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APPLICATION OF THE CONDOR STATISTICAL MODEL IN THE CASE OF THE CLOCOTIȘ ARCHED DAM FROM GORJ COUNTY

Alin PĂTRĂȘCOIU [1] Albert Titus CONSTANTIN [1] Marie-Alice GHIȚESCU [1]

Abstract: The paper presents the application of the Condor Method with direct application for the case of the double-arched dam Clocotiș. The analysis of the measurements was performed by mathematical modelling of a set of significant measurements with the corresponding values obtained throughout the existence of the structure. Thus, it was verified if the variables that identify the behaviour of the structure as well as those related to the environmental and operational conditions are in the range of values obtained previously and if they are consistent.

Keywords: double-arched dam, measurements

1. GENERAL CONSIDERATIONS

Clocotiș Dam is a double arched dam located in Gorj County, on the upper course of the Bistrița River, downstream of the confluence with the Clocotiș Creek, about 4 km upstream from Gureni. The function of the work is exclusively energetic, but related functions of water supply of Pestișani locality and Târgu Jiu city are also fulfilled.

Figure 1. Plan view and dam location in Gorj County

According to the National Technical Standard "Seismic design code - Part I - Design provisions for buildings - code P100-1 / 2016", the location of the Clocotiș Dam located in Gorj county on the Bistrița (Jiu) river is characterized by the following parameters: peak value of the land acceleration ag 0.15g with the average recurrence interval IMR = 225 years and corner period: Tc = 0.7s. The category of importance of the dam is category B and was established according to Technical Standard NTLH - 021, this category imposing the need for special monitoring of the work, respectively the existence of the special monitoring project. As a result, the dam is equipped with measuring and control devices for external loads, respectively for the supervision of constructions and their foundation.

Table 1 shows the measuring and control devices provided by the project, installed and in operation.

Table 1. Measuring devices

Crt. no.	Device name	Quantity		
		Provided	Mounted	In Operation
1.	Air temperature transducer	1	1	1
2.	Tele-pluviometr	1	1	1
3.	Concrete temperature transducer	64	61	55
4.	Total pressure transducer	10	11	9
5.	Interstitial pressure transducer	15	12	12
6.	The reverse slope	4	4	4
7.	Tele-pendule	3	3	2
8.	The direct slope	1	1	1
9.	Rock-meter	5	4	3
10.	Deformed bolts	30	29	25
11.	Hydro-geological drilling	6	6	6
12.	Levelling landmarks	65	52	46
13.	Fundamental levelling landmarks	4	2	2
14.	Tableware fixture	44	38	34
15.	Pillars of micro-triangulation	6	7	6
16.	Metallic wonder	1	1	1
17.	Level transducer in the lake	1	1	1
18.	Tarot overflow	2	2	2
19.	Drainage boreholes	46	46	46

Figures 2 and 3 show the arrangement of significant measuring and control devices for the plan view of the dam, respectively from its cross section. In

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[1] Politehnica University of Timişoara, Department of Hydrotechnical Engineering, Spiru Haret Street, no. 1A, 300022, Timişoara, Romania, alin.patrascoiu@student.upt.ro , albert.constantin@upt.ro , alice.ghitescu@upt.ro

Figure 2 is illustrated the plan view and control and measurement devices location (AMC).

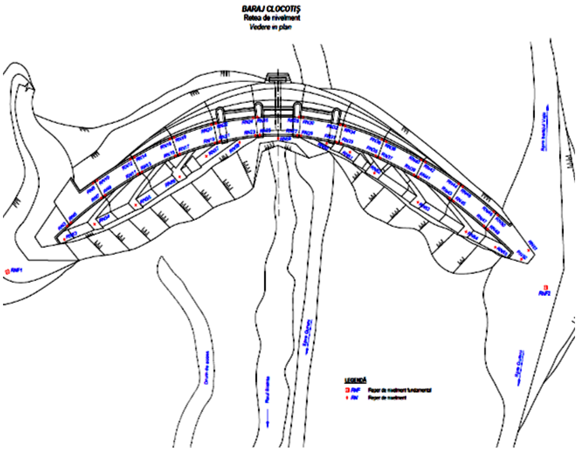


Figure 2. Dam plan view, and AMC displacement.

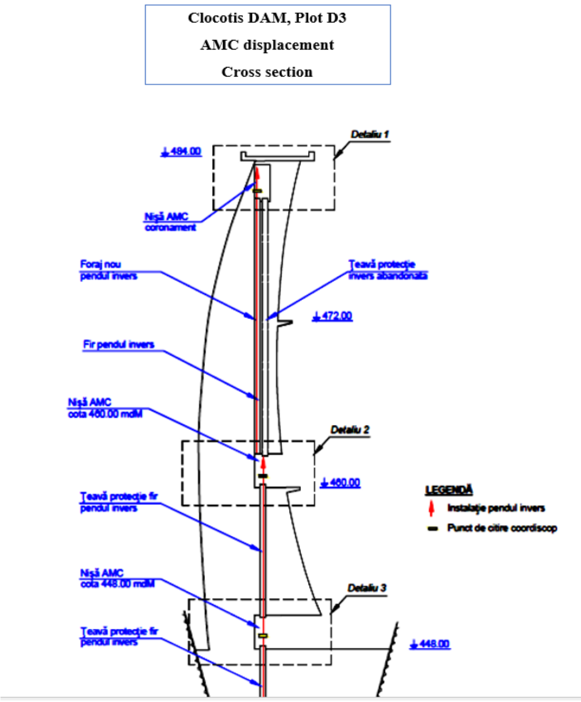


Figure 3. AMC displacement in main dam cross section

The measurements performed on the measuring and control devices of the dam are analysed and interpreted by means of known mathematical methods. The interpretation of the data collected through the system of monitoring and direct inspections is necessary to assess the safety of the work. The basic models used for the interpretation of data obtained from dam surveillance are currently of several types: deterministic, statistical, based on neural networks, hybrids, etc.

2. STATISTICAL MODELS

2.1 STATISTICAL MODELLING

In the case of the statistical model, the analysis of the measurements is performed by statistically comparing a set of significant measurements with the corresponding values obtained during the existence of the structure. Thus, it is verified if the variables that identify the behaviour of the structure as well as those related to the environmental and operational conditions are included in the range of values obtained previously and if they are consistent. Also, through the statistical processing, the eventual evolutions of the work in time are highlighted, separating the reversible phenomena, related to the variations of the retention rate, to the thermal state of the work and the precipitation regime, to the irreversible phenomena.

The weight and efficiency of the statistical criterion increases with the life of the structure, it makes it possible to verify the calculation model and the parameters that define it.

Regressive models are the best known of the mathematical models, being the most commonly used, because they are simple to use and do not require complicated processing. They can be used to check all the parameters actually measured (displacements, infiltrations, etc.). The models used must allow:

- determining the construction response for each request taken separately;
- highlighting the evolutionary phenomena in time;
- highlighting any behavioural anomaly with a higher accuracy than that provided by the classical method;
- assessing the credibility of monitoring systems.

The calibration of a mathematical model is performed respecting the following steps:

- it is admitted that the studied phenomenon is related to a certain number of variables (hydrostatic load);
- the unknown relation of a phenomenon and the external variables are replaced by an arbitrary algebraic function of these variables, a function whose form tries to translate as accurately as possible the foreseeable influence of the external variables on the measured parameter; thus, a model is defined in which the variables and the coefficients of these variables appear;
- the model is calibrated according to measurements already made, i.e. the values of the coefficients that best adapt the model to the set of measurements are sought; it is important to note that these coefficients represent the unknowns necessary to be determined; the model will represent the reality the better it is calibrated on a larger number of measurements;
- it is accepted that the model represents the phenomenon in the time period corresponding to the measurements that served the calibration (reference period); the method allows a comparison of the real behaviour with the reference one.

To calibrate the model defined above, the "least squares" method is used.

2.2 STATISTICAL MODELS APPLIED TO CONCRETE STRUCTURES

In the case of concrete dams, the statistical model under identical conditions (of compensated measurements), consists in separating the effect of temperature and hydrostatic pressure from that of irreversible trends. The general shape of the model is [1]:

$$Y = f(Z) + f(T) + f(t) \pm \varepsilon \qquad (2.1)$$

where:

Y: effect measure.

f(Z)= polynomial that reflects the influence of hydrostatic loading

f(T) = polynomial that reflects the influence of air temperature

f(t) = polynomial of the time elapsed since the “zero” measurement, but after the end of the first load

ε = unexplained residue (random component depending on ignored phenomena and measurement errors).

Based on the measurements obtained at the pendulums, the statistical modelling of the dam displacements was performed, on the upstream-downstream direction. The statistical model used takes into account the following cause sizes:

- water level in the lake at the time of measurement
- air temperature modelled by a trigonometric function;
- time variable.

The general form of the model equation is:

$$Y = A_0 + f(Z) + f(T) + f(t) \qquad (2.2)$$

where:

Y- movement;

f(Z) – lake water level function;

f(T) – air temperature function;

f(t) – time function.

The function of the water level in the lake has the following general form:

$$f(Z) = A_{0,Z} + A_1 Z + A_2 Z^2$$

where:

$$Z = \frac{H - H_{talveg}}{H_{NNR} - H_{talveg}}$$

$H_{thalweg}$ = 435,00 maSL; H_{NNR} = 480,00 maSL.

The air temperature function takes into account a function of four trigonometric terms (cosine and sine) that actually models the seasonal variation of air temperature:

$$f(T) = A_{0,T} + A_3\cos(s) + A_4\sin(s) + +A_5\sin^2(s) + +A_6\sin(s)\cos(s)$$

where:

s = (360/365) x (actual date – 01.01. current year).

The time function has the following general form:

$$f(t) = A_{0,t} + A_7 e^{-t} + A_8 t + A_9 t^2$$

The final statistical model has the following form:

$$Y = A_0 + A_1 Z + A_2 Z^2 + A_3\cos(s) + A_4\sin(s) + +A_5\sin^2(s) + A_6\sin(s)\cos(s) + A_7 e^{-t} + A_8 t + A_9 t^2 \qquad (2.3)$$

The quality of the modelling is given by two representative statistical indicators: the correlation coefficient “R” and the square mean deviation “s”.

he correlation coefficient is calculated with the relation:

$$R = \sqrt{1 - \frac{\sum_{i=1}^{n}(\hat{Y_i} - Y_i)^2}{\sum_{i=1}^{n}(\hat{Y_i} - \bar{Y})^2}} \qquad (2.4)$$

where:

$\hat{Y_i}$ – measured values;

Y_i – computed values;

$\bar{Y}$ – mean measured value;

n – number of measures.

It is the main means of evaluating the quality of modelling. R can vary from 0 - a situation that shows the lack of any connection between series and 1, when the series coincide perfectly, the model fully reproducing the measured phenomenon. Its dimensionless character and its clearly defined range of variation allow comparisons:

- between the R values for a measuring point, obtained over different time intervals, the variations may indicate changes in the behaviour of the structure;

- between the results obtained at the same construction, at the same type of device, in different measurement points, establishing a relation R (s), a significant decrease of the value of the correlation coefficients at the points with small values s (small amplitudes of variation) highlights the limit the accuracy of the device;

- between the results obtained for devices of different types, which measure similar sizes, the differences allow the evaluation of the performances of each type of device.

- The mean square deviation s of the series of measured quantities, which expresses the width of the dispersion band of these values around the mean:

$$s = \sqrt{\frac{\sum_{i=1}^{n}(\hat{Y_i} - Y_i)^2}{n-1}} \qquad (2.5)$$

The analysis of its evolution over time can be a first indication of the behaviour of the structure. If the variation of the external stresses (levels) occurs within approximately constant value ranges, “s” will also remain approximately constant, in the case of the normal behaviour of the measuring equipment and the dam. The confidence interval was determined considering the mean square deviation:

$$Y_{i,\ superior\ limit} = Y_i + 2s$$

$$Y_{i,\ inferior\ limit} = Y_i + 2s$$

The calculation period used for calibrating the model is 01.01.2006 ÷ 31.12.2020.

In order to determine the warning limits, the string with the calculated values together with the square mean deviation (s) of the residue of the statistical model determined the upper and lower limits of each behaviour situation, respectively the attention and alert situation, thus:

- limits of attention:

inferior limit: Yc - 2 s

superior limit: Yc + 2 s

- alert limits:

inferior limit: Yc - 4 s

superior limit: Yc + 4 s

At the warning limit, in addition to exceeding that value, which may not lead to an abnormal phenomenon, the dam-foundation assembly and other measurements must be taken into account, which can confirm that there is indeed an increased risk to safety of the dam. In this sense, the visual observations and the functionality of the hydromechanical equipment have an important role in declaring the state of alert.

The alarm limit cannot be specified by a simple figure, it must take into account a number of other factors that may contribute to an abnormal phenomenon and a potential risk to the dam.

In the triggering of the alarm state, the evolution of the phenomena that can lead to the dam damage is essential. In this case, an increasingly important role is played by visual observations made permanently on the affected areas and which can highlight evolutionary phenomena (displacement, infiltration).

Standard deviation σ_{b0} of the series of differences ε, between measured and calculated values (average calculation error):

$$\sigma_{b_0} = \sqrt{\frac{\sum (\varepsilon_i)^2}{n-k-1}} \qquad (2.6)$$

where:

n – measurements number.

k – equation terms number.

Uses of σ_{b_0} indicator is:

- measures the performance of each calculation model, making an objective comparison of them;
- constitutes, like σ an indicator of stability of the construction behaviour in time.

The explanation coefficient Ie of the phenomenon is like the correlation coefficient. While the correlation coefficient is the established mathematical indicator, the explanatory one is a more expressive engineering indicator, expressing as a percentage, between 0 and 100% the success of the modelling.

$$I_e = R^2 \qquad (2.7)$$

3. DETERMINATION OF MODELS OF CORRELATION OF MEASURES MEASURED AT PENDULUMS

3.1 ABSOLUTE MOVEMENTS MEASURED AT PENDULUMS

To determine the absolute displacements, the application “Monitoring hydraulic structures behaviour over time (UCCH)-Statistical Modelling HST” [2] was used for the pendulums in plot P0 and plot D3. The modelling was done for the measurements on the upstream-downstream direction located at the elevations of 448.00 maSL, 460.00 maSL and arched dam. The statistical indicators of the analysed series of measurements are presented in table 2-1.

Table 2-2 shows the synthesis of the statistical description for each pendulum.

Table 2-1. Statistical indicators

Point	Nr. .	Measured values					Model			
		min	med	max	var	σ_{b0}	S	R	Ie	Ecart
Plot 0 Elev. 448.00 maSL dir. DS-US	550	-9,50	0,02	6,70	16,20	2,78	2,26	0,591	35	4,53
Plot 0 Elev. 460.00 maSL dir. DS-US	575	-12,30	-2,99	5,70	18,00	4,07	1,40	0,940	88	2,81
Plot 0 crest elev. dir. DS-US	566	-24,70	-7,46	6,50	31,20	7,23	2,49	0,940	88	4,98
Plot 0 crest elev. compared with 460.00maSL elev. dir. DS-US	560	-14,10	-4,44	1,70	15,80	3,59	1,33	0,930	86	2,66
Plot 3D elev. 448.00maSL dir. DS-US	553	-1,00	2,24	4,70	5,70	1,01	0,51	0,863	75	1,03
Plot 3D elev. 460.00 maSL dir. DS-US	579	-1,40	4,99	8,50	9,90	2,36	1,00	0,907	82	2,01
Plot 3D Crest elev. dir. DS-US	556	-13,70	0,96	8,00	21,70	3,92	1,81	0,888	79	3,62
Plot 3D crest elev. compared with 460.00 maSL elev. dir. DS-US	551	-12,80	-4,15	1,40	14,20	2,77	1,85	0,749	56	3,70

Table 2-2. Statistical Synthesis description of each pendulum

Name		Plot 0 Elev. 448.00maSL dir. DS-US	Plot 0 Elev. 460.00maSL dir. DS-US	Plot 0 Crest elev. dir. DS-US	Plot 0 Crest Elev. compared with 460.00maSL elev. dir. DS-US
A_0		17,46	-1,24	-17,53	-16,22

A_1	Z	-42,14	2,89	40,10	36,91
A_2	Z^2	21,75	-8,45	-34,39	-25,85
A_3	$\cos s$	-0,07	-3,07	-7,40	-4,30
A_4	$\sin s$	-0,28	-3,73	-5,62	-2,02
A_5	$\sin^2 s$	-0,260	0,943	1,549	0,665
A_6	$\sin s \cdot \cos s$	0,20	0,08	0,42	0,27
A_7	e^{-t}	-0,08	0,43	-0,14	-0,56
A_8	t	0,03	-0,03	0,004	0,038
A_9	t^2	5,73	8,17	8,13	0,06
N_{min}		435.00	435.00	435.00	435.00
NNR		480.00	480.00	480.00	480.00
H_{NNR}		45.00	45.00	45.00	45.00
Initial data		01-01-2006	01-01-2006	01-01-2006	01-01-2006

Table 2-2. Statistical Synthesis description of each pendulum (continue)

Name		Plot 3D Elev. 448.00maSL dir. DS-US	Plot 3D Elev. 460.00maSL dir. DS-US	Plot 3D Crest elev. dir. DS-US	Plot 3D Crest elev. compared with 460.00maSL elev. dir. DS-US
A_0		-2,57	1,63	17,94	12,68
A_1	Z	5,25	-6,73	-61,31	-44,17
A_2	Z^2	-3,17	3,76	34,11	23,40
A_3	$\cos s$	-0,62	-0,64	-3,02	-2,46
A_4	$\sin s$	0,12	0,69	-0,36	-1,14
A_5	$\sin^2 s$	0,12	0,36	1,18	0,85
A_6	$\sin s \cdot \cos s$	-0,03	-0,03	0,48	0,33
A_7	e^{-t}	0,65	1,25	1,77	0,45
A_8	t	-0,032	-0,048	-0,066	-0,014
A_9	t^2	1,11	2,49	7,97	4,96
N_{min}		435.00	435.00	435.00	435.00
NNR		480.00	480.00	480.00	480.00
H_{NNR}		45.00	45.00	45.00	45.00
Initial data		01-01-2006	01-01-2006	01-01-2006	01-01-2006

3.2 PROCESSING RESULTS

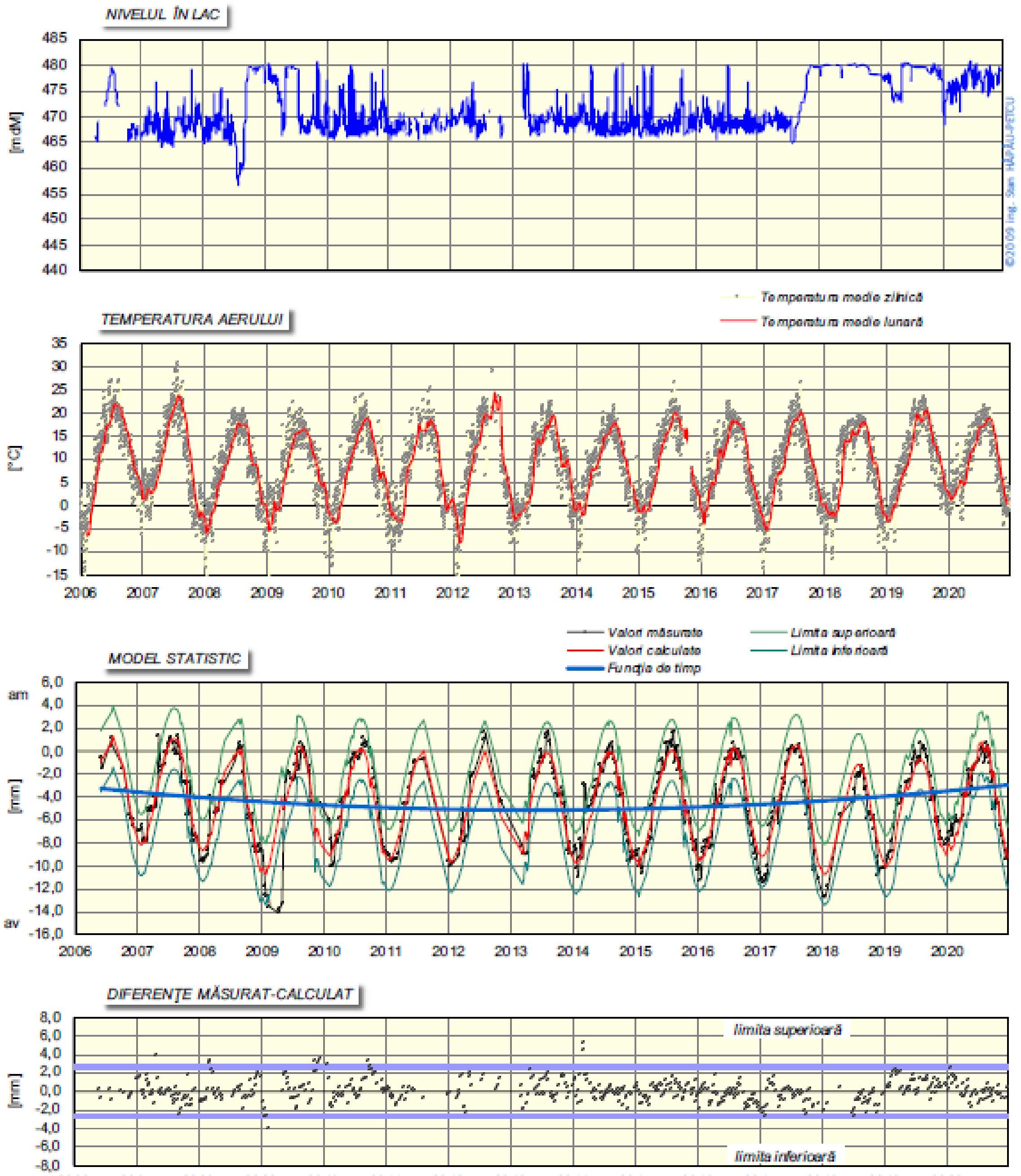
The main results of the calculations and graphical processing are presented in the following figures, as follows [3]:

- chronological graphs of the series of measurements, compared to the chronological evolution of the external demands.

- the comparison of measurements - model synthesized in the measured - calculated diagrams, respectively the measured - calculated comparison.

- influence graphs for determining the construction response for each request taken separately;

- monitoring diagrams of the measurements compensated by the effect of external stresses, the purpose of the diagram being to highlight the evolutionary phenomena in time.

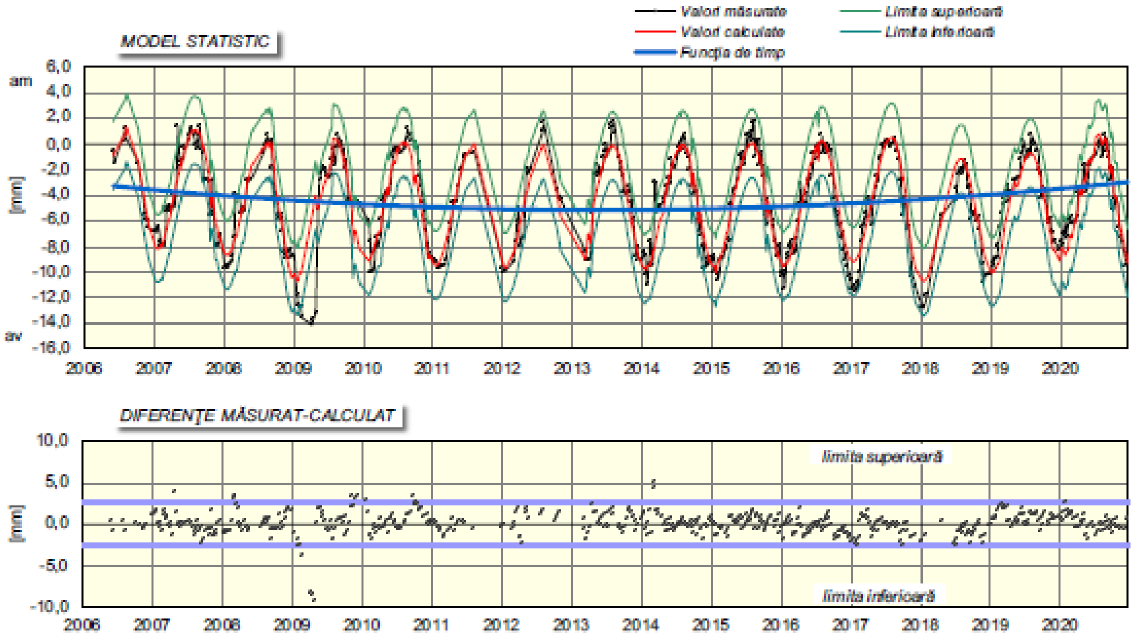


Yc = f(Z; Z^2; cos s; sin s; sin^2 s; sin s · cos s; t; t^2; e^-t)

Yc = 17.46 -42.14*Z +21.75*Z^2 -0.07*cos s -0.28*sin s -0.26*sin^2 s +0.20*sin s · cos s -0.08*t +0.03*t^2 +5.73*e^-t

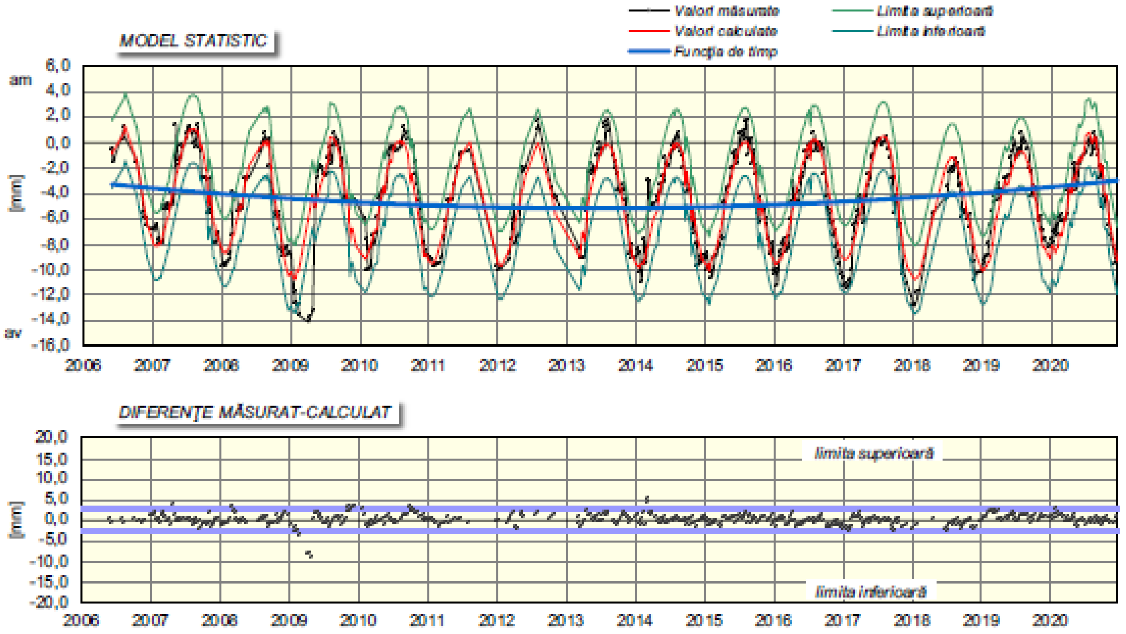
R = 0.591 s = 2.264

Figure 4. Clocotiș Dam. Statistical Model
Measured displacements at the pendulum, Plot 0, crest elevation 448.00 maSL direction downstream-upstream (DS/US)



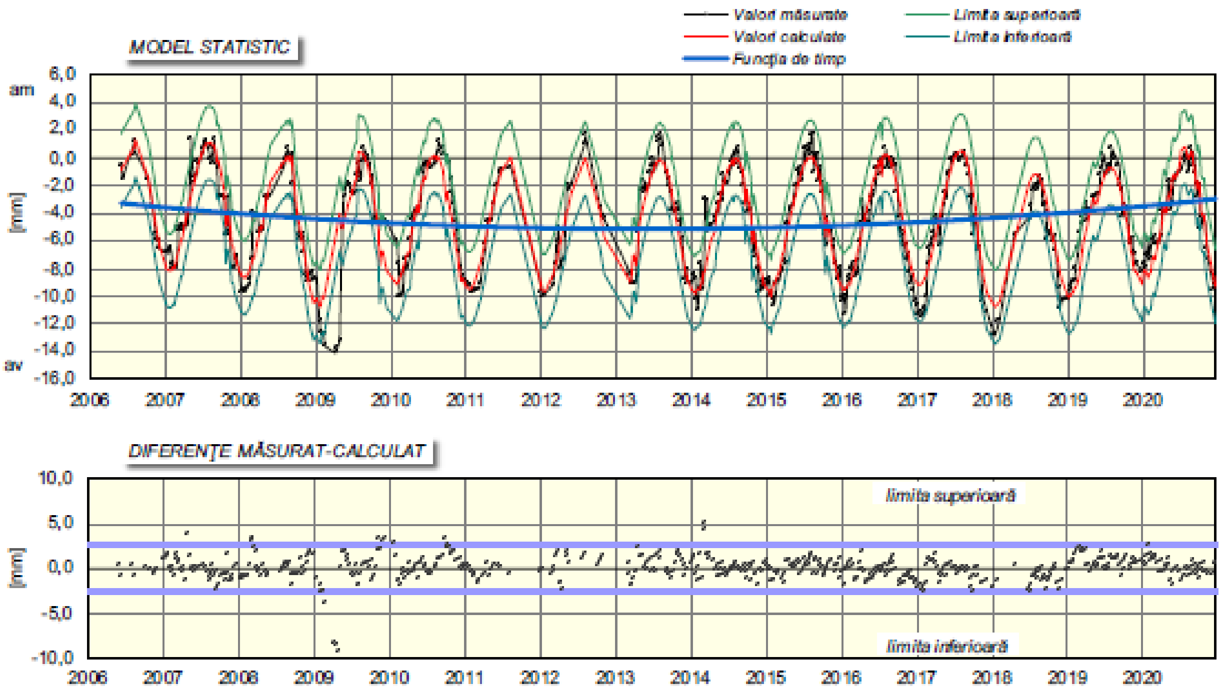
Yc = f(Z; Z^2; cos s; sin s; sin^2 s; sin s · cos s; t; t^2; e^-t)
*Yc = -1.24 +2.89*Z -8.45*Z^2 -3.07*cos s -3.73*sin s +0.94*sin^2 s +0.08*sin s · cos s +0.43*t -0.03*t^2 +8.17*e^-t*
R = 0.940 s = 1.404

Figure 5**.** Clocotiș Dam. Statistical Model
Measured displacements at the pendulum, Plot 0, elevation 460.00 maSL direction DS/US



Yc = f(Z; Z^2; cos s; sin s; sin^2 s; sin s · cos s; t; t^2; e^-t)
*Yc = -17.53 +40.10*Z -34.39*Z^2 -7.40*cos s -5.62*sin s +1.55*sin^2 s +0.42*sin s · cos s -0.14*t +0.00*t^2 +8.13*e^-t*
R = 0.940 s = 2.491

Figure 6**.** Clocotiș Dam. Statistical Model
Measured displacements at the pendulum, Plot 0, crest elevation direction DS/US



$$Yc = f(Z;\ Z^2;\ \cos s;\ \sin s;\ \sin^2 s;\ \sin s \cdot \cos s;\ t;\ t^2;\ e^{-t})$$

$$Yc = -16.22 + 36.91 \cdot Z - 25.85 \cdot Z^2 - 4.30 \cdot \cos s - 2.02 \cdot \sin s + 0.67 \cdot \sin^2 s + 0.27 \cdot \sin s \cdot \cos s - 0.56 \cdot t + 0.04 \cdot t^2 + 0.06 \cdot e^{-t}$$

$R = 0.930$ $s = 1.331$

Figure 7**.** Clocotiş Dam. Statistical Model

Measured displacements at the pendulum, Plot 0, crest elevation compared with 460.00 maSL elevation direction DS/US

4. CONCLUSIONS

Figures 4 to 7 illustrate statistical analysis performed with the CONDOR model of the upstream-downstream movements recorded at the direct pendulum from plot 0 at the Clocotiş Dam.

In the analysed period (January 2006 - December 2020), the displacements measured on the pendulums in plot 0 had an evolution mainly influenced by the thermal averages of the air in the site. The direct pendulum reveals a typical behaviour of the structure, in accordance with the demands to which it was subjected.

Thus, there are more pronounced downward movements recorded between December 2018 and January 2019 against the background of an extremely cold season. These extreme values are mainly determined by the readings at the telepath at 460 mSL, being confirmed by the manual measurements performed in January - February 2019. Another noteworthy situation is the maximum annual values of upstream dam movements recorded during 2018, with approx. 10 mm lower than the previous period at the arch. Again, an important role for this behaviour is played by the loads in the thermal component, the maximum daily and monthly values recorded at the site being much lower than those normally recorded during operation. This behaviour is similar to that recorded in the previous analysis period, but the maximum downstream displacements being slightly lower due to lower thermal loads.

In conclusion, the Statistical Models are simple to apply and allow the rapid detection of behavioural anomalies, alarm signals that require rapid action to restore the work within normal limits of behaviour.

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