Flow measurements in non-standard conditions

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Summary

The flow rate of water, and the accuracy used to measure it, is important to know. Numerous international and national standards exist, defining the conditions for flow measurement. However, the needed "standardized flow conditions" are often impossible to satisfy in field and they can be used just as guidance. This paper presents four cases with such non-standard conditions, where the author had to perform the flow rate measurement. For each case the approach used is explained, the results obtained are given and the achieved accuracy is assessed. All measurements were performed using electromagnetic (EM) velocity measurement probes, specifically designed to suit local conditions. Parallel to direct velocity measurement, CFD (Computational Fluid Dynamics) was used to analyse the flow conditions and get better insight into the flow field, with an idea to extract the data from modelled flow field in order to perform the flow meter calibration. Throughout the presented cases, which cover last two decades, clear developments of both hardware and knowledge can be seen.

Keywords: flow measurement, non-standard conditions, Electromagnetic probes, CFD

1. INTRODUCTION

Knowledge about water flow rate, with acceptable accuracy, is fundamental for the whole hydro-ecological engineering as well as for other scientific fields. Different measuring techniques are developed to optimally suit the environmental conditions at the measurement site. Available measuring hardware varies in terms of accuracy, cost and robustness (Prodanović, 2007). In situations with the full-pipe (pressurized) flow, the flowing cross-sectional area is known in advance and usage of more accurate equipment is possible (with accuracy of even 0.5% or better, Baker 2002). For the free surface (open channel) flow, or a mixture of free surface and pressurized flow (mixed flow conditions), the flow cross-sectional area is variable and has to be measured together with velocity and with the minimum and maximum flow rate range of 1 : 1000 or even higher (Hager, 2010)). The expected accuracy of flow measurement in such conditions is much below 1%.

It is important to accurately measure flow rate for many reasons. Water (as well as other more precious fluids) has its price; distribution of water among users is not only an economical issue but more often a political one; water deficiency, or more often its abundance in floods, is a key development component for certain area; water quality is directly related to flow rate; technical parameters of the systems depend on flow and velocities, etc. Numerous international and national standards exist, defining the conditions for flow measurement and applicable measurement system. Each standard insists on providing "standardized flow conditions" that can easily be replicated and quantified. For the most measurement methods, the long straight upstream and downstream sections are needed, with stable and steady flow conditions throughout the whole reach, for example. Or, in most volumetric devices, the minimum working pressure has to be maintained to prevent cavitation.

In reality, the standards for certain type of flow measurement could be used just as a guidance, since the standardized flow conditions are hard to fulfil (Simonović, 1990). Such situations require adaptation for specific flow conditions (Bertrand-Krajewski *et al.*, 2021). For example, the international standard ISO 15769 (ISO, 2010) recommends specifications for Doppler ultrasonic (US) sensors when used for flow measurement in sewers. The straight approach section of constant flow conditions required by the standard is too long, and in most real situations the sensor is installed just upstream of a cascade in manhole. Another example are the measurements of the turbine hydraulic efficiency in hydropower plants (HPPs) are defined by guidelines (Performance Test Code, 2002) and standards (IEC 60041, 1999). Flow measurement has to be performed within the full pipe (tunnel) flow with a long straight reach, with predefined large number of current meters in cross section. However, in Kaplan or bulb turbines, with short intake structures, there is no possibility to fulfil the standard's recommendation.

To assess the flow measurement uncertainty in non-standard conditions, some redundant system is needed

(Chaundry, 2008). In most situations, the semi-integrative or velocity sampling temporary techniques could successfully perform this task. The most used ones are the ultrasonic (US) transit-time or Doppler profiling devices and electromagnetic (EM) flowmeter probes.

This paper presents several cases where the author was involved in the flow rate measurements in non-standard flow conditions for which there was no ISO or EN standard that can be directly applied. All measurements were conducted using EM type flowmeters, with different probe's design, fitted for specific conditions. Although the US devices are more common in recent years and the author is normally using them in certain more standard conditions, the EM probes were used because of their robustness, clear physically based principle of direct measurement of water's velocity, acceptable price and, maybe the most important reason, good cooperation with the company that produces high quality EM probes (Svet Instrumenata, 2021).

Throughout the presented cases, which cover about two decades of work, clear developments of both the hardware and knowledge of the experts from Hydraulic and Environmental Engineering department, Faculty of Civil Engineering at University of Belgrade is evident.

2. METHODS

2.1. Velocity measurement using EM

The operating principle of electromagnetic (EM) flow/velocity sensors is based on the Faraday's law of induction (Fig. 1, left side). The motion of the conductive fluid (Fig. 1, right side) through a transversal magnetic field generates a voltage (Shercliff, 1962). To allow for the stationary analysis of the electromagnetic induction phenomenon, some electric and magnetic properties of the environment are assumed (Michalski *et al.*, 2001). Originally, under these assumptions, Kolin (1936) has given the basic relationship for the EM theory (1):

$$\nabla^2 E = \operatorname{div}\left(\vec{V} \times \vec{B}\right) \tag{1}$$

where $\vec{V}$ is the streamwise velocity field, $\vec{B}$ is the magnetic induction and div$(\vec{V} \times \vec{B})$ is treated as a charge distribution. The raw output signal is the voltage $E = E^1 - E^2$, induced between the electrodes of the EM sensor. The relations used in the electrical networks motivated an idea to describe how each part of the flow contribute to the output voltage E. Equation (1) can be written as integral within the control volume τ (2):

$$E = -\int_{\tau} \left(\vec{V} \times \vec{B}\right) \cdot \vec{j}\, d\tau \tag{2}$$

or with the weight function w (Shercliff, 1962) using the weight vector $\vec{W}$ (Bevir, 1970):

$$E = \int_{\tau} \vec{V} \cdot \left(\vec{B} \times \vec{j}\right) d\tau = \int_{\tau} \vec{V} \cdot \vec{W}\, d\tau \tag{3}$$

where the cross product $\vec{B} \times \vec{j}$ defines Bevir's weight vector $\vec{W}$, τ is the control (sampling, or integrating) volume of the EM sensor (Fig. 1, right side) and $\vec{j}$ is the virtual current vector (i.e., the current density set up in the liquid by driving an imaginary unit current between a pair of electrodes). Since the Faraday's law of induction is governed by the right-hand rule, the dominant contributor to the output E is the longitudinal component of the velocity vector, V_x, or streamwise component, which is needed for flow measurement.

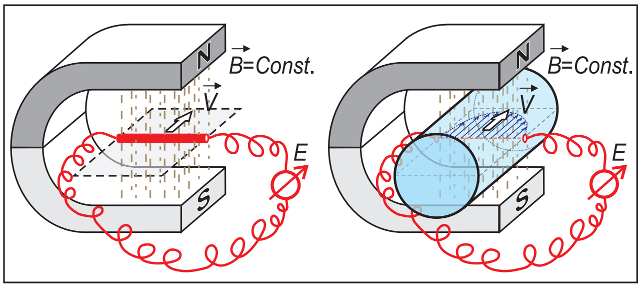

Figure 1. Basic Faraday's law of induction (left side) applied to (conducting) liquid flowing through the full pipe within the magnetic field (right side)

EM principle for flow measurement in full pipe allows accuracies of 1% to 0.5%, and with special attention, it can achieve the accuracy of 0.2%. However, the EM devices (or EM flow meters) are calibrated on flow rigs, mostly using volumetric systems. The actual velocity field and true magnetic field distribution within the profile (1)–(3)) are not important, since the calibration is carried out for integral component $E = f(Q)$.

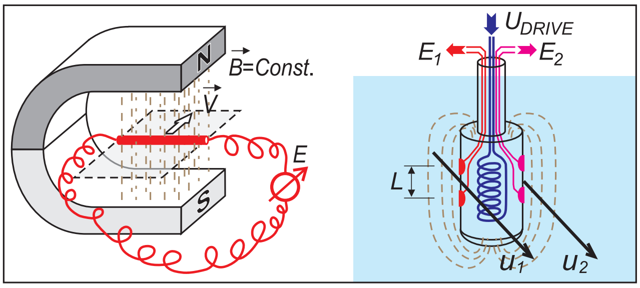

Figure 2. Same principle used for velocity measurement using inserted EM probe

The same Faraday's principle of induction can be applied from within the water, in order to measure the average velocities within the small sampling volume. Fig. 2, right side, presents the construction of such device (or EM probe): the EM coil used to generate the magnetic field is inserted into the water, and electrodes are relatively close, making the control volume τ (2) close to the inserted probe. There are numerous constructions of such device. Fig. 2, right side, presents the probe that measures the same velocity component in two adjacent control volumes, u_1 and u_2, producing electrical output signals E_1

and E_2. By averaging those two components, bigger sampling volume is used with more stable signal, or by differentiating two components, Reynold's shear stress can be calculated.

The EM probes are calibrated for velocity, using either standard towing tank where probe is moved with controlled speed through the still water (ISO, 2007) or in potential core of water jet. The basic accuracy of velocity measurement is 1-2%, while for better probes it can be up to 0.5%. The main benefit of EM probes is a wide measurement range of velocity, from several cm/s to 10 m/s. With longer averaging times (10–20 s) the EM probes can measure velocity down to 1 mm/s.

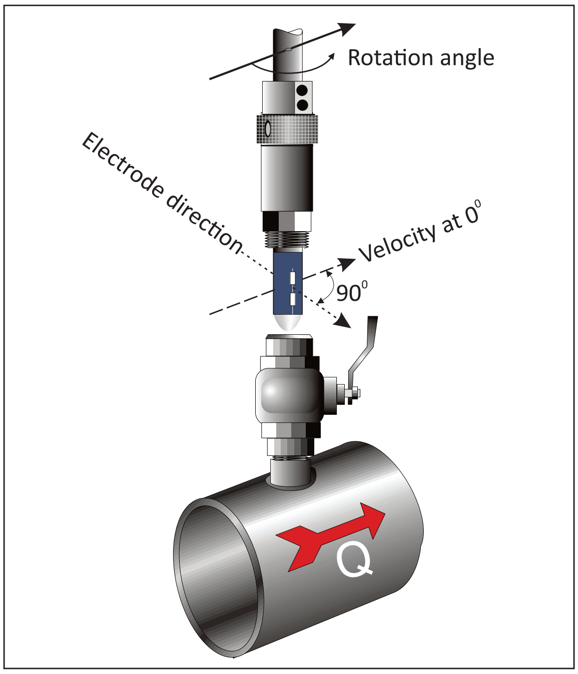

Figure 3. 1D EM probe (LOG-type) installed in pressurized pipe

The EM probe is not a contactless measurement device, i.e., it will disturb the true velocity field with its inserted body to a degree depending on the probe's shape. It is important to take this into account during both the calibration process and probe application. Different geometries of EM probes for velocity measurement, and different velocity components could be found on the market, and it is up to the user to select the optimal one:

- Cylindrical rod with 1D or 2D velocity measurement, that penetrates the fluid flow field (Figs 3–5). This type of probe is commonly named "LOG probe" since axisymmetric log-law velocity distribution is assumed and the flow is computed from measuring the velocity in one point.
- Specifically shaped LOG probes, for example one shown in Fig. reff26, or "MF pro – Water Flow Meter" made by OTT (2021).
- Flat "almost contactless" 1D, 2 × 1D or 2D probes designed to be fastened on pipe wall (Fig. 7), suitable for flow measurements in sewers.
- Full 3D spherical probes (Fig. 8) for measurement of all velocity components.

1D LOG-type EM probe is mostly used in water supply systems since it is cheaper and less accurate version of the EM full pipe flow meter. Probe can be inserted into the pipe under working pressure, without stopping the flow, and can be used to check actual velocity distribution by moving the probe along the pipe's diameter (so called "velocity profiling"). The probe's diameter is from 12 mm (for smaller pipes, to reduce the probe's blockage of the flow), mostly is 18 mm (with lengths in the range 300 mm – 1300 mm) and can be up to 50 mm for larger pipes with higher velocities, where oscillation of thinner probe is possible.

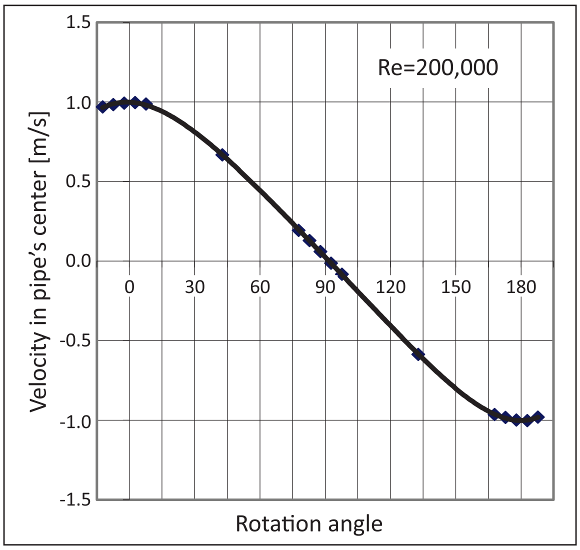

Figure 4. Angular 1D EM probe's sensitivity

Since the working principle of EM probes is based on vector multiplication of two fields (2), the cylindrical shape of probes allows the almost perfect cosines angular sensitivity (Fig. 4) covering direct and reverse flows. The true velocity direction can be achieved by rotating the 1D probe, searching for maximal velocity. If two more pairs of electrodes are added to the probe (Fig. 5), full 2D measurement is possible for velocity in the plane orthogonal to the probe's axis.

Main benefit of using EM LOG probes is that the user can either position the sampling volume in the area where mean velocity is expected, or move the probe along its axis and obtain the velocity distribution (velocity profiling). For permanent installation, special care has to be taken for possible debris and blockage of probe, so specific shapes are used in such situations (Fig. 6).

In sewer systems with highly polluted and dirty water, with lot of debris and junk, flat EM probes are developed that are installed on the inner side of pipe's wall (Fig. 7) or

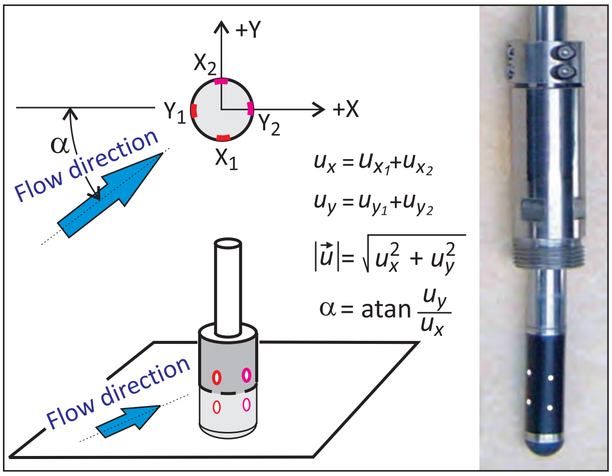

Figure 5. 2D EM LOG probe for velocity measurement (intensity and direction) in orthogonal plane

Figure 6. Different types of EM probes: 1D LOG-type for fixed installation in large tunnels

can be inserted from the outer side to be flush mounted, thus reducing the penetration. The length and width of the probes can be different, ranging from small ones (150–200 mm of length and 50 mm of width) for measurements in home sewer systems, medium size (Fig. 7) for larger sewers and sewer tunnels, and up to 700 mm (Fig. 18) for big tunnels.

Flat probes are mostly used for flow measurement in mixed conditions (pressurized and open flow) and they can be equipped with pressure sensor for water level measurement. The major drawback of flat EM flowmeter is limited depth of magnetic field and hence the near-by integration zone. For large pipes or tunnels, this can be a fraction of the "wet" cross section. Also, additional measures need to be taken in order to reach the desirable level of accuracy in mixed flow conditions (Ivetić, Prodanović and Stojadinović, 2018). One of the possibilities is to add more flat probes around the diameter, increasing the stability and reliability of flow measurement. Depending on the implementation, the price of such measuring site can be kept low if only one logger is used to drive all those probes (on the expense of losing the information on velocity distribution). To resolve the unknown velocity-pattern irregularity, the Site-Specific Calibration (SSC) is needed (Ivetić *et al.*, 2017b). It can be done using redundant

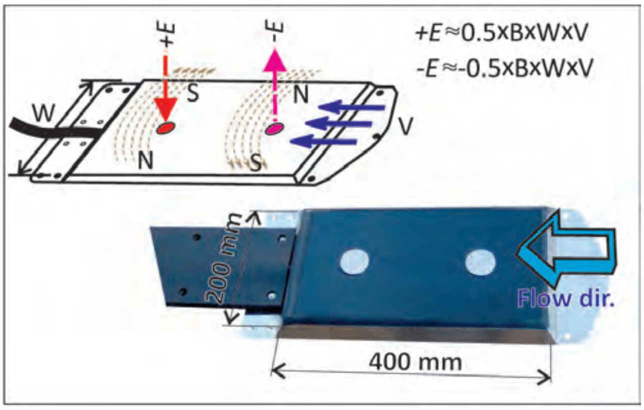

Figure 7. Modified version of EM probe suitable for flow measurement in sewer systems: Flat probe for wall mounting

temporal measurement system (Steinbock *et al.*, 2016) and combining with Computational Fluid Dynamics (CFD, Weissenbrunner *et al.*, 2016).

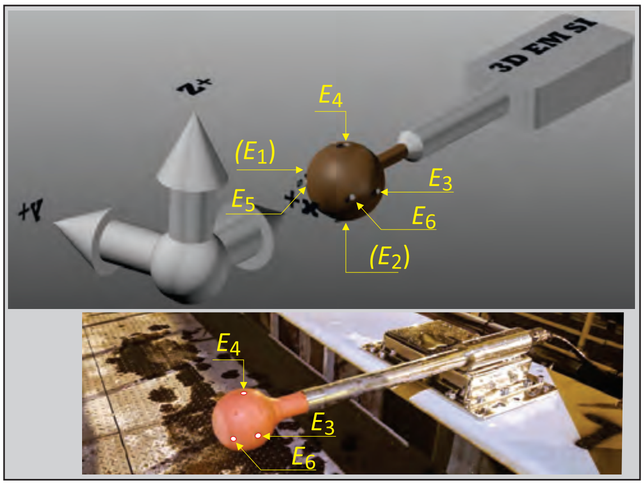

Figure 8. 3D EM probe with possibility to measure the streamwise (X) component with two separate pairs of electrodes.

The most advanced EM probe design has the possibility to measure (almost) 3D velocity field. With more than one magnet coil in the spherical head, and several electrodes, the probe can measure X, Y and Z component of the velocity (Fig. 8). Since probe's body will influence the velocity field when water is coming from behind the probe, the calibration chart is not ideal as for 2D probe (Fig. 4) and has to be established for each supporting frame used in certain application. The calibration of angular sensitivity is not as easy task as it might look, so the overall accuracy will depend on the effort involved.

To analyse the effect of flow separation on the spherical EM probe, the most important streamwise (X) component on the EM probe (Fig. 8) is measured using the electrodes E_1 and E_3 on 90° positions (electrodesE_2 and E_4 could be used also) and using electrodes E_5 and E_6 on 45° positions of the front side of the sphere (the probe is

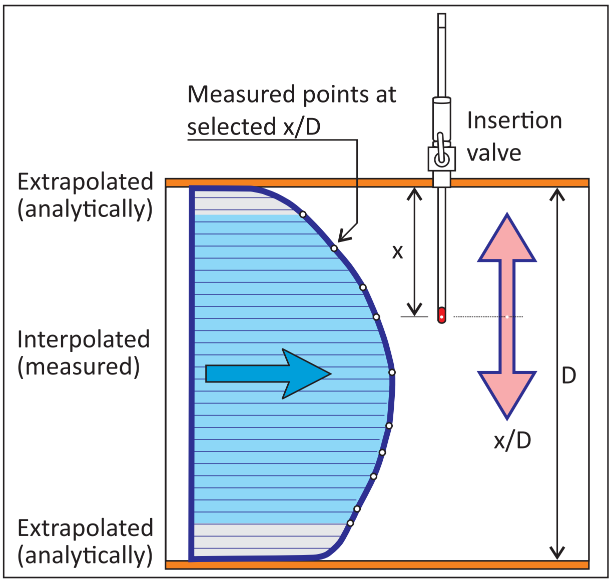

Figure 9. Basic setup for flow calculation, i.e., integration of measured velocities across the pipe's diameter.

called 3+D type). Comparing these two measurements, flow separation can be observed and taken into account.

2.2. Velocity profiling in unsteady flows

One of the most popular methods of flow measurement, with almost constant price/pipe diameter ratio, is point velocity measurement (or index velocity) and conversion of velocity into the flow rate. If EM probe is positioned at $0.121x/D$ from the pipe wall, assuming theoretically developed velocity profile, it will measure the true average velocity. In most cases, however, theoretical velocity profile is just a rough approximation of real conditions. Even in long straight pipes, the position of mean velocity is not constant, and it depends on the flow regime (Knudsen and Katz, 1958). The flow measurement error is difficult to estimate if the real velocity profile is unknown, and, according to the author's experience, the overall error is often an order of magnitude higher than expected (Prodanović, (Prodanović and Pavlović, 2003).

The velocity profiling (Fig. 9) is often used for accurate flow measurement in pipes where no flow meters are installed or for recalibration purposes of an existing flow meter that is too bulky to be calibrated on external calibration rig. To penetrate the pipe under the line pressure with the velocity sensor, an insertion hardware is needed (detail can be seen in Fig. 3). The probe is moved from one position to another, deeper into the flow field, recording the true velocities. As the first iteration, linear interpolation between the measurement points is suggested, and extrapolation using an analytical profile calculated for flow regime based on the measured velocities.

Although the process of velocity profiling should be straightforward, it is a rather time-consuming operation (in each measurement point the user has to wait for few minutes to perform good averaging), and the flow unsteadiness can introduce new errors. Fig. 10 presents a setup which can help in reducing the effect of unsteadiness. Since the mean flow is not constant during velocity profiling, correction to point velocities has to be applied before integration. An uncalibrated flow meter under the test can be used as an indicator of relative flow change.

In case where no fixed flow meter exists, second insertion-type meter can be used. The setup often used by the author is shown in Fig. 11 (Prodanović and Pavlović, 2003). It allows velocity profiling in two orthogonal directions and at the same time the correction for change in mean flow: during profiling along direction 1, probe 2 is fixed at one point and used for total flow monitoring,

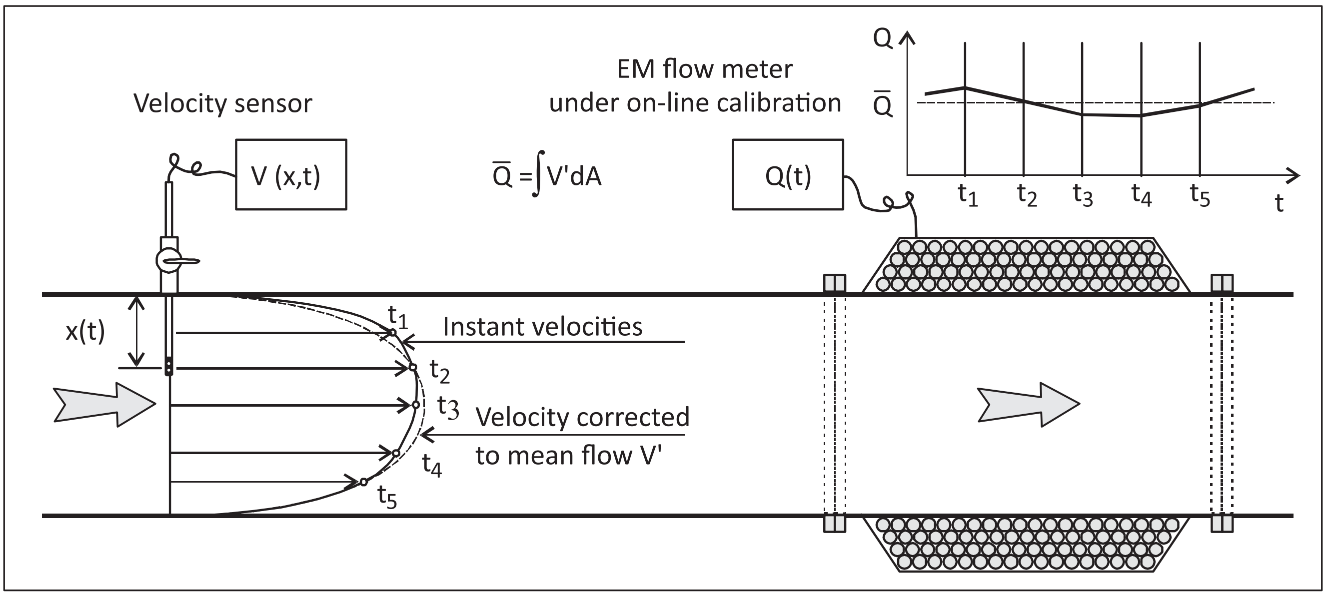

Figure 10. Recalibration of fixed flow meter by velocity profiling in unsteady conditions.

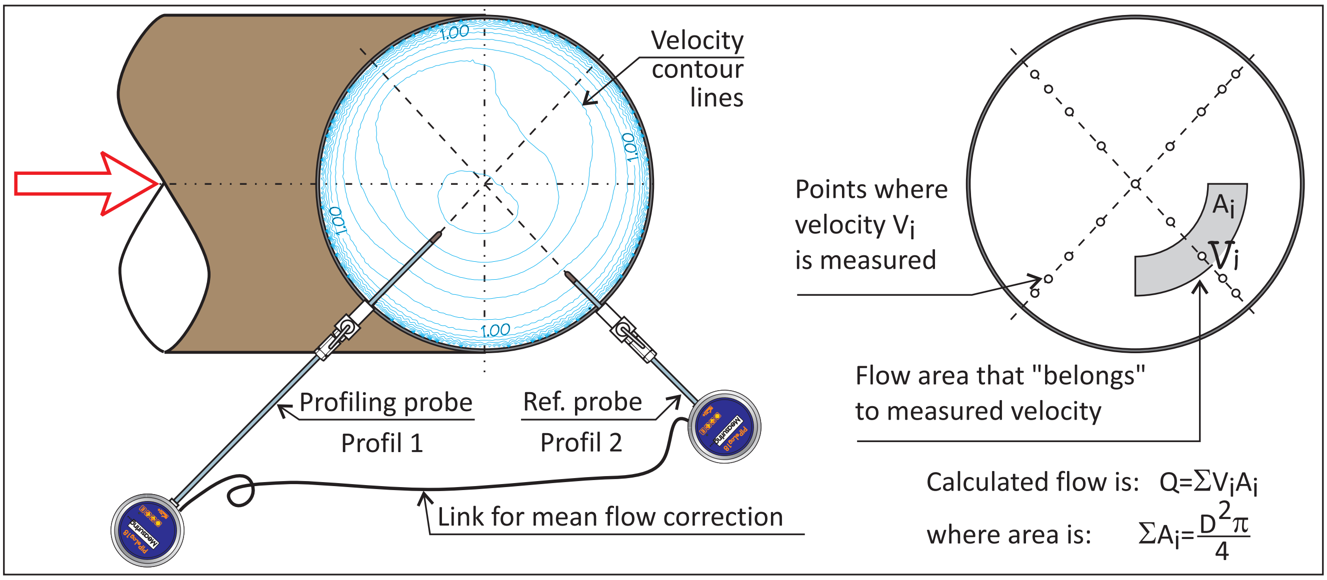

Figure 11. If there is no flow measurement, then second probe can be used as reference.

and vice versa for profiling in direction 2. Depending on the geometry used for velocity profiling, appropriate flow areas (Fig. 11, right side) have to be used for velocity integration.

3. CASE STUDIES

3.1. Case 1 – WTP Štrand, NS

The main source of drinking water in Novi Sad city (about 300.000 consumers) is central Water Treatment Plant (WTP) "Štrand" that treats groundwater from the Danube River banks. The capacity of WTP was 2×750 L/s in 2000 when the measurements were performed. Fig. 12 shows a schematic of WTP, which also includes the storage tanks of clean water under the filter stations that are not shown in the figure. Data for this case are taken from an earlier study (Prodanović and Ivetić, 2000), while today's situation is rather different.

At the inlets to the WTP, two old venturimeters were installed, which were out of function. Input to the new filter was measured using electromagnetic EM-900 flow meter, which was never calibrated, while input to the old filter station was not monitored. The bypass pipe leverages the operation of two filters, making the system highly dynamic.

Using the procedure described in section 2.2, with one EM probe of sufficient length for profiling and another shorter EM probe as the reference, the profiling was performed along two directions at EM-900 (position named $MP:N$ in Fig. 12). Signal from the reference EM was used to compensate for instabilities in flow since the signal from the existing EM-900 was hard to connect to the used logger due to grounding problems.

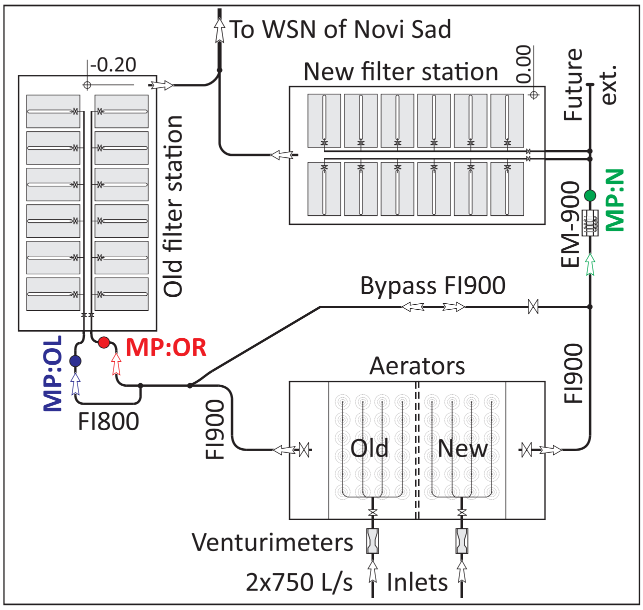

Figure 12. Schematic layout of the water treatment plant „Štrand“ (as in 2000).)

Flow measurement on the old filter station was much harder to achieve. Figure 13 presents the axonometric presentation of the pipes: one common pipe with diameter FI900 (under the ground) is divided into the two FI800 pipes, which are raised above the ground and enter the building. There is no adequate place to measure the flow easily, neither in the common incoming pipe nor in two "smaller" pipes. Photo of the pipes entering the old filter station is given in Fig. 14.

Solution for the flow distribution measurement was to perform profiling along three directions (labelled 0°, 45° and 90° in Fig. 13), capturing the true velocity profile. Since there is no indicator of the overall flow rate,

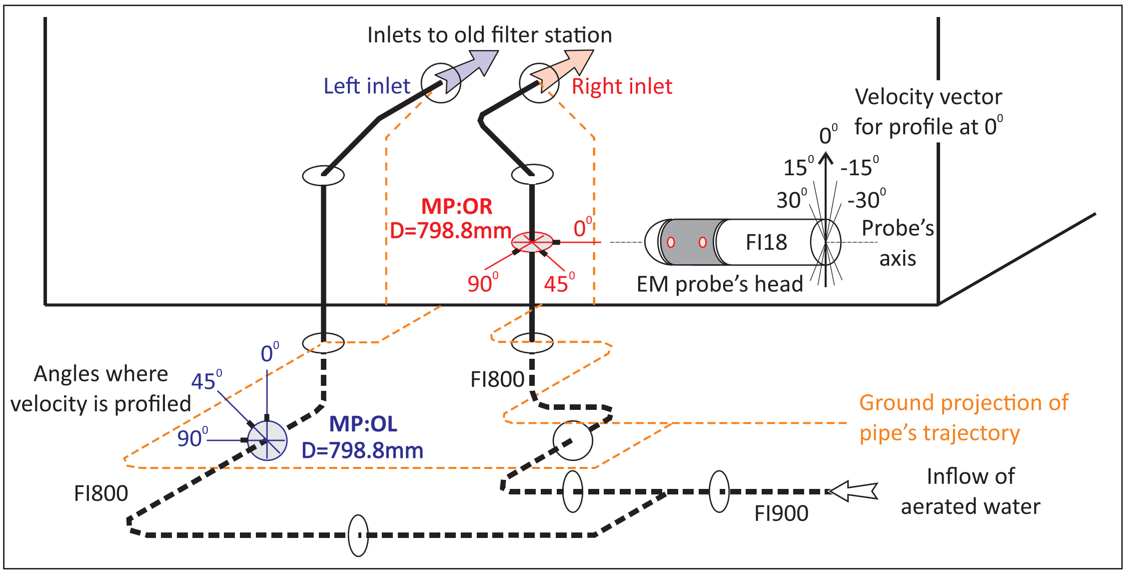

Figure 13. Two inlets to the old filter station (schematic drawing, pipe center lines shown with scaled cross sections)

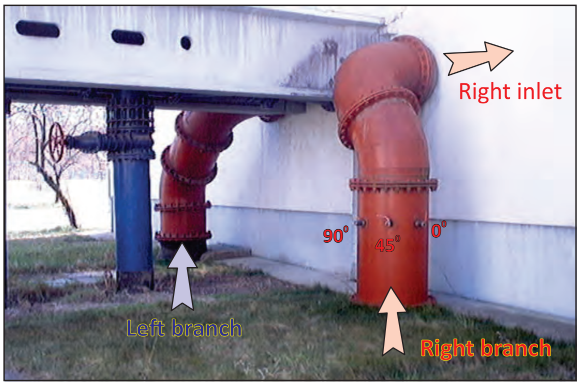

Figure 14. Photo of two pipes entering the old filter station

the methodology with two profiling probes was used (Prodanović and Ivetić, 2000). Measurements were performed at MP:OL position (connections were under the ground, some digging work was needed!) and MP:OR (connecting ball valves are visible in the Fig. 14).

3.2. Case 2 – Verification of built-in flow meters on large pipes in Topčiderska dolina

Flow measurement in large pipes (over 500–600 mm) is cheaper using Ultra Sound Transit Time (USTT) method then with bulky and heavy EM flow meters. The basic accuracy of USTT can be compared with EM flow meters (Danfoss, 2004) if flow conditions are satisfied. Misled by manufacturer's excellent specifications of the equipment, the common practice is to install the flow meter without any operational check of achieved accuracy. Main source of wrong expectation is that the USTT are named as "absolute sensors". However, they are absolute for average velocity measurement along one path between an electrode pair, but the connection between that measured velocity (or velocities for multiple path USTTs) and true flow rate depends on flow regime and local flow conditions.

The operation and accuracy of two newly installed USTTs flow meters in Belgrade's water supply system was checked during 2004 (Prodanović, 2004). Two large mains from the "Banovo Brdo" WTP, with FI1500 mm and average 2 m^3/s per pipe, are laid after a sharp turn through the "Topčider" valley (left part of Fig. 15), with a crossing over the "Topčiderka" river (Fig. 15, lower right corner). USTT's were installed at positions 11 and 12, relatively close to the sharp upstream elbow and downstream river crossing.

The only suitable place where flow rate could be checked was at positions 13 and 14, just downstream the river crossings, where a large manhole is located. Using the methodology of velocity profiling in unsteady conditions, where existing USTT flow meters were used as the reference, two types of current meters were used: the EM probes (Fig. 3) and SPECTRASCAN (Biwater Spectrascan, 1998) probes (micro turbine type). Due to physical limitations (small manhole), only one profiling line per pipe was used (Prodanović and Pavlović, 2004).

The first results indicated that the uncertainty of newly installed USTT flow meters is much higher than declared by the manufacturer. To confirm the findings, the CFD analysis of the flow conditions through the whole valley was performed and the results confirmed that the positions 11 and 12 are not optimal for USTT. Adequate profiles were available further downstream the valley (not shown of Fig. 15).

3.3. Case 3 – Flow measurement in large tunnels within the Trebišnjica system

The Trebišnjica River catchment in Eastern Herzegovina (Bosnia and Herzegovina) is one of the most complex

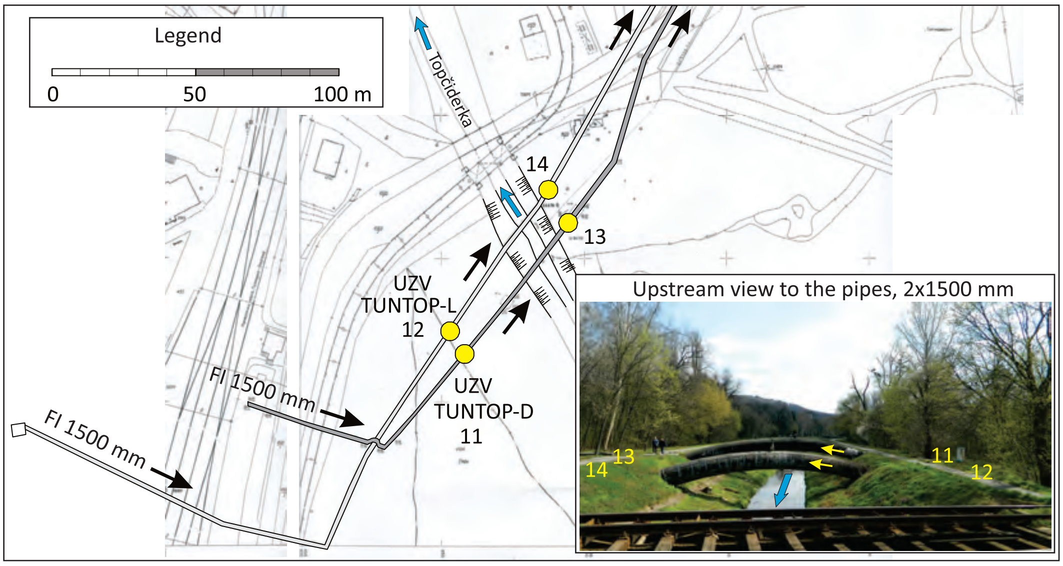

Figure 15. Two mains (FI1500 mm) along the "Topčider" valley with river crossing

karst areas in the Balkan region. It is characterized by complex karst landforms and drainage systems including karst poljes, ponors, springs, estavelles, developed underground connections, as well as underground bifurcation zones (Milanović, 2006). The area is a part of the Dinaric karst region, characterized by very irregular karstification caused by tectonics, compression, reverse faults and overthrusting structures (Jaćimović *et al.*, n.d.).

Figure 16. Catchment area of Dabarsko polje

In order to prevent flooding of karst poljes and utilize at the same time an exceptionally high hydropower potential, construction of a complex water resources system started in 1960s. The system has evolved in several stages, including construction of dams, tunnels and hydropower plants (HPPs), and is still evolving.

Important part of the system are two large tunnels that connect the Dabarsko polje and Fatničko polje (D-F tunnel), and Fatničko polje with Bileća reservoir (F-B tunnel). Two tunnels with their catchments (direct and indirect) are shown in Fig. 16.

To measure the flow rate in those tunnels is a non-standard task: the tunnels are large, flow is intermittent (during summer there is no flow, while during some periods tunnels are full of water but without flow rate) with high minimum-to-maximum ratio. The flow is in mixed conditions (mostly pressurized flow but can be also with free surface), and flow direction can be reversed. Additionally, water can carry large stones and gravel, together with other debris.

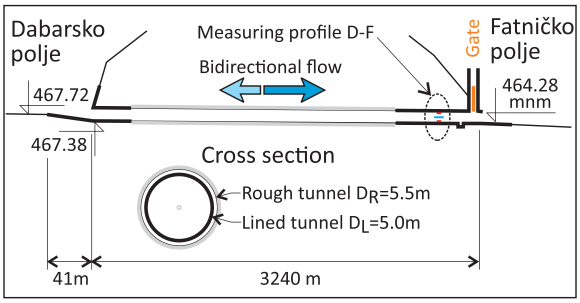

Figure 17. D-F tunnel with bidirectional flow

The flow through D-F tunnel mainly occurs in direction from Dabarsko to Fatničko polje with rates up to 60 m^3/s. The tunnel length is 3.24 km, diameter is 5 m in sections where it is lined and 5.5 m in other sections (Fig. 17). During some rainfall events, runoff response from the Fatničko polje catchment can be faster than that in Dabarsko polje and water can flow in opposite direction (with rates up to −40 m^3/s). The tunnel can be closed to prevent the reverse flow, which would be a loss for the hydropower system.

Measuring profile in the D-F tunnel is located 50 m before the exit to Fatničko polje. Details of the cross section

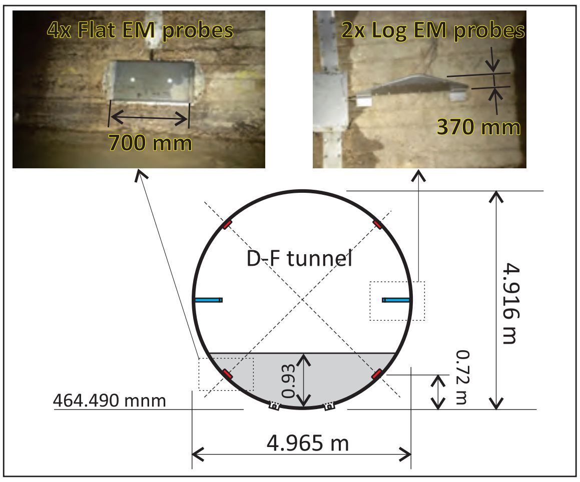

Figure 18. Measuring cross section in D-F tunnel

are presented in Fig. 18. Similar setup was used for other two measuring sites in the F-B tunnel.

Four large Flat EM probes were used per measuring cross section, to cover larger measuring volumes and improve the velocity integration if non-symmetrical velocity distribution occurs. Since flow in the tunnel can be with free surface (as shown on Fig. 18), two lower Flat EM probes were positioned below the expected minimum flow. Water level during free-surface flow is measured using two pressure sensors near the cross-section's bottom.

To assess the accuracy of "constructed" flow measurements, two approaches were tested:

- Usage of second, redundant type of measurement during certain period. The pair of LOG-EM probes is installed for one flow season (October-June) as a reference. These probes are less robust solution and are more susceptible to failure since they penetrate the flow profile, but they are closer to the mean velocity point for given flow conditions.
- CFD modelling of longer tunnel section, with detailed Flat EM representation. The model gives an insight into the expected velocity distribution for different flow conditions, helps in positioning of EM probes and estimating calibration parameters.

Second tunnel, from Fatničko polje to Bileća reservoir (Fig. 19) has 15.6 km length. The diameter is variable along the tunnel, depending on the slope and whether it is lined or not. At the inlet of the tunnel, there is a large dividing structure and inlet gate (Fig. 19, lower left part).

The measurement profile F-B_{IN} is positioned just upstream of the inlet gate and has 6.5 m in diameter. Expected flow rate is up to the 130–160 m^3/s (Water Institute „Jaroslav Černi", 2016).

Along the F-B tunnel, due to karst formations, water can infiltrate or exfiltrate, depending on the hydraulic conditions in the tunnel and surround terrain. Because of that, the outflow from the tunnel is not the same as the inflow and has different dynamics. The outflow measurement profile F-B_{OUT} is prepared upstream from the tunnel curve and contracting section (Fig. 19, lower right part, CFD model).

Fig. 19 shows one more flow measuring system just upstream of exit gate, labelled "Not operational flow measurement". In contracted section, the multi-trace US TT system was previously installed. Working conditions were such that velocities are too high with low pressures, so cavitation can easily develop. Mixture of air and water covered the US probes, prevented the transmission of ultrasonic pulses whenever flow rate exceeded 10-20 m^3/s. This location was therefore abandoned.

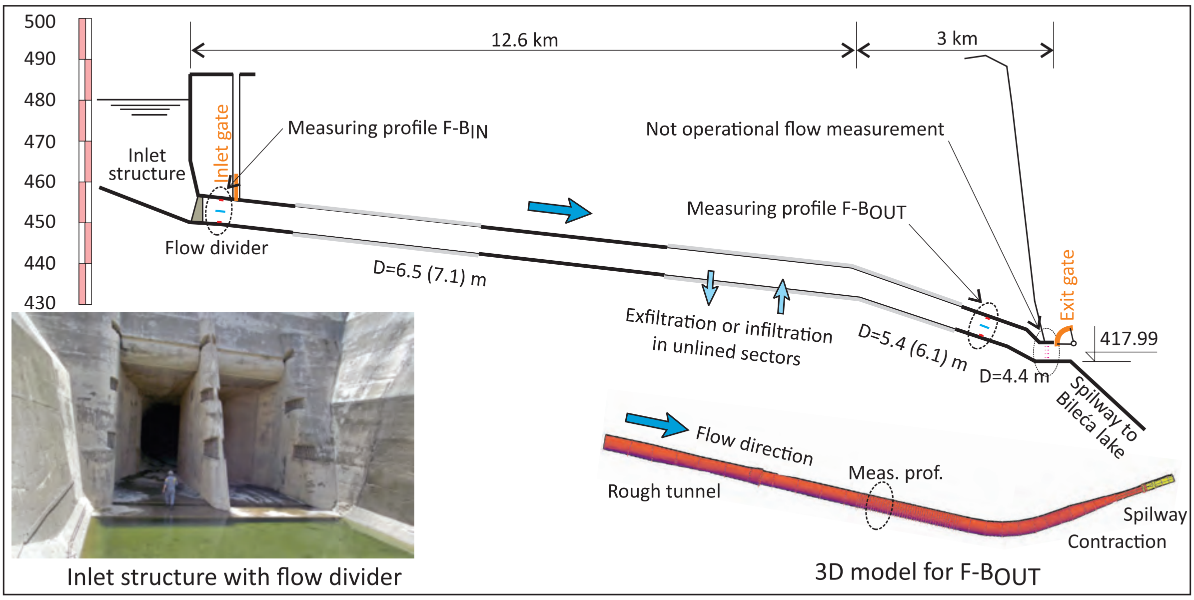

Figure 19. F-B tunnel with two flow measurement positions, at inlet and at outlet

Figure 20. F-B tunnel, inlet cross section F-B$_{IN}$ before installation of equipment (left) and during the installation (right)

3.4. Case 4 – Flow measurement on intake of Djerdap 2 turbine

Hydraulic conditions around short structures in most cases prevents the existence of cross sections with parallel streamlines and fully developed turbulent flow profile. There is no "universal flow measuring device" that can be used in such conditions with adequate accuracy. This is the case with flow measurements at the intake of the aggregates of the Iron Gate 2 HPP (or HE "Djerdap 2", Fig. 21).

Figure 21. Iron Gate 2 (Djerdap 2) hydropower plant (taken from Google Earth, 2009; location: 44°18'24.61" N/22°33'53.54" E)

Both Serbian and Romanian HPPs at Iron Gate 2 are equipped with 8 turbines in the main plant and 2 turbines in the additional plant (total of 20 turbines). Total installed discharge is 8500 m^3/s (www .eps .rs). Figure 22 presents the longitudinal section through one bulb turbine (low head Kaplan type). The turbine has short intake part, close trash rack and fast service gate. The supporting wall below the turbine acts as a flow divider and straightener. The pressure taps are made in that wall, one at upstream part and two at left and right sides, creating the differential Winter-Kenedy (WK) flow measuring device. Standard procedure is to perform detailed measurements of relation between flow rate and measured differential pressure, for different working conditions, and determine the WK coefficients. Measurements could be done only on a scale model, in a controlled laboratory environment. The assumption is that the same WK coefficients will be applicable on the full-scale turbine.

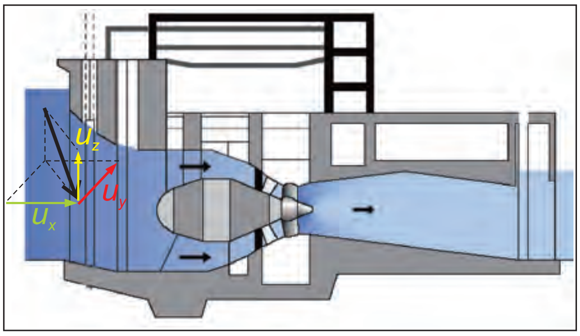

Figure 22. Bulb turbine with highly irregular conditions for proper flow measurement

Due to its position in the Danube (it can be seen from Fig. 21 that the Danube is not flowing orthogonal to Iron Gate 2 HPP) and leftovers of preconstruction works in riverbed, there is a significant incoming angle of water toward the turbines. The streamlines angle is larger at the Serbian side then at the Romanian side, and it depends on working conditions of spillways. Because of that, the incoming velocity vector is shown in Figure 22 with strong horizontal component parallel to the trash rack, U_Y (Prodanović *et al.*, 2011). The vertical component U_Z is typical for short turbine intakes.

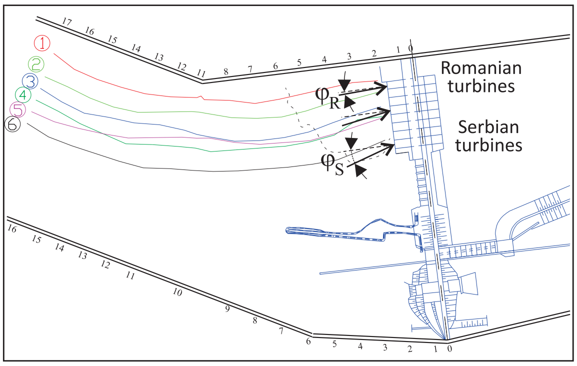

Figure 23. Scale model with streamlines (Water Institute „Jaroslav Černi", 2006)

To assess the influence of flow regime on operation of each turbine, the scale model was made (Fig. 23, Water Institute „Jaroslav Černi" 2006). Model clearly demonstrates that the Romanian turbines are better positioned than Serbian turbines, and that the curved in-

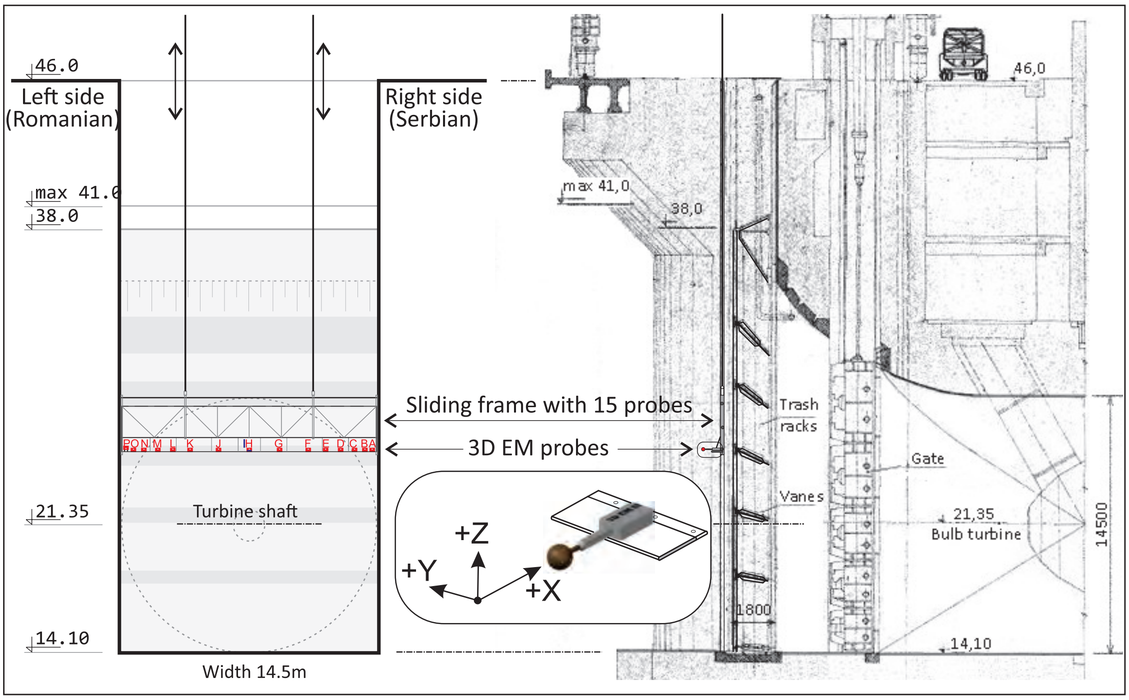

Figure 24. Suggested flow measurement method by profiling velocity field using one row of 3D EM probes == Streamwise view at the turbine's inlet (left side) and longitudinal section through the bulb turbine (right side)

coming streamlines are the reason for turbine's lower efficiency coefficients. However, the influence of curved streamlines on WK coefficients could not be assessed from the scale model. Flow rate measurements in situ and recalibration of WK coefficients was the only solution.

Since the HPP is equipped with Kaplan's short turbines and there is no regular cross section where flow can be measured using standard methods, available measuring methods for velocity field measurement were analysed by Prodanović *et al.* (2011). Figure 24. presents the suggested solution, which is the velocity field profiling using probes capable to measure all three velocity components at the same time. The equipment can be positioned in front of the trash racks. To reduce the blockage effect and to avoid increased head drop, a narrow sliding frame is suggested, with one row of probes installed.

3D velocity measurement was performed using newly developed EM probes (Fig. 8). Fifteen probes were installed on the frame, positioned to follow the expected velocity profile. The 3+D version of the EM probes were used, with which the streamwise velocity component is measured with increased accuracy. The frame is raised for approx. 27 m. The approach suggested in "Velocity profiling in unsteady flows" (section 2.2) was used, where the referent flow was taken from WK system and checked by turbine operational data (power, head loss, etc.). Since these complex measurements are conducted with numerous sensors working in real time, specialized software for data acquisition and for data analysis was developed (Water Institute (Water Institute „Jaroslav Černi", 2020).

4. RESULTS AND DISCUSSION

4.1. Flow measurement in complex unsteady situation (Case 1)

The recalibration of existing flow meter (Fig. 12, $MP : N$), equipped with a new electronic transmitter, was performed using two 1D EM probes (Fig. 25). Because of irregular position, two profiles (under angle of ±27° to vertical direction) were used for velocity distribution measurements. The genuine flow signal from the built-in flow meter was available only for manual reading since it was electrically complicated to connect to the used data loggers (grounding problems). Therefore, one longer EM probe was used for profiling, while the other EM probe ("reference") was used as flow indicator, measuring velocity at one point. This velocity is used in the normalization process. Output from the new transmitter was, as mentioned, manually recorded.

When switching from one profile (+27°) to another (−27°), both probes were fixed for certain period at the same position (same x/D), to create the correlation between the two points and use it in the velocity normalization process. Since EM probe gives instantaneous velocity at a point, which always has variations due to turbulence, it is a common practice to average the signal over certain period of time. The averaging time usually corresponds to the criteria that the variance of measured velocity is $\sigma_V \leq 1.0\%$. This criterion can be used, however, only for low turbulence intensity flow, where small vortices are predominant.

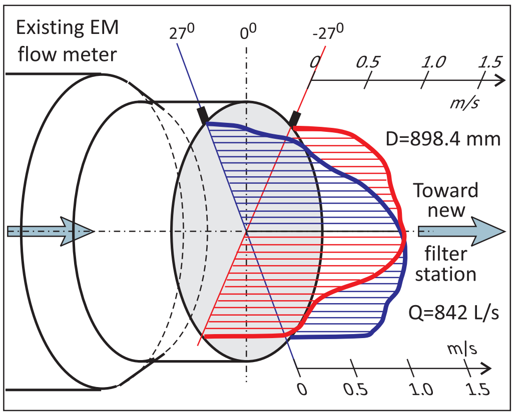

Figure 25. Recalibration of the built-in flow meter in dynamic conditions

Having large pipe's bend upstream of the EM under the recalibration (Fig. 12), slow helicoidal disturbance is recorded, with periods of about 2 minutes or longer. In Fig. 25, the upper diagram shows the 10-second averaged velocity in the reference position. Standard criteria of minimizing the standard deviation σ_V could not be used, so in order to provide the same conditions for all measuring points during profiling procedure, the reference signal was used to trigger the 1-minute averaging period on profiling probe (marked areas on lower diagram on Fig. 26). Obtained mean point velocities were then corrected for mean flow changes during profiling measurements (red and blue velocity profiles on Fig. 25), and then used for velocity integration.

Flow measurement at the inlets to the old filter station (Fig. 12) was even a bigger challenge. The flow conditions were far from standard, with several 90° bends in horizontal and vertical plane. At each pipe, three profiles for velocity distribution measurement per cross section were used (Fig. 27).

Daily variation of flow at two inlets is presented in upper part of Fig. 27. For each cross section ($MP : OL$ and $MP : OR$), profiling along three directions lasted for approx. 3 hours. Recorded velocities, normalized, are presented in Fig. 27 and show expected irregularity. This indicates that including one more profile (along 135° angle) would reduce uncertainty of the obtained results.

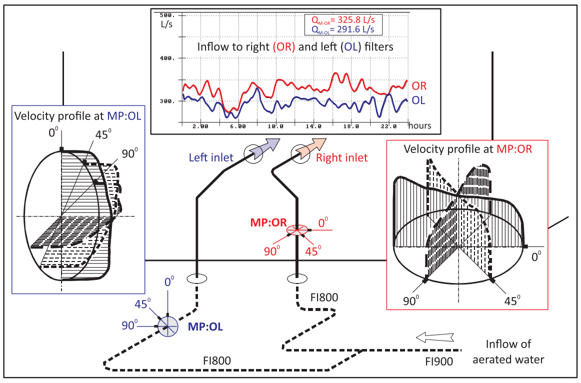

Figure 27. Velocity profiles at measuring points for two inlets to old filter station

Measurements at WTP "Štrand" were performed during the year 2000. At that time, the author did not have an operational 2D EM LOG probe, as shown in Fig. 5. Using the 1D EM LOG probe, oriented to measure orthogonal velocity component (at 0°, Fig. 28), the flow can be directly calculated. However, to "see" what the true velocity direction is, it is possible to rotate the probe around its axis. Fig. 28 presents the obtained result for one point in the 0° measured profile. The point was close to the wall and the EM probe was rotated in the range of angles of ±30°. The obtained maximum velocity was around the angle of +10°.

The problem associated to the approach of probe's rotation is the slow measurement process, which is undesirable due to global variations of inflow. If full 2D EM LOG probe had been available at that time, both components would have been recorded simultaneously, thus increasing the users' understanding of the full flow velocity pro-

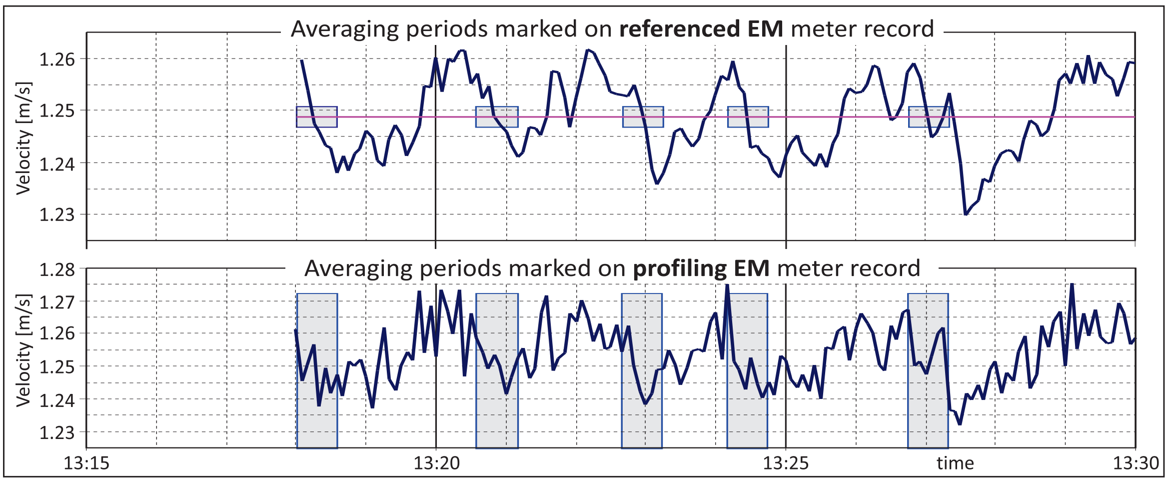

Figure 26. Velocities from reference probe and from profiling probe

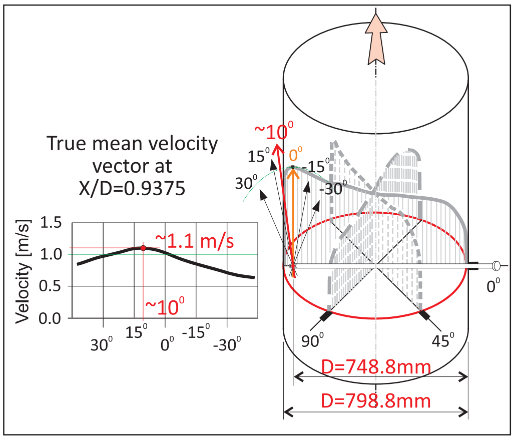

Figure 28. True angle of velocity vector near the pipe's wall

file. However, only the streamwise 1D component would then be used for flow computation.

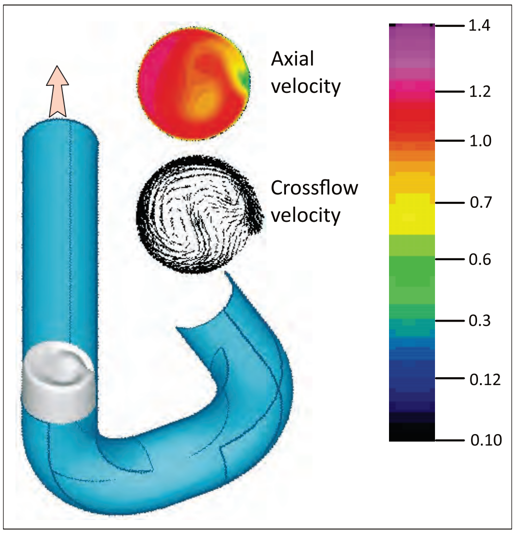

Figure 29. 3D flow simulation through doubled bend (Sontex Presentation CD, 2002)

To improve the understanding of expected velocity profile, the results of simulation of flow though the double bend done by Sontex Presentation CD (2002) is shown in Fig. 29. The bends are not in one plane; diameter is $D = 200$ mm and radius of curvature is $1.5D$, Reynolds number is $Re = 65,000$, turbulence model applied is $k\&e$ and the inlet profile (boundary condition) has ideal turbulent profile. The geometry is almost identical to situation at the WTP "Štrand" site, only with a different Reynolds number: in the presented simulation it was $Re = 65,000$ and on site it was $Re = 480,000$. The simulation result predicts helicoidal stream near the measurement profile, which was confirmed during the measurement.

4.2. Verification of large flow meters with the support of CFD (Case 2)

Two water mains, important for supplying the central part of the Belgrade city with drinking water, are laid cross the Topčider valley. Each pipe is 1500 mm of diameter, and they carry about half of total Belgrade's consumption. As described in section 3.2, the flow rate measurement in each pipe is done using USTT with two horizontal paths. Nominal accuracy of installed flowmeters is 0.5% (Danfoss, 2004). Flowmeters were installed upstream of pipe's crossing of the Topčiderka River. They were assembled in situ and only the geometry of US paths was checked. The overall flow measurement accuracy was not verified.

To verify the accuracy of USTT flowmeters, velocity profiling downstream the "Topčiderka" river was done. The existing manhole was used to drill a tap into the pipe and put the 1D EM LOG probe inside. Due to space limitations, only one direction for profiling was used. Also, since the pipe is large, it was impossible to move the EM probe to the end of the profile, so only 2/3's of the cross section was profiled.

To compensate the flow variations, the signal from existing USTT's logger was used. Measurement was repeated using the same tap connection, with the SPECTRASCAN (Biwater Spectrascan, 1998) probe, which uses the micro turbine for velocity measurement. Basic accuracy of the 1D EM LOG probe is 1% for velocity measurement, and accuracy of SPECTRASCAN is 2%.

Figure 30 presents the obtained measurements using two types of probes: green squares for EM probes and red circles for SPECTRASCAN corrected for mean flow variation (Prodanović and Pavlović, 2004). Since the measurements did not cover the whole profile, the three expected and possible profiles were extrapolated, and consequently, three possible flow rates were computed: Q_{13} in the range of 1.59–1.72 m^3/s and Q_{14} in the range 1.77–1.92 m^3/s.. At same time, the average $Q_{11}(= Q_{13}) = 1.59$ m^3/s and $Q_{12}(= Q_{14}) = 2.17$ m^3/s. Although the uncertainty of the computed control flow rates is high, it is obvious that $USTT_{11}$ is close to its nominal characteristics and that $USTT_{12}$ is overestimating the flowrate: even if the highest extrapolated value is used as the "accurate" flowrate, the error of $USTT_{12}$ is +10%.

Dashed line in Fig. 30 presents the theoretical velocity profile for flow rates as "seen" by USTT. The left diagram supports the conclusion that $USTT_{11}$ is "probably" within the nominal accuracy. However, the right diagram shows that $USTT_{12}$ is clearly out of the specified range. The word "probably" is used here because the overall recalibration method could be argued. Calibration was done with the instrument of lower accuracy (velocity measurement of 1–2%), and the integration methodology has even higher uncertainty (from diagrams it can be estimated to 3–4%) which gives combined uncertainty of 5%. Therefore, an instrument with a ten times lower accuracy was used to check the existing flow meter! However, having the difference between the obtained results even higher than the assessed 5% range, as in the case of $USTT_{12}$, leads to the only conclusion that the tested flow meter is not within the specified characteristics.

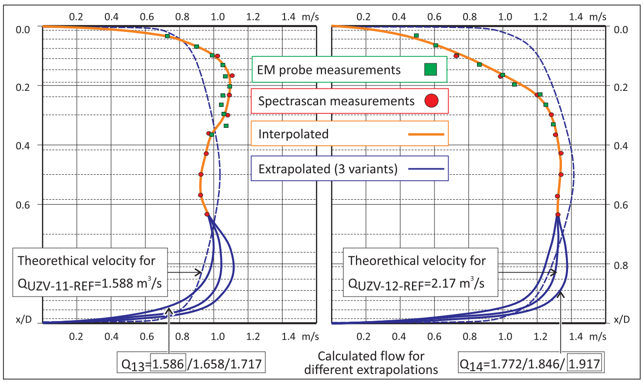

Figure 30. Measured velocity profiles downstream the river crossing, position 13 (left) and position 14 (right figure)

To have a third check of these conclusions with "not-so-perfect" insertion-type velocity meters, the CFD simulation of flow was performed. The idea was to inspect the assumed extrapolations in Fig. 30 and to look at the flow profile at the places where USTT were installed, trying to understand what the reason for the obtained results was.

The CFD model was created for the whole reach of the main where MM12 and MM14 are positioned (total length 450 m, pipe's diameter 1500 mm). Finite volume method was used, and flow area was divided in 610,836 volume elements, axisymmetric, with smaller volumes near the walls and around the bends (*Results of flow simulation in Topčider mains*, n.d.). Small detail of the model is given in Fig. 31, showing also computed streamwise velocities near the crossing over the Topčiderka River. Simulations were made by the FLUENT software (v. 6.1), with direct solution of turbulence based on the Reynolds-Stress-Method (RSM), applying stationary flow rate $Q = 1.917$ m^3/s. Several wall roughness values were tested ($\delta = 1.2$ mm, $\delta = 2.5$ mm and $\delta = 3.5$ mm), assuming uncompressible fluid and including the gravity force in the momentum conservation equation. The boundary condition at the downstream end was «OUTFLOW», where pressure and velocities are the same as previously calculated.

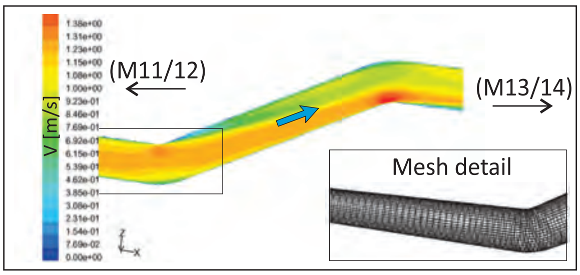

Figure 31. Detail of the CFD model, bend before the crossing over the Topčiderka River

Computed velocity profile at the position of USTT$_{12}$ (MM12) is presented at Fig. 32. The profile is not symmetrical nor fully developed. When the velocity profiles along the two US paths are linearly averaged (as USTT is doing), the computed mean velocity is greater than it should be and the installed flow meter shows greater flow rate. Since the whole reach where the USTTs are installed is under strong influence of the upstream bend, it was just a matter of luck which profile would provide positive/negative bias or accurate operation of installed meters.

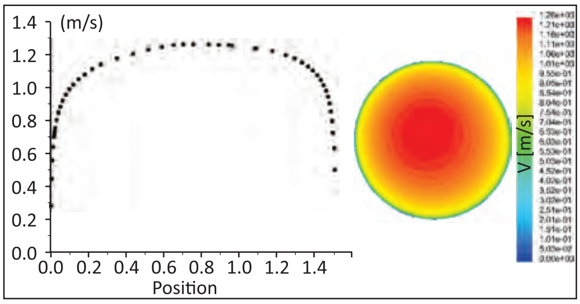

Figure 32. Velocity distribution at MM12 profile differs from an "ideal" symmetrical one

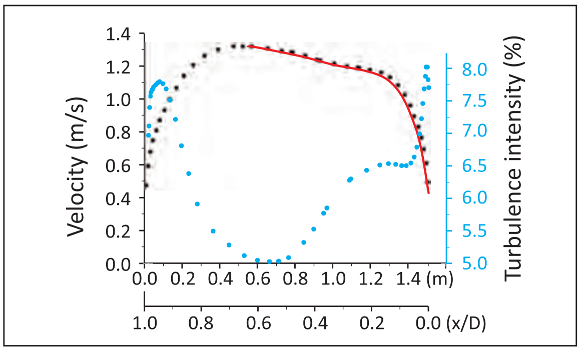

Figure 33. Results of CFD simulation for MM14 along the profiling direction: velocities (solid line represents measurements) and turbulence intensity

To check the assessed uncertainty of 3–4% for possible velocity extrapolation along the measured profile at MM14 (Fig. 30, right part, three possible solutions for extrapolation), the CFD result for the same cross section and the same direction of profiling is plotted in Fig. 33. Solid line shows velocities obtained by the measurement, and dotted line is the result of the CFD simulation. The shape of the line suggests that the applied extrapolation method with the highest flow rate is acceptable. The assessed uncertainty due to extrapolation is probably even lower then suggested!

Using the CFD simulation, it was possible to search for the best position where USTT should be installed. Close to the end of the Topčiderka River valley, the mains have a straight reach. The simulation shows that the velocity distribution is almost as theoretical one, with stable and symmetrical turbulence intensity. If USTTs were installed at that position, they would have (close to) the rated measurement error.

4.3. Site specific calibration in large tunnels (Case 3)

Calibration of a flow measuring device (permanently installed working meter) means that user can occasionally conduct parallel measurements by some higher accuracy equipment and use these measurements to calculate the calibration coefficients of the operating flow meter. In some situations, such a "site specific" calibration is hard to organize due to different reasons. e.g., due to large tunnel diameter and intermittent water flow as in the presented case of flow measurement in tunnels of the Trebišnjica system (section 3.3). In such cases, some other calibration methods are needed (Ivetić *et al.*, 2017b).

In case of the Trebišnjica tunnels, the permanent flow meter was constructed using flat EM probes attached directly to the walls (flush mounted, Fig. 18, left side). Such solution is robust and can resist the expected impact of debris and stones that can be dragged by the water. To improve the robustness of the solution, four probes were placed within one cross section. The main drawback of the solution with flush mounted EM probes is that velocity distribution near the wall is not equal to the mean velocity and depends on the flow conditions (Reynolds number).

According to the Pope (2008), velocity distribution in highly turbulent symmetrical pressurized flow can be calculated using exponential low:

$$V_x(z) = V\left(\frac{2z}{D}\right)^{1/n}\frac{(n+1)(2n+1)}{2n^2} \tag{4}$$

where $V_x(z)$ is streamwise velocity component, z is distance from the wall, D is pipe's diameter, and n is the exponent (coefficient) of power law. Pope (2008) suggested the following equation to calculate coefficient n as a function of Reynolds number:

$$n = 1 + \sqrt{\frac{Re}{50}} \tag{5}$$

The coefficient n can be calculated also using Nikuradze's equation (1932) with logarithmic relationship:

$$n = 0.5261(\log Re)^2 - 3.853\log Re + 13.1537 \tag{6}$$

For the place where flat EM probes are installed, the calibration coefficient is

$$C = \frac{V_{\text{mean}}}{V_{\text{meas}}} \tag{7}$$

where V_{meas} is the velocity measured by flat EM and V_{mean} is the mean velocity used to calculate the flow rate: $Q = V_{\text{mean}} \times A$ (A is the area of cross section). Looking to the red lines in Fig. 34, which represent the variation of the calibration coefficient with flow rate for flat EM probes, it is obvious that uncertainty is high, since two widely accepted

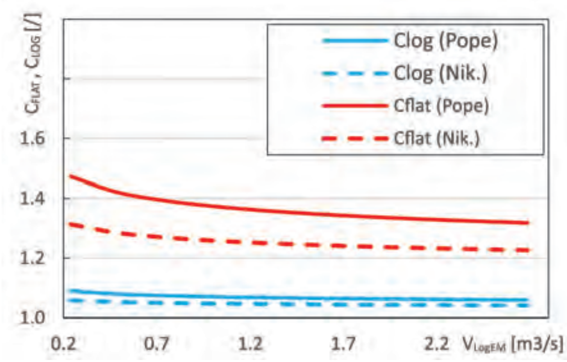

Figure 34. Comparison of Pope's and Nikuradze's equations for velocity distribution, for locations of flat EM and log EM probes

theoretical equations differ more than 10% and that dependence of coefficient with the flow rate is high.

The approach used in such situation was to temporarily install another set of EM probes having lower uncertainty (LOG based EM probes that penetrate into the flow field, Fig. 18, right side), but are less robust. The calibration coefficient for such probes is stable (Fig. 34, blue lines) regardless of the theoretical velocity distribution and flow regime. Also, the velocity field within the integration volume of EM probes (Fig. 35) is more homogenous for LOG type probes (as is in towing tanks used for probe's velocity calibration) than for flat probes at the tunnel's wall.

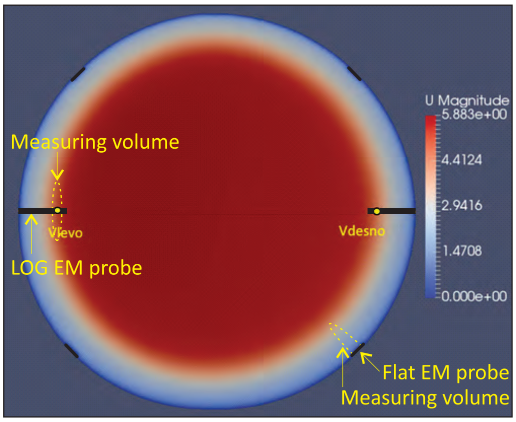

Figure 35. Comparison of measuring volumes for flat and LOG EM probes, for F-B tunnel

The setup with permanently installed four flat EM probes and temporarily added two LOG EM probes was used for all three measurement profiles: in D-F tunnel and two profiles in F-B tunnel. The calibration was performed using data collected for one season (December – Jun) for all flow regimes. After one year period, the temporarily installed LOG probes were removed from one profile and installed on another.

Some results for D-F tunnel during one season of calibration are presented in Fig. 36 (Ivetić, Prodanović, Cvitkovac *et al.*, 2018). The relative theoretical calibration coefficient for flat EM is plotted (corrected using LOG

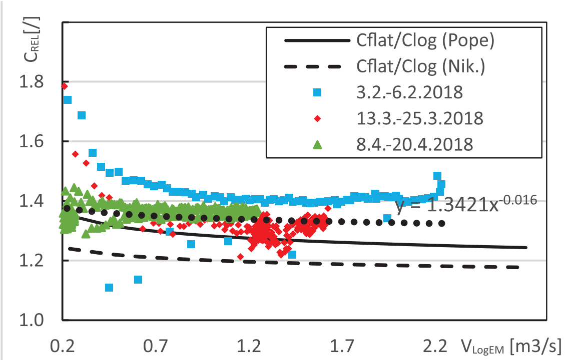

Figure 36. One season of flat EM calibration on DP-FP profile

EM probe data) for three events, including one with the reverse flow direction, from Fatničko polje to Dabarsko polje. Dashed and solid lines are for distributions given by equations (6) and (5) respectively. Final accepted velocity distribution based on recorded events is given by dotted line (Ivetić *et al.*, 2017a).

In situations where no secondary measuring systems could be installed (as LOG EM probes here), the authors tried to simulate possible output from the flat EM probe using equation (3). A detailed CFD model for all measurement profiles was created. Number of elements was between seven and eight million (10 times higher than in Case 2), since it was important to capture both long effects of flow through the tunnel (length about 100 m, 4 times shorter than in Case 2) and fine details around the EM probes (scale of few millimetres). The OpenFOAM finite volume model was used. Upstream boundary conditions were represented with given theoretical velocity distribution and the downstream conditions with constant pressure. Two turbulence models were tested, the $k-\varepsilon$ model and $-\omega$ (Shear Stress Transport model – SST). For the free-surface flow modelling, the Rigid-Lid approach was used (Ivetić, 2019).

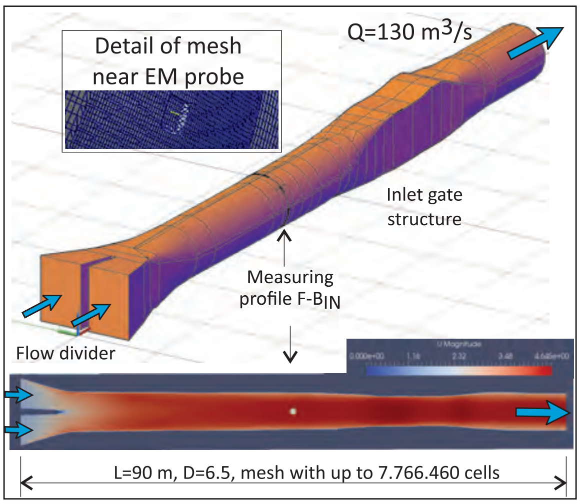

Figure 37. Detail of CFD model for F-B_{IN} measurement profile, between inlet flow divider and gate structure

Model of F-B tunnel inlet is presented in Fig. 37 (Water Institute „Jaroslav Černi", 2016). The influence of input flow divider on the velocity field can be seen. Slight flow instability was observed, which was averaged using four EM probes in cross section. Using results from the CFD model, the velocity distribution within the measuring probe's volume is plotted in Fig. 38, for lower EM1 and higher EM3 positioned in the left part of the cross section. Dashed line in the same figure shows the Bevir's weight vector (3), representing the strength of magnetic field versus distance from flat EM probe's surface (this curve can be obtained from EM probe manufacturer, or by direct measurement of magnetic field, Ivetić (2019); Stojadinović *et al.* (2018).

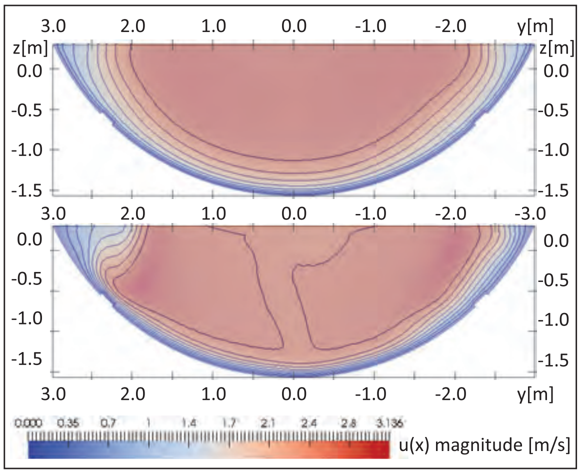

Figure 38. Relation between the strength of Bevir's weight vector (Eq. 2.3, dashed line) and velocity versus distance from flat EM1 and EM3 probes (solid lines)

To achieve the "site specific" calibration of flow meter, integration of two functions (dashed and solid line, Fig. 38) has to be performed. However, this solution assumes that velocity distribution computed using CFD has low uncertainty, with all local effects considered. To test this "hypothesis", numerous simulations were performed for all three measurement profiles in the Trebišnjica system. Dispersion of CFD results were very high because there were no referent measurements that could be used to "calibrate" the numerical solution. Therefore, the lack of higher quality data that can be used for calibration of flat EM probes (as mentioned at the beginning of this section), which we tried to bypass by employing CFD, is just translated to the problem of missing good data to calibrate the numerical model!

To illustrate high uncertainty of the uncalibrated CFD model, two simulations of free-surface flow regime are presented in Fig. 39. The two velocity distributions near the flat EM probes are computed for the same depth and flow rate but using different turbulence models. Which one is "better"? It is hard to say without detailed measurements. In similar situations, the scale model in labo-

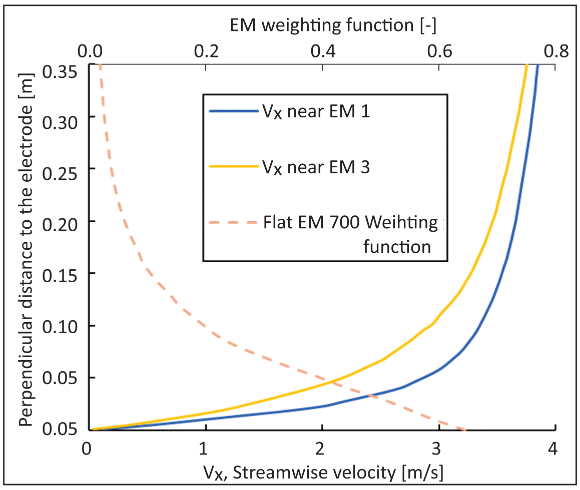

Figure 39. Example of two numerical solutions using different model parameters for the same flow conditions

ratory would be created, detailed measurements would be used to calibrate the CFD model that can then be used to predict the velocity distribution in the tunnel with much higher confidence.

Once when the flow measuring equipment in selected profiles were installed within the F-B tunnel (Fig. 19), it was possible to perform the water balance analysis. The tunnel is built in leaky karst formations, so it was expected that inflows and outflows would not be in balance, and that the difference would depend on water pressure within the tunnel.

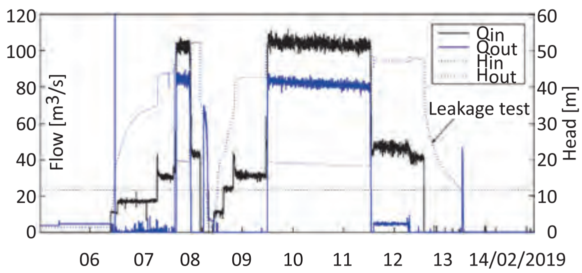

Figure 40. Water balance of F-B tunnel

During several days of February 2019, water balance test in F-B tunnel was performed. Fig. 40 shows inflow and outflow hydrographs using solid black and blue lines respectively, while pressure head is presented using dotted lines. Downstream pressure was controlled by exit gate. It can be shown that water loss ΔQ is exponentially related to the pressure head measured upstream of exit gate. During 12th of February, a test was performed with the downstream gate closed (small leakage under the exit gate can be seen). During that period, the inflow into the tunnel was about 40 m^3/s, representing the flow that fills karst caverns, thus representing the loss to the main flow.

4.4. Flow measurement in 3D unsteady velocity field of turbine intake (Case 4)

To perform the measurement of flow rate at the intake of turbines, where the conditions for standard techniques as described in IEC 60041 (1999) do not exist, the approach to map the whole velocity field is accepted. The turbine at "Djerdap 2" Hydro Power Plant (HPP) is a low head Kaplan turbine, which is sensitive to additional head losses that can occur if the whole cross section would be covered with current meters. Therefore, the horizontal profiling technique using a row of current meters with dynamic flow corrections is applied.

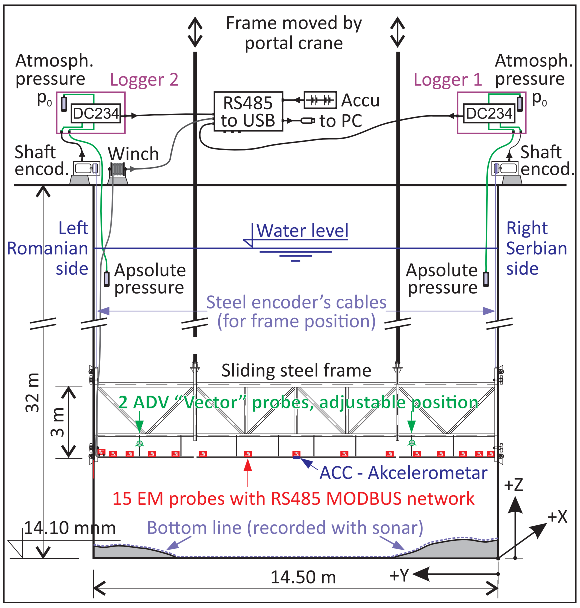

Figure 41. Measurement rig used for velocity field mapping

The method applied for velocity profiling is presented in Fig. 24. Details of the system are given in Fig. 41 (Ivetić *et al.*, 2021). The steel frame (14.5 × 3 m) is designed to minimize the flow disturbances and vibrations (accelerometer was added to central EM probe). The frame is hanged on portal crane (Fig. 42) and is positioned just upstream of the trash rack. The frame can be traversed vertically through the whole flow cross section, even during the highest flow rates.

Figure 42. Steel frame used during the measurement (in the most upper position)

Total of 15 3+D (streamwise velocity component is measured at two positions) EM velocity meters (Fig. 8, accuracy better than 1% for streamwise components in the range of 0–3 m/s) were mounted on the lower part of the steel frame in a horizontally symmetrical, but unevenly distanced pattern (Fig. 43, lower right part). Redundant and control velocity measurements were performed using two Nortek "Vector" (NORTEK, 2020) acoustic doppler velocity meters (ADV, accuracy 0.5% for all velocity components), mounted at height of 0.5 m above the EM meters (Fig. 43, upper left part). Continuous water level measurements were carried out via two fixed pressure transducers (accuracy better than 0.1%) installed at both sides of the intake. The position of the steel frame was precisely monitored with two UniMeasure "HX-EP" position transducers – shaft encoders (UniMeasure 2020, accuracy better than 0.025%) installed on the platforms (right and left) above the intake. Prior to the discharge measurements and the mounting of the equipment on the steel frame, four sonars were mounted on the positions of the EM meters (total of 15 positions can be used) for echo sounding the bottom-line profile.

The 3+D EM probes were calibrated in tawing tank prior to measurements, using the same geometry of supporting frame as one of the sliding steel frame. The influence of 3+D EM probes on ADV sensor is also checked in the towing tank.

All 3+D EM probes, two water level meters and two frame position transducers were connected in RS485 network with MODBUS protocol. All sensors have their internal loggers and accu-batteries for backup. The external large accu-battery was used to power the system, capable of two days mains free operation. The ADV meters were used as control redundant meters, and they were not connected to the RS485 network. They used the internal battery and data logger, with real-time clock to be synchronized to the rest of the system.

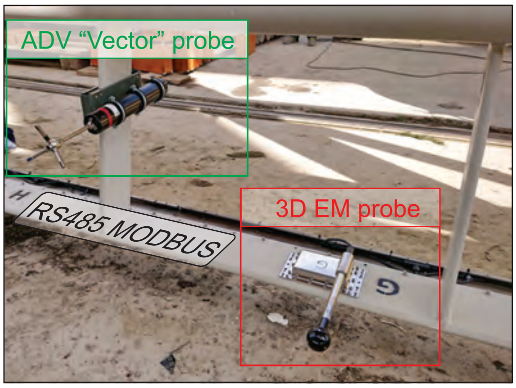

Figure 43. Steel frame with installed EM and ADV probes

Once powered on, the measurement system is continuously collecting data in real-time (except for the ADVs). Using specially developed Real-Time Monitoring software, data are processed and visualized. The sampling (for all the sensors) and visualization frequency is adjustable, with the highest frequency of 1 Hz.

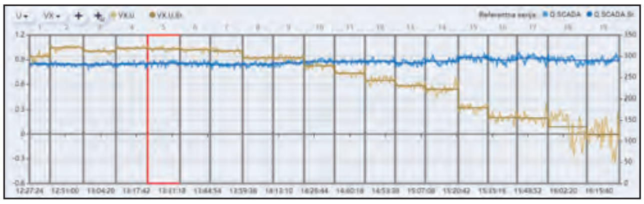

Figure 44. Turbine power during the velocity field traversing, used for unsteady turbine compensation (blue line) and streamwise component along the "U" vertical section (orange line) shown on Fig. 45

The measurement system can be operated in two modes, continuous and incremental. In the continuous mode, the steel frame is continuously traversed from bottom to the top with the lowest possible crane's speed of about 5 cm/s. This mode allows for the full velocity profiling to be taken in 6 to 7 minutes. In the incremental mode, the frame is traversed upwards between the semi-equidistant profiles (usually 17 to 20 profiles). In each of the profiles, the frame is kept still for about 10 minutes. In this manner, one discharge measurement can last for several hours. In both modes it is recommended to keep as stable as possible flow conditions at the examined turbine and two neighbouring ones.

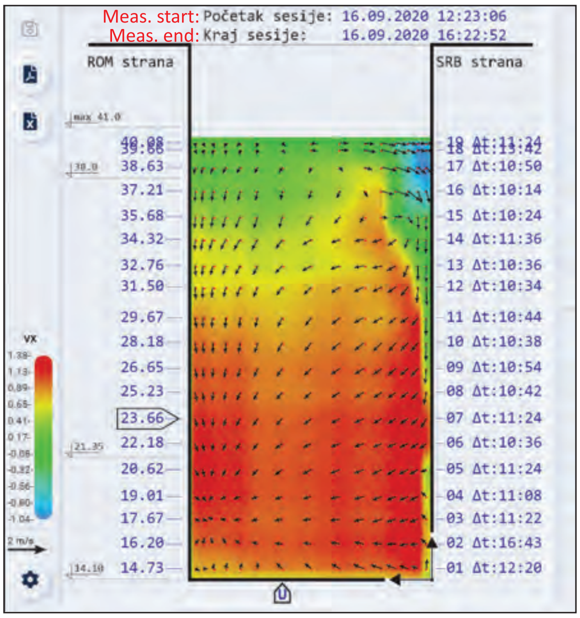

Figure 45. Velocity field, streamwise component colour coded, Y and Z components drawn by the vector (scales are in the lower left corner)

All measurements were synchronized with HPP's SCADA and ADVs using real time clock and merged off-line using Analysis software. This specifically tailored software performs data post-processing, correction for unsteady flow periods (Fig. 44), inspection of each probe's operation, plot of velocity field (Fig. 45), comparison of EM and ADV results, plot of horizontal or vertical profiles (Fig. 46), selection the criteria for interpolation and extrapolation of velocities, measurement uncertainty assessment and discharge computation (Fig. 47).

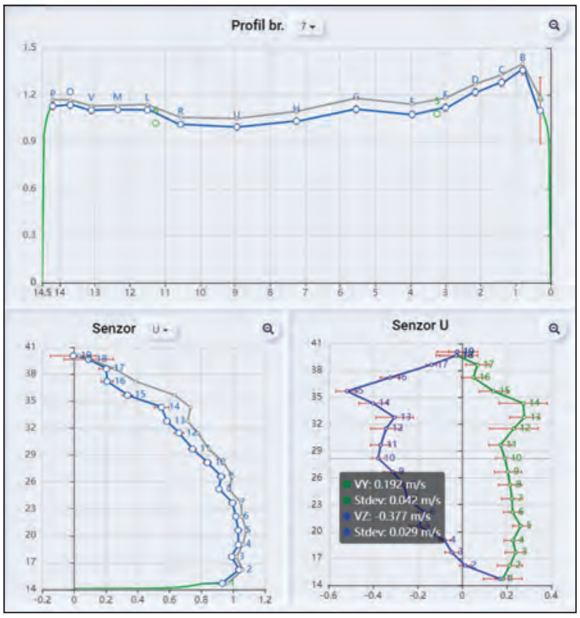

Figure 46. Velocity components with standard deviations: Streamwise velocity in horizontal cross section 7 (upper diagram) and selected components of velocity at vertical cross section *U* (lower diagrams)

Plot of velocity field (Fig. 45) gives the user a fast overview of the whole system operation. User can change the scales for each velocity component. Also, it is possible to plot velocity components and the standard deviation, where velocity instabilities could easily be observed. Selecting different horizontal profile (no. 7 at 23.66 m a.s.l., marked in Fig 45) and vertical section (U), the velocity profile can be visualised (Fig. 46), with standard deviation plotted as bars around each measured point.

Final step in data processing is the total flow calculation. The user can see the flow components for different areas of cross section (Fig. 47): the largest central part, which is interpolated between corrected EM measurements, and four extrapolated parts (user can select the type and parameters of the extrapolation functions). The bottom part will exclude the deposits at the bottom, if measured using the sonars.

Integral part of total flow calculation is the calculation of uncertainty budget. The uncertainty assessment procedure is developed according to GUM (Joint committee for Guides in Metrology, 2008) and all components are clearly presented to the user. As expected, the combined uncertainty is low (1.11%) for incremental type profiling and during measurement cycle when turbine operation is held constant (4 hours for the measurement shown in Fig. 45, starting at 12 : 23 : 06 and ending at 16 : 22 : 52). For continuous type of profiling, uncertainty of final calculated flow rate ranges from 2% to 5%.

5. CONCLUSIONS

The paper presented four cases of flow rate measurements, done by the author and his colleagues from the Hydraulic and Environmental Engineering department, Faculty of Civil Engineering at University of Belgrade. All selected cases include non-standard flow conditions where commonly used equipment and existing ISO or EN standard could not be used.

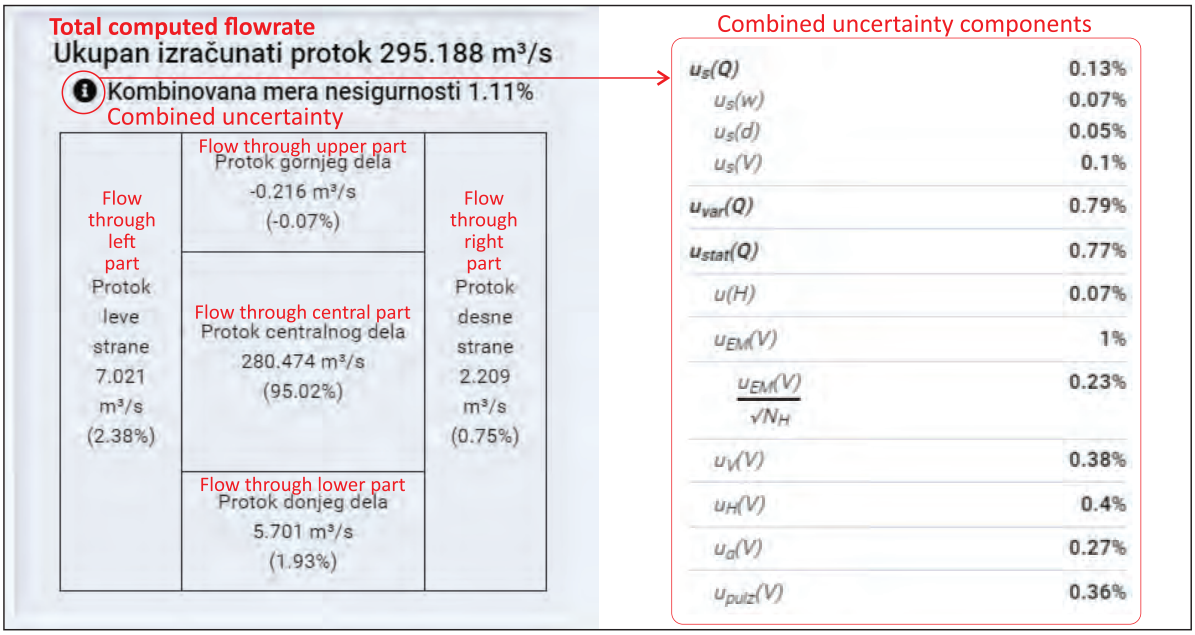

Figure 47. Example of calculated flow components with all components of uncertainty

The author has chosen to perform all presented measurements with EM type probes due to several reasons: EM measurement principle is physically based (2) and water velocity (not the velocity of particles within the water) is directly measured; all probes have full bidirectional measurement; intrinsic to EM principle of operation is the cosine rule (Fig. 4) which is essential for flow measurement in non-standard conditions where streamlines are not perpendicular to cross section; probe shape can be fitted for different purposes and flow conditions; it is possible to construct the 1D, 2D, 3D or 3+D (where streamwise component is measured at two positions, Fig. 8) probes; the EM probes are robust and can measure small velocities from few mm/s up to several m/s; and EM probes can work in harsh environments in sewers, even when covered with the sediments (due to space limitations, such a case is not shown here, but the details could be found in Ivetić *et al.* (2019); Prodanović *et al.* (2012) and Ivetić (2019).

Although the EM probes were used throughout all presented cases, one main drawback must be underlined: the EM probe has to be inserted into the flow field to conduct the measurement, thus it behaves as an obstacle. Measurement with inserted EM probes is not a contactless measurement (although Flat EM probes are close to the contactless type). Other techniques exist that allow true contactless velocity measurement, like PIV (Particle Image Velocimetry), laser Doppler, US Doppler or transit time. But all these contactless techniques do not measure true water velocity but the velocity of a certain tracer!

Finally, one interesting lesson has been learnt from the presented cases, related to the use of the CFD modelling in measurements. If sufficiently detailed modelling grid is prepared, CFD is expected to help the user to see true velocity field in advance, allowing the prediction (computation) of the calibration coefficient for the specific measurement position. However, it was shown that CFD can be used only to describe the flow field qualitatively, give an insight into the expected phenomena, help in selecting the best position for flow meter and give the proof for the results obtained using EM probes. If CFD model itself is not calibrated, it cannot substitute true calibration measurements.

Special thanks

All measurements presented in this paper are the result of team work of colleagues from Hydraulic and Environmental Engineering department, Faculty of Civil Engineering (FCE) at University of Belgrade, during last 30 years. The author wishes to give a special credit to Prof. Čedo Maksimović (Imperial College) and his visionary support for the field of measurements in hydraulic engineering, establishing the final-year course in mid 1980's. All developments in construction of EM probes and other electronic equipment were done by Mile Cvitkovac (Svet Instrumenata). Major field work in the first two cases, together with the help in laboratory tests and equipment calibration, was performed by Dragutin Pavlović (FCE). CFD model used in the second case and Flat EM probe were developed as a part of projects founded by the Serbian Ministry of science. Two last case studies were done under the projects conducted by Water Institute „Jaroslav Černi" (IJČ) for HET Trebišnjica. Damjan Ivetić (FCE) did a great job with his PhD work on EM behaviour when covered with sediments, design of flow measuring systems in cases 3 and 4, and in application of CFD. Many thanks to Predrag Vojt (IJČ) for his support in design and calibration of 3+D EM probes and ADVs for case 4, and for hard field work. Lastly, the author wishes to express gratitude to Branko Hrkić (FCE), retired craftsman and modeler whose support in laboratory and field work was invaluable, and his successor Ivor Koković, with a promising future.

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