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THE ANALYSIS OF VERTICAL DISPLACEMENTS FOR A HYDROTECHNICAL FACILITY USING GEOSTATISTICS

PART I. STRUCTURAL ANALYSIS AND ESTIMATION OF DISPLACEMENTS

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Abstract: The effect of geostatistical studies, including structural analysis, modelling, estimation and forecast, is the cartographic characteristic of the displacements of the hydro-technical object – the Opatowice weir. In the nodes of the spatial grid, covering the object analyzed, the average estimated values Z^* of displacements were calculated together with the assessment of the uncertainty of estimation – the standard deviation of estimation σ_k. If necessary, the parameters Z^* and σ_k can be determined directly in the kriging calculation, at every point of the object. The obtained variograms, raster maps and block diagrams represent the spatial visualization of the results of the various displacements, derived from the geodesic monitoring of the dam.

Applying an ordinary block kriging it is possible to separate the clear boundaries of the zones of the subsidences and to determine the elevations of the hydro-technical object, marking on the raster maps the distributions of the average Z^* values, which can be interpreted as the areas of local deformation that are important when the safety of buildings is considered.

The maps of quick interpolation allow identification of a general background of displacements, without the accuracy estimation of the interpolated values Z^*.

Probability maps enable us to predict the significant risk areas associated with a possible change in the geometry of an object, i.e., its local deformation.

Due to an area–time prognosis we can determine the forecasted values Z^* of displacements for the following year (1999), with reference to the history of this process, i.e. the estimations from prior years (e.g., 1987, 1991).

Taking account of a wide range of different applications of geostatistical techniques, we can conclude that they are also effective tools in the analysis of spatial displacement, in this case, for a relatively small hydro-technical object (weir).

The research undertaken may be useful for a complete monitoring of relevant environmental factors, differing only “seemingly identical” objects, and not only for the results of successive control measurements of displacements. This concerns a proper treatment of all spatial and time factors associated with the interpretation of the displacements, which allows the deterministic safety operation of a hydro-technical object to be identified.

1. INTRODUCTION

Solving complex problems that emerge during the study of continuous, regionalized phenomena through the measurement of discrete points of a specified variable is possible by estimating parameters in multidimensional space. In such a procedure, the scale of the phenomena should be fixed and the appropriate techniques applied in analyzing the data collected. The considerable variation in the values of regionalized variables often makes them unusable in mathematical functions describing, while their use in classical statistical methods leads to the loss of essential information describing the complex structure of the phenomena studied in space.

The research methodology associated with geostatistics was developed several years ago and allows obtaining reliable information about the distribution of parameters describing phenomena occurring in space. Geostatistical methods are being increasingly applied in various scientific fields as well as in the study of macroeconomics. Geostatistics is composed of a set of statistical techniques based on the theory of random functions taking into account spatial and temporal features (characteristics) in data analysis. Geostatistics, in contrast to traditional statistical methods, allows not only a quantitative analysis, but – most importantly – a qualitative evaluation of the data structure for the phenomenon selected in the space of study. Geostatistics is a branch of applied statistics with boundaries overlapping those of related fields such as spatial statistics, mathematical morphology, remote sensing and image analysis. The basic premise of geostatistics is that regionalized variables can be correlated. Traditional deterministic solutions require many simplifications and thus the models obtained by these methods are less accurate. In comparison, geostatistical methods offer new possibilities, especially when the geometry and characteristics of the study area or object are complicated. With the goal of approximating the probabilistic features of geostatistical methods, the authors propose their wider use in a variety of research problems for which modelling and predicting the range of phenomena are particularly justified.

Geostatistics was first applied in geology and in the mining industry for predicting the ore metal grades in mineral deposits, their spatial distribution as well as obtaining quantitative characteristics. The first work of this kind was conducted in South Africa and then it was further developed in France. The original methods were based on statistical estimates; however, the estimates were proved to be too optimistic in the areas with poor ore deposits and also inadequate in the areas that were resource-rich. This was not due to specific characteristics of the deposits, but is a common feature of all variables occurring in any space.

Geostatistical methods are applied to a variety of problems in the natural sciences, including both theoretical research (mathematical methodology, e.g., in economics) and experimental research in a wide range of topics related to the Earth sciences. In particular, these methods are used in geology, mining, environmental protection as well as in geodesy and cartography. This development is documented in the wide range of cartographic works. Although not all geostatistical methods are probabilistic in nature, the most significant achievement in estimating and predicting based on the probabilistic approach was made in the research of stochastic processes and timing analyses. The theory of geostatistical methods together with examples of their application can be found in numerous works [1]–[4], [6]–[9], [12], [18], [22], [24].

Geostatistics is effective in processing and analyzing information in databases and appears to be an adequate tool for computer-aided research with the Geographical Information System (GIS). The GIS databases generated allow instant access to materials with different analytical content and can be subject to geostatistical analyses, i.e. comprehensive estimates of regionalized variables for the parameters studied in 2D and 3D systems. Therefore, using GIS systems offers considerable opportunities for conducting virtually any spatial analysis in the area of environmental protection. Some examples may include evaluating the effects from mining excavations of drives or galleries as well as a soil pollution in the immediate vicinity of industrial facilities [8]–[20].

Geostatistical techniques can be applied in many spatial analyses in the fields of higher and satellite geodesy. In particular, noteworthy applications include local vector estimates of the Earth's gravitational field and the creation (based on numerical terrain models) of gravity anomaly maps, gravity gradient maps and density mass topographical maps [5], [21].

The use of geodesic measurements and geological information for the analysis of spatially correlated data appears to be particularly appropriate for describing natural phenomena with a large spatial and temporal scope such as current movements of the Earth's crust [23]. Geostatistical studies in this field are also useful during the design and siting of objects and structures that are particularly sensitive to the phenomena of this type. Examples include engineered hydraulic structures such as dams and reservoirs for which modelling and predicting the structure and dynamics of deformation with time, taking into account the variability of geotechnical subsurface parameters, is necessary to ensure a safe structure operation.

The authors present some selected results of spatial analyses based on the geodetic databases developed. The displacement values in the databases were obtained by the continuous monitoring for many years of the selected hydraulic structure – the Opatowice weir on the Oder River in Wrocław, Poland.

2. RESEARCH METHODOLOGY

This study applies geostatistical methods which have not yet been used in the research of phenomena based on geodetical measurements. Geostatistical studies are a continuation and expansion of the analyses conducted in the Department of Hydro-Engineering and Geodesy in the Institute of Geotechnics and Hydrotechnics at the Wrocław University of Technology. These studies have focused on the displacements of various engineered structures (stacks, cooling towers, masts, weirs and hydroelectric power stations) under the influence of changing external conditions. The changing external conditions analyzed mainly include solar radiation and temperature as well as the effects of loading such as the height of water behind a dam and the loading caused by wind action on tall, slender structures.

Comprehensive monitoring conducted for the state of engineered hydraulic structures is required for their safe operation. This monitoring not only includes geodetical studies related to the position of the structure in space, but should also enable the evaluation of the probability of displacement for the entire structure. A key aim of such a monitoring is to determine the geometric characteristics of the structure allowing estimation of local displacement, i.e. deformation (strain) which is particularly relevant to the safety of the structure. In order to determine the size, tendency and dynamics of the changes observed in the values of the displacement or deformation parameters of the structure, it is necessary to consider the following:

- applying an appropriate measuring and control system,
- determining the accuracy of this system,
- designating certain (true) acceptable and limiting values of the phenomena observed,
- using the appropriate methods for interpreting the geodetical monitoring results.

Research related to the comprehensive monitoring shows current problems of the geodetical interpretation of displacement and deformation of engineered hydraulic structures, e.g., assessing the safety of sectoral weirs throughout their life cycle on the Oder River that are located in a variety of subsurface conditions. This analysis includes:

- The creation of numerical databases:

a) compiling a geodetical database of the respective current and total displacements, p_a and p_c, in an X–Y coordinate plane as well as including time in a 3D system (X, Y, T) from the long-term monitoring of the displacements of engineered hydraulic structures on the Oder River,

b) compiling a geological database consisting of hydrogeological subsurface parameters obtained from the geotechnical site investigation required for the economical and technical aspects of weir design and construction.

- Summarizing the parameters for the analysis.
- Conducting a preliminary statistical analysis of displacements and geotechnical subsurface parameters using the geostatistical software package Isatis.
- Conducting the geostatistical analysis includes:

a) performing a structural analysis of displacement variability to obtain reliable information about the distribution of parameters in an area (2D) for the subject of study (displacement of an engineered hydraulic structure),

b) determining the distribution of the average estimator Z^* and the distribution of the estimated standard deviation σ_k of the analyzed current p_a and the total p_c displacements of the structure,

c) determining the distribution of the average interpolated estimator Z^* of the analyzed current p_a and the total p_c displacements of the structure, using the methods of quick interpolation,

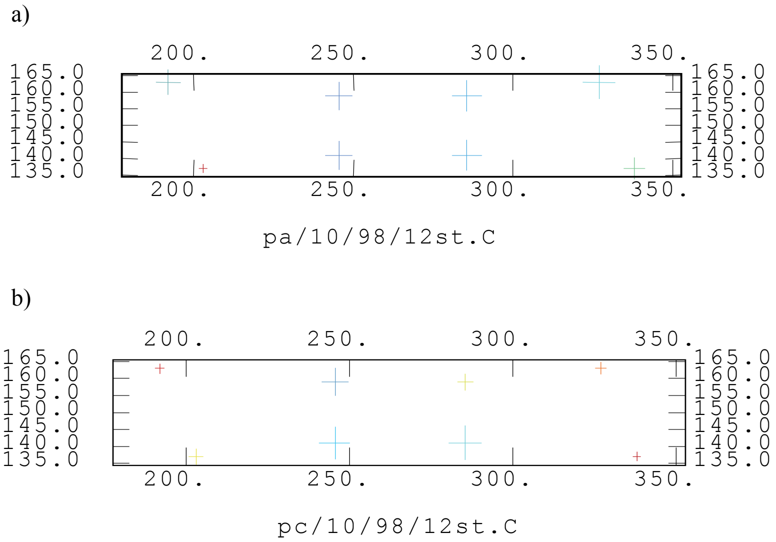
d) determining the probability distributions of displacements along with defined subareas having a varying susceptibility to certain deformation thresholds being exceeded,

e) determining the distribution of the average estimator Z^* and the distribution of the estimated standard deviation σ_k of the analyzed current p_a and the total p_c displacements of the structure, including time (3D) along with the proper estimate of their values (Z^*, σ_k) in the subsequent period of operation for the engineered hydraulic structure.

- Interpreting the results of the spatial analyses.

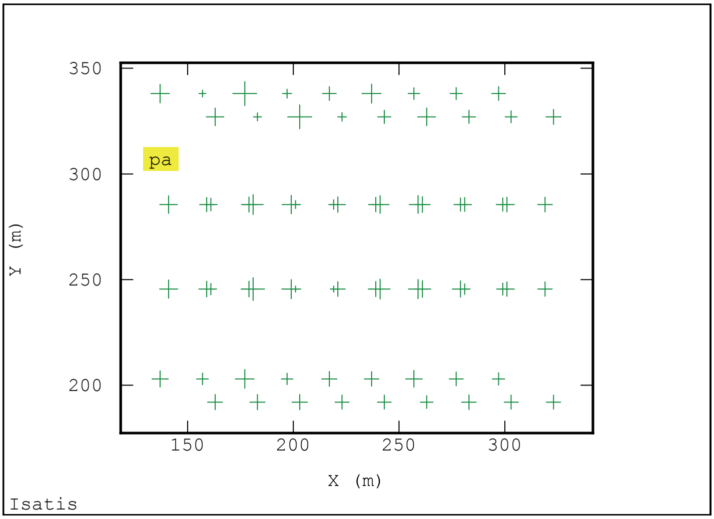
3. PRELIMINARY STATISTICAL ANALYSIS

In the preliminary statistical assessment, the original data, i.e., the displacements of control points of the engineered hydraulic structure – the Opatowice weir on the Oder River in Wrocław, Poland, were monitored from 1986 to 1998 and compiled in a geodetical database. Maps show the locations of the current vertical p_a and total p_c displacements of control points on the weir crest in the monitoring period (figure 1a, b), while also taking into account the temporal distribution of these displacements in a 2D system for a nine year monitoring period (figure 2a, b). In figure 2, different cross sizes indicate different values of displacement.

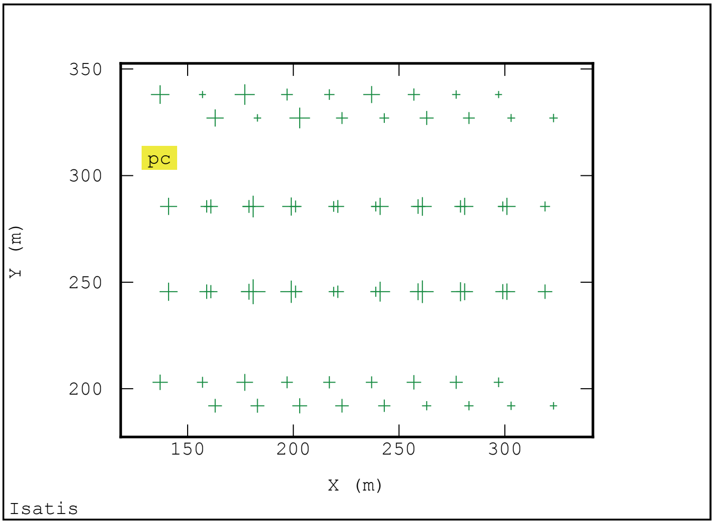


Figs. 1. Maps of vertical displacement: current p_a (a) and total p_c (b) for a specific monitoring period

a)



b)



Figs. 2. Maps of vertical current p_a (a) and total p_c (b) displacement for the entire monitoring period

The fundamental statistics determined from the vertical current p_a and the total displacements p_c of the control points of the engineered hydraulic structure (table 1) together with the distribution histogram (figure 3a, b) complete the statistical analysis of the geodetical measurements obtained.

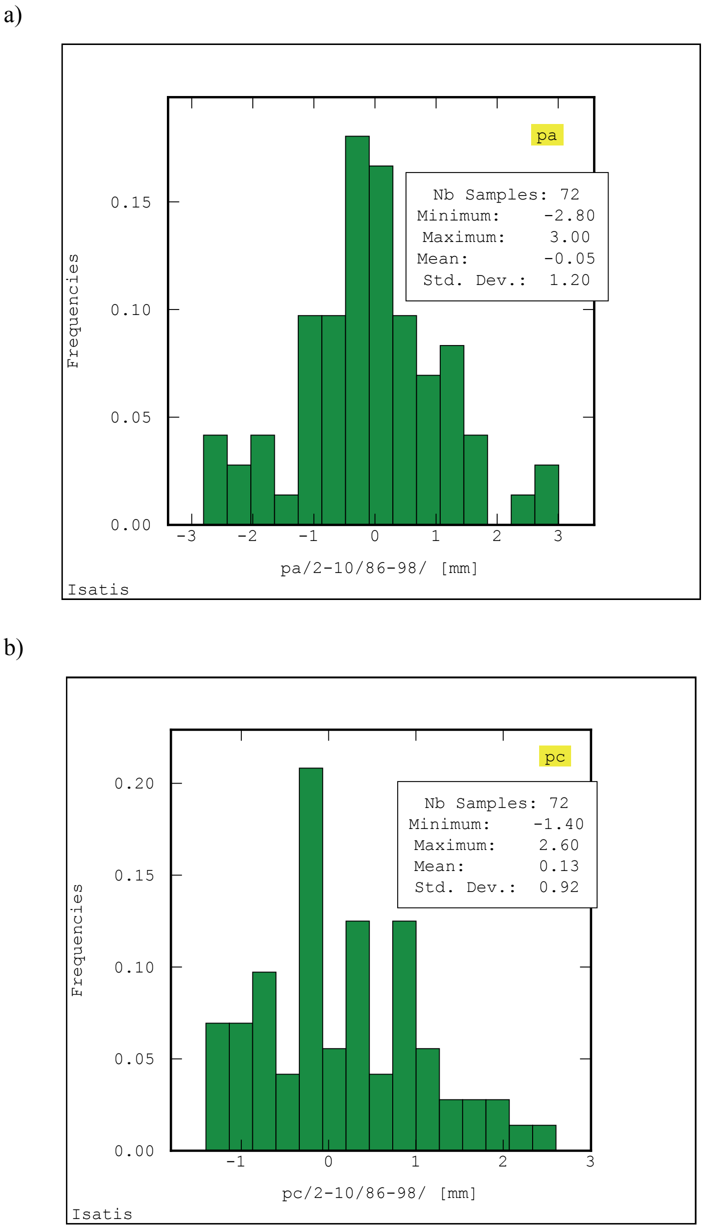


Fig. 3. Histograms of vertical displacement distribution:
current p_a (mm) (a) and total p_c (mm) (b) of the Opatowice weir for the entire monitoring period

The histogram representing the current vertical displacement p_a (figure 3a) has almost symmetrical distribution (the skewness coefficient $g_1 = 0.03$). In addition, the histogram of the total vertical p_c displacement (figure 3b) is characterized by multimodality with a dominant main modal class. This distribution shows a slight tendency towards right-sided asymmetry (the skewness coefficient $g_1 = 0.43$).

Table 1

Fundamental displacement statistics of the Opatowice weir
(calculated from the original data)

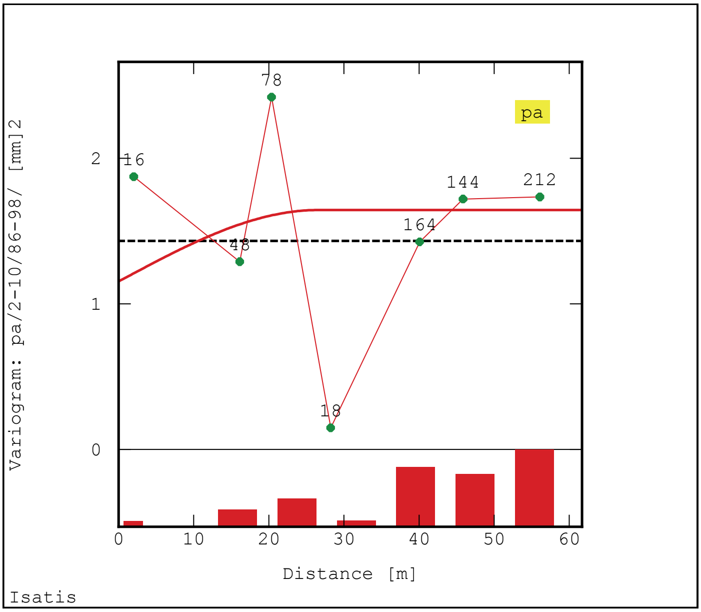
Structure name	Parameters		Sample size N	Min. Value $X_{\min}$ (mm)	Max. Value $X_{\max}$ (mm)	Average value $\overline{X}$ (mm)	Standard deviation S (mm)	Coefficient of variation V (%)
Opatowice weir	Current displacement p_a	p_a (total)	72	–2.80	–0.05	+3.00	±1.20	2400
		p_a (positive)	34	0.00	+1.05	+3.00	±0.80	76
		p_a (negative)	38	–2.80	–0.93	0.00	±0.86	92
	Total displacement p_c	p_c (total)	72	–1.40	+0.13	+2.60	±0.92	708
		p_c (positive)	34	+0.10	+1.01	+2.60	±0.64	63
		p_c (negative)	38	–1.40	–0.62	0.00	±0.42	68

Table 1 provides the fundamental statistical parameters of the displacement for the Opatowice weir. It should be stressed that if the calculations are done separately for the positive and negative values of p_a and p_c, the coefficients of variation V are much lower and they have a high variability. Higher values of V are obtained for the displacements p_a. When the whole population is considered in the calculation, the coefficient of variation V reaches extremely high values (table 1).

4. ANALYSIS OF VARIOGRAMS

The primary stage of geostatistical studies is the structural analysis (variographic) of the parameter variation conducted by using a variogram function. The determined geostatistical models of isotropic variograms for the current p_a and the total displacements p_c, being analytical theoretical functions, were applied to approximate the course of the displacement. Isotropic empirical variograms of displacements p_a and p_c along with their theoretical models are presented in figure 4a, b; the parameters of these models are given in table 2.

a)



b)

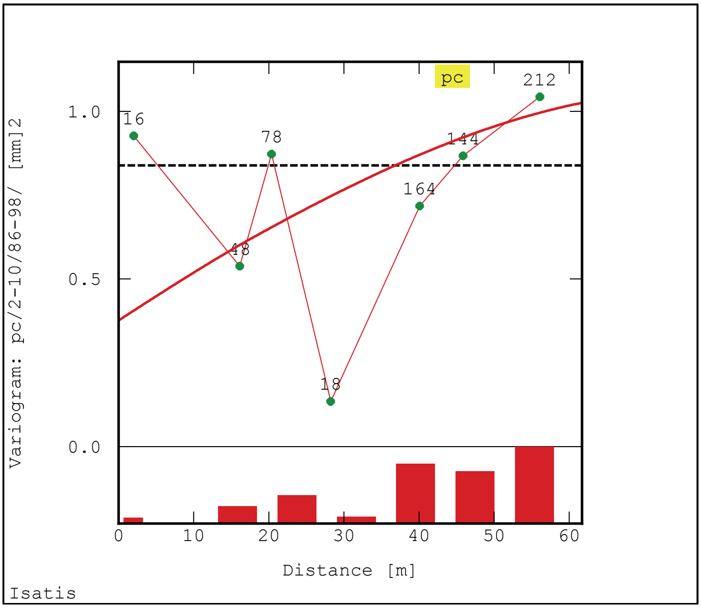


Fig. 4. Isotropic empirical variograms of the current p_a (a) and the total p_c (b) displacements (mm)^2 for the Opatowice weir approximated by applying the theoretical model

Table 2

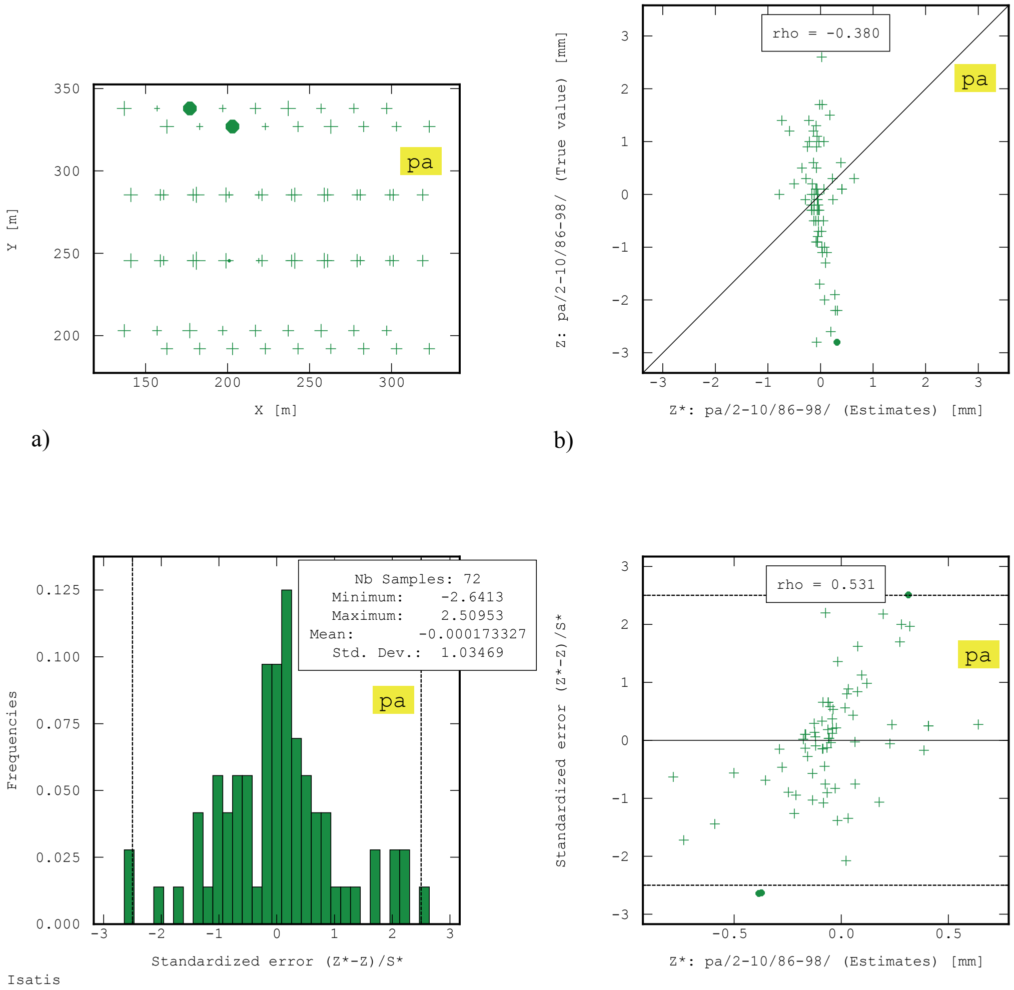
Parameters of geostatistical isotropic empirical variogram for the displacements of the Opatowice weir

Parameters	Nugget effect C_0 $(\mathrm{mm})^2$	Partial variance C' $(\mathrm{mm})^2$	Total sill variance $C = C_0 + C'$ $(\mathrm{mm})^2$	Range of influence a (m)	Model type
Current displacement p_a	1.24	0.52	1.76	26.54	spherical
Total displacement p_c	0.37	0.58 0.07	1.02	75.81 17.85	spherical spherical

The isotropic variograms of displacement are diversified because the variogram displacements p_c show a clear tendency towards the value of the function $\gamma(h)$ increasing together with the distance h (figure 4b). This cannot be seen on the variogram p_a (figure 4a). In addition, the higher correlation of the variable p_c means a wider range of influence (table 2). A greater value of the sill variance C for the displacements p_a and a stronger nugget effect C_0 on the variogram p_a provide evidence of rapid changes (table 2). A much higher value of C_0 indicates that there is a larger share of the random component in the total variation C of the value p_a.

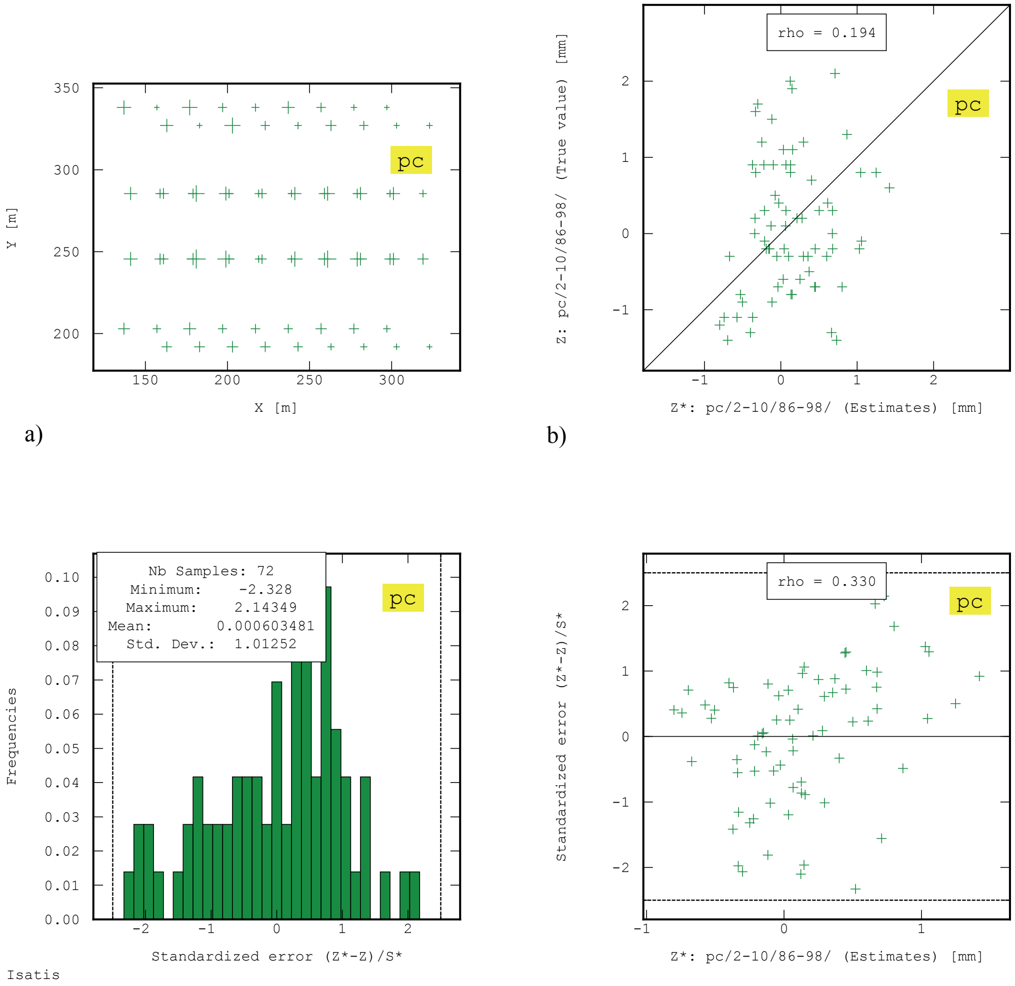
5. RESULTS OF THE CROSS-VALIDATION

The fitting of theoretical models to empirical variograms is verified by the cross-validation procedure, using the ordinary kriging point (figures 5 and 6) and adopting a unique kriging ‘neighborhood’. This means that while determining the average estimator Z^* by means of elementary grid blocks, the sampling of the entire population should be taken into consideration. The results of the cross-validation are presented in tables 3 and 4 and can be used in further procedures for estimating parameters. The cross-validation was conducted based on the following data values: test data ($n = 72$) (table 3) and robust data ($n = 70$) (table 4). The most often obtained value of the variance from standardized error was 1.0 (table 3); only the displacement p_a analyzed based on the robust data produced a lower value of about 0.84 (table 4).



a) b) c) d)

Fig. 5. Cross-validation results for the isotropic theoretical model of the empirical variogram of the current displacement p_a for the Opatowice weir, taking into consideration the unique kriging ‘neighborhood’: base map of the variable analyzed (a); graph of the dependence of the actual value Z on the value of the average estimator Z^* (b); histogram for the distribution of the standardized error values $(Z^*–Z)/S^*$ (c); graph for the dependence of the standardized error values $(Z^*–Z)/S^*$ on the average estimator Z^*(d)



a) b) c) d)

Fig. 6. Cross-validation results for the isotropic theoretical model of the variogram for the total displacement p_c of the Opatowice weir, taking into consideration the unique kriging ‘neighborhood’:
base map of the analyzed variable (a);
graph of the dependence of the actual value Z on the value of the average estimator Z^* (b);
histogram for the distribution of the standardized error values $(Z^*–Z)/S^*$ (c);
graph for the dependence of the standardized error values $(Z^*–Z)/S^*$ on the average estimator Z^* (d)

Table 3

Calculation results from the cross-validation for the isotropic theoretical model
of the empirical variograms of displacement for the Opatowice weir, taking into consideration
the unique kriging 'neighborhood' (test data)

Parameters	Sample size *N*	Test data			
		Average error (mm)	Variance of error $(mm)^2$	Average standardized error	Variance of standardized error
Current displacement p_a	72	–0.00044	1.61857	–0.00017	1.00000
Total displacement p_c	72	+0.00077	0.90186	+0.00060	1.00000

Table 4

Calculation results from the cross-validation for the isotropic theoretical model
of the empirical variograms of displacement for the Opatowice weir, taking into consideration
the unique kriging 'neighborhood' (robust data)

Parameters	Number of mesh nodes *n*	Robust data			
		Average error (mm)	Variance of error $(mm)^2$	Average standardized error	Variance of standardized error
Current displacement p_a	70	+0.09596	1.34668	+0.07451	0.83763
Total displacement p_c	72	+0.00077	0.90186	+0.00060	1.00000

6. ESTIMATION TECHNIQUES

The average values of the parameter Z^* – the displacement with evaluating the accuracy obtained from estimating this variable – are estimated using the estimated standard deviation σ_k with geostatistical estimation techniques. This study uses the following methods of estimation:

- ordinary kriging block method,
- geostatistical indicator technique,
- quick interpolation technique (linear kriging model and the inverse distance squared method).

These methods, except for quick interpolation techniques [18], are based on the variogram function [8], [9], [24] and are used to examine the spatial structure of displacement time. Modelling the structure of the theoretical function leads to determining the values of the geostatistical parameters describing the correlation between the test variables, i.e., the range of influence, the value of the sill C and the nugget effect C_0. This allows determining the shares of the random and non-random components in the total variation C at the value of the parameter analyzed.

The kriging calculation was conducted by applying the ordinary kriging block method and an elementary mesh in 2D and 3D systems. For the 2D system the dimensions of an elementary block of the mesh were 2.5 m along the X-axis and 5.0 m along the Y-axis. The number of block elements was as follows: 48 along the X-axis and 69 along the Y-axis. Overall, the estimation (2D) of the average Z^* for the current p_a and total p_c displacements included the total number of blocks $n = 3312$. Furthermore, in the 3D system, the assumed dimensions of an elementary block of mesh were 2.5 m along the X-axis, 0.5 m along the Y-axis and one year along the Z-axis of time. The number of block elements in the mesh was as follows: 68 along the X-axis, 59 along the Y-axis and 10 along the Z-axis. The total number of spatial mesh block centers n used to estimate (3D) the average Z^* for the total displacement p_c was 40120.

6.1. ESTIMATION USING THE ORDINARY KRIGING BLOCK METHOD

Having set the values of the geostatistical model parameters, the ordinary kriging block method was used to determine the average estimator Z^* for the displacement and related to this the estimated standard deviation σ_k. In calculating the average Z^* and deviation σ_k, the unique kriging 'neighborhood' was taken into consideration, i.e., the subareas of all samples searching (measuring locations). From the 2D estimations the raster maps with a rectangular coordinate system were drawn. They show the distribution of the average Z^* for the displacements p_a and p_c (figures 7 and 9) and correspond to the distribution of the estimated standard deviation σ_k (figures 8 and 10).

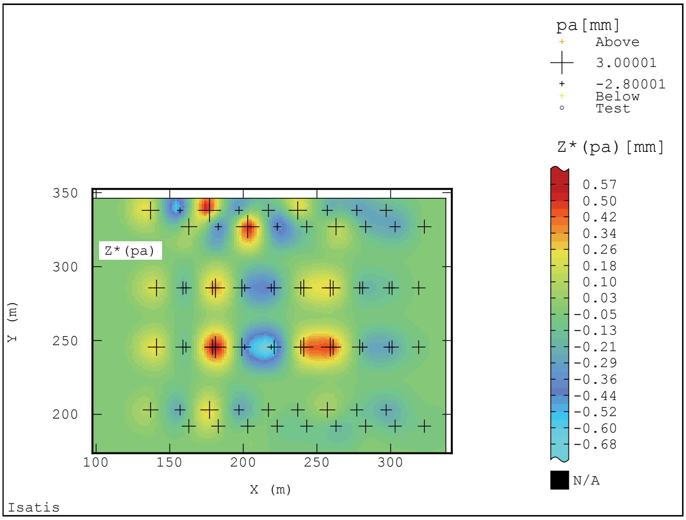


Fig. 7. Raster map of the distribution of the average estimator Z^* values (mm) for the current displacement p_a of the Opatowice weir with marked control points

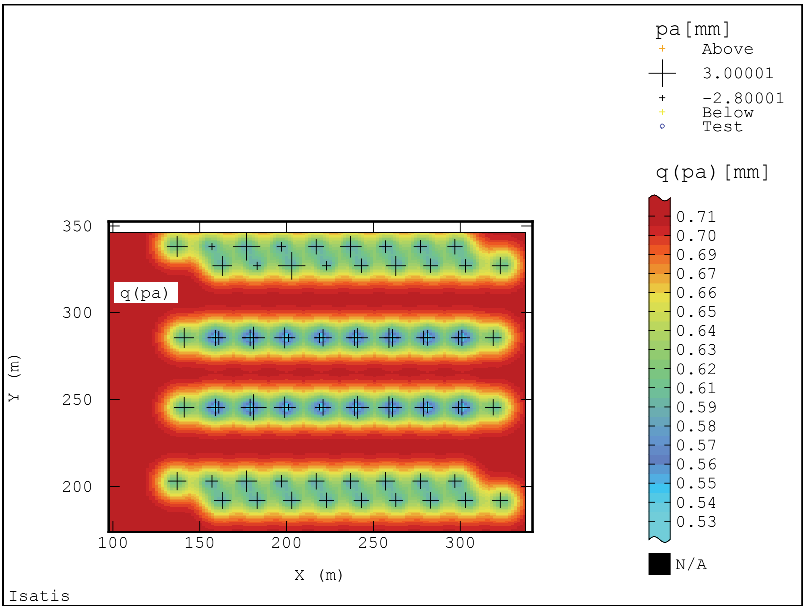


Fig. 8. Raster map of the distribution of the estimated standard deviation σ_k values (mm) for the current displacement p_a of the Opatowice weir with marked control points

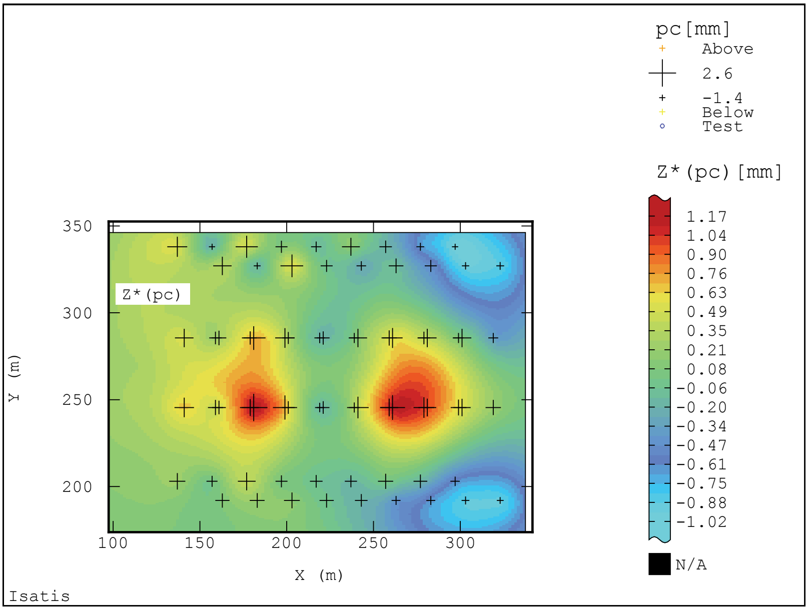


Fig. 9. Raster map of the distribution of the average estimator Z^* values (mm) for the total displacement p_c of the Opatowice weir with marked control points

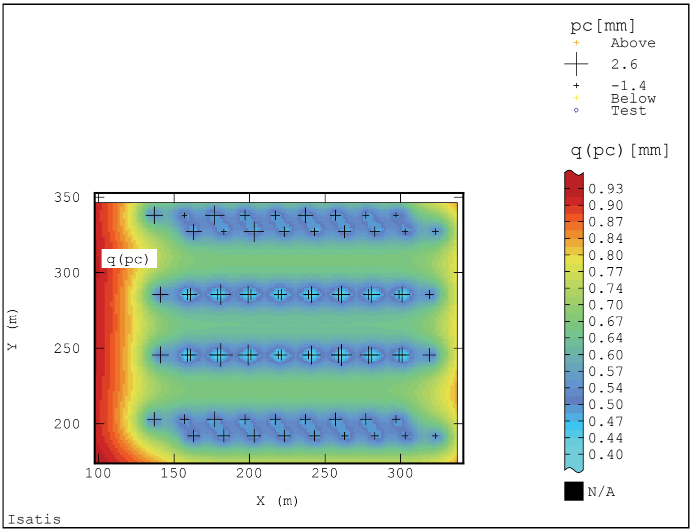


Fig. 10. Raster map of the distribution of the estimated standard deviation σ_k values (mm) for the total displacement p_c of the Opatowice weir with marked control points

The global statistical values of the geostatistical parameters for the current p_a and total p_c displacements of the Opatowice weir obtained during the estimation process are presented in table 5.

Table 5

Global statistical values of the geostatistical parameters for the displacements of the Opatowice weir (using the ordinary kriging block method)

Parameters	Geostatistical parameter	Number of mesh nodes N	Min. Value $X_{\min}$ (mm)	Max. Value $X_{\max}$ (mm)	Average value $\overline{X}$ (mm)	Standard deviation S (mm)	Coefficient of variation V (%)
Current displacment p_a	Average of the estimator Z^*	3312	–0.85	+0.74	–0.11	±0.31	282
	Estimated standard deviation σ_k	3312	+0.57	+1.04	+0.75	±0.07	9
Total displacement p_c	Average of the estimator Z^*	3312	–1.02	+1.17	+0.12	±0.41	342
	Estimated standard deviation σ_k	3312	+0.40	+0.94	+0.65	±0.11	13

The average values of the estimator Z^* of the current displacement p_a were determined from control points during the entire time of weir operation from 1986 to 1998 and ranged from –0.68 to +0.57 mm (figure 7). There are two zones of increased values of uplift in the area of the second pillar and some areas of slight uplift on the left abutment of the weir. The estimated standard deviations σ_k of the displacement p_a at the control points do not exceed the values of about ±0.60 mm. Definitely, the lowest values of σ_k, i.e., ±0.53 mm, were obtained for the area of the two pillars of the weir (figure 8). The average Z^* values of the total displacements p_c of the structure are higher, ranging from –1.02 mm to +1.17 mm. They also cover larger subareas than the displacements p_a. Definite uplift occurs on the second pillar, while the centers of subsidence are found in the area of both weir abutments (figure 9). The standard deviations σ_k of displacement p_c directly at the control points do not exceed ±0.47 mm and are clearly the smallest (±0,40 mm) on both weir pillars (figure 10).

6.2. METHODS OF QUICK INTERPOLATION

In the next stage of the spatial analyses, quick interpolation techniques were used such as the linear kriging model and the method of inverse distance squared, which do not require calculating an empirical variogram and modelling its course with an analytical theoretical function. In the computations performed, the unique kriging 'neighborhood' was taken into consideration. Interpolations using these techniques are less labour-consuming and the resulting raster images of the distribution of the average values of the test parameter Z^* allow us to define quickly the general nature of its variability. It should be noted that during the determination of the average interpolated Z^*, the values of the estimated standard deviation σ_k are not calculated. The raster maps of the Z^* values of displacement calculated using both techniques are shown in figures 11–14.

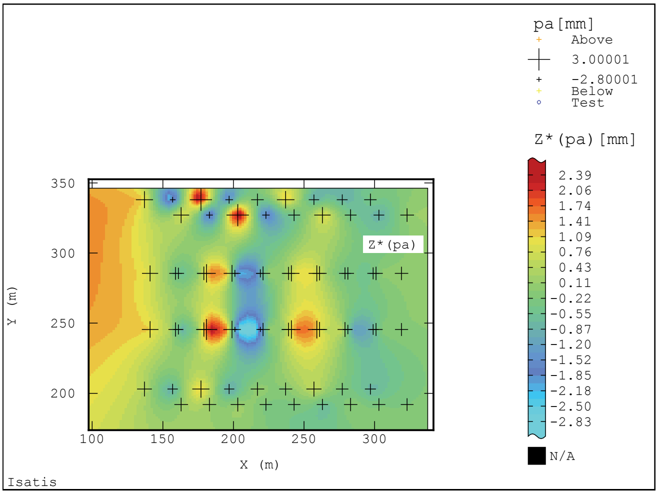


Fig. 11. Raster map of the distribution of interpolated values of the average Z^* (mm) for the current displacement p_a of the Opatowice weir with marked control points; linear kriging model

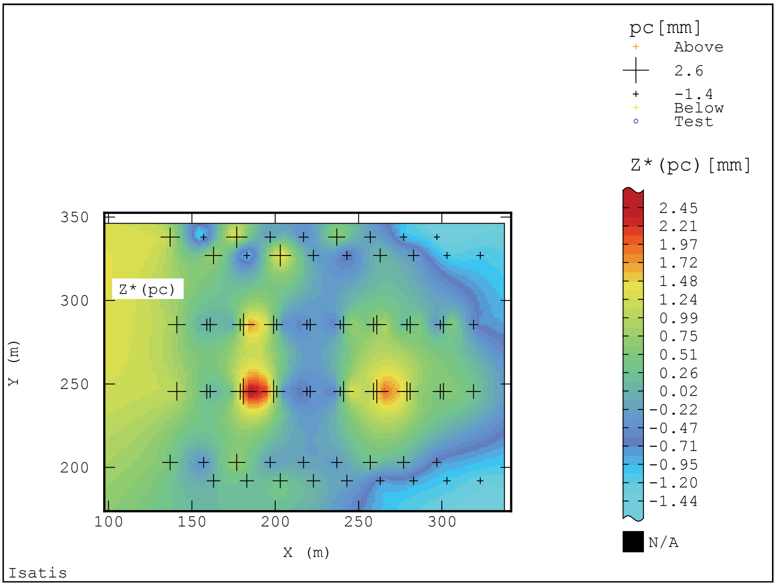


Fig. 12. Raster map of the distribution of interpolated values of the average *Z** (mm) for the total displacement p_c of the Opatowice weir with marked control points; linear kriging model

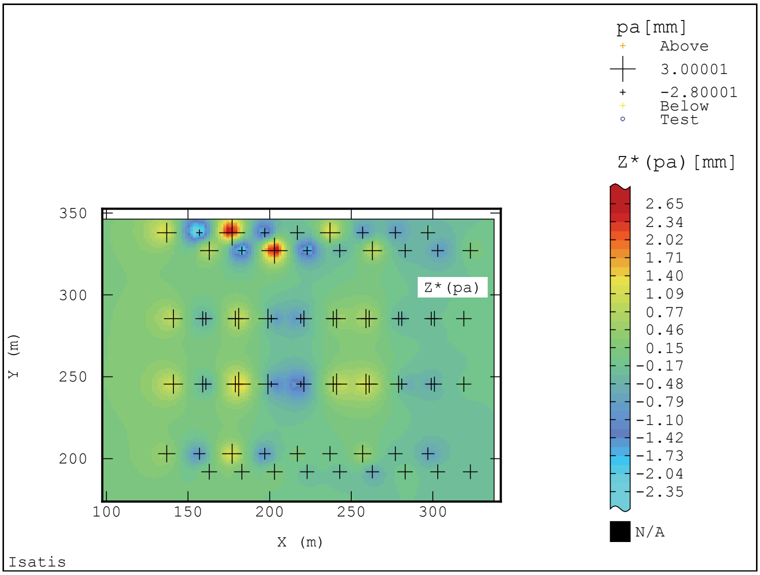


Fig. 13. Raster map of the distribution of interpolated values of the average *Z** (mm) for the current displacement p_a of the Opatowice weir with marked control points; inverse distance squared method

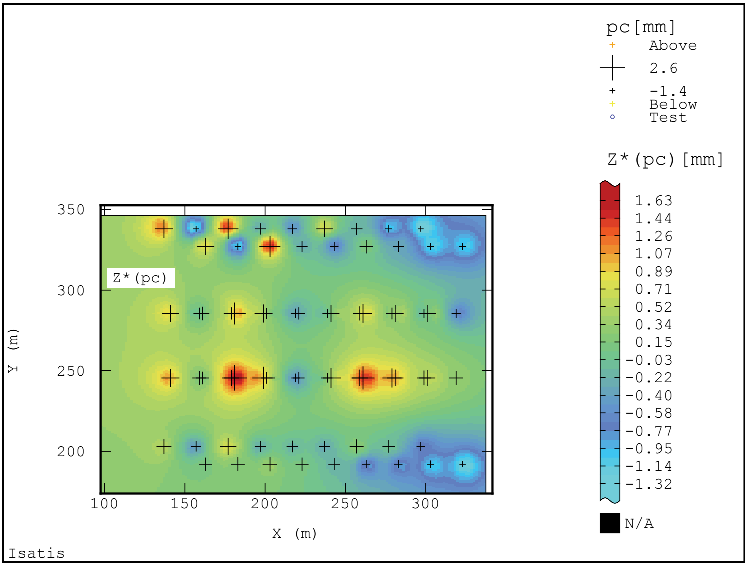


Fig. 14. Raster map of the distribution of interpolated values of the average Z^* (mm) for the total displacement p_c of the Opatowice weir with marked control points; inverse distance squared method

The basic statistics of the average interpolated Z^* for the current and total displacements using the linear kriging model and the inverse distance squared method are presented in table 6.

Table 6

Basic statistics of the average interpolated Z^* for the displacements of the Opatowice weir on the Oder River using the linear kriging model and the inverse distance squared method

Methods of quick interpolation	Parameters	Number of mesh nodes N	Min. value $X_{\min}$ (mm)	Max. value $X_{\max}$ (mm)	Average value $\overline{X}$ (mm)	Standard deviation S (mm)	Coefficient of variation V (%)
Linear kriging model	Current displacement p_a	3312	–2.83	+2.39	+0.15	±0.72	480
	Total displacement p_c		–1.44	+2.45	+0.22	±0.72	327
Inverse distance squared method	Current displacement p_a	3312	–2.35	+2.65	–0.02	±0.38	1900
	Total displacement p_c		–1.32	+1.63	+0.16	±0.43	269

The interpolated values Z^* for the current displacement p_a were determined using both interpolation techniques and fall in the range from –2.83 mm to +2.39 mm (figure 11) and from –2.35 mm to +2.65 mm (figure 13); much larger differences in displacements on the structure are given in the raster map calculated using the linear kriging model (figure 11). In this case, the variability is more precisely characterized. When using the inverse distance squared method, the diversifying of zones with large subsidence and uplift is small (figure 13). Low (measured) values of the current displacement p_a interpolated with this method were flattened. The interpolated values of Z^* for the total displacement of the structure ranged from –1.44 mm to +2.45 mm (linear kriging model, figure 12) and from –1.32 mm to +1.63 mm (inverse distance squared method, figure 14). The zones of the uplift and subsidence related to the higher values of the total displacement p_c on the structure were clearly evident when using the inverse distance squared method (figure 14).

7. CONCLUSION

Geostatistical studies, covering a structural analysis, modelling, estimation and forecasting, were carried out and displacements of a hydro-engineering structure, i.e. the Opatowice weir, were mapped. Displacement averages Z^* and the associated standard estimation deviation σ_k (expressing estimation uncertainty) in the nodes of the 3D elementary grid covering the structure investigated were analyzed. If the need arises, the parameters Z^* and σ_k can be determined in each point of the structure while doing kriging calculations. The obtained variograms, raster maps and block diagrams constitute a 3D visualization of the results of different displacement analyses made as the part of the geodesic monitoring of the weir.

Thanks to the use of ordinary block kriging the boundaries of the subsidence and uplift zones (which can be interpreted as local deformation areas critical to the safety of the structure) became clearly visible on the raster maps of averages Z^*.

Quick interpolation maps enable one to indentify the general background of the displacements without evaluating the accuracy of the estimation of the interpolated averages Z^*.

Probability maps enable one to predict the zones of major hazards connected with a possible change in the geometry of the structure, due to its local deformations.

An area-time forecast was made to determine the values of the forecasted displacement averages Z^* for a year in advance (1999), based on the displacement process history, i.e., the estimates for the previous years (e.g., 1987, 1991).

The application spectrum of geostatistical techniques is very wide and the present studies indicate that these techniques are effective tools also for the spatial analysis of the displacements of such relatively small hydro-engineering structures as weirs.

The research undertaken in this field can contribute to the creation and extension of a civil engineering structure specification. The latter should be understood as the comprehensive monitoring of major environmental factors (differentiating only seemingly identical structures), and not merely as the results of the successive control measurements of displacements. This means that all the spatial and time factors essential for the interpretation of the measured displacements should be taken into account in order to isolate the deterministic factors having a bearing on the operational safety of the considered hydro-engineering structure.

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