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THE ANALYSIS OF VERTICAL DISPLACEMENTS FOR A HYDROTECHNICAL FACILITY USING GEOSTATISTICS

PART II. DETERMINING THE PROBABILITY OF DISPLACEMENT OCCURRENCE AND ITS PREDICTION

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Abstract: The results of the geostatistical spatial analyses of measuring data that reflect the monitoring of vertical displacements of a small hydrotechnical facility are presented. Of some weirs on the Oder River the Opatowice facility was chosen due to the scale of the displacements measured. The databases of current displacements p_a and total displacements p_c obtained in the *X–Y* (2D) and *X–Y–Z* (3D) coordinate systems formed the basis for the geostatistical investigation. The application of variogram function enabled establishing the theoretical parameters of analytical functions that approximate the isotropic and directional empirical variograms of present and total displacements and, as a result, determining the variation of specified parameters for the geostatistical model. Consequently, using the ordinary block kriging method and the methods of quick interpolation, i.e., the inverse distance squared method and the linear kriging model, the raster maps of the mean estimated distributions Z^*, estimated standard deviation σ_k and also interpolated values of Z^* were calculated for the facility analyzed. In further analyses, indicator variograms and raster maps of the probability distributions for displacement occurrence were constructed. This allows determining the subregions with various susceptibilities to exceeding particular probability thresholds of deformation occurrence. A spatial-time prognosis was also made enabling us to calculate of the predicted Z^* values for the displacements in successive periods (block diagrams) of hydrotechnical facility operation.

1. INDICATOR GEOSTATISTICS

The previous article (part I) presented the research methodology for estimating displacements based on geostatistics; an evaluation of basic statistics; the results of the structural analysis of the variability of the parameters analyzed, i.e. variograms and variogram models as well as cross-validation; and the estimation of the results from applying the ordinary block kriging method and the methods of quick interpolation (kriging linear model and the inverse distance squared method) of the average Z^* values for the displacements [21].

In the next stage of research, indicator geostatistics was applied to determine the probability of displacement occurrence for structures [9], [10], [13], [17], [18], [22]. The original displacement data p_a were transformed into indicator values in the range of 0–1. Indicator variograms related to evaluating the accuracy of displacements at fixed control points on the structure were then calculated for the assumed threshold values (+0.3 mm and –0.3 mm) (figures 1a, b) after making them comparable with geodetical observations. The assumed threshold values (+0.3 mm and –0.3 mm) do not exceed the maximum values for the average error of the displacement obtained after the levelling observations: $m_{pa} = m_{pc} = \pm 0.3$ mm. The indicator variogram for the threshold of +0.3 mm approximated the exponential model by the nugget effect C_0, assuming the following geostatistical parameters: $C_0 = 0.007$ [mm]^2, partial variance $C' = 0.282$ [mm]^2, sill variance $C = 0.289$ [mm]^2 and range of influence $a = 80$ m (figure 1a). In contrast, the indicator variogram for the threshold of –0.3 mm approximated a combination of spherical, linear and exponential models by the nugget effect having the following global values of geostatistical parameters: $C_0 = 0.060$ [mm]^2, $C' = 0.186$ [mm]^2, $C = 0.246$ [mm]^2 and $a = 75$ m (figure 1b). In the indicator variogram for settlements, there is a clear contribution of the random factor C_0 of displacement to the general variability C.

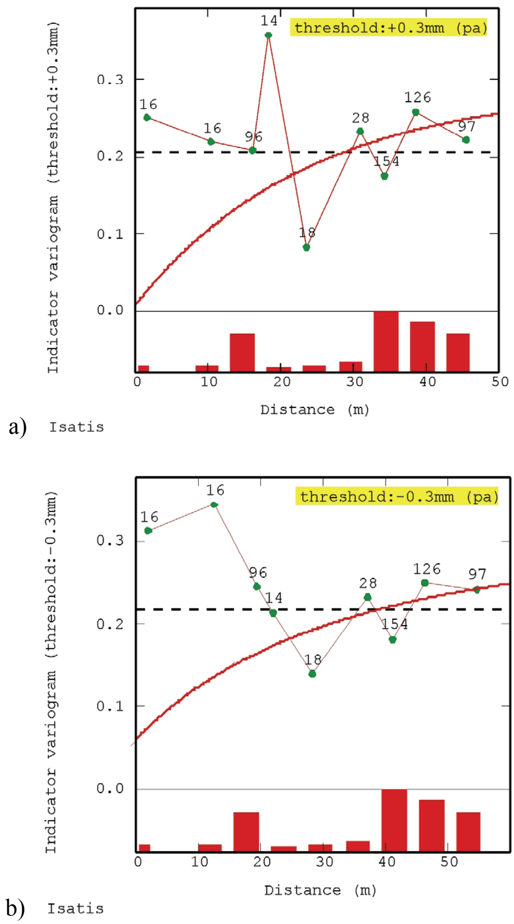


Fig. 1. Indicator variograms of current displacements p_a approximated by theoretical models assuming the threshold values of +0.3 mm (a) and –0.3 mm (b) for the Opatowice weir

Then, an estimation was performed based on the indicator data ranging from 0 to 1, using the ordinary block kriging method. From these calculations raster maps were obtained showing the probability of the displacements of control points on the structure studied or with the assumed threshold values, i.e., +0.3 mm (uplift) and –0.3 mm (settlement) (figure 2a, b). Higher values of probability may suggest a hypothetical location of local deformation for the structure studied.

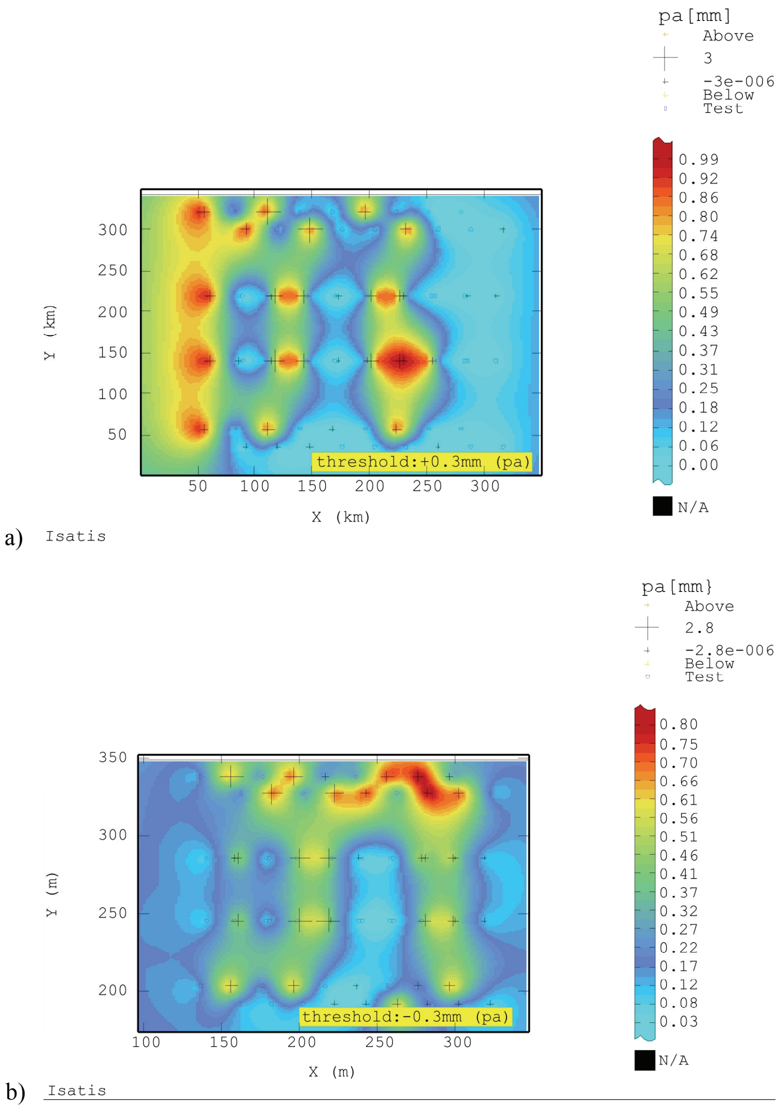


Fig. 2. Raster maps of the probability distribution of the current displacements p_a at the upper threshold value of +0.3 mm (a) and lower threshold value of –0.3 mm (b) for the Opatowice weir

The highest probability values of uplift in the range from 0.86 to 0.99 prove that the raster maps were calculated with the assumed threshold uplift value of +0.3 mm and these values characterize the subarea of the right weir pillar (figure 2a). In addition, high values of probability ranging from 0.70 to 0.80 are visible on the raster map with the assumed settlement threshold of –0.3 mm and they characterize the subarea of the left abutment of the weir (figure 2b).

2. SPATIAL-TIME PREDICTION

For the analysis of the set of copious data obtained based on the operation of the hydrotechnical structure over a multi-year period, geostatistics applied in a 3D system turns out to be very useful. It allows optimally determining the average estimator Z^* of vertical displacements of control points on the structure. The geodetical measuring data from the databases were therefore put into a 3D system [9], [10]. The Z-axis represents time in the coordinate system, i.e., the period of observation during the years 1986–1998. The directional variogram of the total displacements p_c along the time Z-axis was calculated. This variogram allows us to distinguish a small periodicity in the changes of the variogram function value $\gamma(h)$. The shape the directional variogram approximates a spherical model by a large nugget effect C_0. This variogram shows a large contribution of the random component $C_0 = 0.595$ [mm]^2 to the total variability $C = 0.710$ [mm]^2 of the displacement p_c (figure 3). The range of the influence of the variogram is 8 years.

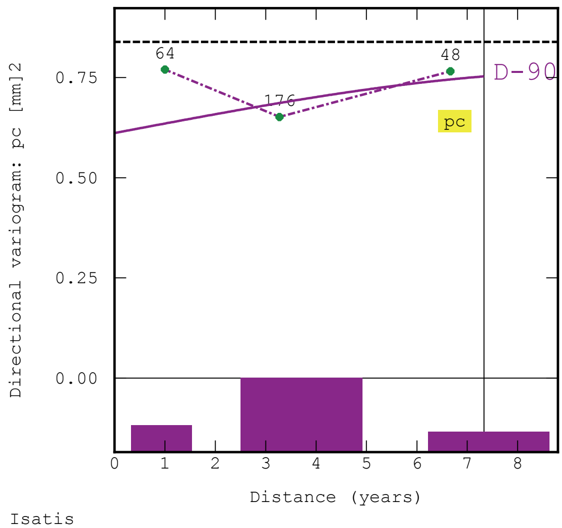
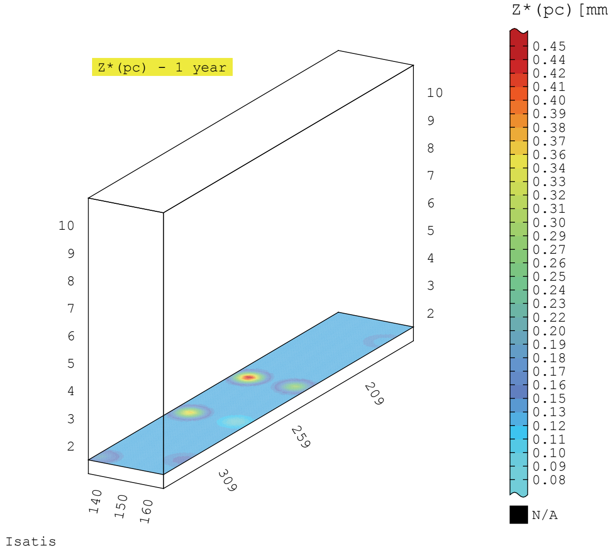
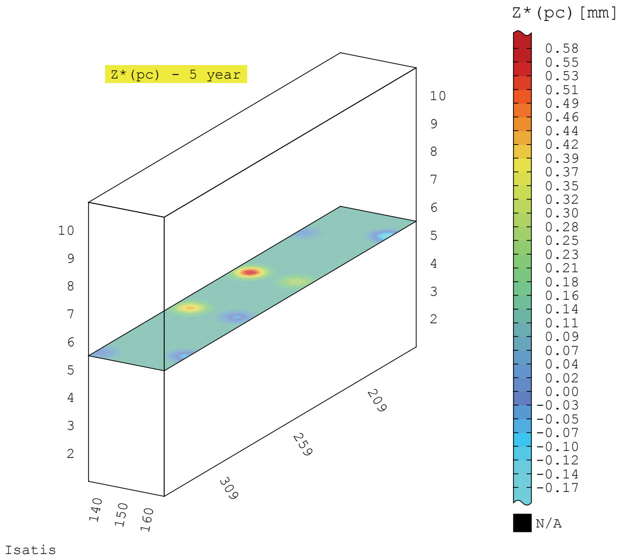


Fig. 3. Directional variogram of total displacements p_c [mm]^2 for the Opatowice weir along the time Z-axis approximated by the theoretical model from the years of observation (1986–1998)

In the next step, the value of Z^* was estimated and predicted for the total displacements using the ordinary block kriging method, by assuming a unique kriging "neighbourhood", i.e., a sample search area. This means that all the samples were taken into account when estimating the network node. The raster map with the distribution of the predicted Z^* values of the displacement p_c for the year 1999 (block diagram, figure 4c) can be compared with the results of the estimation obtained earlier, i.e. from 1987 and 1991 (block diagrams, figures 4a, b).



a)



b)

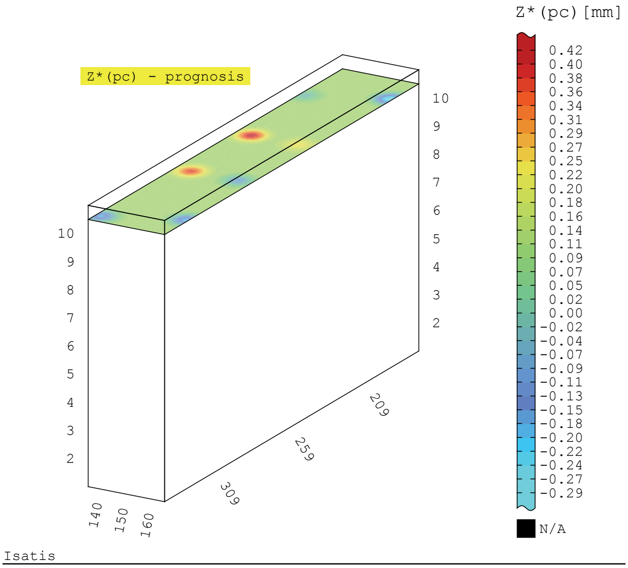
c) 

Fig. 4. Block diagrams for the distributions of the average estimator Z^* [mm] for the total displacements p_c of the Opatowice weir during the years 1987 (a) and 1991 (b) along with the predicted values of Z^* [mm] for the year 1999 (c)

The values of the average estimator Z^* for the total displacements p_c after the first year of geodetical monitoring (1987) fall within the range of –0.08 ÷ +0.45 mm (figure 4a) in which there are small but visible areas containing higher uplift and settlement values. However, after the fifth year of observation (1991) the displacements p_c reach significantly higher values ranging from –0.17 to +0.58 mm. The boundaries of this area are more firmly established corresponding to the second pillar of the weir from the upper water side (figure 4b). In addition, the boundaries show new centers of displacement on the structure. In the diagram of the predictions for the year 1999, it is important to note that the settlement p_c increases to a value of –0.29 mm while the local uplift of the two pillars on the upper water side stabilizes around the value of +0.42 mm (figure 4c).

3. CONCLUSION

The spatial characteristics, specifically a cartographical representation of the displacements of the hydrotechnical facility, the Opatowice weir, were obtained through the geostatistical investigation involving a structural analysis, modelling, estimating and predicting. In the nodes of the elementary spatial grid representing the structure analyzed, the values of the average estimator Z^* of displacement were calculated along with the associated estimated standard deviation σ_k. This allows the construction of confidence intervals for the assumed significance level α. If necessary, the specified parameters, i.e., the average Z^* together with the values of the standard deviation σ_k, can be determined directly during the kriging calculations for every point of the structure. The obtained variograms, raster maps and block diagrams comprise a visual spatial representation of the results from the various analyses of displacements which were measured during the geodetical monitoring of the weir.

Distinct boundaries separating the zones of settlement and uplift for the hydrotechnical facility resulted from applying the ordinary block kriging technique. These boundaries are formed by the distributions of the average Z^* on the raster maps which can be interpreted as subareas of local deformation that are critical and should be thoroughly considered for the safety of the structure.

The maps of quick interpolation enabled identification of general background displacements without evaluating the accuracy of estimation for the interpolated values of Z^* and thus also for the estimated standard deviation σ_k.

Probability maps allow us to predict the zones posing a significant risk related to the possibility of changes in structure geometry caused by the occurrence of local deformations.

Spatial-time predictions allowed determining the predicted values of Z^* of displacements for a successive year (1999) by taking account of the history of the process, i.e., by taking calculations from earlier years, such as 1987 and 1991.

The geostatistical techniques considered in this study in terms of a wide spectrum of their possible applications lead to the conclusion that they are effective tools in the analysis of spatial deformations and in this case for relatively small hydrotechnical facilities such as weirs.

This subject of research may be useful for initiating and expanding the monitoring of significant environmental factors to permit the differentiation of "seemingly identical" structures, and not only the results of successive, controlled displacement measurements. This concerns the proper treatment of all spatial and time factors crucial for interpreting the displacements obtained with the aim of identifying the deterministic factors related to the safe operation of the hydrotechnical structure.

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