METHODS OF WATER INFLOW MEASUREMENT IN THE BEDŘICHOV TUNNEL

METODY MĚŘENÍ PŘÍTOKU PODZEMNÍ VODY DO VODNÍHO PŘIVADĚČE BEDŘICHOV

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Abstract

In the paper, we describe methods for continual measurement of flow rates at several points of the tunnel water inflow, following the previous 5 years of manual measurement in the Bedřichov site. The aim of the measurement has to precise the time changes and spatial distribution of the inflow. Various approaches are used and further adapted or improved from their standard use. Tipping buckets are used for small flow rates (including drops) and outflow through a hole from a vessel with level measurement for medium or changing flow rates. For total inflow rates in various parts of the tunnel, we used weirs placed in a collection canal. For the detailed distribution of total inflow along the tunnel, we used the dilution method. The methods are evaluated and compared regarding possible disturbances or inaccuracies.

Abstrakt

V článku popisujeme kontinuální metody měření přítoku podzemní vody do vodárenského přivaděče Bedřichov, navazující na předchozí pětileté ruční měření. Kontinuální měření by mělo pomoci zpřesnit časové změny a prostorové rozložení přítoků. Různé postupy měření jsou upraveny či přizpůsobeny charakterům přítoků či jejich umístěním ve štole. Pro malé přítoky (včetně kapajících) jsou použity překlopné člunky. Pro prameny se středním či proměnlivým přítokem jsou použity měrné nádoby (danaidy). Celkový přítok do tunelu je měřen ve sběrném kanálu v počvě štoly pomocí přelivů. K získání podrobného rozložení přítoků podél štoly je použita směšovací metoda. V článku je diskutováno vyhodnocení získaných dat, obsahující různé typy šumů.

Keywords

granite, groundwater, hydraulics, flow-rate measurement, tipping buckets, dilution method, Bohemian massif, Jizera mountains

Klíčová slova

granit, podzemní voda, hydraulika, měření přítoku, překlopné člunky, metoda ředění, Český masiv, Jizerské hory

1 Introduction

The tunnel inflow is one of the possible sources of data for studies of groundwater flow. Measurement of flow rates of the various forms of water discharge from the rock to the tunnel requires several adapted or improved approaches, in particular a matching to the inflow rate range and to the available space at the measurement place. In a separate work (Hokr, 2013); the evaluation of the inflow related to e.g. surface water infiltration is discussed. In this paper, we focus on the measurement methods and its adaptation to the in-situ conditions. The work is a part of the complex monitoring project at the site by several institutes, including online transmission of the data (Hokr et al., 2010; Špánek et al., 2011).

1.1 Bedřichov site

Our site of interest, the water supply tunnel built in granite massif in Jizera Mountain (Czech Rep.) near the Liberec city, is studied as an industrial analogue of nuclear waste repository (Klomínský and Woller, 2010). It was built around 1980 through compact granite rock. It is 2600 m long with 3.6 m diameter, and up to 150 m deep.

The tunnel was excavated in two ways, first 885 m by tunnel boring machine and remaining part with drill-and-blast method. Different parts of the tunnel are shown in Fig.1 (a – bored part, b – border between bored and blasted part, c – bare rock blasted part, d – less stable blasted part with shotcrete). Inflow water from the tunnel sides is caught to a collection canal. The collection canal, about 0.4 m wide, covers whole length of the tunnel. Through the shaft-covers, the canal is more-less regularly accessible in 50 m interval.

Based on studies of Bělohradský (2008), the dominating inflows occur in shallow parts (near the end or the beginning of the tunnel) and it is about 2 – 3.5 $l.s^{-1}$ (with seasonal changes). Inflow from deep massif (between 200 – 2200 m chainage) contributes about 5 – 10 % of whole inflow and is covered mainly by discharges from few fault zones or large fractures. The scheme of the tunnel is shown on Fig. 2.

Fig.1 Different parts of the tunnel (explained in the text)

1.2 Flow rate measurement methods

Measurement of the free water discharge or the open-channel flow is well developed in many applications but it still has a lot of compromises in its accuracy and reliability. The measurement methods are typically based on the level measurement (weirs, discharge vessel), for which pressure (tensometric) and ultrasonic sensors are used. The tipping bucket device is a standard for precipitation measurement in the automatic weather stations and there are also several examples for a small inflow to excavations or caves (Vysoká et al., 2009).

Most of the devices are very sensitive to proper and precise installation (positions and shapes of the weirs, holes, sensors...) and local flow condition (still water surface).

Therefore the interest in this work is to evaluate the experience with various equipment including own improvements or adaptations, where the use was under several compromises due to e.g. available space or larger range of a varying inflow.

2 Methods of inflow measurement

The continual measurement of the inflow follows the older regular manual measurement, which has been held from 2007 (Bělohradský, 2008), and its goal has to precise the time changes from second/minute to seasonal. The detailed inflow progress can be viewed from the flow-rates in selected underground water springs (i.e. either particular fractures with collecting grooves or shotcrete covered fault zones with tubes, collecting water through the cover) – some of them are depicted on the Fig. 2 (marked V_x). The following two methods are used, depending on inflow magnitude:

- tipping buckets;
- vessels with holes.

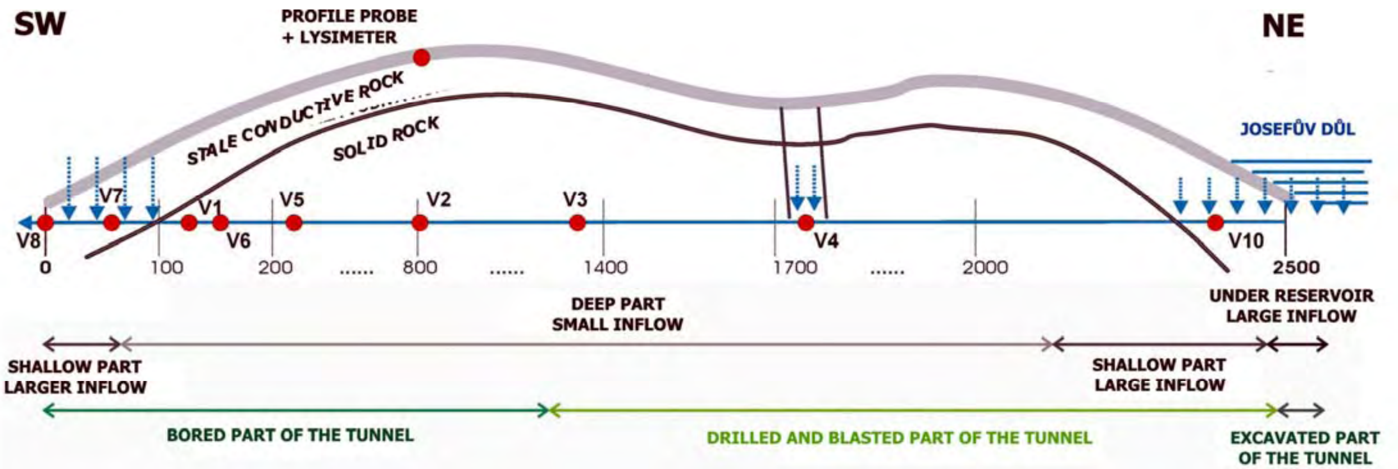

Fig.2 Simplified scheme of the tunnel with respect to inflow

For the view of global distribution of the inflow, we measure flow-rates in several places in the collection canal. Difference between flow rates in different places represents the total inflow in the particular part of the tunnel. The flow rates in the collection canal are measured by two methods:

- weirs (V-notch);
- dilution method.

2.1 Tipping buckets

Tipping buckets are suitable for springs with small inflows (including drops). After filling up the bucket (with known volume) with water, the impulse induced by the tip is detected and recorded. Bucket volumes were chosen such, that the order of

Fig.3 Tipping buckets

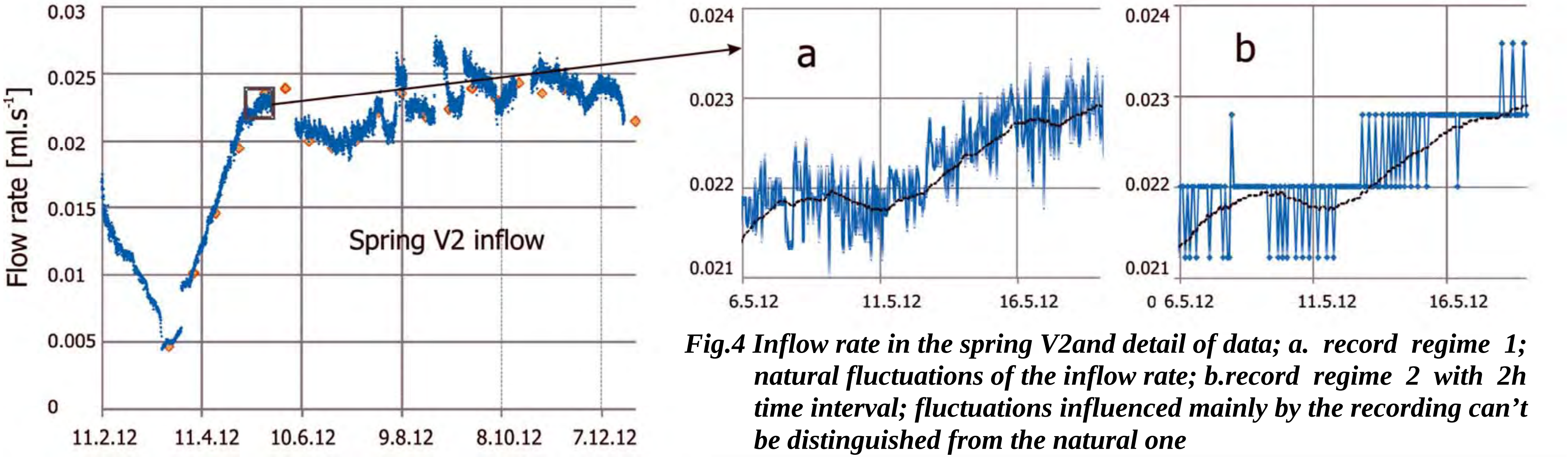

***Fig.4** Inflow rate in the spring V2and detail of data; a. record regime 1; natural fluctuations of the inflow rate; b.record regime 2 with 2h time interval; fluctuations influenced mainly by the recording can't be distinguished from the natural one*

the time intervals between tips are minutes. Two examples of tipping buckets are shown in the Fig. 3. On the left, there is the "home" rain gauge used at the spring V2, combined with the datalogger MicroLog T3 (EMS Brno, 2011). On the right, there is the tipping bucket of our own construction based on Jez (Vysoká et al., 2009), used at the spring V5, with built-in cells for sensors. The impulses are recorded by the electronic system, developed at the Technical University of Liberec (Špánek, 2011).

Generally, two types of record regime (r.r.) are possible: either every tipping time (r.r.1) or the total number of tips in particular time interval is recorded (r.r.2). The left graph on the Fig. 4 shows the recorded data from spring V2 in the regime 1. The only post-processing to the data here is an averaging of the two successive tipping time intervals, which corrects a potential differences caused by the non-perfect horizontal position of the bucket. The graph shows a good agreement between continual and manual measurement. The general course of the inflow rate can be seen directly from this graph. The segment of the data (graph *a* on the Fig. 4) shows the disturbances of the flow rate in the short time scale. These disturbances are supposed to be caused just by the natural disturbances of the inflow rate. Data, obtained by the r.r. 2, are typically clustered (integer values for number of tips). An example of the same data segment as in graph *a*, how would be recorded in the regime 2, is shown in graph *b* on Fig. 4. The general course of the inflow rate in this graph is less evident, a post-processing is needed (black line in the graph *b* represents the moving average for 48 values). From this type of the data, we cannot distinguish the natural disturbances from those caused by the measurement. For a comparison, the black line on the graph *a* represents the same type of the moving average (for data from the r.r. 1).

2.2 Discharge vessels

Discharge vessels are useful for springs with medium high or variable inflow. We use the relation between the water level and the rate of outflow from the hole in the vessel (theoretically calculated and laboratory calibrated). The size of the hole needs to be adjusted for the assumed (observed) inflows. While the discharge depends on the square root of the water level, preferred working range of the vessel rather should not be located in (very) small height, where the sensitivity of the discharge to the height is biggest (Fig. 5).

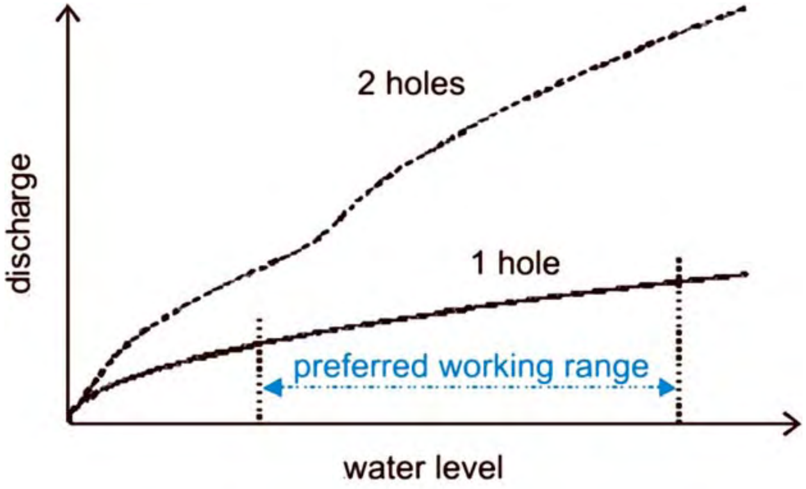

Fig.5 Calibration curves

For inflow with great variation – e.g. in spring V7 (Fig. 6), where the inflow varies between 0 and 250 ml.s^{-1}, the working range of the vessel is enlarged with using more holes, distributed vertically. The distribution of the holes was adjusted to cover the most common values of the inflow. The water level in the vessel is measured and recorded regularly by the Levelogger probe (Solinst, 2013) with integrated recorder.

The long term continual record of the inflow at the spring V7 is shown on the left graph on the Fig. 6 (together with manual measurement). In the case of strong inflow, the water level is very unstable, which causes visible disturbances in the measured data (section *a* on the Fig. 6). With adjusted number and size of holes, the

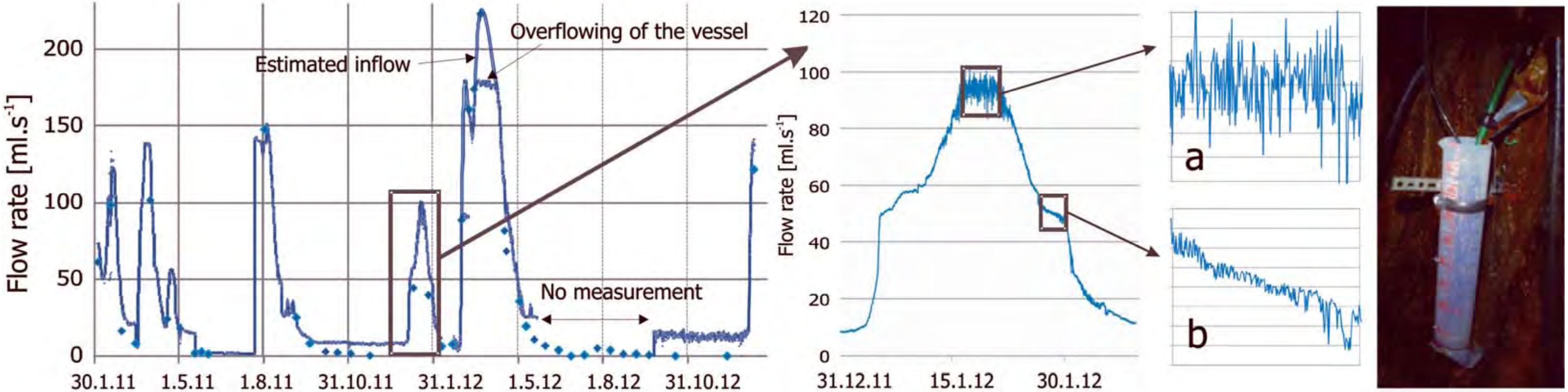

Fig.6 Spring V7; long term record and detail of data

vessel can well match the large range of the inflow rate – after an overflowing of the vessel in the 2012 spring time, the working range of the vessel was enlarged. The variant of the vessel with more holes has the only disadvantage in the imprecision of the measurement just in the case, when the water level rises over the hole. Also, the combined calibration curve is more complicated (Fig. 5).

Another example of data is from the spring V4. From the observation, the spring has the very stable inflow in a long term (6 – 6.5 $ml.s^{-1}$), but in a short time interval (in order of tens of seconds) it is expected to be infiltrated by the air, collecting behind the shotcrete layer, and the inflow varies in order of 3 – 5 %. The water level in the vessel is observed to be very calm, but fluctuates in order of centimetres in real time. So the data disturbances are supposed to be caused mainly by the natural disturbances of the inflow (Fig. 7).

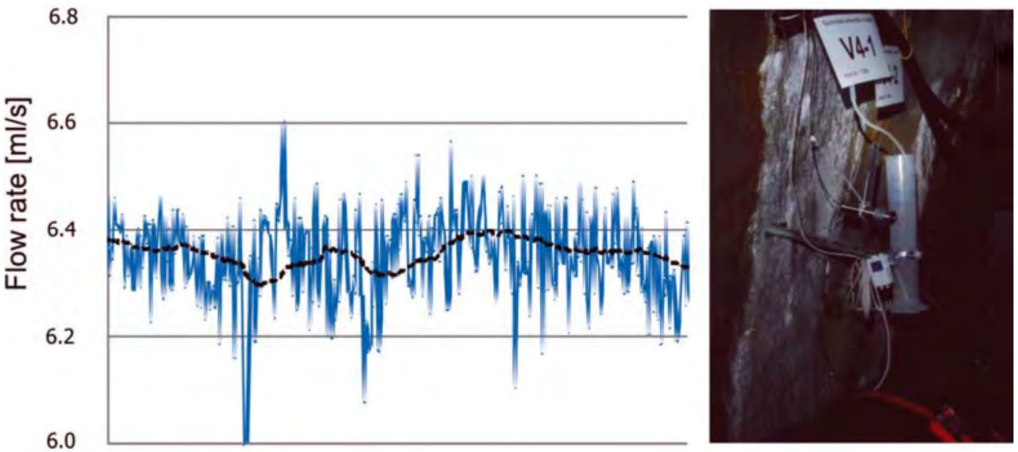

Fig.7 Spring V4; detail of data

2.3 Weirs

The weirs are used in five places in the tunnel (at 0 m, 100 m, 249 m, 1995 m, and 2450 m chainage). From the whole set of accessible points to the canal, we selected five points, which divide the tunnel to five sections of typical inflow and rock state properties (defined in previous measurement of Bělohradský, 2008). The weirs were provided and installed by the Aquamonitoring Brno Ltd. The water level can be measured by two ways:

- directly by the ultrasound probe;
- indirectly by the pressure sensor.

For the direct measuring of the water level, the ultrasound probe US1200 with a control unit Fiedler-Mágr M4016 (Fiedler, 2013) are used. For the indirect pressure measurement, either Levelogger probes or LMP307i sensors (BD, 2013) with Comet logger (COMET SYSTEM, 2010) are used. The obtained data can be disturbed either naturally (from the fluctuating water level – section *a* being on Fig. 8) or by the recording regime (section *b* on Fig. 8 – record regime 2 represses the information of natural disturbances of the inflow and need a post-processing).

2.4 Dilution method

Differences of the flow rates in the collection canal can be used as the inflow value for a particular tunnel section (Fig. 9). If the two flow rates are measured independently with a certain error, the error of the evaluated difference can be very large when subtracting flow rates close to each other. The dilution method can be arranged so that part of the error source is common for all the positions along the canal. The method successfully catches the ratio of these inflows. Its principle is to inject a solution of the tracer (with given concentration

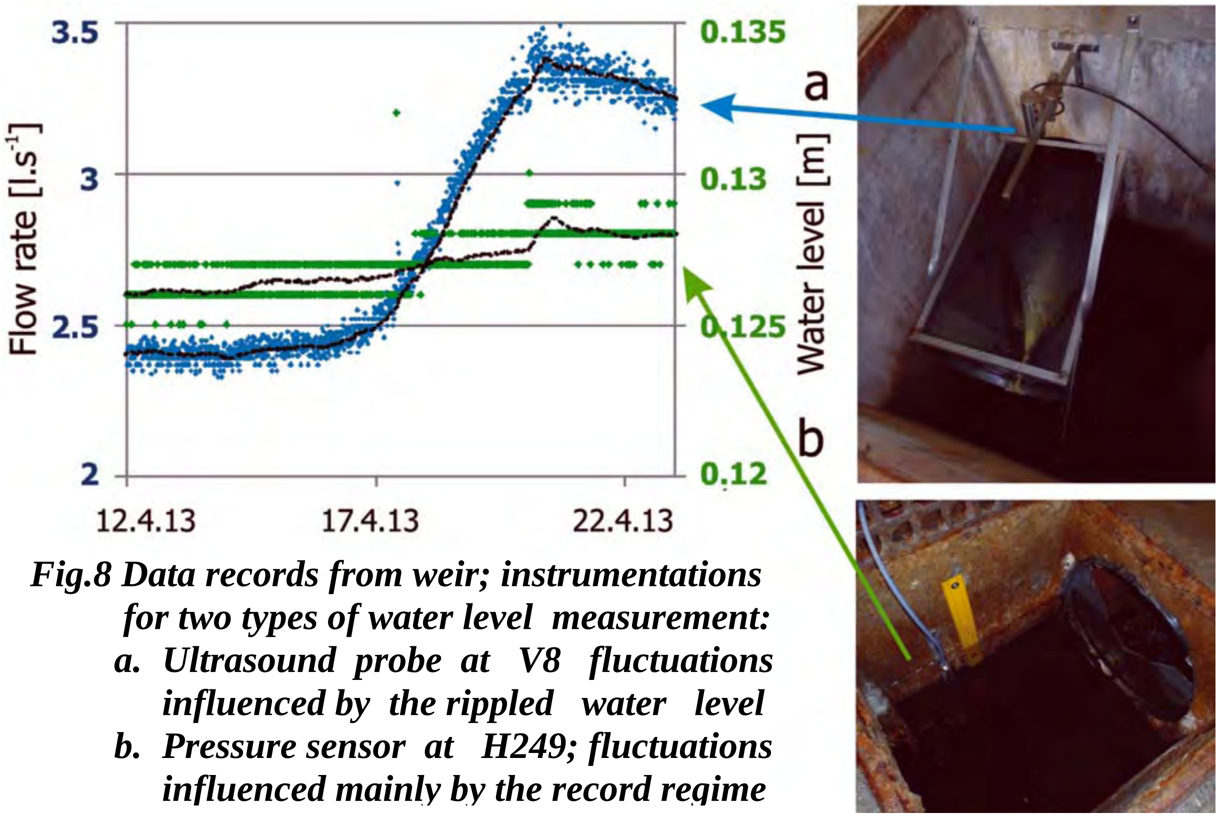

Fig.8 Data records from weir; instrumentations for two types of water level measurement:

a. Ultrasound probe at V8 fluctuations influenced by the rippled water level

b. Pressure sensor at H249; fluctuations influenced mainly by the record regime

and flow-rate) to the canal and then measure decreasing concentrations of the tracer in diluted solution along the canal (Fig. 10). This measurement can be provided at various places at the same time.

The experiment and principles of the adjusted dilution method is in detail described in (Hokr et al., 2012) – evaluation for the sequence of places along the canal and an improved calibration procedure. If we consider a large contrast of both concentrations and flow-rates, between the canal water and the injection, the mixing process can be described by mixing equation $Q = q \times c_1 / c_2$, where Q [$m^3 \times s^{-1}$] is the measured flow rate in stream/canal, q [$m^3 \times s^{-1}$] is the injected flow rate, c_1 is the injected concentration and c_2 is the observed concentration below injection.

The concentration can be detected by measuring electrical conductivity, which is easy with basic equipment. We need a correct evaluation of the concentration from a relation between concentration and conductivity in the process of dilution (can be done in laboratory). We have used the solution of *KBr* for our experiment. It matched the linear dependence of concentration on the conductivity for such range of conductivities, several times overcoming the range needed for the experiment. The instrumentation is shown on Fig. 11 (an injection of the tracer into the collection canal; an automatic measurement provided by the MS6D data logger (COMET SYSTEM, 2011); manual conductivity measurement with the multi-meter WTW Multi 3430 (WTW, 2011)).

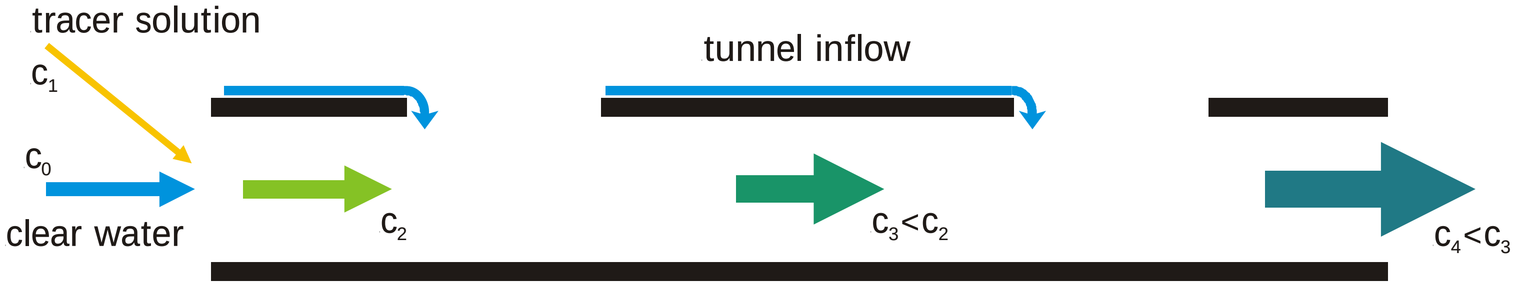

Fig.10 Dilution of the tracer solution along the canal

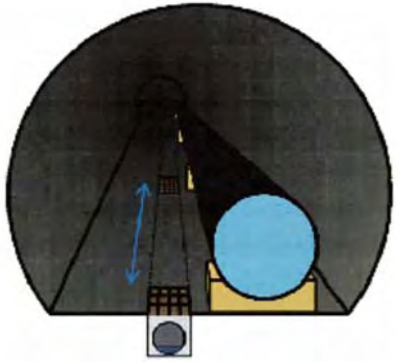

Fig.9 The collecting canal

Fig.11 Arrangement of the experiment

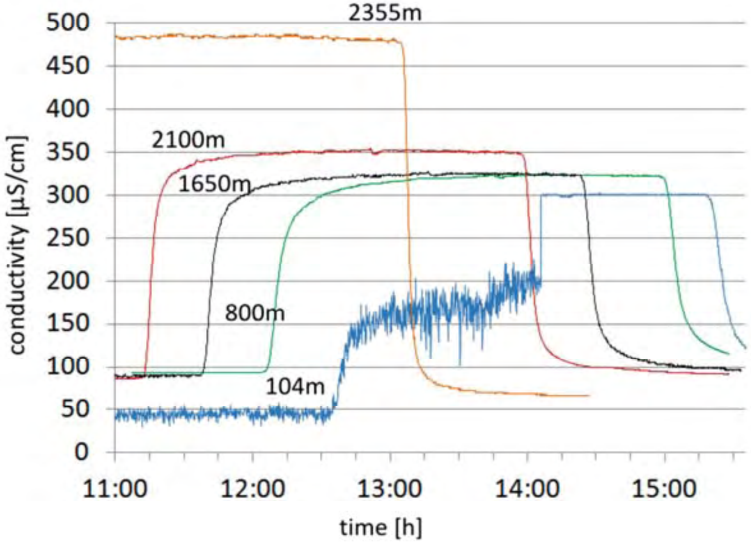

Fig.12 Automatic measurement

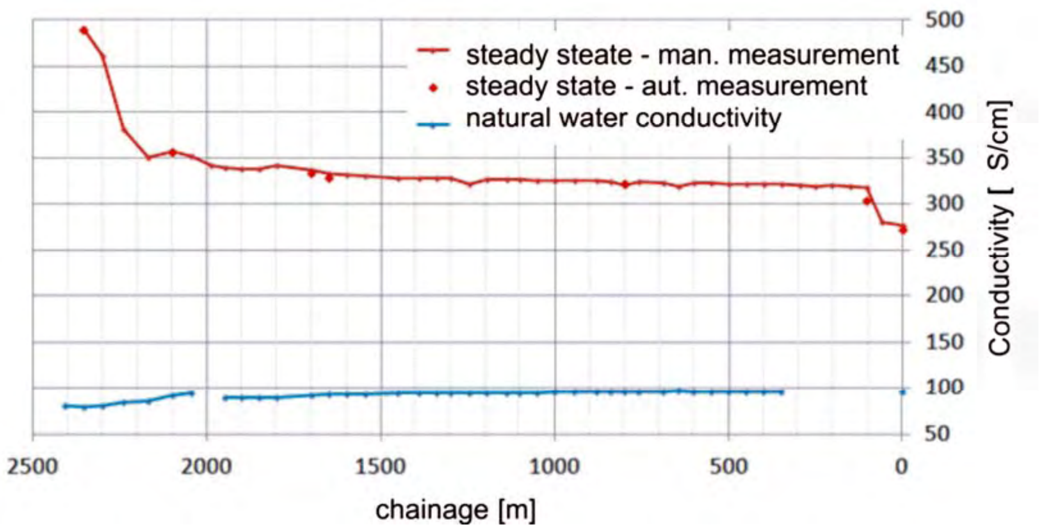

Fig.13 Measured conductivities along the canal

Continual conductivity measurement has been done (due to its demands of equipment) only in points, where the weirs are installed. Figure 12 documents the course of the conductivity in time for each continually observed point (with the clearly reached steady state condition). The manual measurement has been done in every accessible point in the canal. In common points, it is in good agreement with continual measurement (Fig. 13) and it validated the remaining manual measurement (as the steady state).

Computed detailed distribution of flow rates along the collection canal from manual measurement is shown in Fig. 14. The red line is for the experiment made in August 2012, the blue line is for the experiment made in April 2013 (in the early spring, the inflow to the tunnel is usually higher due to the snow melting). The inflow rates in chosen five sections of the tunnel, evaluated with the data from two experiments, are listed in Tab. 1. For comparison, the third column of the tab. 1 shows the inflow values measured by Bělohradský in 2004 (the mobile weirs were used). Despite the possible inaccuracy of the method used in 2004, the results are comparable and they all confirm the inflow distribution generally known from the observation. The results for the last experiment from April 2013 correspond with the data from the new weirs.

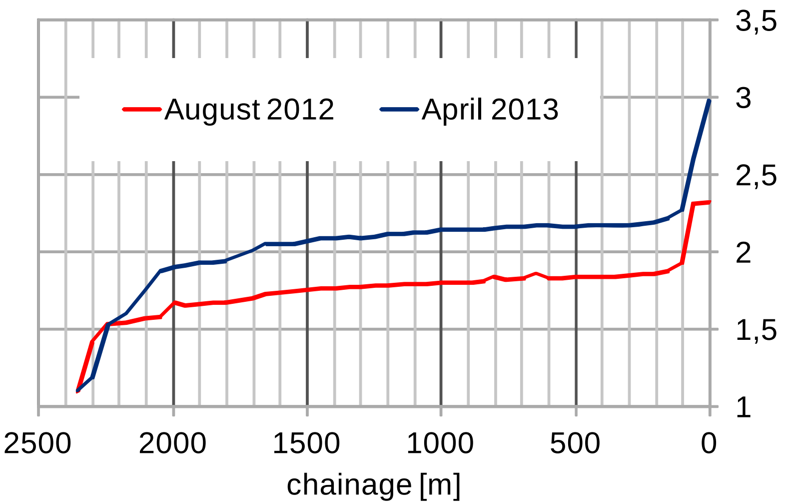

Fig.14 Flow rate distribution along the canal

There remain some unanswered questions: the decrease of the conductivity of the tracer solution along the tunnel was not strictly monotonous (in both experiments). Moreover, the calibration curve for the tracer was done by dilution with one type of water (from the one place in the tunnel), while the natural conductivity of the inflow changes along the tunnel.

3 Conclusions

We presented several methods of the flow rate measurement applied to the tunnel inflow. The measurement with tipping buckets and vessels can be well adapted for the individual inflow sources. The discharge range of the vessel can be extended by using more holes. Its precision can be provided by the proper placement of the holes.

In the post-processing, it is important to distinguish the possible sources of disturbances, which can be quite diverse, either from the measurement method (record regime) or from the natural behaviour of the inflow source.

The total inflow rates in various part of the tunnel are measured as differences between flow rates in different points in a collection canal. Continual measurement can be provided with the weirs, but it is not suited for evaluation of small differences between adjacent points. Detailed distribution of flow rates along the tunnel can be evaluated by the dilution method - with only one injection place of the tracer, we obtain the flow rate distribution along the canal better for the difference evaluation. The steady state condition can be proved by the automatic measurement; in our experience the method was well repeatable.

Tab.1 Total inflow to the tunnel

Section position [m]	Total inflow [l/s]		
	August 2012	April 2013	April 2004
0–150	0,44	0,76	1,4
150–885	0,08	0,08	0,17
885–1995	0,13	0,24	0,16
1995–2424	0,57	0,85	0,15
2424–2600	1,1	1,05	1,67
0–2600	**2,32**	**2,98**	**3,55**

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References

BĚLOHRADSKÝ, V. Hydrogeologická měření v bedřichovském tunelu (úsek A*), Studium dynamiky puklinové sítě granitoidů ve vodárenském tunelu Bedřichov v Jizerských horách – Etapa 2006-2008* (Klomínský J., ed.), Zpráva SÚRAO, 2008, p. 83-88. (In Czech)

BD SENSORS, s.r.o., LMP 307, *http://www.bdsensors.cz/vyska-hladiny/ponorne-sondy/detail/produkt/lmp-307/*, 2013.

COMET SYSTEM, s.r.o., LOGGER S6021, *http://www.cometsystem.cz/products/data-loggers/dual-chann-0-20ma-current-datalogger-with-display/reg-S6021*, 2010.

COMET SYSTEM, s.r.o., MONITORING, DATA LOGGING AND CONTROL SYSTEM MS6D, *http://www.cometsystem.cz/products/monitoring-systems/ms6d-data-logger/reg-MS6D*, 2011.

EMS Brno, User manual MicroLog T3, *http://www.emsbrno.cz/r.axd/pdf_v_MicroLog__T3__userman_u_pdf.jpg?ver=*, 2011

FIEDLER-MÁGR, User manual M4016-G, *http://www.fiedler-magr.cz/sites/default/files/dokumenty/manual_m4016-v113.pdf*, 2011

HOKR, M. et al. Tunel Bedřichov – charakterizace granitoidů in situ (Bedřichov tunnel – in situ characterisation of granitoids), *Technical report*, *Radioactive Waste Repository Authority*, 2010, 116p. (In Czech)

HOKR, M., RÁLEK, P., BALVÍN, A. , Dynamika přítoku vody do vodárenského přivaděče Bedřichov, submitted to *Zpr. geol. výzk. v roce 2012*, 2013.

HOKR, M., RÁLEK, P., BALVÍN, A. , Channel flow dilution measurement used for tunnel inflow evaluation, *Latest trends in environmental and manufacturing engineering (Proceedings of WSEAS EG '12)* (Ponis S et al, eds.), WSEAS Press, 2012, p. 171-176.

KLOMÍNSKÝ, J., WOLLER, F. Geological studies in the Bedřichov water supply tunnel. *Technical report 02/2010, SÚRAO* (RAWRA).

SOLINST CANADA Ltd., *http://www.solinst.com/Prod/3001/3001.html* (2013)

ŠPÁNEK, R. ET AL., Bedřichov tunnel – automated measurement of physical quantities, *EGRSE Journal 2011/2*, *2011*, *pp. 73-80.*

VYSOKÁ, H., KAMAS, J., BRUTHANS, J.,CHURÁČKOVÁ, Z., JEŽ, M., Charakter proudění a střední doba zdržení vody v nesaturované zóně krasu (Ochozská jeskyně, Moravský kras), *Zpr. geol. výzk. v roce 2008*, 2009, p. 255-258. (In Czech)

WTW GmbH, Multi 3430, *http://www.wtw.de/no_cache/en/downloads-support/operating-manuals.html*2011.

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