

Statistical quality control method for automated water flow measurements in concrete dam foundation drainage systems

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Abstract

Seepage through the foundation is a relevant condition for the structural assessment of concrete dams. The knowledge of the water flow measured in the drainage system installed to reduce the uplift pressure in a dam's foundation is, therefore, a main issue in the safety control of concrete dams. Monitoring systems include measuring devices to determine the water collected from drains and weirs in order to evaluate the amount of water that flows through the dam. In most large concrete dams, both manual and automated water flow measurements are possible.

This paper proposes a statistical quality control method for automatic measuring systems based on simultaneous manual water flow measurements and the knowledge of the corresponding measurement uncertainties. Experimental tests performed in a weir of a Portuguese concrete dam are described and paired water flow estimates and corresponding measurement uncertainties are presented and applied to the proposed method. The results of this study show that the method allows statistical quality control of automated water flow measurement systems applied in concrete dam drainage systems.

1. Introduction

The majority of recorded failures in concrete dams, not including issues related with appurtenant structures, are due to problems in the foundation, such as erosion and internal dissolving of rock masses, which often lead to a loss of strength and lack of shear resistance in weak planes of unfavorable direction [1].

Concrete dams are always founded in rock masses, characterized by a significant number on discontinuities or joints, which are very important for the mechanical and hydraulic behaviour of the foundation. Despite impermeabilization works done during construction in the foundations to minimize the water flow, leakage and seepage occur in all concrete dam foundations. The amount of water flow is a function of the reservoir level, watertightness of joints, foundation permeability, reservoir and ambient temperatures, and grout curtain or cutoff effectiveness [2].

Continued measurement of seepage can provide an indication of progressive dissolution or erosion in a dam foundation or abutment [3]. The types of measurement instruments used to monitor

seepage include weirs, flow meters and standard recipients [4].

In general, manual measurements of the water flow in the drainage system is obtained by an operator from the filling time measurement of a standard recipient with known volume. In this paper, this measurement system is denoted as Manual Data Acquisition System (MDAS).

Measurement estimates from MDAS are subjected to an in situ quality control procedure, being compared with previously defined threshold values. These control limits allow the detection of gross measurement errors and are established taking into account the measurement range and extreme values observed in prior records [5].

Many large concrete dams also operate with Automated Data Acquisition Systems (ADAS), which allow water flow measurements in weirs without direct human intervention [1,6,7]. This measurement system has the advantage of performing continuous measurements, being a fundamental tool for real time safety control of concrete dams. Therefore, a high level of confidence in the obtained automatic

measurements is required in order to perform a robust and reliable safety analysis, thus implying the need to adopt a periodic evaluation of ADAS metrological performance.

This evaluation is traditionally achieved by calibration of the measuring system in situ or in laboratory. However, in this case, it reveals to be a complex task since in situ calibration of ADAS lacks reference measurement standards with an acceptable accuracy, while laboratorial calibration is unpractical considering the need to temporarily remove the automatic measurement chain from the concrete dam.

Therefore, to provide traceability to the system, an alternative is proposed: the use of a statistical quality control method based on simultaneous water flow measurements by MDAS and ADAS, and the knowledge of measurement uncertainties found in both measurement methods (manual and automated).

In this paper the identification of uncertainty sources in both measurement methods for each input quantity is presented. The output quantity – water flow – measurement uncertainty is evaluated using the Guide to Expression of Uncertainty in Measurement (GUM) [8]. However, due to the recognizable non-linearity of the applied mathematical models, a Monte Carlo method (MCM) [9] is applied in order to validate the accuracy of the first order GUM approximation results of measurement uncertainty.

The proposed statistical quality control method is applied to experimental data obtained in a Portuguese concrete dam – the Alto Lindoso dam – where the MDAS and ADAS for water flow measurement coexist in three weirs. This study only focuses on results obtained from water flow measurements obtained from the weir named “Bica 1”. The described experimental procedures provided estimates for measurement uncertainty evaluation and statistical quality control analysis of a wide range of automated water flow measurements in concrete dams.

2. Water flow measurement in concrete dam drainage systems

2.1 Water flow measurement by Manual Data Acquisition System

In the MDAS, the water flow measurements in drains and weirs are performed using standard recipients with known volume. The filling time is FLOMEKO 2019, Lisbon, Portugal

manually measured with a stopwatch, thereby obtaining the water flow quantity by

$$Q = \frac{V}{t}, \quad (1)$$

where Q is the water flow (usually expressed in L/min), V is the recipient's volume and t is the recipient filling time.

The recipient choice, and consequently its volume, depends on the magnitude of the water flow observed in a particular drain or weir of the concrete dam. A commonly adopted empirical rule states that a recipient's filling time of less than 10 seconds is not recommended as it decreases the accuracy of the measurement results.

2.2 Water flow measurement by Automated Data Acquisition System

The water flow measurements by ADAS are usually done in weirs located inside the drainage gallery of the concrete dam.

In most concrete dams, the ADAS performs a level measurement using a brass or stainless steel V-notch weir with the following design and installation requirements (see Figure 1) [10]: $0,05 \text{ m} \leq h \leq 0,6 \text{ m}$; $25^\circ \leq \alpha \leq 100^\circ$; $A \leq 0,10 \text{ m}$; $h/A \leq 1,2$; $H/L \leq 0,4$; $L \geq 0,60 \text{ m}$; and $2 \cdot B \geq 1,5 \cdot h$.

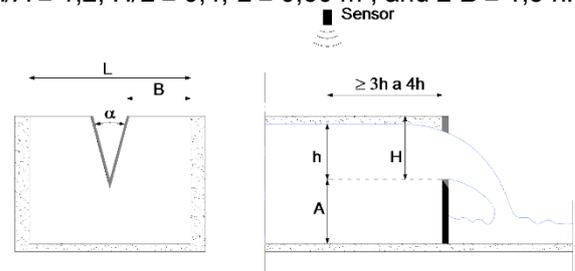


Figure 1: V-notch weir design and installation requirements.

In this type of weir (V-notch), and considering a uniform flow regime, a functional relationship between water level and flow can be established, allowing an indirect evaluation of the water flow. This mathematical relation is generally expressed by the Kindsvater-Shen formula [11]:

$$Q = \frac{8}{15} C_d \cdot \tan\left(\frac{\alpha}{2}\right) \cdot h_e^{\frac{5}{2}} \cdot \sqrt{2 \cdot g} \quad (2)$$

where Q is the water flow (m^3/s), C_d is the discharge coefficient (dimensionless), α is the V-notch angle (rad), g is the gravitational acceleration (m/s^2), $h_e = h + k_h$ is the effective head above the crest of the weir, h (m) is the total head, and k_h is a head correction factor that takes into

account surface tension and viscosity influence (m).

The system's measurement chain is composed of several elements, including an ultrasonic sensor to evaluate the water level in the weir basin and a computational unit where the measurement results are stored.

3. Statistical quality control method

The proposed quality control method of simultaneous ADAS and MDAS water flow measurements is supported in the statistical test of the estimate's difference of the population means, $\Delta = \mu_{Q_{ADAS}} - \mu_{Q_{MDAS}}$. For this purpose, two populations are considered (MDAS and ADAS measurements) with standard deviations, σ_{ADAS} and σ_{MDAS} , each one assumed equal to the correspondent value of the standard measurement uncertainties, $u(Q_{ADAS})$ and, $u(Q_{MDAS})$, respectively.

The statistic is defined as the difference between sample means and the null hypothesis corresponds to zero difference between population means, so that the alternative hypothesis states that difference between population means is not zero,

$$\begin{aligned} H_0 : \mu_{Q_{ADAS}} - \mu_{Q_{MDAS}} &= 0 \\ H_A : \mu_{Q_{ADAS}} - \mu_{Q_{MDAS}} &\neq 0 \end{aligned} \quad (3)$$

In this study, it is assumed that both types of measurements follow Gaussian Probability Distribution Function (PDF), and that they are considered independent of each other.

Once the water flow quantity has a Gaussian PDF, $Q \sim N(\mu_Q, \sigma_Q)$, its mean value PDF corresponds $\bar{Q} \sim N\left(\mu_Q, \frac{\sigma_Q}{n_Q}\right)$, where n_Q corresponds to the sample dimension.

Hence, the statistical test, z , is given by

$$z = \frac{(\bar{Q}_{ADAS}) - (\bar{Q}_{MDAS}) - (\mu_{Q_{ADAS}} - \mu_{Q_{MDAS}})}{\sqrt{\frac{\sigma_{ADAS}^2}{n_{Q_{ADAS}}} + \frac{\sigma_{MDAS}^2}{n_{Q_{MDAS}}}}, \quad (4)$$

and follows a Gaussian PDF, testing the equality of the two Gaussian population means, $\mu_{Q_{ADAS}}$ and $\mu_{Q_{MDAS}}$, based upon independent random samples. The variance of a sample mean depends upon the sample size and the variance of the population from which the sample is selected. Consequently, the sizes of the two samples and the variances of the two populations will influence the comparison of the sample means.

If a significance level equal to 5 % ($\alpha = 0,05$) is considered, the critical values of z are $-1,96$ and $+1,96$. As a consequence, the decision rule is such that if $z < -1,96$ or $z > +1,96$, the null hypothesis H_0 is rejected.

4. The case study of the Alto Lindoso concrete dam

The proposed quality control method for automated water flow measurements was tested in the Alto Lindoso dam (see Fig. 2). Built in 1992, it is a double curvature concrete arch dam located in a symmetrical valley in the North of Portugal, and currently exploited by EDP (a Portuguese company for electricity production). It is 110 m high with a total crest length of 297 m, having three internal horizontal galleries and a drainage gallery close to its foundation.



Figure 2: The Alto Lindoso concrete dam.

All the water gotten from drains and leakages is collected in three weirs. Weir named "Bica 1" collects a portion of the water drained in the left bank.

MDAS are performed both in drains and weirs using a stopwatch and available standard recipients with volumes equal to 0,1 L, 0,25 L, 0,5 L, 1 L, 2 L, 5 L and 10 L. In addition, at the three weirs, ADAS measurements are also available through the use of ultrasonic sensors to evaluate the water flow.

The ADAS flow meters installed consider a V-notch angle of $\pi/6$ rad. The output quantity - water flow - is obtained through the use of the Kindsvater-Shen formula (eq. 2) considering, as suggested by the equipment supplier, a head correction k_h equal to zero and a discharge coefficient C_d equal to 0,62.

The main metrological characteristics of the ultrasonic sensor for distance measurement installed at the Alto Lindoso concrete dam are: (i) water level measurement range up to 100 mm; (ii) linearity below 0,2 %; (iii) repeatability equal to 0,3 %.

MDAS water flow measurements recorded in weir “Bica 1” from January 2010 to March 2019 are presented in Fig. 3 (manual measurements were scheduled each two weeks and the time of the measurement was not recorded).

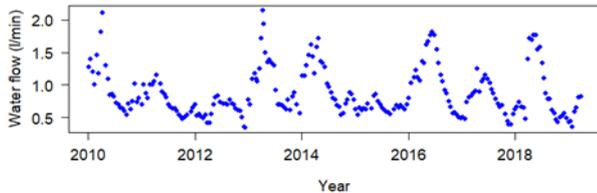


Figure 3: MDAS measurements in the weir Bica 1 (2010-2019).

4.1 Measurement uncertainty evaluation

The following sections present the measurement uncertainty evaluation performed for the MDAS and ADAS. A first approach for uncertainty propagation for indirect measurement of water flow (see expressions 1 and 2) was done using the GUM method. The model obtained by the GUM method is easier to use than the model based on the MCM, as it requires less computational effort, and its implementation and use is simpler and more direct than the MCM. However, due to non-linearities, some representative MCM results were obtained in order to validate the GUM results. After being properly validated through the MCM, the model based on the GUM method can be adopted.

4.1.1 Water flow measurement using MDAS

Two input quantities are measured when using the MDAS for indirect measurement of water flow: (i) the standard recipient volume; (ii) the corresponding filling time interval. In this study, the following probabilistic formulation is considered: (i) the nominal volume, V (L/min), of the standard recipient is assumed as the measurement estimate and a triangular PDF is adopted; this function is centred at the volume estimate and its variation limits are within $\pm 2,5$ %, accounting for calibration and temperature uncertainty sources. The triangular PDF is adopted for uncertainty components since limit values for its dispersion are known but there isn't enough information to evaluate if it has a probabilistic gaussian behaviour; (ii) the main uncertainty sources of the filling time measurement, t (min), are considered to be the repeatability and the reproducibility related to the manual measurement through the use of a stopwatch; the PDF for this quantity is triangular and centred at the estimate obtained and variation limits are within $\pm 0,75/60$ min.

The application of GUM's Uncertainty Propagation Law (correlation parameters are null) allows the expression of the MDAS water flow variance as

$$u^2(Q_{MDAS}) = \left(\frac{\partial Q}{\partial V}\right)^2 \cdot u^2(V) + \left(\frac{\partial Q}{\partial t}\right)^2 \cdot u^2(t), \quad (5)$$

where the sensitivity coefficients are equal to $\frac{\partial Q}{\partial V} = \frac{1}{t}$ and $\frac{\partial Q}{\partial t} = -\frac{V}{t^2}$. Based on the above mentioned formulation, the input measurement standard uncertainties are $u(V) = \frac{0,025}{\sqrt{6}} \cdot V$ and $u(t) = \frac{0,75}{60\sqrt{6}}$ min. The 95 % expanded measurement uncertainty relative, $\frac{U_{95\%}(Q_{MDAS})}{Q_{MDAS}}$, is given by

$$\frac{U_{95\%}(Q_{MDAS})}{Q_{MDAS}} = 1,98 \cdot \sqrt{\frac{2,6 \cdot 10^{-5}}{t^2}} + 1,04 \cdot 10^{-4}, \quad (6)$$

with t (min). Based on the previous expression, Fig. 4 presents the estimate and 95 % relative expanded measurement uncertainty evolution according to filling time interval and recipient volume.

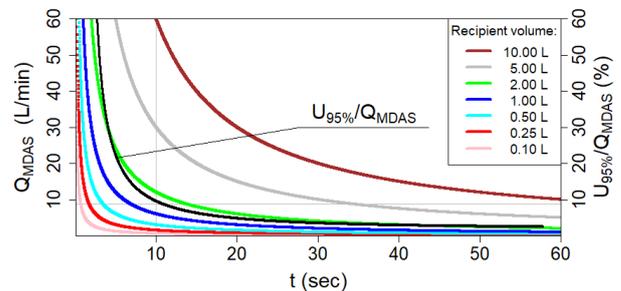


Figure 4: Water flow estimates and relative 95 % expanded uncertainty function of filling time interval and recipient volume.

Fig. 4 confirms the adequacy of the filling time interval rule which states that measurements should only be made with time intervals above 10 s in order to reduce measurement uncertainties. It is possible to observe that, in a filling time interval between 10 s and 60 s, the 95 % relative expanded measurement uncertainty related to the water flow reduces from, approximately, 6,5 % to 2,3 %.

4.1.2 Water flow measurement using ADAS

According to expression (2), three different input quantities are required for ADAS water flow indirect measurement: (i) the discharge coefficient; (ii) the weir's V-notch angle; (iii) the water level above the weir's V-notch. The following probabilistic formulations are considered: (i) a discharge coefficient estimate equal to 0,62 is used in the

parameterisation of the water level measurement equipment; for this input quantity, C_d , a triangular PDF is considered, centred at the mentioned estimate with variation limits within $\pm 0,01$; therefore, the related measurement standard uncertainty is given by $u(C_d) = \frac{0,01}{\sqrt{6}}$; (ii) the nominal V-notch angle for weir “Bica 1”, α , is equal to $\pi/6$ rad; this value is used as the centre of a triangular probability distribution function with variation limits equal to $\pm \pi/360$ rad, corresponding to a measurement standard uncertainty given by $u(\alpha) = \frac{\pi}{360 \cdot \sqrt{6}}$ rad; (iii) the main uncertainty sources for the water level measurement, h , are the linearity and the repeatability related to the ultrasound measurement equipment, and the floatation on the water crest. The in situ experimental observation of the water floatation phenomenon allows representing its probabilistic behaviour by a Gaussian PDF, with a null central value and standard deviation equal to 1,5 mm. The combined standard uncertainty is equal to $u(h) = \sqrt{1,3 \cdot 10^{-5} \cdot h^2 + 2,25 \cdot 10^{-6}}$ m. Using GUM's Uncertainty Propagation Law, an expression for the ADAS water flow variance can be obtained,

$$u^2(Q_{ADAS}) = \left(\frac{\partial Q}{\partial C_d}\right)^2 \cdot u^2(C_d) + \left(\frac{\partial Q}{\partial \alpha}\right)^2 \cdot u^2(\alpha) + \left(\frac{\partial Q}{\partial h}\right)^2 \cdot u^2(h), \quad (7)$$

where the sensitivity coefficients are the following,

$$\frac{\partial Q_{ADAS}}{\partial C_d} = \frac{8}{15} \cdot \tan\left(\frac{\alpha}{2}\right) \cdot h^{\frac{5}{2}} \cdot \sqrt{2 \cdot g}, \quad (8)$$

$$\frac{\partial Q_{ADAS}}{\partial \alpha} = \frac{4}{15} \cdot C_d \cdot \left(\tan^2\left(\frac{\alpha}{2}\right) + 1\right) \cdot h^{\frac{5}{2}} \cdot \sqrt{2 \cdot g}, \quad (9)$$

$$\frac{\partial Q_{ADAS}}{\partial h} = \frac{4}{3} \cdot C_d \cdot \tan\left(\frac{\alpha}{2}\right) \cdot h^{\frac{3}{2}} \cdot \sqrt{2 \cdot g}. \quad (10)$$

The development of the previous variance expression, supported in the discharge coefficient and V-notch angle estimates for weir “Bica 1”, allows writing the 95 % relative expanded measurement uncertainty as

$$\frac{U_{95\%}(Q_{ADAS})}{Q_{ADAS}} = 2,622 \cdot 10^{-2} \sqrt{1 + \frac{8,018 \cdot 10^{-2}}{h^2}}. \quad (11)$$

Based on this expression, Fig. 5 shows the absolute and 95 % relative expanded measurement uncertainty in a wide range of water flow measurements by ADAS.

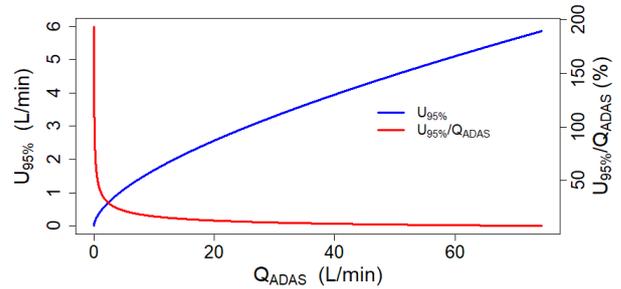


Figure 5: Absolute and relative expanded uncertainty (95 % confidence level) for ADAS water flow measurements.

For the case of the ADAS related to weir “Bica 1”, where the water level measurement range is between zero and 100 mm, the 95 % relative expanded measurement uncertainty of the water flow is close to 30 %, for a water flow near 2 L/min and converges to 8 % for higher water flow estimates. These results were validated by MCM for a wide range of water flow values (0,5 L/min, 1 L/min, 2 L/min, 5 L/min, 10 L/min, 20 L/min, 30 L/min, 40 L/min, 50 L/min and 60 L/min). The PDF, provided through the MCM, shows that the studied measurement range has a Gaussian shape.

4.2 Experimental work

The main objective of the experimental work was to obtain simultaneous MDAS and ADAS water flow measurements in weir “Bica 1” in order to apply the proposed quality control method to a wide measurement interval. The first measurements were obtained under natural operational conditions of the dam (water flow values below 2 L/min). Artificial water flows were introduced in the weir in order to achieve high water flow values (up to 35 L/min).

The water flow measurement procedure by MDAS included a visual inspection of the weir to determine the existence of residues that could constitute obstacles to the water flow. Each water flow increment over the studied range was followed by a stabilization time interval of the water surface inside the weir before recording any measurement.

During the test, the ADAS was programmed to record measurements each minute. During this test, a total of approximately 350 measurements were made. The results are presented in Fig. 6. From the obtained results, pairs (Q_{MDAS}, Q_{ADAS}) were selected based on the time of measurement. Fig. 7 shows good agreement between the pairs of water flow values as they can be located,

approximately, along an ideal straight line ($Q_{MDAS} = Q_{ADAS}$).

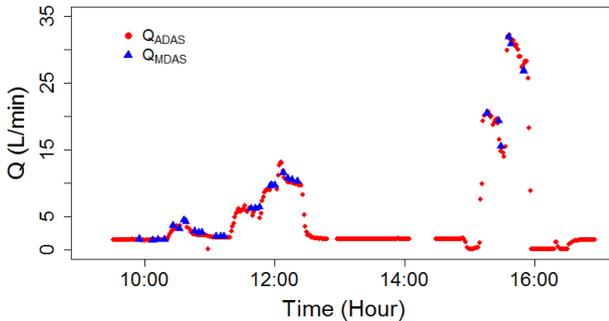


Figure 6: MDAS and ADAS flow measurements in weir Bica 1.

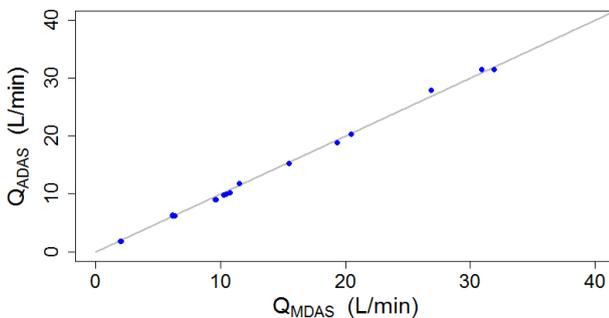


Figure 7: Paired water flow observations.

The statistical quality control method proposed is applied to the previously collected data to verify if there is evidence of rejection of the null hypothesis. The results presented an absolute z value minor than 0,75, whereby there is no evidence to reject the null hypothesis for a significance level equal to 5 %.

5. Final remarks

This study indicates that the ADAS device for water flow measurement in weir “Bica 1” at the Alto Lindoso dam has an acceptable metrological performance for the intended use, based on the experimental work activities.

Measurement uncertainties were also evaluated, showing that the MDAS has a 95 % relative expanded measurement uncertainty between 6,5 % and 2,3 %, considering filling time intervals between 10 s and 60 s. In the case of the ADAS, the relative expanded uncertainty obtained assumes high values (30 %) for the water flow near 2 L/min and converges to 8 % for higher water flow estimates.

The experimental activity regarding simultaneous measurements with MDAS and ADAS revealed

that a uniform water flow regime in the weir is critical for the accuracy of the automatic measurements since it affects the stability of the water surface and, consequently, the water level reading. Regular weir cleaning is recommended in order to improve the stability of the water flow and remove any residues on the water's surface, eliminating changes in its viscosity and superficial tension.

The proposed method is suitable to perform statistical quality control of automated water flow measurements by ADAS in concrete dams. However, to do so, it is recommended that ADAS measurements are obtained in a synchronized way with MDAS water flow measurements scheduled in a dam's observation plan.

6. Acknowledgements

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