Quality Control of a Dam Geodetic Surveying System

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Key words: Geodetic Surveying Systems, Monitoring Displacements, Quality Control.

SUMMARY

Geodetic surveying systems used to monitoring displacements at large concrete dams must be carefully designed and materialized, not only as a response to required submilimeter accuracies but also in regard as to their lifetime, witch is expected to last as long as the dam. This special care should be extended to the choice of the measurement equipment and procedures and to the use of adequate adjustment and quality control procedures.

The most common sources of errors are: instrument calibration, atmospheric conditions, operative methods, human errors and mistakes and, last but not the least, the unexpected behaviour of the reference frame.

This paper deals with a real situation, which took place in the geodetic surveying system of a Portuguese dam, where unexpected variations of its horizontal control network's observables, suggesting an apparently abnormal behaviour of the dam, were detected by means of statistical quality control tests. The paper describes the "Monte Novo" dam geodetic surveying system, the measurements carried out along time and its quality control statistical tests, and presents an explanation to the apparently abnormal behaviour of the dam.

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1. INTRODUCTION

Large dams need a careful safety control along its life span, since its failure might cause great losses in lives and property. The safety control of a large dam lies on the analysis of its structural behaviour, based on monitoring of a large set of variables which describe the relations between the actions (gravity, temperature, hydrostatic pressure, etc.) and the corresponding structural responses (stresses, displacements, etc.), taking into account the properties of the materials used in the construction (concrete, embankment, masonry, etc.). The displacements of a discrete and representative set of points on the structure, its foundations and surrounding terrain, are fundamental control variables to structural behaviour analysis of large dams.

The geodetic surveying systems used for monitoring absolute displacements of object points on concrete dams are based on separate horizontal and vertical control networks which rely on horizontal and vertical reference frames (Casaca *et alia*, 2002). The reference frames are composed of sets of reference points which location is carefully chosen: in stable ground, not far from the dam, though out of its influence area. The minimum number of reference points depends upon the type of the network (vertical, horizontal or three dimensional). A good strategy is to choose a redundant set of points, in order to allow the reference frame's stability control.

Figure 1: Monte Novo dam

The paper presents a real study case: the analysis of several measurements of the horizontal control network of the "Monte Novo" dam. This analysis, based in statistical quality control methods, was used to identify unstable points within the reference frame of the dam's horizontal control network.

2. THE GEODETIC SURVEYING SYSTEM OF “MONTE NOVO” DAM

“Monte Novo” dam was built on the river “Degebe”, in the South of Portugal, for water supply and irrigation purposes. It’s a concrete gravity dam, with a maximum height from the foundation of 30m and a crest length of 160m. After the construction of the dam was completed, in 1982, a geodetic surveying system was designed and materialized.

The purpose of the dam’s geodetic surveying system, which consisted of a triangulation network and a geometric levelling line, was the monitorization of horizontal displacements of sixteen object points on the downstream face and vertical displacements of ten object points on the crest of the dam, with submilimetric accuracy. It was important that the system had a very simple configuration, so it could be observed by a small team, in a short time, with the use of one precision electronic theodolite and one precision optical level with invar rods.

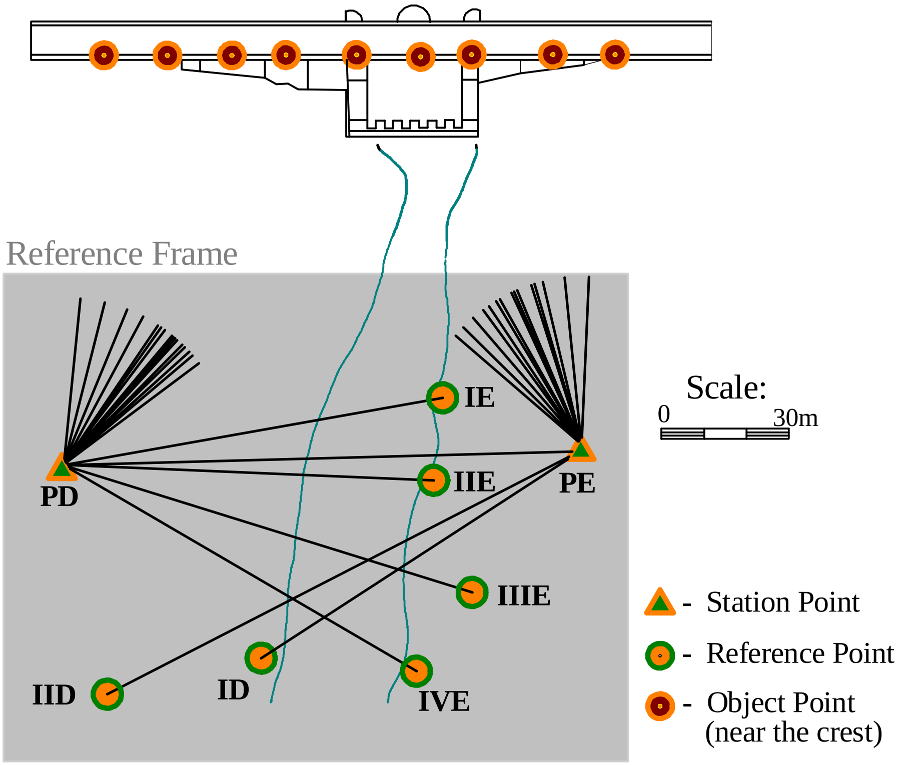

Figure 2: Positions of points of the network

The triangulation network (Fig. 2) consisted of sixteen optical targets, at the dam´s downstream face (Fig. 4), two station points, materialized by small concrete pillars (Fig. 3), and six references, materialized by optical targets. The two station points and the six references, which were supposed to be fixed along time, materialized the network’s reference frame.

The mean distance between the points of the reference frame was 106m. The station points, one in each bank of the river, were made in concrete and had forced centering pieces and thermic isolation (Fig. 3). Due to the valley’s topography, the reference points, four in the left bank and two in the right bank, were sighted only from the station point on the opposite bank (Fig. 2).

Figure 3: Station point

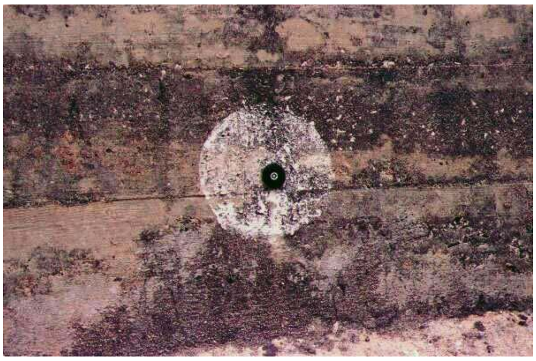

Figure 4:Target point

A prior statistical analysis of the network was carried out on the presumption of a 3dmgon standard deviation for the differences of two horizontal angles and a 0.1mm standard deviation for the position of the eight points of the reference frame. The resultant error ellipses for the displacements had semi-axis lesser than 1.5mm, for a 0.95 probability level. The local redundancy numbers of the network's observables were medium (~0.50), for the horizontal angles involving the object points, and high (~0.90), for the horizontal angles involving only the reference points.

3. THE MEASUREMENTS

National Laboratory for Civil Engineering (NLCE) surveying teams carried out twelve measurement campaigns at the dam's geodetic surveying system. The measurement of the horizontal angles was realized with electronic theodolites, by the method of the rounds, near the sunrise to avoid steep horizontal thermic gradients.

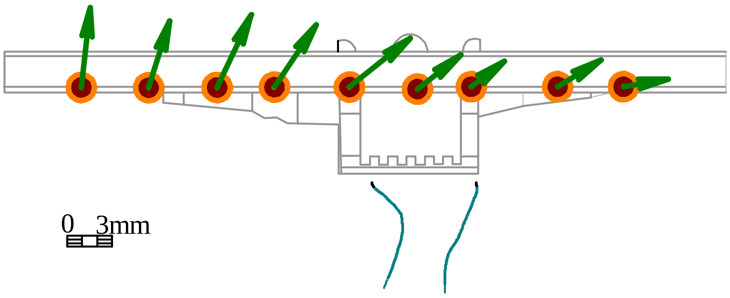

Figure 5: Horizontal displacements of the object points near the crest

The differences between the horizontal angles measured at the 2nd,...,12th epochs and the horizontal angles measured at the first epoch were adjusted with a general least squares model that provides the displacements of the object points, the residuals, the standard deviation of the unit weight, etc. (Casaca, 2001).

Although all vertical displacements agreed to the dam's structural expected behaviour, the horizontal displacements resulting from the last four measurement epochs did not agree to the dam's expected structural behaviour. Fig. 5 presents unexpected horizontal upstream displacements of the object points near the dam's crest, between the last and the first measurement epochs: the expected displacements were directed towards downstream.

Simultaneously, the standard deviations of the unit weight estimated for the last four measurement epochs were significantly higher than the standard deviations estimated for the previous measurement epochs.

4. THE QUALITY CONTROL PROCEDURE

The quality control of the measurements may be supported by statistical tests on the quadratic random variate (v) derived from the vector of the residuals:

$$v = \Delta^{T} \Sigma^{-1} \Delta \tag{1}$$

where Δ stands for the m-dimensional vector of the residuals and Σ stands for the m-order variance matrix of the observables (where m is the number of observation equations). The variance matrix is built taking into account correlation between the horizontal angles measured from the same station point by the method of the rounds (Casaca *et alia*, 1985).

Under the null hypothesis, v has a chi-square distribution with f (= m–n, where n is the number of unknowns) degrees of freedom:

$$H0 \equiv v \in \chi^{2}(f) \tag{2}$$

Under the alternative hypothesis, v is proportional to a non-central chi-square distribution, with f degrees of freedom:

$$HA \equiv v \in \kappa \chi^{2}(f, \theta) \tag{3}$$

where κ is an unknown positive parameter and θ is a positive non-centrality parameter.
To test the null hypothesis against the alternative hypothesis, the variable of the test (v) is compared to the acceptance (RA) and critical (RC) regions:

$$RA = [0, q\ ], \quad RC =]q, +\infty\ [\tag{4}$$

where q is the 0.95 quantile of the central chi-square distribution with f degrees of freedom.
For the triangulation network of Monte Novo dam, where m = 104 and n = 48, the 0.95 quantile of a chi-square distribution with f (= 56) degrees of freedom is $q \approx 75$. The chart on Fig. 6 presents the quantile (q) and the values of the test's statistic (v) for the eleven adjustments.

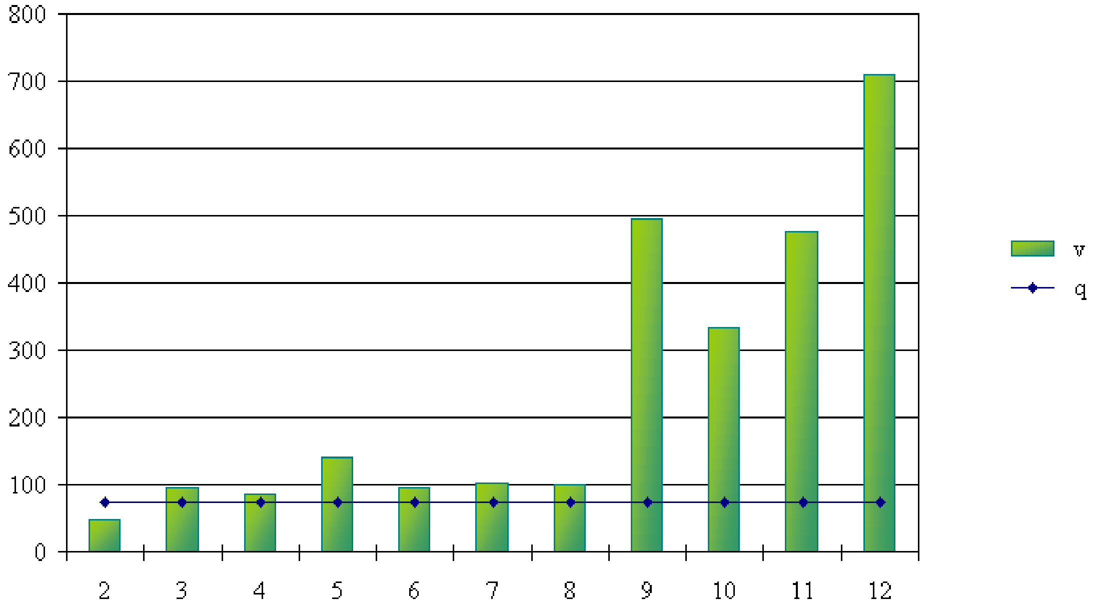

Figure 6: Values of the test statistic (v)

The analysis of the chart on Fig. 6 shows that, except for the second measurement, all the other measurements fall in the critical region. Although, for the first measurements, the rejection is not very significant, after the eighth measurement, the rejection is quite significant.

Quality control of the network strongly rejects the null hypothesis for the last four measurements. This means that very significant gross errors occurred in the measurements or that points belonging to the reference frame, supposed to be fixed along time, were suffering significant displacements. The higher local redundancy numbers of the observables linking the points of the reference frame corroborates the second hypothesis (Henriques *et alia*, 2000).

5. IDENTIFICATION OF THE PROBLEM

To find out if the rejection problem was related with the reference frame, a chart was made, with the evolution of the horizontal angles measured within this frame (see Fig. 2), since the first measurement epoch.

The chart on Fig. 7, shows that the horizontal angle measured from the station PE, to the reference ID and to the station PD has an increasingly significant variation from the 9th measurement on. The joint analysis of the chart and of the disposition of the points (Fig. 2) makes also possible the following conclusions: i) The reference ID is not responsible by the variation of the angle ID-PE-PD, since the angle ID-PE-IID doesn't have large variations; ii) The angle ID-PE-IID doesn't show very large variations; iii) pillar PD doesn't have large displacements, otherwise the four angles measured from this station would reveal this situation. As a conclusion, the station point PE is not likely to have behaved as a fixed point.

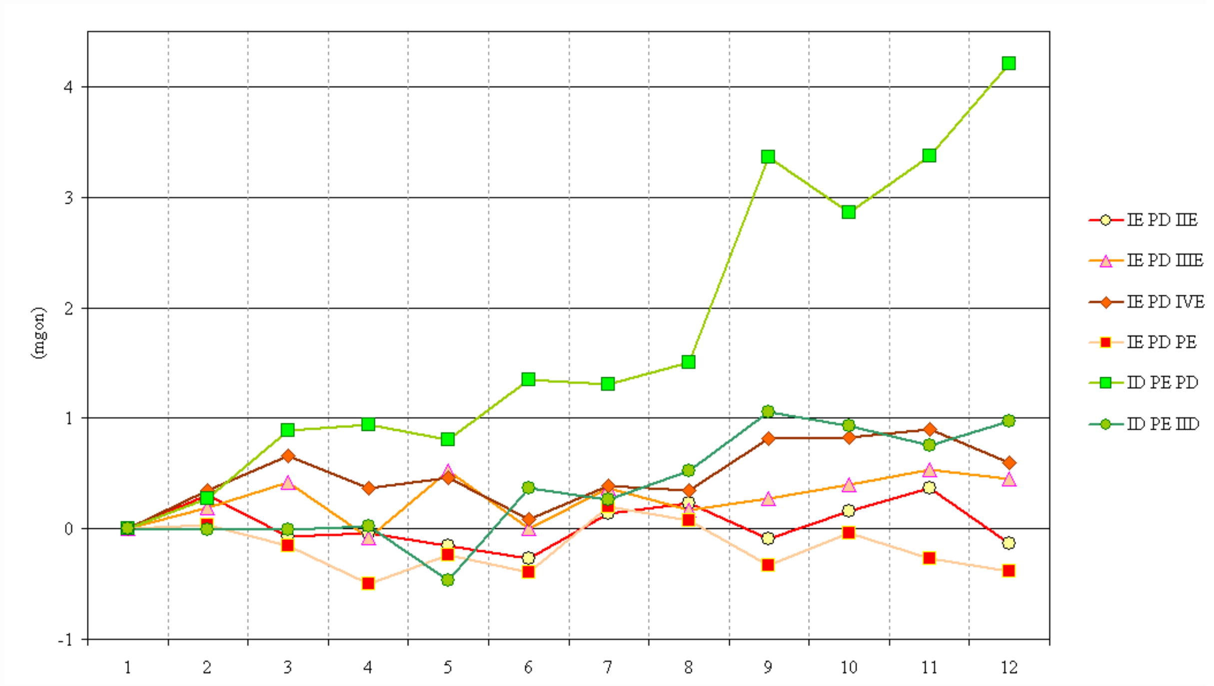

Figure 7: Variation of the horizontal angles within the reference frame

The computation of the displacements was repeated with the station point PE set free (i.e., not fixed). The tests were also repeated, with the 0.95 probability quantile of the central chi-square distribution with 54 degrees of freedom (since there are less two equations, m = 102). The chart presented at Fig. 8, shows that all the measurements fall in the acceptance region or slightly in the critical region.

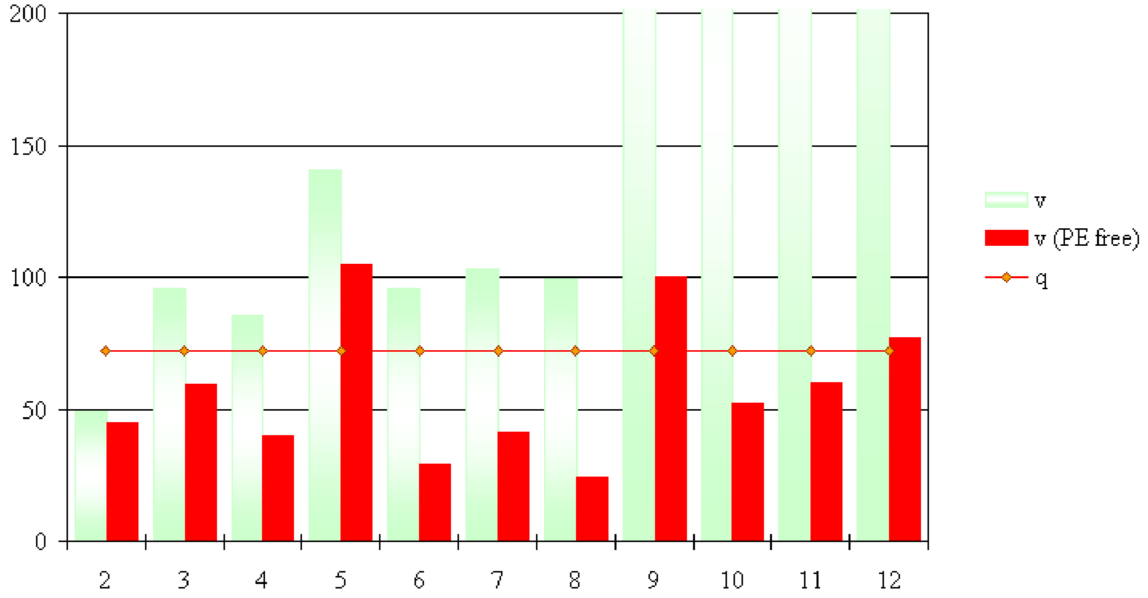

Figure 8: Values of the test statistic (v)

When the station point PE is set free, the resulting displacements suffer a large alteration. Fig. 9 shows the displacements of the object points, computed from the 12th measurement, when PE is set free and when PE is fixed. The displacements of the object points computed with the station PE set free are directed towards downstream as it was expected.

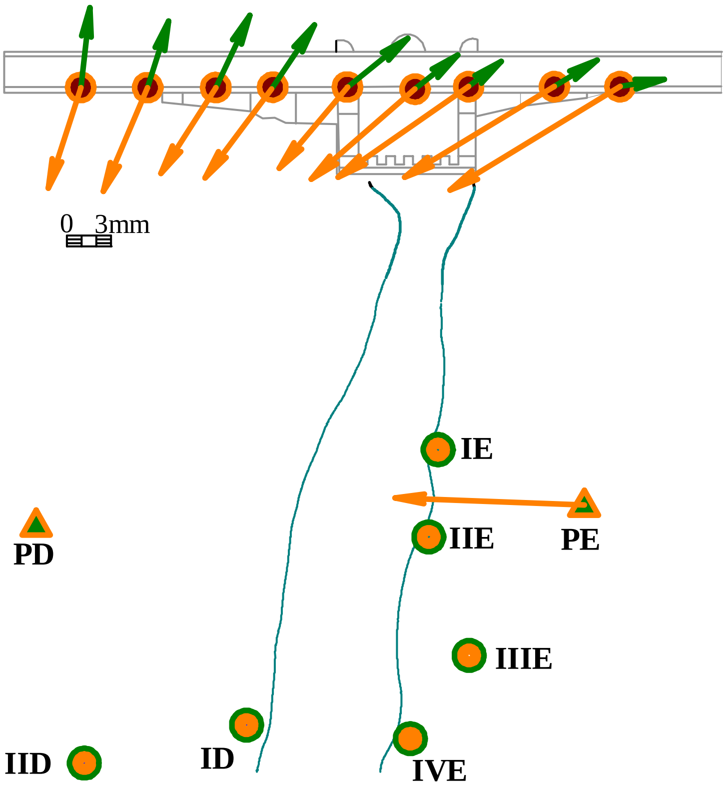

Figure 9: Planimetric displacements of the network points (PE free)

6. CONCLUSIONS

Statistical tests are a powerful tool to carry out quality control of the measurements. However, the tests are effective, if and only if, the local redundancy numbers of the observables are homogeneous and large (Henriques *et alia*, 2000).

As the previous analysis proved that the unexpected displacements were mainly a result of the instability of the reference frame, it's important to consider the improvement of the network. An adequated improvement strategy must result in a better control of the reference frame, namely by choosing new reference points, each of these sighted from both stations, and by measuring the distance between the two stations with a precision EDM. The new reference points should be materialized by forced centering pieces, so that the distances from the stations to these points could also be measured.

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BIOGRAPHICAL NOTES

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