±2.50A |

Observation Results

As is clear from the measurement principles and Equation (4), the shift $E_0$ of the zero point needs to be known for making corrections on the measurement values for the measured potential difference. The comparison of the observation results over the years showed that the amount of zero point shift itself was changing with time as shown in Table 2. If the period of instability before and after the cleaning and reinstallation of the electrodes immediately after the flow observation in February 1989 is ignored, there is a long-term variation of 1 to 2 μV. This variation in the zero point shift is thought to be due to the variation in the in-phase noise synchronous with the magnetisation frequency of 2.5 Hz passing through the coil and is surmised to be attributable ultimately to the accumulation of dirt around the electrodes, but the details of its mechanism is not clear.

Table 2 Variation of zero point in the Ayase river

| Case | Shift of zero point (μV) |
|---|---|
| 880926 | −4.0 |
| 890206 | 0.4 |
| 890308 | 7.3 |
| 890918 | 0.2 |
| 900709 | −2.6 |
| 900723 | −1.3 |

It had been thought that the electric resistance of the riverbed on a non-insulated channel could be expressed by the inverse of the average physical value $\sigma_2$ (electric conductivity of riverbed) and could be regarded for practical purposes as being constant. When the inverse $1/r_2$ of the apparent riverbed resistance was calculated backward from the observation data for 26th September 1988 using Eqs. 5 and 6, it was discovered that the values for $1/r_2$ showed a linear increase with the water level. (See Figure 6. This phenomenon has also been observed in laboratory tests.) It would be appropriate, therefore, to use the following equation in addition to Eqs. 5 and 6 in correcting the flowing water and riverbed conductivity.

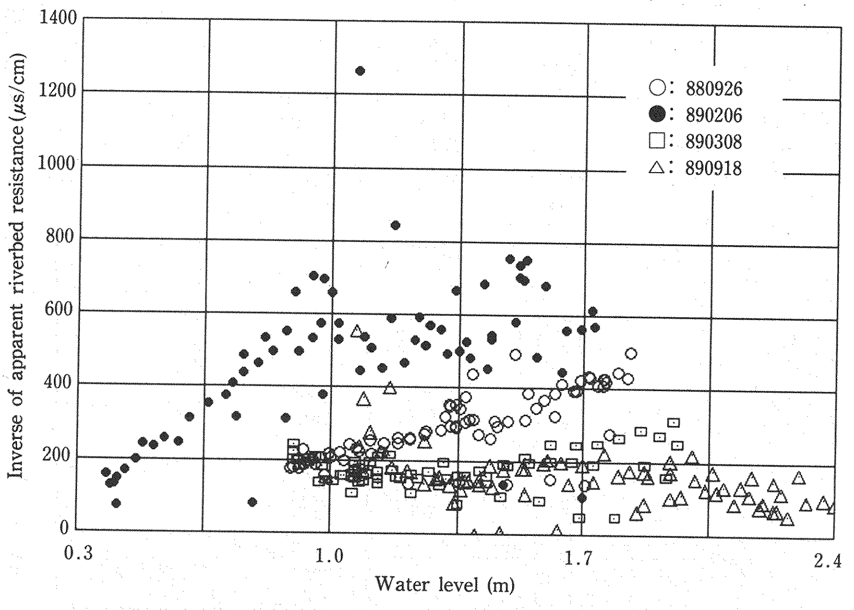


Fig. 6 Relationship between water level(h) and inverse of apparent riverbed resistance($1/r_2$) (Ayase river, 1988/9 ∿ 1989/9)

$$I/r_2 = \alpha \cdot h + \beta \quad (7)$$

where,

$\alpha$, $\beta$: constants identified from discharge observation

The error in the discharge observation was reduced through use of this correction procedure from 4.5 $m^3/s$ to 2.7 $m^3/s$.

It was then discovered that the values for $1/r_2$ calculated thus was also varying with the accumulation of dirt and cleaning of the electrodes as shown in Figure 6 between September 1988 and February 1989. Furthermore, the dependence of $1/r_2$ on the water depth has been barely observable after the re-installation of the electrodes and its variation has been reduced in comparison with before the re-installation. These phenomena are consistent with the fact that in the laboratory tests the inverse of the apparent riverbed resistance could be reduced significantly just by insulating the electrode pits. Therefore, these phenomena may be due to the apparent increase in the earthing resistance resulting from the prevention of the direct contact between the electrodes and the riverbed by the installation of the electrodes covered with foaming ceramic in wooden frames.

It was discovered that there was a variation in the system on the electromagnetic flow meter on the Ayase River. Shown in Figure 7 is the relationship between the conventional discharge observation results and the corrected potential difference, obtained by applying the new flowing water/riverbed conductivity correction method using Eqs. 5, 6 and 7 to the measured potential differences after calibrating $E_0$, $\alpha$ and $\beta$ through the comparisons with the conventional discharge observation results, for the cases by September 1989. The results indicate that a consistent relationship can be obtained between the discharge and the measurement signals by carrying out regular calibration using discharge observation results and making corrections with this equivalent circuit model.

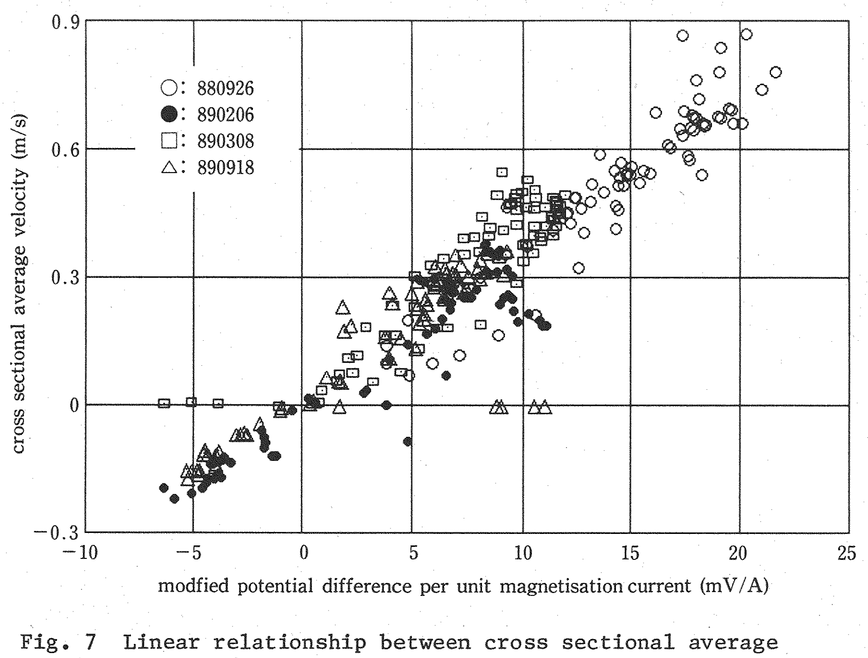


Fig. 7 Linear relationship between cross sectional average velocity(V) and modified potential difference per unit magnetisation current($E_t/I$) (Ayase river, 1988/9∿1989/9)

In the investigations outlined above, clarification was made on the relationship between the water level and the riverbed resistance, as well as on the characteristics and the appropriate correction procedure for the variation in the relationship between the water level and $1/r_2$ and in the zero point shift. Although some of the details of the physical mechanism remain unknown, the rms errors have been maintained below ±2.0 $m^3/s$ and ±8 cm/s for the time being and, as far as can be judged from the characteristics of the electromagnetic flow meter on the Ayase River, it seems possible to conduct continuous automatic measurement and recording of the discharge so long as calibrations ar made at regular intervals using the low flow observation results.

## CONCLUSION

It has been demonstrated that the open-channel electromagnetic flow meter has reached a certain level at which it can be applied to practical use on channels with widths of up to 30 m or so which can be regarded as being insulated. Sufficient accuracy can be maintained even on non-insulated channels by making appropriate corrections to the measured potential difference. Even in cases where variation is observed in the measurement characteristics, the meter can be made to provide sufficiently accurate data through regular calibration. The task in the future will be to render the system less prone to variation through accumulation of observation data on real rivers and investigations on improved installation methods for the electrodes and calibration procedure on site.

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