ASSESSING RELIABILITY OF CONTINUOUS GEOTECHNICAL MONITORING MEASUREMENTS

Dainora Jankauskiene[1], Benita Tautaviciene[1], Viktoras Dorosevas[1, 2], Sergio Antonio Neves Lousada[3, 4, 5, 6, 7]

[1]Klaipeda State University of Applied Sciences, Lithuania; [2]Vilnius Gediminas Technical University, Lithuania; [3]University of Madeira, Portugal; [4]CITUR – Madeira – Centre for Tourism Research, Development and Innovation, Portugal; [5]VALORIZA – Research Centre for Endogenous Resource Valorization, Portugal; [6]Research Group on Environment and Spatial Planning (MAOT), University of Extremadura, Portugal; [7]RISCO – Civil Engineering Department of University of Aveiro

d.jankauskiene@kvk.lt , b.tautaviciene@kvk.lt , v.dorosevas@kvk.lt , slousada@staff.uma.pt

[7] RISCO – Civil Engineering Department of University of Aveiro, 3810-193 Aveiro, Portugal

Abstract. Modern information technology provides the assumptions and wide opportunities for recording monitoring data in real time. This makes it possible to install various monitoring systems in important facilities, such as a seaport. However, when processing the data obtained by the monitoring system, the problem of their reliability always arises. In this research paper, an attempt is made to formulate and solve the probability problem of the reliability of the received measurement data of the monitoring system. The long-term data of measurements used for this research work are obtained by measuring the displacements of selected characteristic points of the Klaipeda seaport pier in the presence of the air and water temperature and wind speed changes. All measurement results are obtained using a modern geodetic instrument in the process of diagnostics of the geometrical position of the pier structures built at Klaipeda seaport. The most important attention is paid to the influence of the air temperature and wind speed on the reliability analysis of geometric position measurement results using mathematical statistics methods. The analysis of the obtained results for deviations of the crack width of individual points in the Southern pier allowed to create special algorithms for data processing of monitoring systems, which could be used for improving the global maintenance of seaport piers.

Keywords: monitoring system, pier observation, geodetic instruments, crack-gauge, sensors, crack, analysis.

1. Introduction

All ports in the world are distinguished by their specifics [1; 2]. The port of Klaipeda, which is in the Klaipeda Strait at the border of the section of the cascade aqua system Nemunas – Curonian Lagoon – Baltic Sea, is no exception (see Fig.1) [3-7]. When changing the depth of the water area, the intensity of water circulation depends on the difference in the water levels of the Curonian Lagoon and the Baltic Sea [8-10].

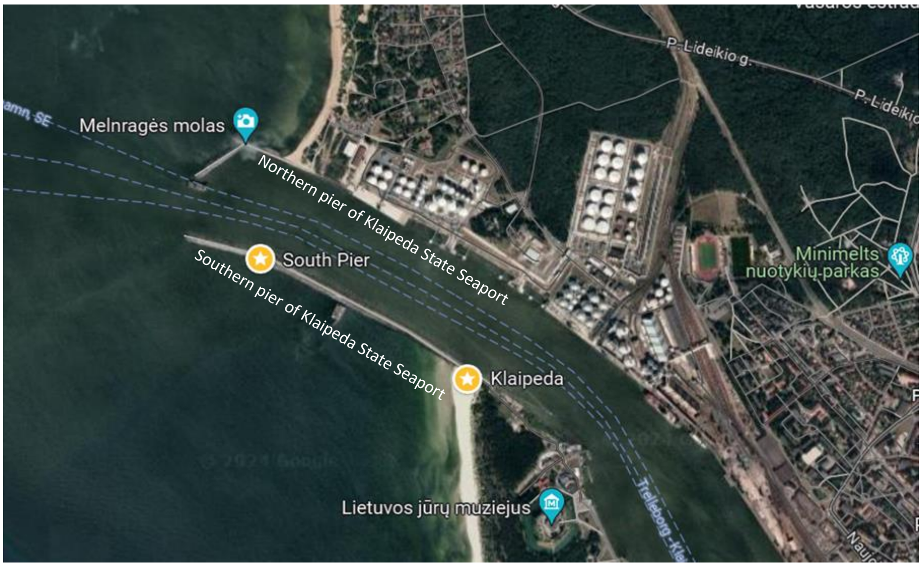

Fig. 1. **Klaipeda state seaport (from Google Map)**

On the other hand, the activities of the reconstructions and existing enterprises in the port are affected by the environment, the port infrastructure, and the construction elements of the structures [11-15]. It is therefore essential to ensure proper monitoring and control of the environment and the structural elements of the port [16-18]. The monitoring system must cover all possible effects and be able to predict their qualitative changes and provide for measures to reduce the negative impact [19-23].

As we can see in Fig. 1, Klaipeda state seaport has two parallel piers, the length of the Southern berth is 1227 m, and the length of the Northern berth is 1158 m [24-26]. In this research we investigated only the South pier sections, which are built on piles and the surface part is made of stones (see Fig. 2) [3; 27-29].

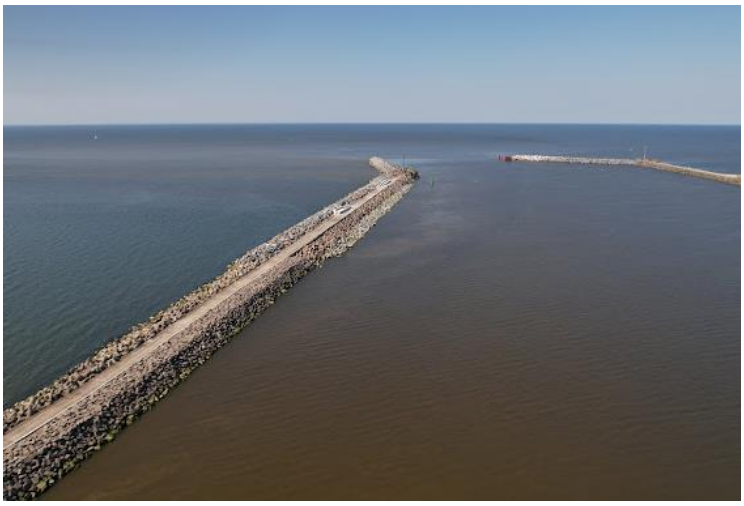

Fig. 2. **Southern Pier**

After deepening the seaport, the piers were reinforced with stones and large concrete blocks. The Southern pier has been under construction from 1847 to 1861 and finally reconstructed in 2002. Thus, the overall structure of the pier elements is heterogeneous and complicated. Therefore, monitoring of structures requires regular observations of construction element cracks using special diagnostic procedures and predict catastrophic damages [30-32]. The conducted multi-year investigations formed the prerequisites for creating and proposing a monitoring procedure based on the pier crack estimation and prediction [25; 33; 34].

For this purpose, a weak element of the chain model can be used in the monitoring system, for example, a crack of the concrete surface of the object. When inspecting the pier construction, 3 cracks were found on the concrete surface suitable for observation in the Southern pier and these places are called point A, point B and point C (see Fig. 3).

Fig. 3. **Measurement points A, B and C**

Location of the points A, B and C was connected to the coordinate of the monitoring system of Klaipeda state seaport from the reference point. As shown in Fig. 3, the distances between the reference point and A, B and C are 493 m, 790 m and 685 m respectively.

2. Experimental procedure

At points A, B and C of the Southern pier, the gadget Geosense VWCM-4000 Crack Meter was used to measure the changes in the width of the existing cracks. The Geosense VWCM-4000 Crack Meter is a steel instrument that contains a VW transducer that is connected to a calibrated spring which is in turn connected to an extending shaft [35; 37]. The ends of the instrument are connected to either side of a crack or joint so that if structural movement occurs, the shaft is moved within the housing (see Fig. 4). The shaft movement changes the tensionof the spring which, in turn, changes the tension in the vibrating wire. When interrogated, the vibrating wire in the transducer measures its tension which can be converted to a linear displacement measurement in engineering units, commonly millimeters.

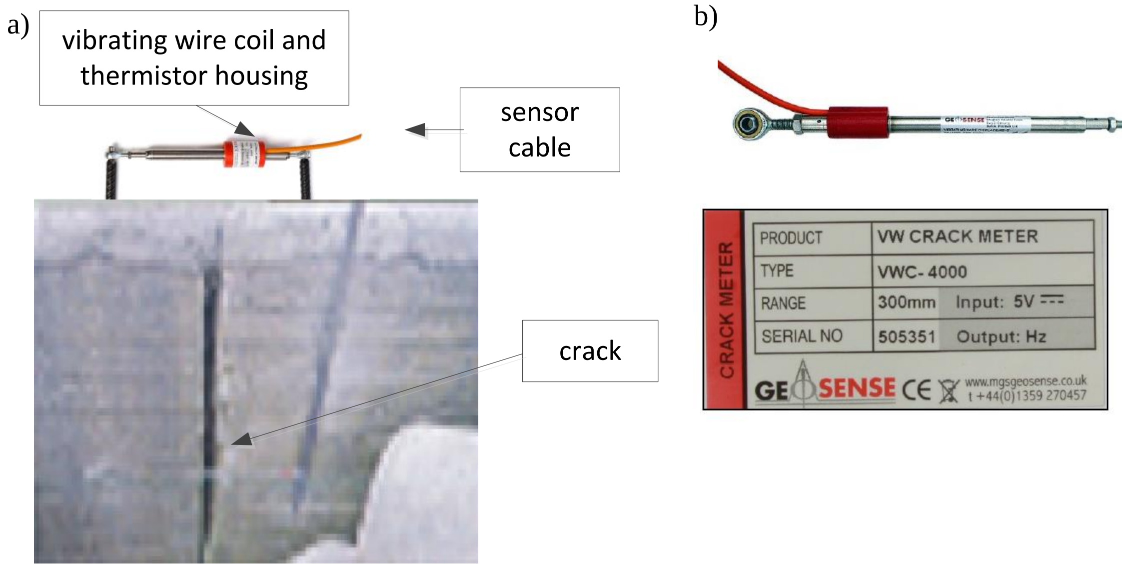

Fig. 4. **Crack of the concrete surface (a), VWCM-4000 Crack Meter device (b)**

For measuring the width of cracks in the selected structural element points A, B and C, three VWCM-4000 Crack Meter devices are installed as shown in Fig. 4 a). The duration of the measurement procedure is 15 months, recording the width of the crack, air temperature and the wind speed every day at the same time 00:00:00. The wind speed and air temperature data were obtained from weather measurement at Klaipeda seaport station of the Lithuanian Hydrometeorological Service under the Ministry of the Environment.

For suitable assessment of the obtained measurement data, a calculation scheme is selected, for example at point A (see Fig. 5), where the initial value of the width of the crack is recorded as a reference point for further analysis of deviations.

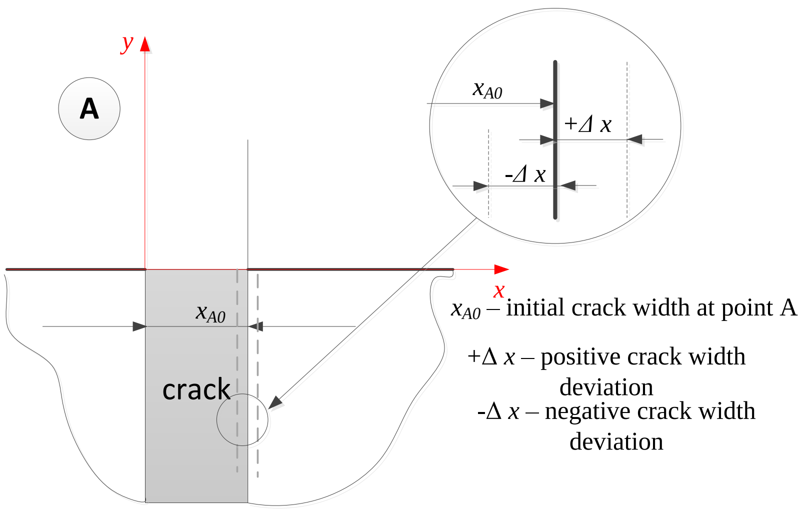

Fig. 5. **Calculation scheme (positive crack width means gap increase)**

Analogical calculation schemes have been drawn up for the analysis of the crack width parameters at points B and C. It should be noted that after assessing the variation in the temperature and wind speed of the data obtained and their possible influence on the measurement procedure, taking in mind that these could be systematic measurement errors, three temperature ranges were selected: the first (-8 ºC to 0 ºC), the second (0 ºC to 8 ºC) and the third (8 ºC to 19 ºC) and two wind ranges: when the wind speed < 12 $m \cdot s^{-1}$ and the wind speed > 12 $m \cdot s^{-1}$.

3. 3. Results and analysis

At the end of the 15-month observation period, at the study sites at points A, B and C, data were collected of the air temperatures, wind speed and width of the crack deviations Δx from their initial parameters x_0.

All calculations of the obtained data were carried out and analyzed through two procedures using methods of mathematical statistics. In the first statistical procedure, the descriptive statistics on the variation in the width of all cracks were calculated and compared with each other. The comparison parameter used was the Fisher's criterion, which clearly showed that the values of the change in the width of the cracks between the different points do not correlate. Therefore, the variation in the width of each point crack is individual and potentially depends on the air temperature and wind speed. For this, we carried out the second procedure of statistical calculations and analysis, assuming that the air temperature and wind speed can be the measurement of each crack width Δx by its own systematic errors.

Table 1

Results of statistical calculation

Monitoring point	Wind speeds up to 12 $m \cdot s^{-1}$					
	Temperature range 1 (-8 ºC to 0 ºC)		Temperature range 2 (0 ºC to 8 ºC)		Temperature range 3 (8 ºC to 19 ºC)	
	1		2		3	
	μ, mm	σ, mm	μ, mm	σ, mm	μ, mm	σ, mm
A	1.103	0.322	0.232	0.352	-0.735	0.285
B	1.196	0.166	0.343	0.654	-1.015	0.545
C	0.674	0.477	0.025	0.818	-1.013	0.490

Table 2

Results of statistical calculation

Monitoring point	Wind speeds above 12 $m \cdot s^{-1}$					
	Temperature range 1 (-8 ºC to 0 ºC)		Temperature range 2 (0 ºC to 8 ºC)		Temperature range 3 (8 ºC to 19 ºC)	
	1		2		3	
	μ, mm	σ, mm	μ, mm	σ, mm	μ, mm	σ, mm
A	1.185	0.332	0.361	0.437	-0.449	0.180
B	1.664	0.250	0.827	0.481	-0.483	0.504
C	0.882	0.242	0.296	0.530	-0.656	0.326

Before the second procedure of statistical analysis, all deviations Δx in the width of each crack are grouped by the air temperature range and wind speed range.

Using mathematical statistical procedures, calculations of the mean values μ and standard deviations σ of the change of the crack width Δx at all points and ranges, and summarizing of the data are given in Tables 1 and 2.

The graphs compiled and presented from these tables for the dependence of the displacements on the temperature range (Fig.6, Fig.7 and Fig. 8) clearly indicate the linear dependencies that can be determined in the change in the deviation width Δx of each crack. The displacement value obtained for each temperature range can be treated as a systemic error.

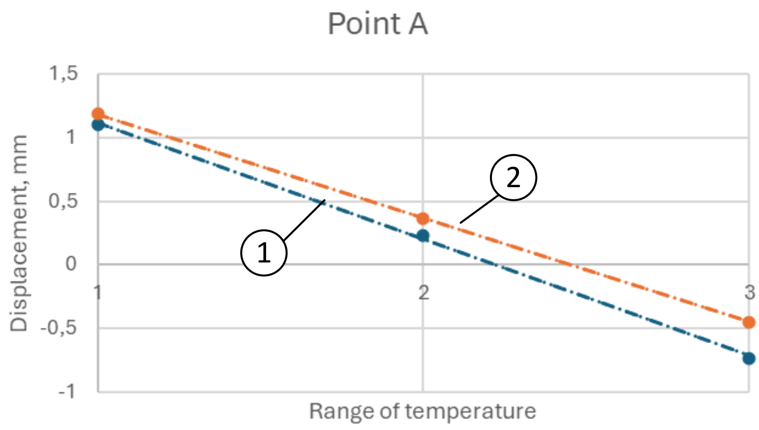

Fig. 6. **Change in the deviation width Δ*x* at point A; the line 1 for the wind speed *v* < 12 m·s^{-1} and the line 2 for the wind speed *v* > 12 m·s^{-1}**

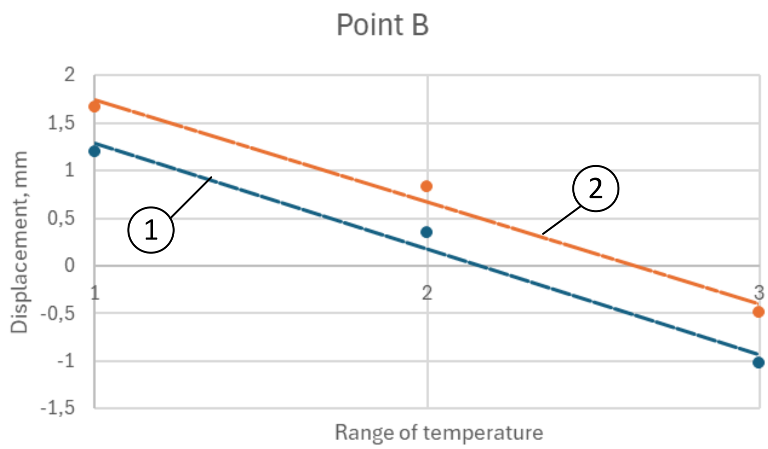

Fig. 7. **Change in the deviation width Δ*x* at point B; the line 1 for the wind speed *v* < 12 m·s^{-1} and the line 2 for the wind speed *v* > 12 m·s^{-1}**

Know, that systematic errors are deterministic values and can always be calculated and subtracted from measurement results.

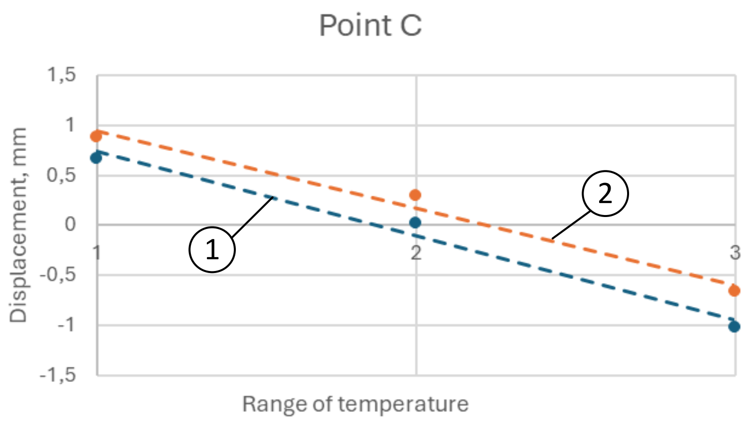

Fig. 8. **Change in the deviation width Δ*x* at point C; the line 1 for the wind speed *v* < 12 m·s^{-1} and the line 2 for the wind speed *v* > 12 m·s^{-1}**

We investigated and analyzed systematic errors of accuracy for measuring values and repeatable measurements on these characteristic points in the 15-month observation period and obtained that the measured value of displacement at the point can be corrected expressed through the air temperature:

$$\Delta s_i = a_i l - b_i , \tag{1}$$

where a_i – temperature coefficient, mm·ºC^{-1};
b_i – constant of the measuring points i, mm;
I – temperature from range (1, 2, 3), ºC.

Using eq. (1) we make assumptions to calculations of the systematic error Δs_i and it is possible to correct the allowable value of monitoring the crack width $x_i - \Delta x$. The measurement results are corrected by corrections, the size of which is equal to the value of the systematic errors Δs_i, but the sign is opposite to them. In view of this, we performed a regression analysis of the measurement data obtained during the entire study period. The results of the regression analysis are presented in Table 3. The coefficient of determination R^2 of all the obtained linear regression models is about 0.98 and it means that the value of the systematic errors Δs_i can be perfectly predicted from the wind speed and air temperature.

Table 3

Results of the regression analysis

Monitoring point	**Wind speeds up to 12 m·s^{-1}**		**Wind speeds above 12 m·s^{-1}**	
	a_i	b_i	a_i	b_i
A	0.9190	2.0380	0.8170	1.9997
B	1.1055	2.3857	1.0735	2.8163
C	0.8435	1.5823	0.7690	1.7120

It should be noted that the constants of these regressions can be mathematically expressed through relative parameters, for example, the ratio of the deviation of the measured width to the initial crack width of the point, expressed as a percentage. However, our goal is to study the accuracy of measurements that we will limit to units of length.

As it can be seen from the data presented in the tables, two regression equations are derived for each point depending on the wind speed, which is divided into two ranges.

On the other hand, it is obvious that the difference between the mean deviations of the crack at a specific point place can be used as a value of the systemic error under the influence of wind. This can be seen very well from measurement distribution of random errors of the given deviations in Fig. 9, Fig. 10, and Fig. 11. For example, at point A, the systematic error of the wind influence between two ranges equals to

$$\Delta s_{wA} = 1.103 - 1.185 = -0.082 \text{ mm.}$$

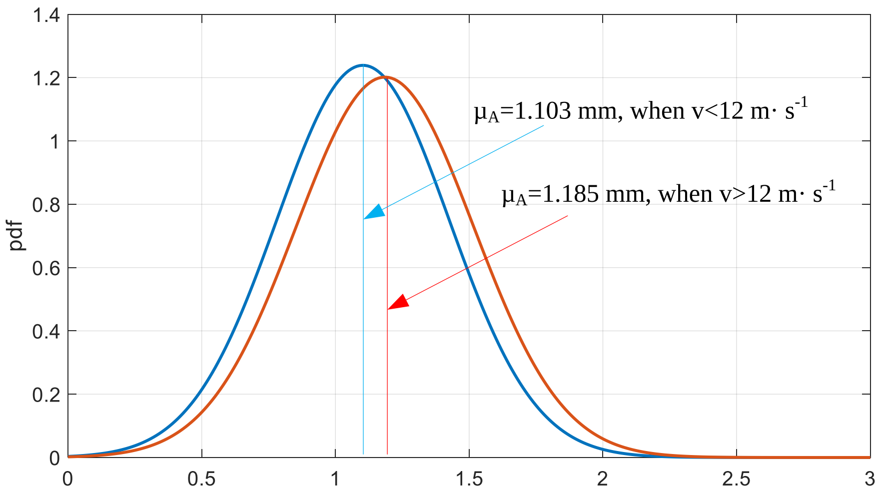

Fig. 9. **Distribution random error at point A (mm)**

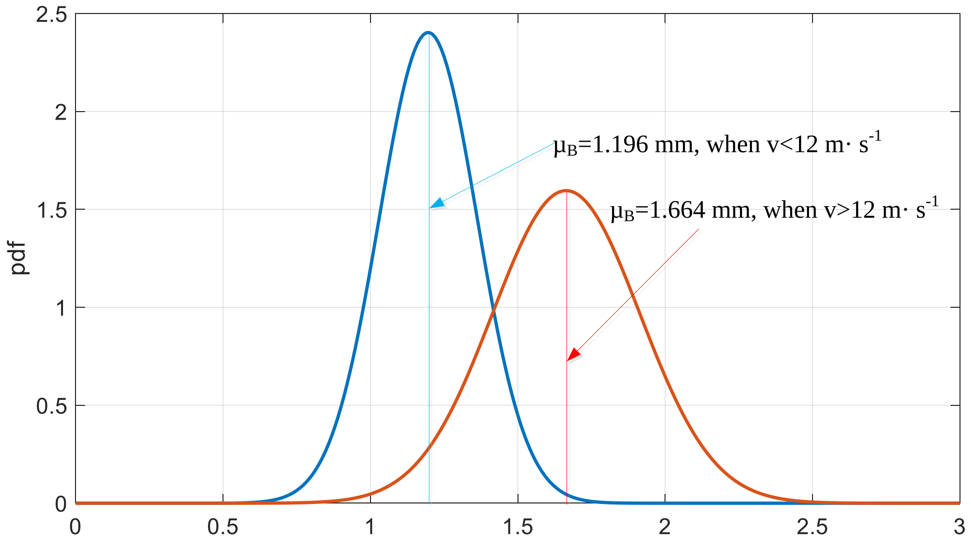

Fig. 10. **Distribution random error at point B (mm)**

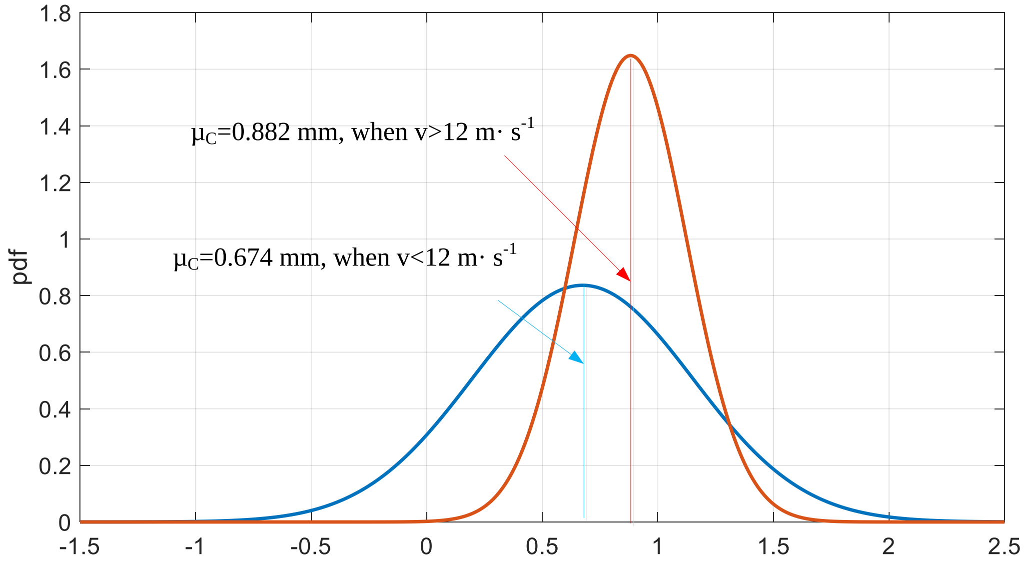

Fig. 11. **Distribution random error at point C (mm)**

As known, the standard deviation defined, for example, at point A:

$$\sigma_A = \sqrt{\frac{\sum_{i=1}^{n} (\Delta x_i)^2}{n}}. \tag{2}$$

The standard deviation of mean defined, for example, at point A:

$$S_A = \sqrt{\frac{\sum_{i=1}^{n} (\Delta x_i)^2}{n(n-1)}}. \tag{3}$$

The standard deviation of the mean s_A represents a measure of how well a measured mean value of the deviation Δx_i represents the true mean deviation of the population. The range over which the possible values of the true mean value of deviation might lie at some probability level P based on the information from the data set, for example, at point A is given as

$$\Delta x_A = \mu_A \pm t_{n,p} \cdot S_A \tag{4}$$

The variable $t_{n,P}$ provides a coverage factor used for finite data sets and referred to as the Student's t variable. It expresses a confidence interval about the mean value, with the coverage factor t at the assigned probability, P%, within which we should expect the true value of x to fall.

In the theory and practice of measurements the concept of uncertainty is used and it is a numerical estimate of the possible range of the error in measurements. For all cases, the uncertainty values assigned to an instrument or measurement system are usually the result of several interacting random and systematic errors inherent to the measurement system, the calibration procedure, and the standard used to provide the known value. On the other hand, individual errors are properties of the instruments, the test method, the analysis, and the measurement system. Uncertainty is a property of the test result. Based on the results of the analysis, an algorithm was obtained that allows to clarify and estimate the uncertainty of the measured value and control the measured deviation of the width of the crack with sufficient probability, predicting qualitative changes in the width of the crack. The scheme of the algorithm is given in Fig. 12.

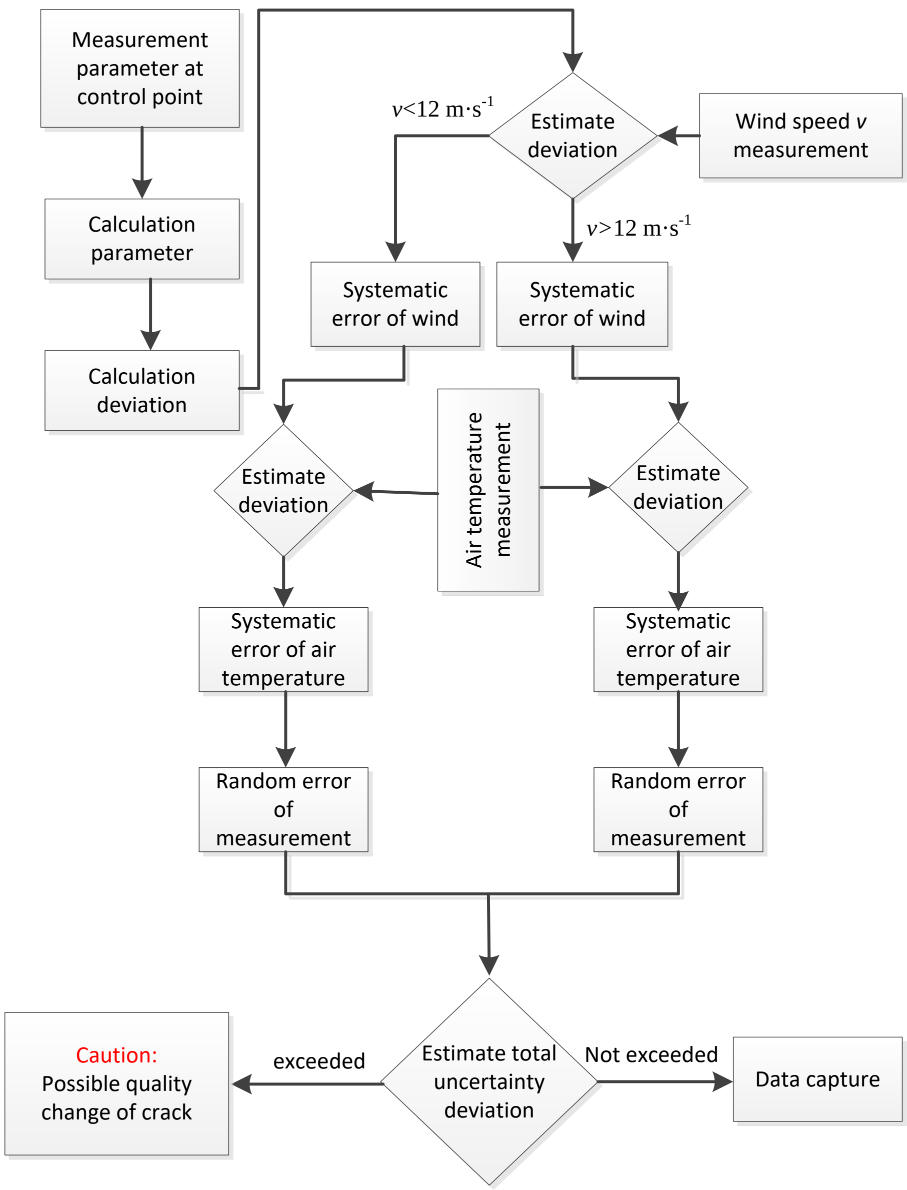

Fig. 12. **Algorithm for estimating the total uncertainty of deviation of the crack width**

4. Conclusions

Carrying out a long-term study, processing and analyzing the data obtained made it possible to draw the following conclusions:

- The air temperature and wind speed influence assessing of the uncertainty of the dimension of the crack, therefore, according to the presented methodology, it is possible to conditionally distinguish a systemic error and, accordingly, evaluate the reliability of the measured crack parameter.
- Calculated and compared with each other the descriptive statistics of deviations in the crack width of all A, B and C points using the Fisher criterion clearly showed that the values of the change in the width of the cracks between the different cracks do not correlate. Therefore, the variation in the width of each crack is individual.
- Statistical analysis of individual deviations in the width of the crack showed a strong correlation with changes in the air temperature and wind speed, which can be calculated as systemic errors and corrected using eq. (1).
- From the analysis of the obtained measurement results we see that by observing an individual crack, it is possible to control and evaluate the uncertainty of the deviation of the width of the crack and predict qualitative changes in the crack according to the deviation values.
- The presented research methodology creates possibilities for the improvement of the seaport monitoring system, using the observation of the width of individual cracks as a weak link in the failure model.

Author contributions

All authors have contributed equally to the study and preparation of this publication. Authors have read and agreed to the published version of the manuscript.

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