Metrological control of electrolytic sensors for measuring angular deviations: application in monitoring displacements of engineering structures

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Abstract. The work evaluates the metrological reliability of electrolytic sensors (electrolevels) used to determine angular deviations of elements of engineering structures. The motivation for the work resulted from its strategic application to control the stability of civil engineering structures, notably with application in geotechnics (e.g.: different types of dams of interest in engineering). The methodology used is based on the metrological consistency associated with the quality control process of a set of electrolevels submitted, simultaneously, to a careful calibration process, with traceability ensured to a standard angular deviation pattern. Mounted on a rigid bar, but pivoted at one of its ends to allow angular displacements, the output of each electrolevel is compared with the previously calibrated standard, for different controlled conditions of angular deviation imposed on the bar articulated to a center of rotation. The result of the analysis of typical calibration data for nine electrolevels allowed to show that the expression of the uncertainties associated with the calibration measurements performed constitutes an essential foundation to ensure the metrological reliability of the electrolevels, having allowed to validate a method of discard of electrolevels not meeting the allowable tolerance for a specific engineering application. Among the conclusions of the work, it was possible to qualify the statistical treatment of the levels of uncertainty as a sufficiently robust strategy to validate the electrolevels as a reliable instrument for angular displacement measurements, with a level of confidence appropriate to its application in civil engineering.

Keywords. Electrolevel; measurement of angular displacement; measurement uncertainty.

1. Introduction

Among other engineering applications, notably in geotechnical engineering, electrolevels are electrolytic sensors strategically used to monitor the behaviour and stability of different types of dams during their complex construction process (e.g.: rockfill dam with a concrete face; water reservoir dams for hydroelectric generation, structural concrete dam with buttresses; earth dams; tailings dams, designed to retain solid waste and water resulting from ore extraction processes). In particular, they are also useful to identify critical regions exposed to the concentration of concentrated loads, notably the bending moment. Considering that these electrolytic sensors are immersed in the dam material at different stages of the construction process, it is necessary to ensure its metrological reliability prior to its installation. Based on the analysis of the mass of data that provides information associated with eventual displacement of dam structures, it is possible to implement adjustments and corrections of the dam even during its construction process.

The continuous monitoring of the dam is also strategic during its operating (i.e. when subjected to full load), and can anticipate nonconformities that may result from unexpected overload of the dam structure as a whole, thus avoiding accidents, usually of unexpected proportions. Based on the uncertainty analysis associated with the measurement of angular displacements, this article proposes a strategy to assure the metrological reliability of electrolytic sensors, considering that its quality control must necessarily take into account not only the metrological rigor of the measurement process but also
the stability of the electrolytic liquid and the integrity of the metal contacts during the electronics manufacturing process.

The careful metrological evaluation of measuring instruments (which includes the expression of associated uncertainties) is a vital tool for the development of any scientific experiment. To reduce the uncertainties associated with any measurement is an absolutely fundamental strategy to assign reliability to routine measurements (TAYLOR, 2012), thus reflecting the true physical meaning of the experiment.

2. Electrolytic sensors for measurement of angular deviations

Electrolytic sensors for measuring angular displacement are known as electrolevels. Widely used for level measurement in various engineering applications, electrolevels were originally designed for applications in the aeronautics industry, also finding application in civil and naval engineering and in the automotive industry (Rocha Filho & Price, 2000).

2.1. Principle of operation of the electrolevel

Physically, electrolevel consists of an ampule of glass, plastic (Figure 1a) or ceramic material (Figure 1b), partially filled with an electrolytic liquid, interconnected to metallic connectors. Among the available options, it may have two or four coplanar electrodes, which penetrate the ampoule and are partially immersed in the liquid, forming what is called a Wheatstone Half Bridge (Figure 1c).

![Figure 1. Examples of different types of electrolevel and its powering electrical circuit.](image-url)

The electrolevel provides an output voltage that is proportional to its inclination angle, measured relative to a previously defined reference axis. The electrical impedance between the electrodes immersed in the electrolytic fluid varies as a function of the inclination imposed on the ampoule, reflecting the correlation that exists between the resistance variation of the electrode and the rotation of the set as a whole. The output signal of the electrolevel varies according to a range defined by the manufacturer based on its physicochemical properties. As a precaution, the electrolevel should not be excited by a DC voltage to prevent against electrolysis processes that adversely may affect the physical characteristics of the electrodes installed inside the ampule, immersed in the electrolytic fluid.

2.2. Fundamentals of the calibration procedure

The purpose of calibration is to adjust the response of an instrument so that it displays a true value relative to a traceable reference. Figure 2 illustrates a standard calibration procedure that aims to provide metrological reliability to the result of angular deviation measurement by means of an electrolytic sensor, fastened to a rigid rod, free to rotate relative to a fixed point. In the context of this calibration procedure, the angular deviation perceived by the electrolevel can be determined by the arc tangent of the angle \( \phi \) (Equation 1), which is the angle generated by the rod when it rotates (around its axis of rotation) from the position of the reference axis to an arbitrary position, forming a triangle of catheter c and hypotenuse h, as defined in Figure 2.

The metrological accuracy of the electrode calibration will therefore depend on (i) the metrological accuracy associated with the measurement of the vertical displacement (y) of the right end of the rigid bar and its length L and (ii) of the correctness of the measurement of the electrical potential difference (expressed by the calibration certificate of the voltmeter used), generated by the electrolevel output, before and after its rotation.
Based on this fundamental calibration procedure, a Calibration Factor (CF) is defined by Equation (2), allowing the conversion of the output signal of the electrolevel to a measure of angular deviation. Figure 3a shows the results of the manufacturer’s calibration of a single-axis electrolevel, with a resolution: $0^\circ 0' 1''$, designed to operate within $\pm 1^\circ$.

$$\theta (\text{rad}) = (\text{CF})_{\text{reference standard}} \cdot \Delta V (\text{mV})$$

Where $(\text{CF})_{\text{padrão}} = 4,9 \cdot 10^{-6} \text{ rad/mV}$, derived from the calibration curve above, therefore allowing to convert the signal measured in millivolts in terms of angular deviation $\theta$. Even though $\phi$ and $\theta$ denotes angular deviation detected by the electrolevel, the first refers to the angle set in the calibration device (see Figure 4), where the latter to angles calculated from the translation equation 2 (conversion from the output of the electrolevel in mV to units of angle in rad).

Figure 3b shows the performance (output sensitivity) of a single-axis electrolevel, Model 0715-4101-99, resolution: $0^\circ 0' 12''$, in its operating range ($\phi \pm 9^\circ$), confirming the linearity of the signal in a narrow range ($\phi \pm 3^\circ$).

### 3. Simultaneous calibration of a set of electrolevels by comparison to a measurement standard

This section reports the results of Ramos (2009), regarding the simultaneous calibration of a set of nine electrolevels, performed by the method of comparison to the reference electrolevel, taken as a standard and whose calibration was described in the previous section.

#### 3.1. Experimental setup

Figure 4 illustrate the experimental arrangement assembled at the PUC-Rio Geotechnical Laboratory, used to simultaneously calibrate, by comparison to a standard of the same kind, the set of nine
electrolevels. It shows a schematic of a rigid metal bar, on which the nine electrolevels (E01 ... E09) were mounted, side by side, together with the measurement standard (reference electrolevel).

![Schematic diagram of electrolevels](image)

**Figure 4.** Experimental set-up of the set of nine electrolevels mounted next to the reference standard.

This calibration procedure can be considered of strategic interest, since the systematization of the process results in time saving and optimization of the research effort, without compromising the quality of the measurement results. In superimposed image, the same figure also shows a photograph of the assemblage, showing the cabling of each sensor, allowing monitoring of the output electrical signal that emerges from the Wheatstone Half Bridge to be measured by a calibrated voltmeter. In this experimental setup, each electrolevel was carefully mounted inside an aluminum capsule, filled with epoxy resin, thus ensuring mechanical protection and absolute sealing of the sensitive elements.

As can be seen in the Fig. 4, at the opposite end of the fixed point of rotation, the metal rod has an endless thread device, which allows the bar angle to be varied, by means of a vertical displacement y, shown in Figure 4. The pitch of the thread is of 2.11 mm, and the length L of the rigid bar 1320 mm. Thus, an angular displacement of 0.0045 rad (0° 15' 0'') is produced for every three turns of the thread.

### 3.2. Comparison calibration results

Table 1 summarizes the results of the simultaneous calibration of the nine electrolevels (Ramos, 2009), whose outputs are compared with the response of the reference electrolevel, calibrated by the manufacturer, in compliance with the usual metrological rigor.

| Experiment # | Tilt angle \( \theta \) (rad) | Electric tension (mV) | E01 | E02 | E03 | E04 | E05 | E06 | E07 | E08 | E09 |
|--------------|-----------------------------|-----------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 1            | 0.0199577                   | 4073                  | 2814| 2565| 3137| 2622| 2642| 2800| 2969| 2898| 2816|
| 2            | 0.0149597                   | 3053                  | 2106| 1921| 2345| 1968| 1966| 2093| 2215| 2163| 2108|
| 3            | 0.0100107                   | 2043                  | 1398| 1271| 1563| 1331| 1298| 1385| 1459| 1427| 1393|
| 4            | 0.0050715                   | 1035                  | 709 | 638 | 789 | 689 | 636 | 688 | 724 | 702 | 694 |
| 5            | 0                           | 0                     | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   |
| 6            | -0.0046942                  | -958                  | -706| -636| -779| -642| -661| -478| -746| -723| -706|
| 7            | -0.0096824                  | -1976                 | -1417| -1297| -1576| -1308| -1350| -1417| -1509| -1472| -1435|
| 8            | -0.0147196                  | -3004                 | -2134| -1952| -2366| -1951| -2029| -2134| -2263| -2218| -2162|
| 9            | -0.0193893                  | -3957                 | -2839| -2602| -3143| -2588| -2703| -2832| -3008| -2947| -2878|

Table 1. Results of simultaneous calibration of nine electrolevel (by comparison to the standard).
The slope angle $\theta$ is calculated by Equation (2), from the measured electrical voltage of the output signal of the reference electrolevel. In the same Table, the output for each electrolevel (expressed in mV) denotes the difference of two output signals associated with the angular positions of the rigid bar: when it is aligned with the reference axis (horizontal position, represented by experiment #5 in Table 1) and when subjected to a rotation $\varphi$.

This is the reason why the output signal associated with the bar in position $\varphi = 0$ indicates zero voltage values (values offset in relation to the output voltage, measured when the rigid bar is aligned with the reference axis; i.e. horizontal).

4. Assigning metrological credibility to the calibration process

This work aims to attribute credibility to measurement results not directly referenced to a direct calibration process, which is the case of the data reported by Ramos (2009), whose associated uncertainty was not reported. Used as a case study, Ramos (2009) data were subjected to a statistical treatment to guide the quality control of the calibrated electrolevels according to a strict criterion of permissible tolerances for geotechnical applications.

4.1. Fitting polynomials

The determination and application of the interpolation polynomial analysis that presents the least adjustment uncertainty, applied to each of the calibrations performed by Ramos (2009), allowed to correct the experimental results, not only eliminating the systematic error inherent to his measurements, but also allowing for interpolating values within the range of the applicable calibration. In accordance with good calibration practices (ISO GUM, 2008), polynomial analysis by the ordinary least square’s method was repeated for each electrolevel and for three different degrees of the interpolating polynomial, therefore yielding 27 interpolating polynomials of the kind expressed in Equation (3).

$$y(x_i) = a_0 + a_1 \cdot x + a_2 \cdot x^2 + a_3 \cdot x^3 + \cdots + a_n \cdot x^N$$  \hspace{1cm} (3)

Although not documented in this paper due to space limitation, each one of these 27 polynomials are properly characterized and graphically represented in the master's dissertation of the first author (González Leaño, 2019). However, just to illustrate the procedure used to organize the data, Appendix A shows an extract of a more comprehensive calibration data spreadsheet of the tilt angles, corrected through the polynomial of degree 2.

4.2. Calculation of the measurement uncertainty associated with the polynomial fitting process

Following the proposed analysis, the data from the simultaneous calibration of the nine electrolevels allowed to calculate (i) the systematic error associated with each interpolator polynomial and (ii) the expanded uncertainty associated with the calibration of each of the electrolevels submitted to the simultaneous calibration process.

After applying each of the 27 polynomials (degrees 1, 2 and 3) to the calibration data, which individually represents the raw data corresponding to each of the nine electrolevels calibrations, corrected values of the tilt angle are finally obtained, more precisely, the angular deviation measured relatively to a reference (horizontal) axis.

Having obtained the adjusted values of the angles through the correspondent interpolator polynomial, which process data obtained from measurements of the output signal of each electrolevel, it is possible to calculate the uncertainty associated with the curve fitting (associated with the polynomial fitting, $u_{fit}$), calculated by Equation (4) and summarized in Table 2 (neglecting the uncertainty components associated with the polynomial coefficients and their correlations, understood of lower order).
\[ u_{\text{fit}} = \sqrt{\left( \frac{1}{n - c} \right) \sum_{i=1}^{n} [y(x_i) - y_i]^2} \]  

(4)

The analysis of these results allowed to identify that, among the polynomials tested, and for the nine electrolevels simultaneously calibrated, the polynomial of degree 2 is the one that better models the physical nature of the calibration (polynomial that yields the lowest value of \( u_{\text{fit}} \)).

**Table 2.** Identification of the polynomial ensuring the least uncertainty associated with the polynomial fitting.

| Polynomial degree | E01 (rad) | E02 (rad) | E03 (rad) | E04 (rad) | E05 (rad) | E06 (rad) | E07 (rad) | E08 (rad) | E09 (rad) |
|-------------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| 1                 | 0.00012762 | 0.00014619 | 0.00010399 | 0.00011642 | 0.00018021 | 0.00058623 | 0.00014067 | 0.00014067 | 0.00016732 |
| 2                 | 0.00008417 | 0.00008927 | 0.00007379 | 0.00010994 | 0.00013392 | 0.00054269 | 0.00011486 | 0.00011545 | 0.00009934 |
| 3                 | 0.00009366 | 0.000070222 | 0.00079388 | 0.00099707 | 0.00117032 | 0.00088259 | 0.00088884 | 0.00046375 | 0.00011019 |

To ensure a more conservative analysis, we considered a Coverage Factor \( k = 2.45 \) (a value obtained from a t-Student distribution for a confidence level of 95%). This value was obtained from the Welch Satterwaite equation (ISO GUM, 2008), when the calibration process is assumed to have 6 degrees of freedom, obtained from the difference \( (n - c) \); i.e., the difference between the number of measurement points \( n \) and the number of coefficients \( c \) of the best polynomial fitting (offering the least adjustment uncertainty \( c = 3 \), for the polynomial of degree 2).

### 4.3. Calculated uncertainty associated with the calibration of each of the nine electrolevels

In accordance with the ISO GUM (2008), the uncertainty component is calculated by taking into account the most important sources of uncertainties, which, for the current case are: (i) \( u_{\text{ref}} \), associated to the reference electrolevel, assessed from the resolution (1 mV) of the digital multimeter used to measure its output (proportional to the electrolevel angular displacement, converted through Eq. (2) to the equivalent resolution in radians, i.e.: \( u_{\text{ref}} = 0.0000014 \) rad); (ii) \( u_{\text{inst}} \), uncertainty associated to the resolution of the digital multimeter (1 mV), used to measure the electrolevel output, whose conversion from mV to rad was obtained through the fitting polynomials; (iii) \( u_{\text{fit}} \), uncertainty associated to the polynomial fitting, calculated through Equation (4) and reported in Table 3. Finally, the expanded uncertainty \( (U_E) \) can be calculated by Equation 6, for the stated Coverage Factor \( (k = 2.45) \).

As can be observed, except for the electrolevel E06, all the experimental results associated with the calibration of the other eight electrolevels present excellent agreement. The results of this round of experiments were grouped and shown in Figure 5, whose horizontal axis denotes the adjusted angle calculated on the basis of the best interpolator polynomial and the vertical axis, denote the sum of the systematic error and the expanded uncertainty, respectively for each data of calibration. For the analyzed data set, it is observed that the systematic error added to the expanded uncertainty does not exceed the value 0.0005 rad, understood as a convenient threshold limiting value that could be used to define the tolerance of the technological application of geotechnical interest.
Table 3. Assessing the uncertainty analysis.

\[ u_{\text{ref}}^2 + u_{\text{inst}}^2 + u_{\text{fit}}^2 = u_c^2 \]  
\[ U_E = u_c \cdot k \]

| Electrolevel | Uncertainty associated to the reference electrolevel | Uncertainty associated to the digital multimeter resolution | Uncertainty associated to the polynomial fitting | Combined uncertainty | Expanded uncertainty |
|--------------|------------------------------------------------------|----------------------------------------------------------|-----------------------------------------------|---------------------|---------------------|
| E01          | 0.00000014                                           | 0.0000367                                               | 0.0000842                                     | 0.0000919          | 0.0002250           |
| E02          | 0.00000014                                           | 0.0000385                                               | 0.0000893                                     | 0.0000972          | 0.0002382           |
| E03          | 0.00000014                                           | 0.0000337                                               | 0.0000738                                     | 0.0000811          | 0.0001988           |
| E04          | 0.00000014                                           | 0.0000409                                               | 0.0001099                                     | 0.0001101          | 0.0002696           |
| E05          | 0.00000014                                           | 0.0000608                                               | 0.0001339                                     | 0.0001471          | 0.0003603           |
| E06          | 0.00000014                                           | 0.0000588                                               | 0.0005427                                     | 0.0005459          | 0.0013374           |
| E07          | 0.00000014                                           | 0.0000576                                               | 0.0001149                                     | 0.0001285          | 0.0003148           |
| E08          | 0.00000014                                           | 0.0000552                                               | 0.0001154                                     | 0.0001280          | 0.0003135           |
| E09          | 0.00000014                                           | 0.0000480                                               | 0.0000993                                     | 0.0001103          | 0.0002703           |

Figure 5 illustrates the graphical representation of the systematic error added to the expanded uncertainty associated with the measurements. “Total error” (so called by product manufacturers) is a concept often used by demanders of measurements results to impose a tolerance level that might be met during to the construction of their products. Of course, manufacturers are free to establish their tolerance levels according to the quality control level imposed to their products.

![Figure 5](image-url)
If it is taken for granted that Ramos data is reliable (hypothesis assumed just to illustrate the practicality of the uncertainty methodology proposed, then the calibration of the electrolevel labelled E06 should be interpreted as a damaged electrolevel, as indicated by the abnormal behavior of the measurement uncertainty depicted in Figure 5, much higher than the other eight equally calibrated electrolevels. This is just hypothesis used as a case study in this paper, even though the value - 478 mV in Table 1, for electrolevel E06, is clearly an outlier value not noticed by Ramos (2009).

To strengthen the analysis, Figure 6 intercompares the performance of all nine electrolevels [standard deviations of their output $\theta$ (rad) vs. the electrolevel output (mV)] vis-à-vis a tolerance criterion of 0.0003, chosen as the reference baseline.

![Figure 6. Intercomparison of the electrolevels response vis-à-vis a tolerance criterion](image)

As shown, the standard deviation of the response of the E06 electrolevel indeed differs from the others, exceeding the tolerance limit, not only in the vicinity of the supposedly outlier experimental point (- 478 mV), but throughout the entire spectrum of the calibration range, therefore ratifying an abnormal behavior.

Looking from this perspective, the methodology could be used as a “disposal criterion” to refuse the E06 sensor as it presents an incontestable deviation from typical performance, therefore indicating that is not suitable for use since it does not conform to the level of the allowed tolerance. Among the possible explanations considered to explain the faulty response of a typical electrolevel, the following causes could be charged: carelessness in the operation of the instrument; possibility of outliers being considered during the measurement process; oxidation of the electrolytic fluid, deterioration of electrical contacts between the electrolytic fluid and the metallic electrodes, micro-rupture of the capsule, all possible reasons which may compromise the integrity of the sensitive element as a whole. Until each of these causes is individually investigated, it is recommended not to make any value judgment and simply discard the electrolevel that exhibits this type of behavior.

5. Conclusions

The proposed measurement uncertainty assessment methodology proved to be effective in assuring the metrological reliability of the simultaneous calibration process of a set of nine electrolevels, ensuring traceability to the International System of Units by comparison to a calibrated standard of angular deviation measurements. As discussed, the proposed uncertainty methodology is either applicable to assess the robustness of calibration data usually reported in the literature or, strategically, to assess the
sturdiness of sensors used in measurement systems, illustrated by the pictorial study case referred in this paper. From this perspective, the methodology proposed could be conveniently used as a discarding criterion to refuse marketed electrolevels that fail to meet acceptable standards of tolerance, compatible with specific applications of interest in Geotechnical Engineering.

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Appendix A: Tilt angles corrected through calibration data (extract from the polynomial of degree 2)

| Corrected values of the tilt angles calculated from the 27 calibration polynomials tested (rad) |
|---------------------------------------------------------------|
| E01     | E02     | E03     | E04     | E05     | E06     | E07     | E08     | E09     |
| -0.0199914| -0.0200075| -0.0199865| -0.0199134| -0.0201975| -0.0200258| -0.0200333| -0.0200142| -0.0149463| -0.0149619| -0.0149328| -0.0149229| -0.0149100| -0.0149476| -0.0149492| -0.0149603| -0.0099319| -0.0099059| -0.0099664| -0.0100787| -0.0099820| -0.0097061| -0.0098843| -0.0098922| -0.0098988| -0.0050814| -0.0050175| -0.0050740| -0.0052130| -0.0049271| -0.0049889| -0.0049441| -0.0049915| -0.0001203| -0.0001257| -0.0001104| -0.0000095| -0.0002032| -0.0002107| -0.0001929| -0.0001844| -0.0001594| 0.0047893| 0.0047155| 0.0047669| 0.0048217| 0.0046686| 0.0035524| 0.0047216| 0.0046852| 0.0047152| 0.0097030| 0.0097097| 0.0097328| 0.0098161| 0.0099961| 0.0097195| 0.0096953| 0.0097051| 0.0146269| 0.0146211| 0.0146310| 0.0146210| 0.0146290| 0.0148085| 0.0146300| 0.0146502| 0.0146375| 0.0194379| 0.0194581| 0.0194253| 0.0193646| 0.0194757| 0.0194037| 0.0194542| 0.0194584| 0.0194523|