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ASSESSMENT OF STORED AUTOMATED MEASUREMENTS IN CONCRETE DAMS

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Abstract. *Scientific and technological advances in monitoring systems allow for the automation of the measurement, transmission and data processing, as happens in the Portuguese dams with automated monitoring systems. However, as measuring has become increasingly easy, the increase in the amount of data available is significant, as well as the number of potential errors associated with the measuring process. The assessment of stored measurements is important because they are one of the main elements used in the activities related to the interpretation of the behavior and to the safety control of concrete dams.*

A detailed assessment of measurements should be performed, for example, through the comparison of the Automated Data Acquisition System (ADAS) measurements, x_{ADAS}, *and other values that may be used as a reference, such as Manual Data Acquisition System (MDAS) measurements,* x_{MDAS}. *In most situations, it is possible to perform both ADAS and MDAS measurements. In the case of MDAS measurements, the instruments used in concrete dam monitoring follow relatively simple physical principles and there is a lot of experience acquired over the years. This allows us to consider that the MDAS measurements are of good quality, which makes them a good reference element for the analysis of ADAS measurements.*

The main idea of the methodology proposed is to assess if ADAS and MDAS measurements from paired samples (x_{ADAS}, x_{MDAS}) *represent the same population. For each pair of measurements* (x_{ADAS}, x_{MDAS}), *very close values are expected.*

Probability density function (PDF) may be used to characterize the measurement distribution of each sample. In the case of paired ADAS and MDAS measurements, two similar probability density functions (not necessarily identical due to random effects) are expected, that is $PDF(x_{ADAS}) \approx PDF(x_{MDAS})$. *If there are differences between ADAS and MDAS samples, these differences will be reflected in each PDF, and the causes may be identified.*

1 ERRORS AND UNCERTAINTY IN MEASUREMENT

The measurement error is the difference between the measurement result and the true value of the physical quantity measured (the measurand). The measurement error, ζ, is constituted by three components, Eq. 1: one methodological component, ζ_m; one instrumental component, ζ_i, and a human component, ζ_h.

$$\zeta = \zeta_m + \zeta_i + \zeta_h \qquad (1)$$

In each of these components, several factors can be found which contribute to the measurement error. As described by Ribeiro [1]:

- In the methodological component, such factors are: the inadequate formulation of the theory of the phenomenon that supports the measurement, the inaccuracy of the relation that determines the measurand estimation, and the discrepancy between the conceptual model and the reality.
- In the instrumental component, such factors are: the inherent imperfections of the instruments, the intrinsic performance of instrumentation and the influence of external factors.
- In the case of the human component, observable in situations where such intervention is influential, such factors depends on the human interpretation of information and includes the decision and the record of an occurrence (a reading record of analogical display elements, for example).

The knowledge of the measurement error is impossible, but its estimation is possible, by means of a calibration process. Credible information about the measurement is possible since the nature of the error and its upper boundary can be known.

According to another classification, the measurement error is composed of the gross errors, systematic errors, and random errors.

The gross error is less common and probably is the easiest to identify. Usually, this type of error is related to the poor use or malfunction of the measurement system. It can be the result of erroneous readings, the erroneous execution of procedures or damage of the measurement system. In general, it is considered that the measurement procedures are sufficiently robust and that these types of errors can be identified and eliminated.

The systematic error assumes the same value under measurements made in identical conditions. The main causes of this type of error are related to constructive aspects of the measuring instrument, with the measurement procedures, with the wear of the instrument components, or with factors related to environmental conditions.

The random error is related to the fact that in repeated measurements, under the same conditions, different results can be obtained. The causes that lead to this dispersion in the measurement results are associated with the existence of vibration, friction, fluctuations in the voltage, or changes in the environmental conditions or other quantities of influence. The random error can be characterized by statistical procedures. This type of error is usually modeled by a normal distribution with zero mean. In practice, when several measurements are made, the average of the random error tends to zero. The random error can be estimated by the variability (standard deviation) of the fluctuations in its measurements. Assuming that a sufficiently large number of measurements is performed, the influence of random error in the average value of the measurements is likely to be negligible. Thus, the mean value of a large number of measurements performed repeatedly is predominantly affected by systematic errors.

If it was possible to quantify each portion of error, the measurement result could be corrected and the true value would be known. Although the systematic error can be approximately well estimated, the random error by its nature is not estimable. As a consequence, the correction of this error is not possible.

The approximate knowledge of the systematic error and the random error is always desirable, because it makes possible a partial correction and estimation of the uncertainty present in the result of a measurement.

2 ASSESSMENT OF STORED ADAS MEASUREMENTS OF PORTUGUESE DAMS

In Portugal, automated monitoring systems have a conventional structure, comprised of an automated data acquisition system, data transmission system, and data processing and management system (Fig. 1). A new data processing and management system for monitoring, diagnosis and safety control, called GestBarragens, has been under development since early 2000 [2,3].

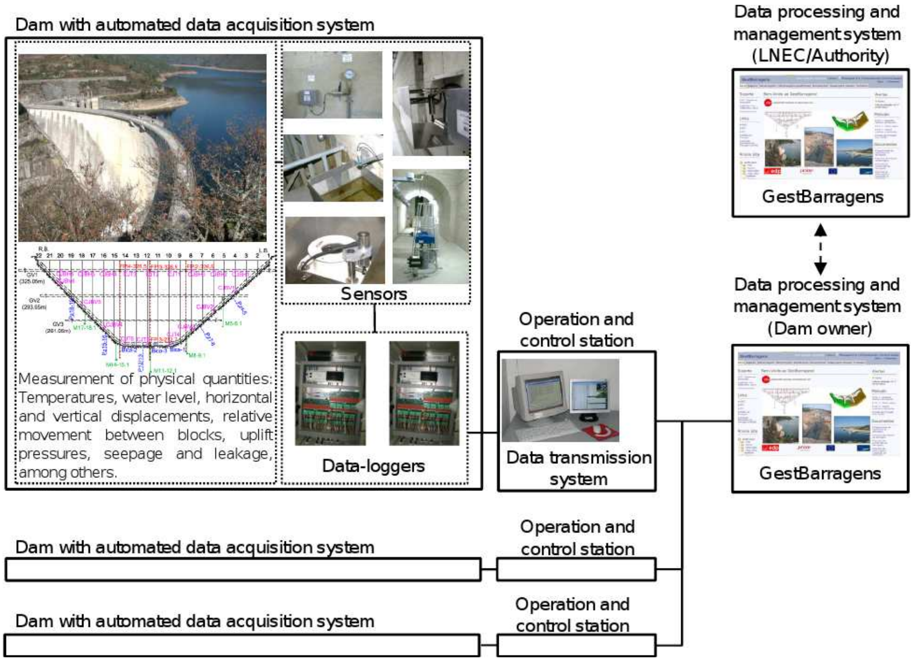

Figure 1: Automated monitoring system of concrete dams in Portugal.

ADAS in concrete Portuguese dams are still in an experimental phase and there are no procedures for quality control of measurements. The implementation of procedures for quality control of measurements (in a schedule along time) is essential to have confidence in the measurements. The assessment of stored measurements (in management information systems, such as GestBarragens) is equally important because they are one of the main elements used in the activities related to the interpretation of the behavior and to the safety control of concrete dams.

Due to the large amount of stored data, a visual and qualitative analyses of the stored measurements should be carried out in order to detect gross measurement errors (for example, through the analysis of figures of ADAS and MDAS measurements along time, as shown in figure 2). Then, a detailed assessment of measurements should be performed, for example, through the comparison of the ADAS measurements, x_{ADAS}, and other values that may be used as a reference (such as MDAS measurements, x_{MDAS}). In most situations, it is possible to perform both ADAS and MDAS measurements. In the case of MDAS measurements, the instruments used in concrete dam monitoring follow relatively simple physical principles and there is a lot of experience acquired over the years. This allows us to consider that the MDAS measurements are of good quality, which makes them a good reference element for the analysis of ADAS measurements.

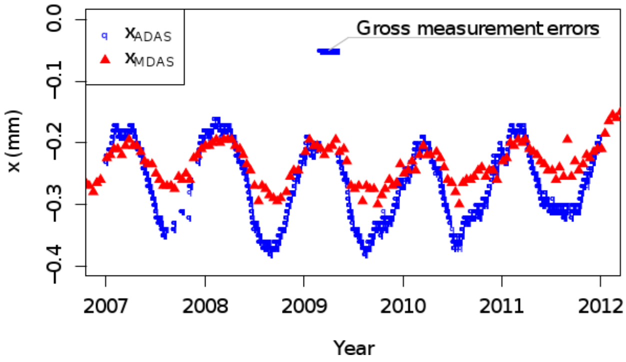

Figure 2: Example of ADAS and MDAS measurements along time. Identification of gross measurement errors.

The main idea of the proposed methodology is to assess if ADAS and MDAS measurements in paired samples (x_{ADAS}, x_{MDAS}) represent the same population. For each pair of measurements (x_{ADAS}, x_{MDAS}), very close values (this is $x_{ADAS} \approx x_{MDAS}$) are expected.

Probability density function (PDF) may be used to characterize the measurement distribution of each sample. In the case of paired ADAS and MDAS measurements, two similar probability density functions (not necessarily identical due to random effects) are expected, that is PDF(x_{ADAS})≈PDF(x_{MDAS}). If there are differences between ADAS and MDAS samples, these differences will be reflected in each PDF, and the causes may be identified.

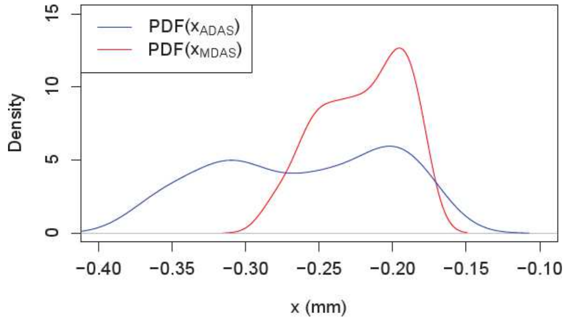

Figure 3: Example of probability density functions of two samples with different average and range.

The difference between ADAS and MDAS measurements in each paired sample, $x_{ADAS} - x_{MDAS}$, allows for the identification of the average value and the dispersion of the difference between ADAS and MDAS measurements. Its representation through the probability density function PDF($x_{ADAS} - x_{MDAS}$) is also useful (Fig. 4).

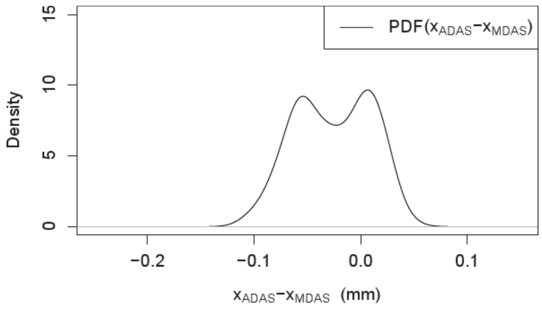

Figure 4: Example of a probability density function of $x_{ADAS} - x_{MDAS}$.

The graphical representation of the paired samples (x_{MDAS}, x_{ADAS}) (Fig. 5) also allows for the visualization of the main differences when compared with the ideal situation (paired samples over the line $x_{ADAS} = x_{MDAS}$).

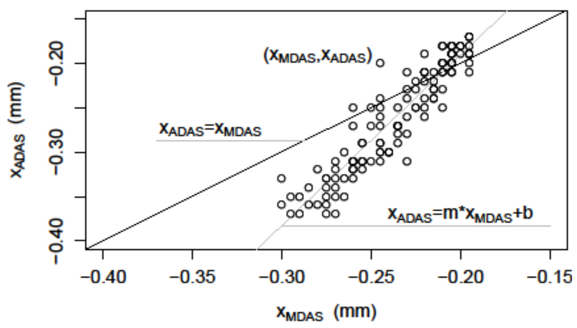

Figure 5: Paired (x_{MDAS}, x_{ADAS}) samples and linear regression model.

In cases where the relation between ADAS and MDAS measurements is linear, the knowledge of the regression model $x_{ADAS} = m * x_{MDAS} + b$ allows for the characterization of the relation between the measurements of the two systems. The elimination of the deviations (of ADAS measurements when MDAS measurements are considered the reference sample) can be performed through Eq. 2 (Fig. 6).

$$x_{ADAS}^{new} = \frac{x_{ADAS}-\bar{x}_{ADAS}}{m} + \bar{x}_{MDAS} \qquad (2)$$

where x_{ADAS}^{new} is the $\bar{x}_{ADAS}$ after correction, x_{ADAS} represents the average of x_{ADAS} samples, $\bar{x}_{MDAS}$ represents the average of x_{MDAS} samples, and m is the regression coefficient of the straight line. After this transformation $(\bar{x}_{ADAS}^{new} = \bar{x}_{MDAS})$.

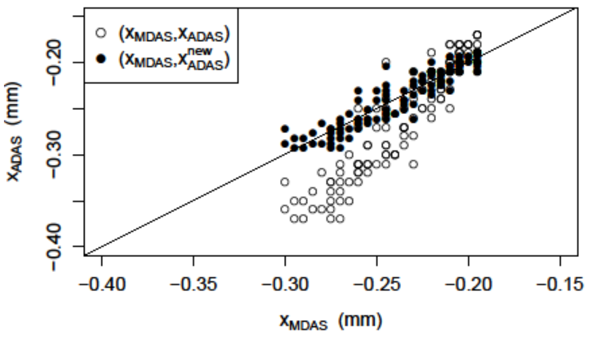

Figure 6: Paired (x_{MDAS}, x_{ADAS}) and paired $(x_{MDAS}, x_{ADAS}^{new})$.

The proposed method for the assessment of stored measurements consists of the combined analysis represented in figures 3, 4, 5 and 6.

3 CASE STUDY

An evaluation of ADAS measurements of all Portuguese dams (stored in GestBarragens) was performed, and a large number of anomalous values were identified through visual analysis of figures with the evolution of physical quantities along time. As a conclusion, it can be stated that the analysis of the dam's behavior through stored ADAS data is not yet possible, and a considerable effort to eliminate gross measurement errors is necessary.

In the scope of this work, a detailed assessment of stored ADAS measurements (from 2007 until 2012) of the Alto Lindoso dam was performed.

3.1 The Alto Lindoso dam

The Alto Lindoso dam is a double curvature concrete dam which construction finished in 1992 in a symmetrical valley of the Lima River, in the north of Portugal (Fig. 7). The dam is 110 m high, the crest elevation is 339.0 m, and the total crest length is 297 m. The thickness of the central block is 4 meters at the crest and 21 meters at the base. There are three internal horizontal inspection galleries (GV1, GV2 and GV3) across the dam and a drainage gallery (GGD) close to the foundation [4].

Figure 6: Alto Lindoso dam.

In accordance with best technical practices, the monitoring system of the Alto Lindoso dam aims at the evaluation of the loads, the characterization of the rheological, thermal and hydraulic properties of the materials, and the evaluation of the structural response [5]. The monitoring system of the Alto Lindoso dam consists of several devices which make it possible to measure quantities such as: concrete and air temperatures, reservoir water level, seepage and leakage in the foundation, displacements in the dam and in its foundation, joint movements, strains and stresses in the concrete, and pressures, among others.

In the recent past, an automated data acquisition system was installed but it is still in a testing phase. ADAS includes the measurement of horizontal displacement along pendulums (telecoordinometers), relative displacements in the foundation (rod extensometers), relative movements between blocks (superficial jointmeters), discharges (in weirs) and the uplift pressure (piezometers). Figure 8 illustrates the location of the ADAS devices of the Alto Lindoso dam. Manual measurement is also possible in these places.

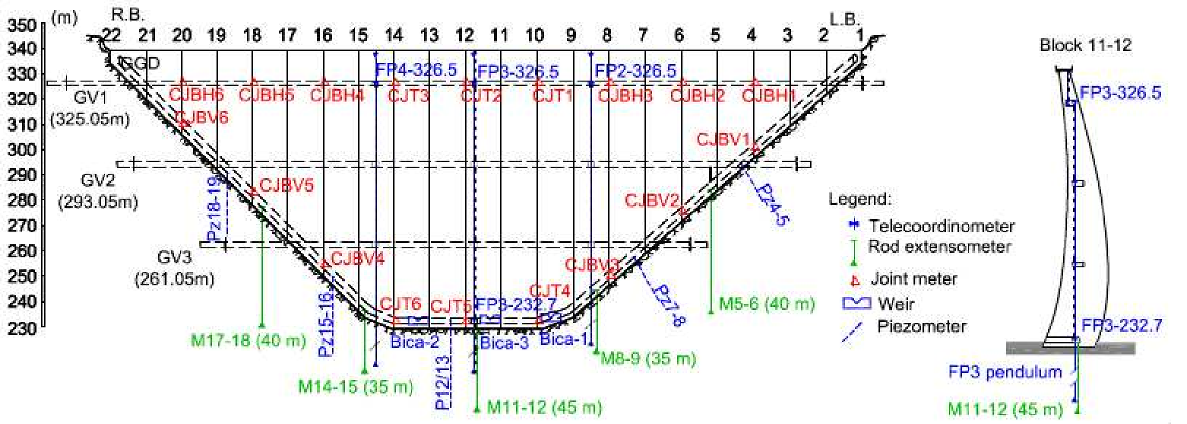

Figure 8: Location of ADAS devices in the Alto Lindoso dam.

In operation since December 2004 (Geoexperts, 2004), the current schedule defines automated hourly readings and their local validation with maximum and minimum thresholds previously established (only the records obtained at 0:00 h, 8:00 h and 16:00 hours are sent and stored in GestBarragens database). Besides the programmed schedule of the readings, the ADAS allows to perform readings whenever requested.

3.2 Assessment of stored ADAS measurements of the Alto Lindoso dam

The stored ADAS measurements of Alto Lindoso dam are taken at 0:00 h, 8:00 h, and 16:00 h. The ADAS measurements recorded at 8:00 h were chosen for the comparison with the MDAS measurements because, up until a few years ago, there was no register of the hour of the MDAS data and because for most of the physical quantities, the ADAS records of the daily amplitudes are very small when compared with its annual variation.

An analysis of the remaining stored ADAS measurements was performed, after the elimination of gross measurement errors. From this analysis it was concluded that, apart from gross measurement errors and small variations due to random effects, there were systematic differences between the ADAS and MDAS measurements.

In telecoordinometers and jointmeters, the differences in the measurements are mainly due to differences in the zero scale and/or to differences in sensitivity (to the same measurand variation). The differences were minimized through equations like Eq. 2. Examples of typical differences are illustrated in figures 9 and 10.

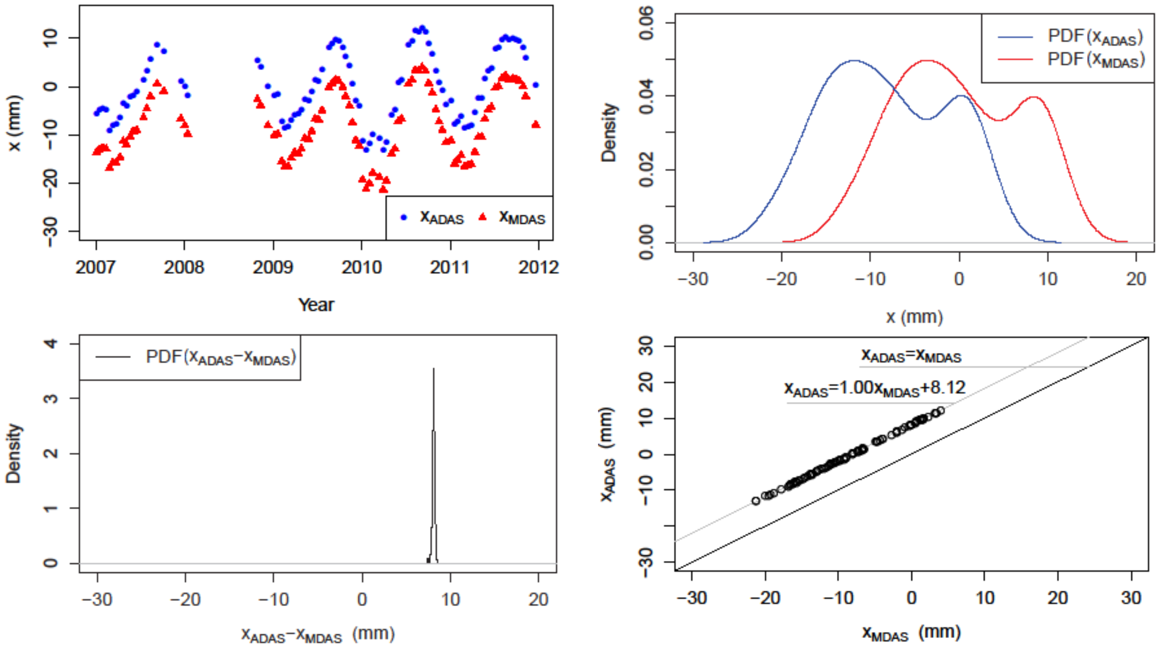

Figure 9: Typical differences between ADAS and MDAS results found in radial displacements measured in pendulums (FP2-326.5 example).

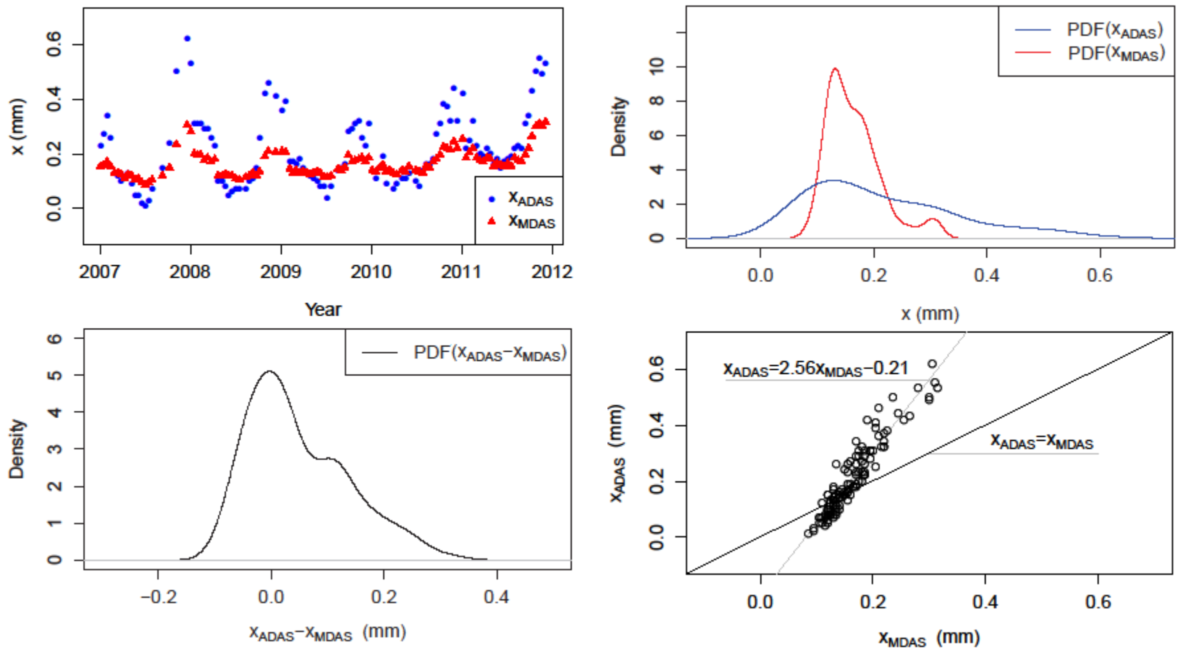

Figure 10: Typical differences between ADAS and MDAS results found in opening-closing movements between blocks (CJT3 example).

In rod extensometers measurements, general problems related to the lack of sensitivity and false trends along time were verified (Fig. 11 and 12).

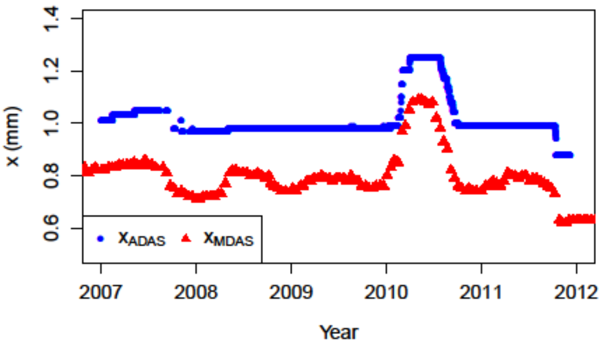

Figure 11: Lack of sensitivity in measurements in rod extensometer (M11-12 (45 m) example).

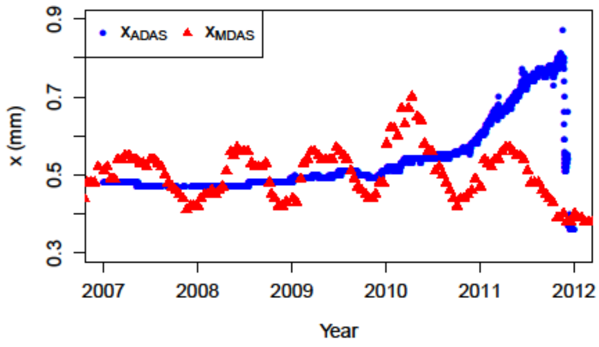

Figure 12: False trend in measurements in rod extensometer (M14-15 (35 m) example).

In weirs, there is evidence that discharges measured are concomitant (Fig. 13). However, a particular reference is made due to the false increase of water height and discharges due to the creation of a layer of residues (Fig. 14). The cleaning of the water surface must be performed on a scheduled basis, in accordance to the manual inspection program.

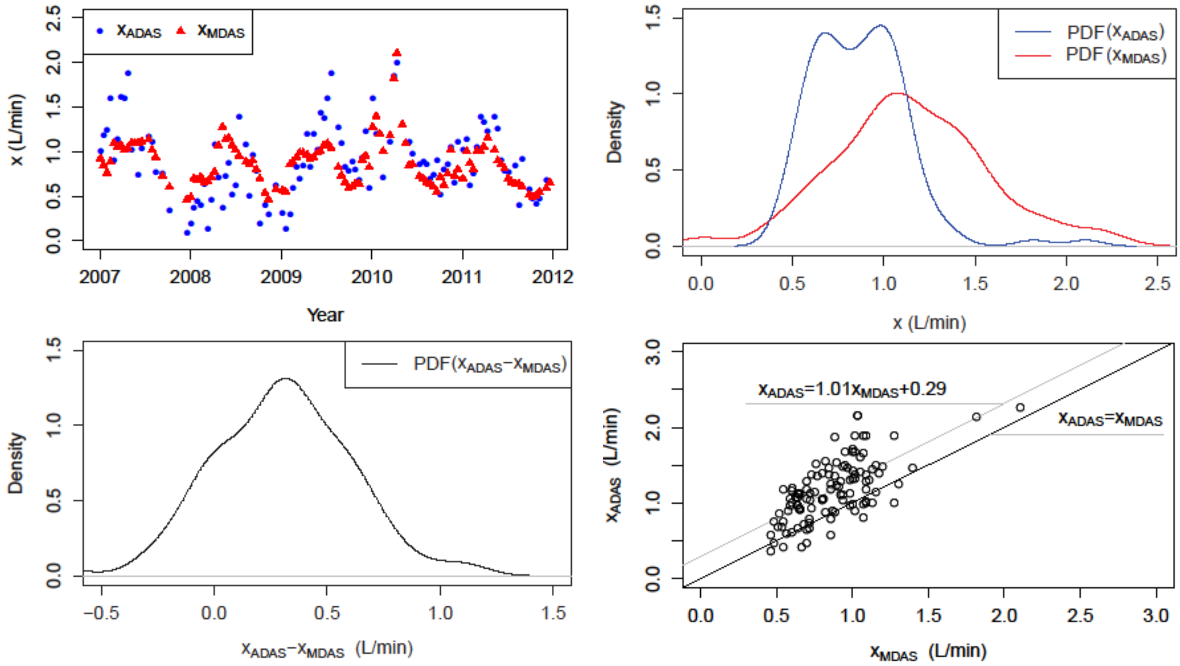

Figure 13: Typical differences between ADAS and MDAS results found in discharge measurements (Bica 1 example).

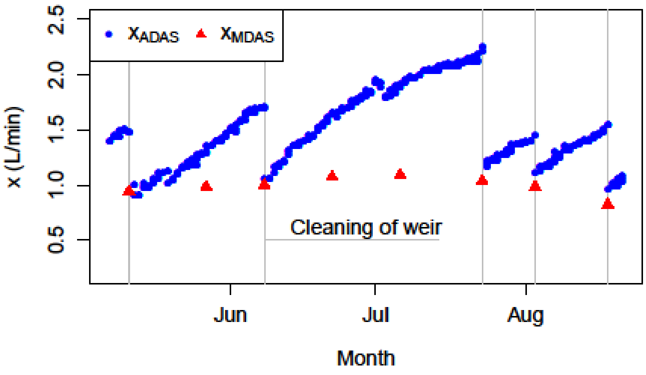

Figure 14: False increase of discharges in weir Bica 1 (Year: 2009, ADAS measurements at 0:00, 8:00, and 16:00).

In piezometers, there is no evidence of differences between ADAS and MDAS measurements.

4 CONCLUSION

As a conclusion, it can be stated that stored ADAS measurements of the Alto Lindoso dam present problems related to gross measurements errors and systematic differences (when MDAS measurements were used as the reference data). In this paper, a procedure for the assessment of stored ADAS measurements and the elimination of systematic differences was presented and may be used in the analysis of stored ADAS measurements of other dams.

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