Quality Control of Dam Monitoring Measurements

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Abstract

The safety control of large dams requires the measurement of some important quantities that characterize their behavior (like absolute and relative displacements, strains and stresses in the concrete, discharges through the foundation, etc.) and on visual inspections of the structures. In the more important dams, the analysis of the measured data and their comparison with results of mathematical or physical models is determinant in the safety control decision process.

The quality of the measurements assumes an important role in a dam's safety assessment, namely in the detection of anomalous behavior related either to accident scenarios or to more delayed deterioration processes. In monitoring system devices operated manually, this quality depends on the order of magnitude of the measured quantity, on the technical characteristics of the measurement device and on the skills of the operator.

This paper deals with the study of the direct influence of these factors on the quality of the monitoring system exploitation and indirectly on the global dam safety control process. The results of an analysis of the repeatability and reproducibility of measurements in a concrete dam are presented, allowing us to estimate the overall measurement error.

Introduction

The collapse or any other serious accident that can occur in large dams can originate the release of the water retained in the reservoir and be the cause of huge economical, social and environmental disasters.

The safety control of concrete dams is carried out throughout the dam's lifetime and is based on the monitoring activities.

The continuous activities of safety control of concrete dams make it possible to carry out a timely detection of possible anomalies and to have an efficient response, should it be necessary. For this reason, the quality of the measurements assumes an important role in a dam's safety assessment [1].

In the real world, there are no existing gauges or measuring devices that give exactly the same measurement readings all the time for the same parameter. There are many factors which contribute to the variability of a measurement process: the standard procedures, the physical quantity, the instrument, the operator, and the environment [2]. In other words, in any process involving measurement of a physical quantity, some of the observed variability may be due to variability in the physical quantity itself, while some may be due to measurement error or gauge variability. In mathematical terms, this means that the total variance is equal to the sum of the variance due to the physical quantity and the variance due to the measurement error, as presented in equation (1).

$$\sigma^2_{Total} = \sigma^2_{Physical\ quantity} + \sigma^2_{Measurement\ error} \quad (1)$$

Measurement system analysis is designed to help quality professionals and engineers assess, monitor, and reduce measurement system variation.

The measurement system variation can be characterized by location (stability, bias, linearity) and accuracy (repeatability and reproducibility).

The determination of the accuracy of a measurement can be done by establishing its repeatability (several measurements taken by the same operator are identical in value) and reproducibility (several measurements taken by different operators are identical in value).

A Gauge Repeatability and Reproducibility study, GRR, is a statistical approach of determining if a gauge or a gauging system is suitable for the process under measurement [2].

The comparison of the measurement system error with the order of magnitude of the observed quantity is a measure of the adequacy of this measurement system component to evaluate the actual behavior of the dam.

Figure 1 shows a typical measurement system analysis model for a generic process.

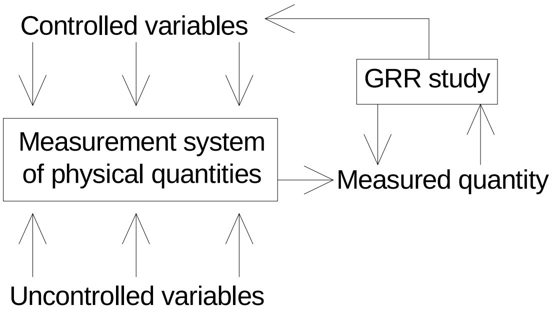


Figure 1: Measurement system process model

In a concrete dam monitoring system we can assume that:

- The *measured quantities* are the absolute and relative displacements, strains and stresses in the concrete, discharges through the foundation, etc;
- The *uncontrolled variables* are the water level, the air temperature and the material properties;
- The *controlled variables* are the quality of the measurement devices, the operator skills, etc.

The paper is organized as follows: first, the research methodology used in the study is described; second, the method for assessment of the measurement system is presented; third, a case study is analysed and the results of the GRR study are reported; and finally, the conclusions and implications of the study are discussed.

GRR study

Introduction

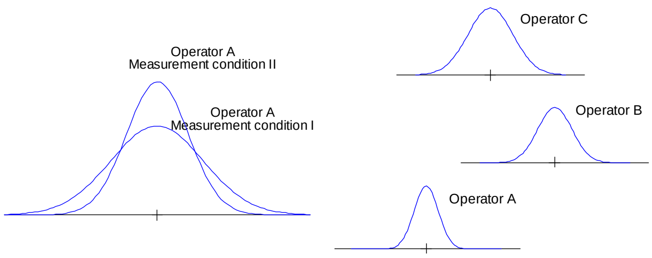
GRR is a measure of the capability of a gauge to obtain the same measurement reading every time the measurement process is undertaken for the same physical quantity. In other words, GRR indicates the consistency and stability of the measuring system.

In this paper the definitions of repeatability and reproducibility used were obtained from the *International Vocabulary of Basic and General Terms in Metrology* [3].

The repeatability (of results of measurements) is defined as "*closeness of the agreement between the results of successive measurements of the same measurand carried out under the same conditions of measurement*". Repeatability conditions include the same measurement procedure; the same observer; the same measuring instrument, used under the same conditions; the same location and the repetition over a short period of time. Repeatability may be expressed quantitatively in terms of the dispersion characteristics of the results, Figure 2 (a), as a variance component, $\sigma^2_{Repeatability}$.

The reproducibility (of results of measurements) is defined as "*closeness of the agreement between the results of measurements of the same measured carried out under changed conditions of measurement*". The changed conditions may include the principle of measurement; the method of measurement; the observer; the measuring instrument; the reference standard; the location; the conditions of use and the time. Reproducibility may be expressed quantitatively in terms of the dispersion characteristics of the results, Figure 2 (b), as a variance component, $\sigma^2_{Reproducibility}$.

In a GRR study, a part is an item that is subject to measurement. In concrete dam monitoring systems, the part corresponds to the physical quantities like absolute and relative displacements, strains and stresses in the concrete, discharges through the foundation, etc.



(a) Repeatability (b) Reproducibility

Figure 2: Repeatability and reproducibility

Previous definitions of repeatability, reproducibility and total gauge variability can be combined [2], as expressed in equation (2).

$$\sigma^2_{Measurement\ error} = \sigma^2_{GRR} = \sigma^2_{Repeatability} + \sigma^2_{Reproducibility} \qquad (2)$$

GRR study is usually applied in many manufacturing-related measurement systems (Figure 3). It has been used as [4]:

- A criterion for judging new measuring equipment;
- A comparison among measuring devices;
- A means for improving performance of measuring instruments;
- A comparison for measuring equipment before and after repair;
- A required component for calculating process variation and the acceptability level for measured quantities;
- A measure of the need for training in how to use measuring instruments.

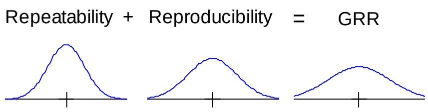


Figure 3: GRR

ANOVA method for GRR study

The two-way random effects ANOVA model is commonly used to estimate the variance components in the GRR study [5].

In a GRR study [6], a ANOVA model is a two-factor design of an experiment under the same conditions of measurement, where one factor is the operator, the other factor is the part, and both are random effects. In this model the k^{th} measurement made by operator j on part i, y_{ijk}, is described in terms of the sum of several parts

$$y_{ijk} = \mu + P_i + O_j + PO_{ij} + \varepsilon_{ijk} \quad \begin{cases} i = 1, 2, ..., p \\ j = 1, 2, ..., o \\ k = 1, 2, ..., n \end{cases} \qquad (3)$$

where:

μ - Measurement mean

P_i - Effect of the part

O_j - Effect of the operator

PO_{ij} - Effect of the interaction between part and operator

ε_{ijk} - Effect of replicate measurements

p - Total number of parts

o - Total number of operators

n - Total number of replicated measurements

The theoretical ANOVA table for GRR study is presented in Table 1.

TABLE 1: TWO-WAY ANOVA TABLE

Source of variation	Sum of Squares	Degrees of Freedom	Mean Square	F Statistic
P	SS_P	$p-1$	MS_P	MS_P/MS_{PO}
O	SS_O	$o-1$	MS_O	MS_O/MS_{PO}
PO	SS_{PO}	$(p-1)(o-1)$	MS_{PO}	MS_{OP}/MS_E
E	SS_E	$po(n-1)$	MS_E	-
Total	SS_{Total}	$pon-1$	-	-

SS_P, SS_O, SS_{PO}, SS_E are the sum squares and MS_P, MS_O, MS_{PO}, MS_E are the mean square due to the part, the interaction part-operator, the operator and the random error, respectively.

To test that there is no effect of the part factor, no effect of the operator factor or no effect of the interaction between the part and operator factors, we calculate the corresponding F statistical test, as presented in Table 1. Each of these ratios follows the F distribution with a number of degrees of freedom equal to the number of degrees of freedom of the numerator and denominator, when the null hypothesis that there was no effect is true.

In (4), the hypothesis to test the effect of the interaction between factors is presented.

$$H_0 : \sigma^2_{PO_{ij}} = 0 \quad \text{vs} \quad H_1\text{: At least one of } \sigma^2_{PO_{ij}} > 0 \qquad (4)$$

The null hypothesis can be rejected if the value obtained exceeds the tabulated value for a specified significance level, or alternatively, if the p-value is less than a specified level of significance [7]. For example, if the F-Statistic is larger than F-Critical, then the interaction between the part and operator factors is statistically significant for the significance level being considered.

When there is interaction between two factors the effect of one depends on the levels of the other. In the presence of a significant interaction effect, each factor alone may be masked by the interaction and the significance test of the influence of each factor may be meaningless. For this reason, it is important to test the interaction effect first, that is, to test the null hypothesis that there is no interaction between the two factors. Its rejection means that the factors are not additive, i.e. the two factors interact. In this situation, there is less importance to test the part effect and the operator effect. The variance components can be estimated through the equations (5) until (9) [8].

$$\hat{\sigma}^2_P = \frac{MS_P - MS_{PO}}{on} \qquad (5)$$

$$\hat{\sigma}^2_O = \frac{MS_O - MS_{PO}}{pn} \qquad (6)$$

$$\hat{\sigma}^2_{PO} = \frac{MS_{PO} - MS_E}{n} \qquad (7)$$

$$\hat{\sigma}^2_{Repeatability} = MS_E \qquad (8)$$

$$\hat{\sigma}^2_{Reproducibility} = \hat{\sigma}^2_O + \hat{\sigma}^2_{PO} \qquad (9)$$

Residual analysis

The predicted values are the averages of measurements obtained for each combination of factor levels. The residuals, e_{ijk}, can be obtained by equation (10).

$$e_{ijk} = y_{ijk} - \overline{Y}_{ij} \qquad (10)$$

where $\overline{Y}_{ij}$ is the average of measurements of the k^{th} measurement made by operator j on part i.

It is necessary to perform residual analysis to verify the validity of the assumptions implicit in the ANOVA model [8]. The simplest analysis consists in the realization of graphical analysis for the validation of the normality of the residual values.

Assessment of the measurement system

The quality measurement usually used for assessing the measurement system is the PTR calculated as

$$PTR = \frac{k \times \sigma_{GRR}}{USL - LSL} = \frac{k \times \sigma_{GRR}}{T} \qquad (11)$$

where T represents the tolerance, USL and LSL are the upper and lower specification limits, respectively [9]. The frequent value adopted for k is 5.15. The value $k = 5.15$ corresponds to limits that contain the middle 99% of a normal population.

Generally, if the PTR value indicated is less than 10%, the measurement system is considered adequate. If the ratio value is between 10% and 20%, it indicates the measurement system is moderately adequate. If the ratio value is between

20% and 30%, it indicates the measurement system is inadequate. Furthermore, a measurement system is unacceptable if the ratio value exceeds 30% [10].

Case Study

Alto Lindoso dam

Alto Lindoso dam is a concrete dam exploited by EDP, the Portuguese company for electricity production. It is a double curvature concrete dam built in 1992 in a symmetrical valley in the North of Portugal (Figure 4). The dam is 110m high and the total crest length is 297m. There are three internal horizontal galleries across the dam and a drainage gallery, close to the foundation [11].

Figure 4: Alto Lindoso dam

The monitoring system of the Alto Lindoso dam consists of several devices which make it possible to observe and to measure quantities such as: concrete and air temperatures, water level, displacements in the dam and in its foundation, rotations, joint movements, strains and stresses in the concrete, pressures and discharges in the foundation.

In this paper the GRR methodology is applied to the measurement displacements in the foundation with rod extensometers.

Rod extensometer

In the Alto Lindoso dam, the foundation displacements are measured with rod extensometers, Figure 5.

A rod extensometer employs a rod, anchored at one end of a drillhole, passing through the drillhole collar. The rod extensometer monitors changes in the distance between one or more downhole anchors and a reference head at the borehole collar.

Relative movement between the end anchor and the reference tube is measured with a dial depth gauge.

The foundation displacements can be obtained by using the equation (12).

$$\delta_n = -\left(LV_n - LV_0\right) \qquad (12)$$

where LV_n, LV_0 are the rod measurement at time n and at the initial time, respectively.

Figure 5: Rod extensometer and dial depth gauge

Data acquisition procedure

In this case study, 3 operators measured 10 rod extensometers 3 times each. The study was conducted so that each operator (one at time) measured one displacement of the rod extensometer, selected randomly, using their 'regular' measurement procedure for this kind of instrument. The operator repeated this measurement process for the other 9 rod extensometers, and then, the same 10 rod extensometers were measured (Figure 6), in random order, for the second trial, then again for the third trial. This same study procedure was used for each operator. Table 2 shows the relation between part and rod extensometer.

TABLE 2: PART AND ROD EXTENSOMETER CORRESPONDENCE

Part	Rod extensometer	Part	Rod extensometer
1	M5-6.1	6	M11-12.2
2	M5-6.2	7	M14-15.1
3	M8-9.1	8	M14-15.2
4	M8-9.2	9	M17-18.1
5	M11-12.1	10	M17-18.2

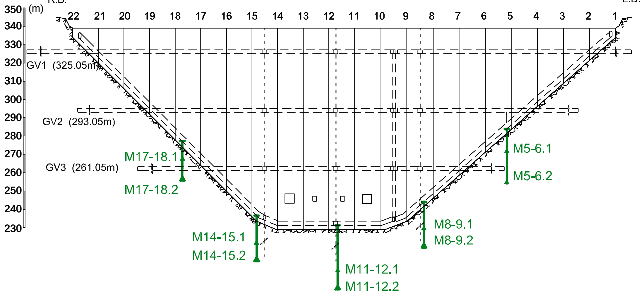


Figure 6: Rod extensometers in Alto Lindoso dam

Table 3 shows the three series of rod extensometer measurements obtained from the three operators on the ten parts. The range of the rod extensometer measurements per operator is presented in Figure 7.

TABLE 3: DATA FOR THE GRR STUDY

Part	Operator A			Operator B			Operator C		
1	5.22	5.21	5.21	5.22	5.22	5.21	5.22	5.21	5.22
2	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.01
3	5.48	5.48	5.48	5.48	5.48	5.48	5.48	5.48	5.48
4	5.15	5.15	5.15	5.15	5.18	5.16	5.15	5.16	5.15
5	5.87	5.87	5.88	5.88	5.88	5.88	5.87	5.87	5.86
6	5.42	5.43	5.43	5.42	5.43	5.43	5.43	5.43	5.42
7	5.19	5.20	5.20	5.20	5.20	5.20	5.20	5.20	5.20
8	5.34	5.34	5.34	5.33	5.34	5.34	5.33	5.33	5.33
9	4.71	4.71	4.71	4.71	4.71	4.71	4.71	4.72	4.72
10	4.93	4.93	4.93	4.93	4.93	4.93	4.93	4.93	4.93

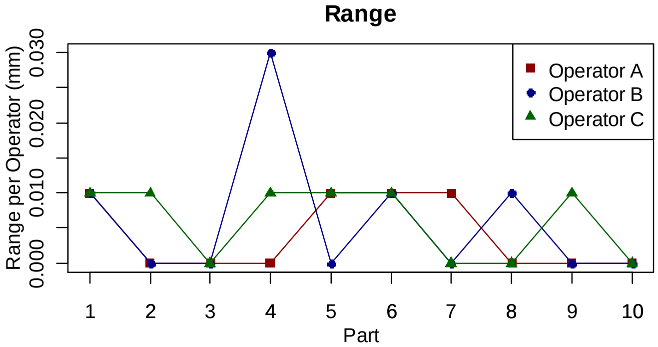


Figure 7: Measurement range

ANOVA method

There are 2 degrees-of-freedom for the operators, the number of operators minus one; 9 degrees-of-freedom for the parts, the number of parts minus one, 18 degrees-of-freedom for the interaction between the operators and the parts, the number of operators minus one multiplied by the number of parts minus one; 89 total degrees-of-freedom, the total number of readings minus one, and 60 degrees-of-freedom for the gauge, total degrees-of-freedom minus the degrees-of-freedom for the operators minus the degrees-of-freedom for the parts minus the degrees-of-freedom for the interaction. The mean-square-error is obtained dividing the sum-of-square divided by the degrees-of-freedom. The ANOVA table can be completed as shown in Table 4. All the calculations were computed with the statistical software R Project for Statistical Computing [12].

The p-value is a measure of the credibility of the null hypothesis. The smaller the p-value, the more evidence we have against the null hypothesis.

A p-value equal to 0.05 is usually taken as reference. For example, p-values less than 0.05 are deemed statistically significant, resulting in rejection of the null hypothesis.

TABLE 4: ANALYSIS OF VARIANCE FOR THE GRR STUDY

Source of variation	SS	DF	MS	F_0	Fcrit	p-value (*)
P	8.48984	9	0.94331	42449	2.04	0.00
O	9.56e-5	2	4.78e-5	2.15	3.15	0.12
PO	0.00077	18	4.82e-5	1.93	1.78	0.03
E	0.00133	60	2.22e-5	-	-	-
Total	8.49205	89	-	-	-	-

The analysis of variance is summarized in Table 3. Notice that the p-value for the interaction effects is less than 0.05, indicating that the interaction effect is significant. As an alternative to using p-values, since $F_{0.05,18,60} = 1.78 < F_0 = 1.93$, we conclude that there is indication of interaction between the factors.

The variance components were computed by using equations (5) to (9). The final values are presented in Table 5.

TABLE 5: VARIANCE COMPONENT ESTIMATION

Source of variation	$\hat{\sigma}^2$	$\hat{\sigma}$
GRR total	0.000029	0.0054
Repeatability	0.000022	0.0047
Reproducibility	0.000007	0.0027
Operator	0.00000	0.0004
Part-Operator	0.000007	0.0026

Residual analysis

The residuals play an important role in accessing model adequacy.

In Figure 8, it can be seen that the graph has tails that don't fall exactly along a straight line passing through the centre of the graph, indicating some small problems with the normality assumption, but the inadequacy from normality is not serious.

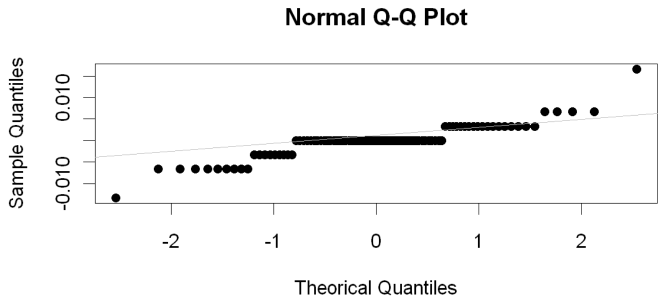


Figure 8: Residual analysis

Assessment of the measurement system

The variance components obtained are from the rod extensometer measurements. Now, we are interested in the physical quantities uncertain for the foundation displacements.

Based on equation (12) and on the propagation of error rule [13], the components of total variance for the GRR study of displacements of the foundation can be obtained, as shown by equation (13). In summary, the confidence intervals can be defined as shown in Table 6.

$$\hat{\sigma}^2_{GRR,\delta} = 2\hat{\sigma}^2_{GRR,LV} \tag{13}$$

TABLE 6: FINAL GRR VARIATION

Confidence Interval	$\hat{\sigma}_{GRR}$	$2\hat{\sigma}_{GRR}$	$3\hat{\sigma}_{GRR}$
	68.26%	95.44%	99.74%
Variation ($\pm$ mm)	0.008	0.015	0.023

Once the $\hat{\sigma}_{GRR}$ value is known, it is possible to assess the measurement system for each of the measured quantities through the calculation of PTR.

The upper and lower specification limits, USL and LSL, can to be estimated for each instrument based on the maximum and minimum values recorded. For example, for the rod extensometer M11-12.2 the tolerance, T, considered is 1.0mm and for the rod extensometer M17-18.2 the tolerance considered is 0.25mm. The corresponding $PTR_{M11-12.2}$ and $PTR_{M17-18.2}$ are:

$$PTR_{M11-12.2} = \frac{5.15 \times \sigma_{GRR}}{T_{M11-12.2}} = \frac{5.15 \times 0.008}{1.00} = 4.1\% \tag{14}$$

$$PTR_{M17-18.2} = \frac{5.15 \times \sigma_{GRR}}{T_{M17-18.2}} = \frac{5.15 \times 0.008}{0.25} = 16.5\% \tag{15}$$

The ratio value $PTR_{M11-12.2} = 4.1\%$ is less than 10%, as a result, the measurement system is considered adequate for this physical quantity. The ratio value $PTR_{M17-18.2} = 16.5\%$ is between 10% and 20% which indicates the measurement system is moderately adequate for this physical quantity.

Conclusions

The variance components of foundation displacement measurements can be estimated by a GRR study, allowing us to know how good the measurements are.

A GRR is a kind of study that aids in ensuring quality at all levels of a measurement process.

The results of this study allow us to say that the foundation displacement monitoring system shows good performance, which means, good instrumentation, operators, methodologies and ambient conditions.

GRR study can be used as an indicator of instrument failure, necessity of instrument calibration, professional training, among others.

If the GRR study is applied periodically, it can be a useful indicator of the measurement quality of concrete dam monitoring systems and its evolution over time.

The research methodology used in the study presented can be extended to other physical quantities, allowing the assessment of the measurement system for all of the key quantities that characterize the dam behavior, improving the quality of the measurements and the quality of the decisions.

This analysis can be combined with the automatic monitoring system for data validation and safety control decision process.

Acknowledgements

The Authors would like to thank EDP – Electricidade de Portugal for permission to publish data relative to Alto Lindoso dam.

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