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Statistical Research of Retaining Walls Displacement on the Results of Geodetic Measurements by Analysis of Variance

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Summary. The analysis of geodetic measurements of retaining walls displacements in the residential quarter of the city of Kyiv is executed. For processing the observations, it was suggested to use a method of analysis of variance (ANOVA). The influence of changes displacement depending on the cycles of observations by one-factor analysis of variance is investigational. Method of one-factor ANOVA allowed also defining that for different retaining walls, a deformation process has a different dynamics. The relationship between cycles and retaining walls placement was determined using two-factor ANOVA. Method three-factor analysis of variance allowed additionally defining influence of location of deformation marks on the value of displacement. It was confirmed that the variance analysis method has great potential for the analysis of geodetic measurements, especially at the large volumes of observations.

Key words: ANOVA, displacement, dispersion relation, the level of significance, retaining wall, landslide, deformation prediction.

INTRODUCTION

At observing the displacements always arises the problem of correct interpretation of measurement results. After many years, many mathematical models for approximation and prediction of engineering structures displacements were developed. However, for modern engineering buildings often impossible to find a single model that will fully describe the deformation process. Actual such problem is for observations on landslides, which have a difficult multisectional structure and hold out different retaining walls [7]. Observations of the retaining walls on the landslides are complex [1, 6]. The nature of displacements on landslide and retaining walls caused by many factors, which is confirmed in researches [1, 6]. In such circumstances, the construction of a predictive model is a very difficult task. Way out of this situation is the use of statistical research methods such as regression analysis [2, 13]. In the geodetic practice have spread prediction models based on polynomial and exponential functions [10], Kalman filtering [5] and fuzzy systems modeling [3]. However, for landslide and retaining walls it is necessary at first determine the nature of the displacement distribution. Get single models predicting a deformation of retaining walls is impossible. In such case, it is necessary to divide the landslide or landslide structures on individual blocks within which to perform the construction of appropriate models of deformation [8]. This problem is quite complex. Even for landslide structures, which are structurally divided into separate blocks deformation process can have the same nature for several blocks or changed within one block. Application of multivariate analysis of variance methods gives the opportunity to explore the distribution and nature of displacements and highlight landslide areas or landslide structures within which can be used a single model of deformations predicting.

PURPOSE OF WORK

The task of work is research of one-factor and multivariable analysis of variance possibilities at determination of various factors influence on the nature and distributing of displacements during observations retaining walls on the example of the observations results of the retaining walls in the residential quarter of the city of Kyiv.

DESCRIPTION THE OBJECT OF RESEARCH

Analysis of variance as a method of research data is known for a long time [4, 11]. In geodesy this method is used recently at research of GNSS measurements and solving navigation tasks [8, 12]. We will apply the analysis of variance for research of nature and connection of retaining walls displacements that hold the landslide slope. A general view and placement of retaining walls are shown on a Fig. 1.

Landslide slope has a height of 30 meters and a width of 20 meters. Landslide is held by four retaining walls (PS-1, PS-2, PS-3, PS-4). The height of retaining walls is in the range of from 8 to 14 meters. Location plan of retaining walls is presented in figure 2.

All retaining walls have a pile foundation with piles at depth of 20 meters.

RESULTS OF MEASUREMENTS

To measure the displacements a spatial geodetic network was built. The network consists of 5 points from which executed minimum twice coordinating deformation marks on retaining walls. According to the results of adjustment, the root mean square error along the coordinate axes were: for reference points m_X = 1,5 mm, m_Y = 3 mm,

Fig. 1. A general view of retaining walls placement

m_Z = 4 mm. The main requirement was to determine with the accuracy of 3 mm displacements in the direction of the X axis. For the rest coordinate axes the displacements are not critical and does not affect the stability of retaining walls. The measurements were performed weekly in the flow of six months. The total number of cycles is 27. Fig. 3 shows the measured displacement in the X axes direction for all marks on the four retaining walls in 27 cycles.

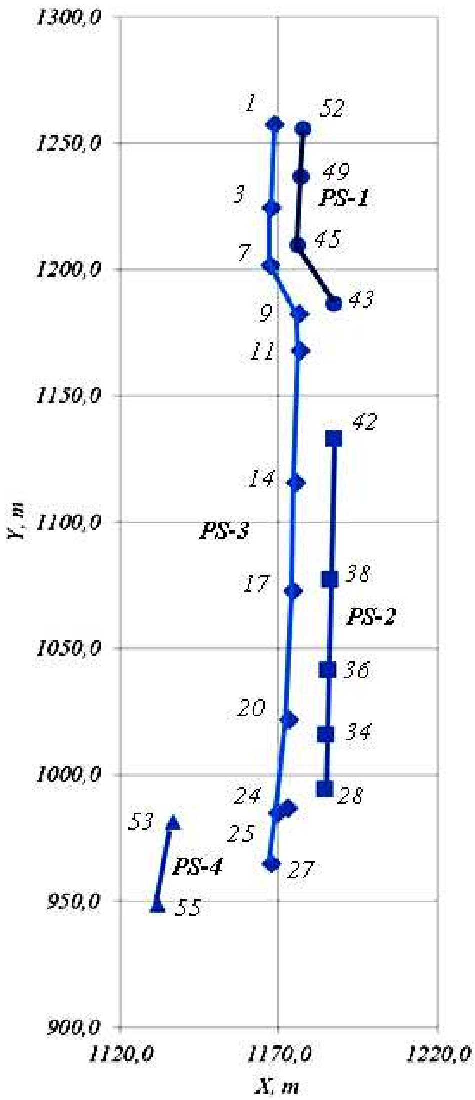

Fig. 2. Location plan of retaining walls and deformation marks numbers

In the direction of the coordinate axes Y and Z the maximum displacement were recorded at 10 mm. Such displacements are not critical and therefore we perform analysis of displacements only along the X axis, which are shown in Fig. 3.

STATISTICAL RESEARCH OF DISPLACEMENTS

The first necessary step of geodetic measurements analysis is to check the form of the distribution law. We used three nonparametric tests: Kolmogorov-Smirnov, Anderson-Darling, χ^2 [4]. The results of testing the hypothesis of normal distribution of the results of measurements are shown in Table 1.

Table 1. Testing the hypothesis of a normal distribution

Kolmogorov-Smirnov			
Sample Size Statistic	1188 0,0982		
q	0,05	0,02	0,01
Critical Value	0,039	0,044	0,047
Reject	Yes	Yes	Yes
Anderson-Darling			
Sample Size Statistic	1188 24,874		
q	0,05	0,02	0,01
Critical Value	2,502	3,289	3,907
Reject	Yes	Yes	Yes
χ^2			
Deg. of freedom Statistic	10 186,670		
q	0,05	0,02	0,01
Critical Value	18,307	21,161	23,209
Reject	Yes	Yes	Yes

Hypothesis testing showed that the data did not submit the normal distribution law. This is not a hindrance to the analysis of variance, but confirms the necessity for statistical check. Deviation of the distribution law of the measured displacements from normal indicates the presence of systematic factors and confirms that all the measured displacement cannot be considered as a whole. The displacements for different retaining walls are different and need to analyze them separately. For clarity, we present

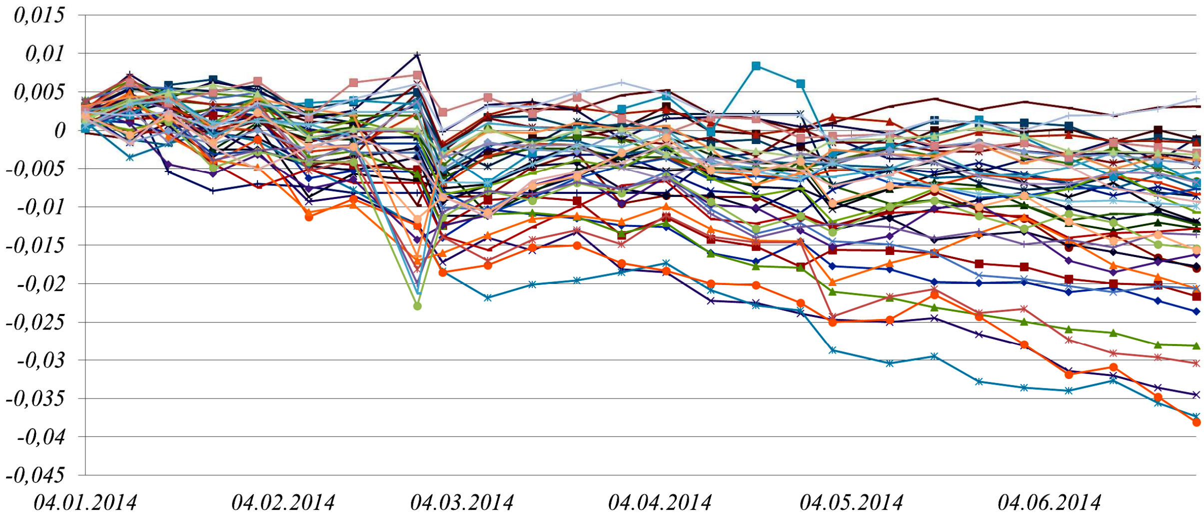

Fig. 3. The results of measurements along X axes for all retaining walls. Each chart is presented by the separate displacement of deformation mark

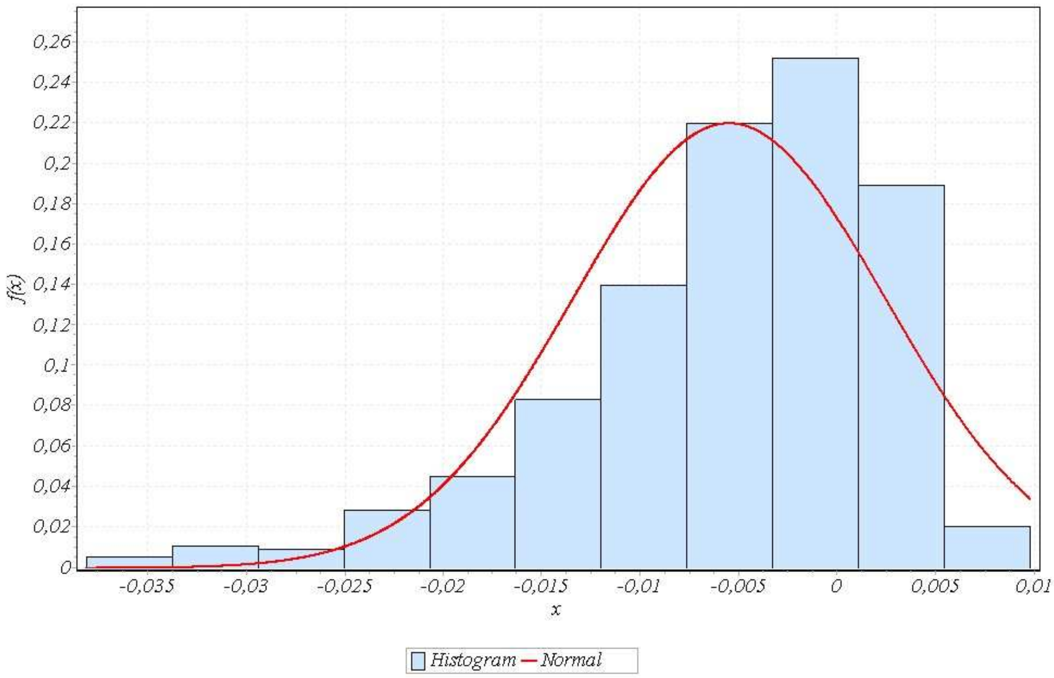

Fig. 4. Histogram and normal probably density function

the histogram and the probability density function of the statistical analysis results.

For establishment of factors, which influence on the nature of the displacement distribution perform analysis of variance of measurements results.

ONE-FACTOR ANOVA

Analyzing the charts in Fig. 3 it is difficult to establish whether the displacement marks vary between cycles of measurements. To determine whether the actual deformation process occurs perform one-factor ANOVA.

The first stage of analysis of variance is to calculate basic statistical characteristics.

If there are k cycles of measurements of displacements x_i, $i = 1, \dots, k$. According to the results of measurements adjustment known that all measurements have the same variance and distribution centers are different. In each cycle performed observing *n* deformation marks. In the *i*-th cycle, we have:

$$\Delta x_{i1}, \Delta x_{i2}, \ldots, \Delta x_{in}.$$

Total number of observations:

$$N = \sum_{i=1}^{k} n_i . \qquad (1)$$

If we assume that factor α is the presence of displacements between the cycles, then in the absence of this displacement the most probable value of the measured value is the arithmetic mean of displacements:

Table 2. Statistical characteristics of displacement measurement

Cycle	Mean	RMS	95% interval for the mean		Max	Min
			Lower limit	Upper limit		
1	0,000	0,000	0,000	0,000	0,000	0,000
2	0,002	0,000	0,002	0,002	-0,000	0,004
3	0,003	0,000	0,002	0,004	-0,004	0,007
4	0,002	0,000	0,001	0,003	-0,005	0,006
5	0,000	0,000	-0,001	0,001	-0,008	0,007
6	0,001	0,000	-0,000	0,002	-0,008	0,006
7	-0,002	0,001	-0,004	-0,001	-0,011	0,004
8	-0,002	0,001	-0,003	-0,001	-0,010	0,006
9	-0,004	0,001	-0,007	-0,002	-0,023	0,010
10	-0,008	0,001	-0,009	-0,006	-0,018	0,002
11	-0,006	0,001	-0,008	-0,004	-0,022	0,004
12	-0,005	0,001	-0,007	-0,003	-0,020	0,004
13	-0,004	0,001	-0,006	-0,003	-0,020	0,005
14	-0,005	0,001	-0,007	-0,003	-0,018	0,006
15	-0,004	0,001	-0,006	-0,003	-0,018	0,005
16	-0,006	0,001	-0,008	-0,005	-0,022	0,002
17	-0,007	0,001	-0,009	-0,005	-0,023	0,008
18	-0,007	0,001	-0,010	-0,005	-0,024	0,006
19	-0,009	0,001	-0,012	-0,007	-0,029	0,002
20	-0,009	0,001	-0,011	-0,006	-0,030	0,003
21	-0,008	0,001	-0,011	-0,006	-0,030	0,004
22	-0,009	0,001	-0,011	-0,006	-0,033	0,003
23	-0,009	0,001	-0,012	-0,007	-0,034	0,004
24	-0,010	0,001	-0,013	-0,008	-0,034	0,003
25	-0,011	0,001	-0,014	-0,008	-0,033	0,002
26	-0,011	0,002	-0,014	-0,008	-0,036	0,003
27	-0,012	0,002	-0,015	-0,009	-0,038	0,004
Total	-0,005	0,000	-0,006	-0,005	-0,038	0,010

$$\text{mean}\Delta x = \frac{1}{N}\sum_{i=1}^{k}\sum_{j=1}^{n_i}\Delta x_{ij} \ . \qquad (2)$$

If the values of displacements is significant, then the mean values:

$$\text{mean}\Delta x_i = \frac{1}{n_i}\sum_{j=1}^{n_i}\Delta x_{ij} \ , \qquad (3)$$

differ considerably from the overall average (2).

For analysis, calculate deviation using expressions (2) – (3):

$$Q = \frac{1}{N}\sum_{i=1}^{k}\sum_{j=1}^{n_i}\left(\Delta x_{ij} - \text{mean}\Delta x\right)^2 , \qquad (4)$$

$$Q_\alpha = \sum_{i=1}^{k} n_i\left(\text{mean}\Delta x_i - \text{mean}\Delta x\right)^2 , \qquad (5)$$

$$Q_r = \sum_{i=1}^{k}\sum_{j=1}^{n_i}\left(\Delta x_{ij} - \text{mean}\Delta x_i\right)^2 . \qquad (6)$$

Dispersions according to expressions (4-6) will be:

$$m^2 = \frac{Q}{N-1}, \quad m_\alpha^2 = \frac{Q_\alpha}{k-1}, \quad m_r^2 = \frac{Q_r}{N-k}. \qquad (7)$$

The critical region is defined as the dispersion relations:

$$F \geq F_q , \text{ where: } F = \frac{m_\alpha^2}{m_r^2} . \qquad (8)$$

A value F_q selected on the basis of the accepted significance level q and the number of degrees of freedom (DoF): $k_\alpha = k-1$, $k_r = N-k$.

Perform ANOVA in which we establish the dependence of the displacement from measurement cycle. The results are shown in Table 3.

By the criterion to confirm the hypothesis about the change displacements between cycles is the level of significance. At confidence probability 95% level of significance should not exceed 0,05. Thus, the fact of displacements between cycles can be regarded as established. Figure 5 shows a graph of the average displacement the whole complex of retaining walls.

To check the influence factor numbers retaining wall on the displacement values performed one-factor ANOVA. A hypothesis was tested that displacement of deformation mark depends on what retaining wall it is located.

The analysis found that the magnitude of the displacements depend on the retaining wall which is deformation mark is located on. The construction of deformation models process must be carry out for every retaining wall separately.

The results of analysis push on an idea about dependence of displacement size simultaneously on that in what cycle and what retaining wall, displacement was fixed on. For verification of such hypothesis the two-factor ANOVA was applied.

Table 3. One-factor ANOVA (Displacement - Cycle)

Feature	Sum of squares	DoF	The mean square	F	Significance level
Between groups	0,023	26	0,001	20,010	0,000
Within groups	0,050	1161	0,000		
Total	0,073	1187			

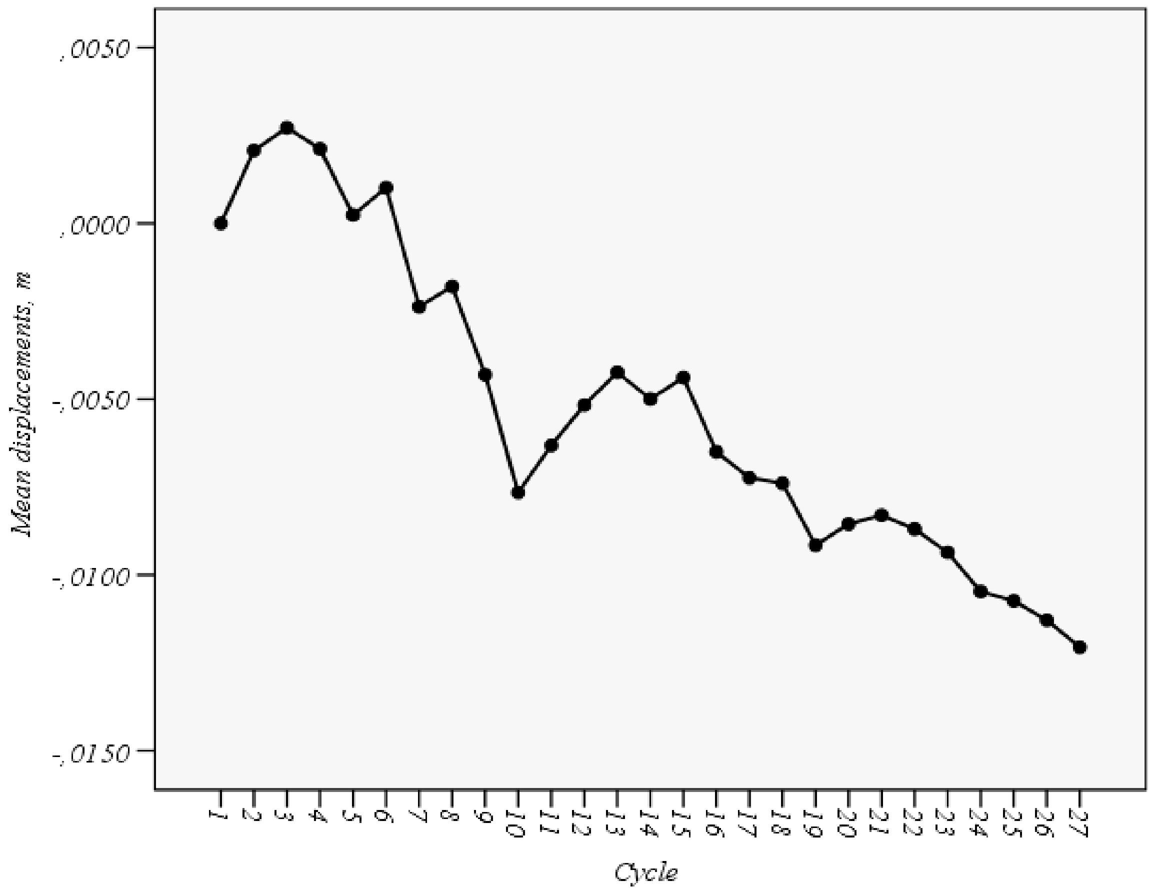

Fig. 5. Mean displacement on *X* axis

Table 4. Statistical characteristics of displacement for retaining walls

Wall	N	Mean	RMS	95% interval for the mean		Min	Max
				Lower limit	Upper limit		
1	594	-0,003	0,000	-0,004	-0,003	-0,018	0,010
2	270	-0,011	0,001	-0,012	-0,009	-0,038	0,006
3	216	-0,007	0,001	-0,008	-0,006	-0,030	0,008
4	108	-0,001	0,000	-0,002	-0,000	-0,007	0,007
Total	1188	-0,005	0,000	-0,006	-0,005	-0,038	0,010

Table 5. One-factor ANOVA (Displacement - Retaining wall)

Feature	Sum of squares	DoF	The mean square	F	Significance level
Between groups	0,013	3	0,004	86,672	0,000
Within groups	0,060	1184	0,000		
Total	0,073	1187			

TWO-FACTOR ANOVA

Under the hypothesis of the presence of several influencing factors used multivariate analysis of variance. We investigate the influence of the factors α (cycle observations) and β (number of retaining wall) on the measurement results. Measurement series can be represented as:

$$\begin{array}{ll}
\alpha_1\beta_1 & \Delta x_{111}, \Delta x_{112}, \ldots, \Delta x_{11k}, \ldots, \Delta x_{11s_{11}} \\
\alpha_1\beta_2 & \Delta x_{121}, \Delta x_{122}, \ldots, \Delta x_{12k}, \ldots, \Delta x_{12s_{12}} \\
 & \ldots \\
\alpha_1\beta_l & \Delta x_{1l1}, \Delta x_{1l2}, \ldots, \Delta x_{1lk}, \ldots, \Delta x_{1ls_{1l}} \\
\alpha_2\beta_1 & \Delta x_{211}, \Delta x_{212}, \ldots, \Delta x_{21k}, \ldots, \Delta x_{21s_{21}} \\
\alpha_2\beta_2 & \Delta x_{221}, \Delta x_{222}, \ldots, \Delta x_{22k}, \ldots, \Delta x_{22s_{21}} \\
 & \ldots \\
\alpha_2\beta_l & \Delta x_{2l1}, \Delta x_{2l2}, \ldots, \Delta x_{2lk}, \ldots, \Delta x_{2ls_{21}} \\
 & \ldots \\
\alpha_n\beta_1 & \Delta x_{n11}, \Delta x_{n12}, \ldots, \Delta x_{n1k}, \ldots, \Delta x_{n1s_{n1}} \\
\alpha_n\beta_2 & \Delta x_{n21}, \Delta x_{n22}, \ldots, \Delta x_{n2k}, \ldots, \Delta x_{n2s_{n2}} \\
 & \ldots \\
\alpha_n\beta_l & \Delta x_{nl1}, \Delta x_{nl2}, \ldots, \Delta x_{nlk}, \ldots, \Delta x_{nls_{nl}}
\end{array}$$

Total number of measurements will be:

$$N = \sum_{i=1}^{n}\sum_{j=1}^{l} s_{ij} . \qquad (9)$$

Overall arithmetic mean would be:

$$\text{mean}\Delta x = \frac{1}{N}\sum_{i=1}^{n}\sum_{j=1}^{l}\sum_{k=1}^{s_{ij}} \Delta x_{ij} . \qquad (10)$$

Particular arithmetic means by the series of measurements calculating:

$$\text{mean}\Delta x_{ij} = \frac{1}{s_{ij}}\sum_{k=1}^{s_{ij}} \Delta x_{ijk} . \qquad (11)$$

Determine the arithmetic mean on the factors for considering factor α_i with (12):

$$\text{mean}\Delta x_{i0} = \frac{1}{N_{i0}}\sum_{j=1}^{l} s_{ij}\,\text{mean}\Delta x_{ij} , \qquad (12)$$

where:

$$N_{i0} = \sum_{j=1}^{l} s_{ij} .$$

for factor β_i:

$$\text{mean}\Delta x_{0j} = \frac{1}{N_{0j}}\sum_{i=1}^{n} s_{ij}\,\text{mean}\Delta x_{ij} , \qquad (13)$$

where:

$$N_{0j} = \sum_{i=1}^{n} s_{ij} .$$

To determine the general empirical dispersion found fluctuations:

$$\text{empirical}\delta_{ijk} = \Delta x_{ijk} - \text{mean}\Delta x . \qquad (14)$$

General deviation using (14) is calculated:

$$Q = \sum_{i=1}^{n}\sum_{j=1}^{l}\sum_{k=1}^{s_{ij}} \text{empirical}\delta_{ijk}^2 , \qquad (15)$$

and proper dispersion: $m^2 = \dfrac{Q}{N-1}$.

Fluctuations of factors α and β are calculated using formulas (10), (12), (13):

$$\left.\begin{array}{l}
\delta_{i0} = \text{mean}\Delta x_{i0} - \text{mean}\Delta x, \\
\delta_{0j} = \text{mean}\Delta x_{0j} - \text{mean}\Delta x, \\
\delta_{ij} = \text{mean}\Delta x_{ij} - \text{mean}\Delta x, \\
\text{empirical}\delta_{ij} = \Delta x_{ij} - \left(\delta_{i0} - \delta_{0j}\right)
\end{array}\right\} \qquad (16)$$

Deviation of factors calculated by the fluctuations (16):

$$\begin{array}{l}
Q_\alpha = \sum_{i=1}^{n} N_{i0}\delta_{i0}^2,\; Q_\beta = \sum_{i=1}^{n} N_{0j}\delta_{0j}^2, \\
Q_{\alpha\beta} = \sum_{i=1}^{n}\sum_{j=1}^{l} s_{ij}\,\text{empirical}\delta_{ij}^2.
\end{array} \qquad (17)$$

Dispersions of factors using deviation (17) will be:

$$m_\alpha^2 = \frac{Q_\alpha}{n-1}, \quad m_\beta^2 = \frac{Q_\beta}{l-1}, \quad m_\alpha^2 = \frac{Q_{\alpha\beta}}{(n-1)(l-1)}. \tag{18}$$

Next, calculate the residual fluctuations:

$$\delta_{ijk} = \Delta x_{ijk} - \mathrm{mean}\Delta x_{ij}, \tag{19}$$

and deviation:

$$Q_r = \sum_{i=1}^{n} \sum_{j=1}^{l} \sum_{k=1}^{s_{ij}} \delta_{ijk}^2 . \tag{20}$$

Suitable dispersion is:

$$m_r^2 = \frac{Q_r}{N - nl}. \tag{21}$$

Thus, we obtain the total contribution of each factor to the total variance:

$$Q = Q_\alpha + Q_\beta + Q_{\alpha\beta} + Q_r,$$
$$(N-1)m^2 = (n-1)m_\alpha^2 + (l-1)m_\beta^2 + $$
$$+ (n-1)(l-1)m_{\alpha\beta}^2 + (N-nl)m_r^2.$$

Influence of factors α and β is determined from the dispersion relations:

$$F_\alpha = \frac{m_\alpha^2}{m_r^2}, \quad F_\beta = \frac{m_\beta^2}{m_r^2}. \tag{22}$$

Critical areas are defined as before on the basis of accepted significance level q and the number of degrees of freedom: $k_\alpha = n-1$, $k_\beta = l-1$, $k_r = N - nl$.

Perform two-factor ANOVA to test the hypothesis according to the value of displacement at the same time from the cycle of observations and numbers of the retaining wall.

Two-factor analysis confirms a hypothesis about dependence of displacements size simultaneously on the cycle of observations and number of retaining wall. The value η^2 in the table shows the percentage contribution of each factor in the total dispersion. The stake of joint influence of observations cycle and number of retaining wall is equal to 17%.

Such index indicates the presence of systematic factors, the nature of which must be found by further analysis of the results of measurements and observations of the slope, retaining walls and atmospheric parameters (air temperature, soil temperature and humidity, amount of precipitation).

Fig. 6 shows the values for each displacement on every retaining wall, and in Fig. 7 the average displacement values for retaining walls.

Table 6. Two-factor ANOVA (Displacement-Cycle-Number of retaining wall)

Feature	DoF	The mean square	F	Significance level	η^2
α	26	0,001	22,494	0,000	0,351
β	3	0,004	152,875	0,000	0,298
α * β	78	8,1E-5	2,823	0,000	0,169
Error	1080	2,9E-5			
Total	1188				

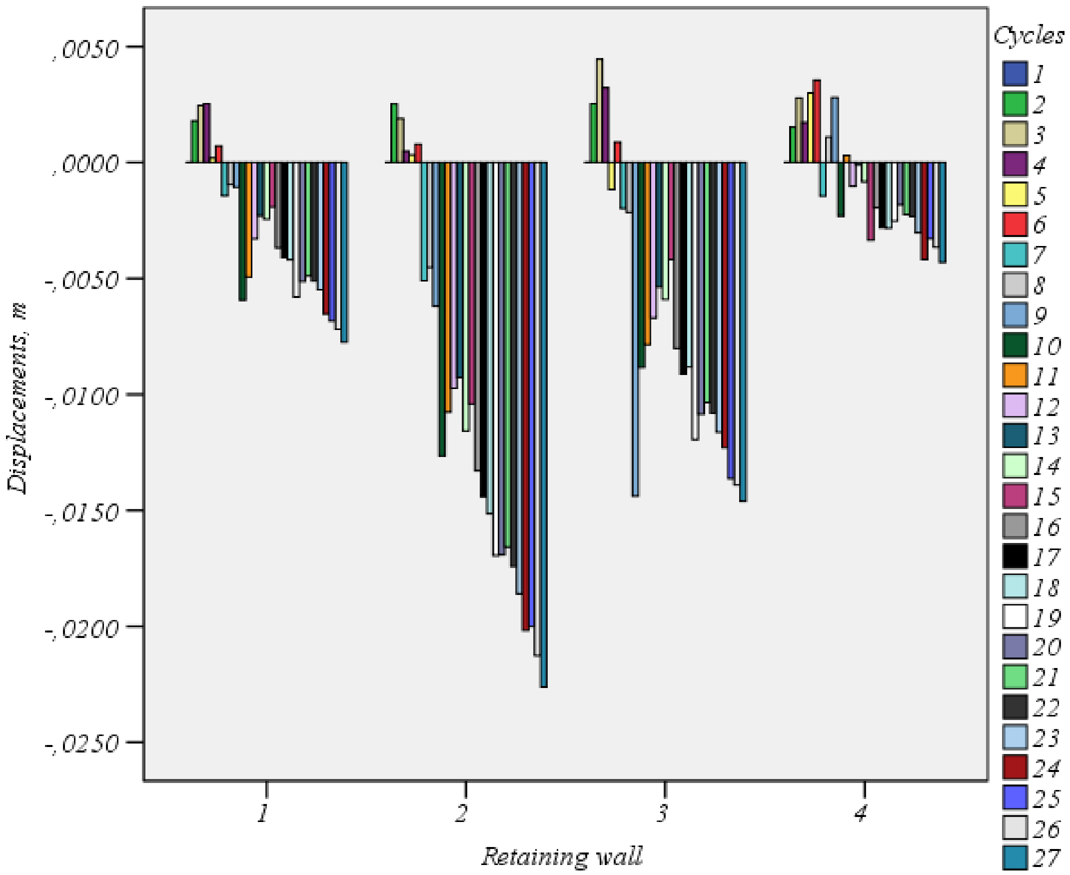

Fig. 6. Displacement on every retaining wall

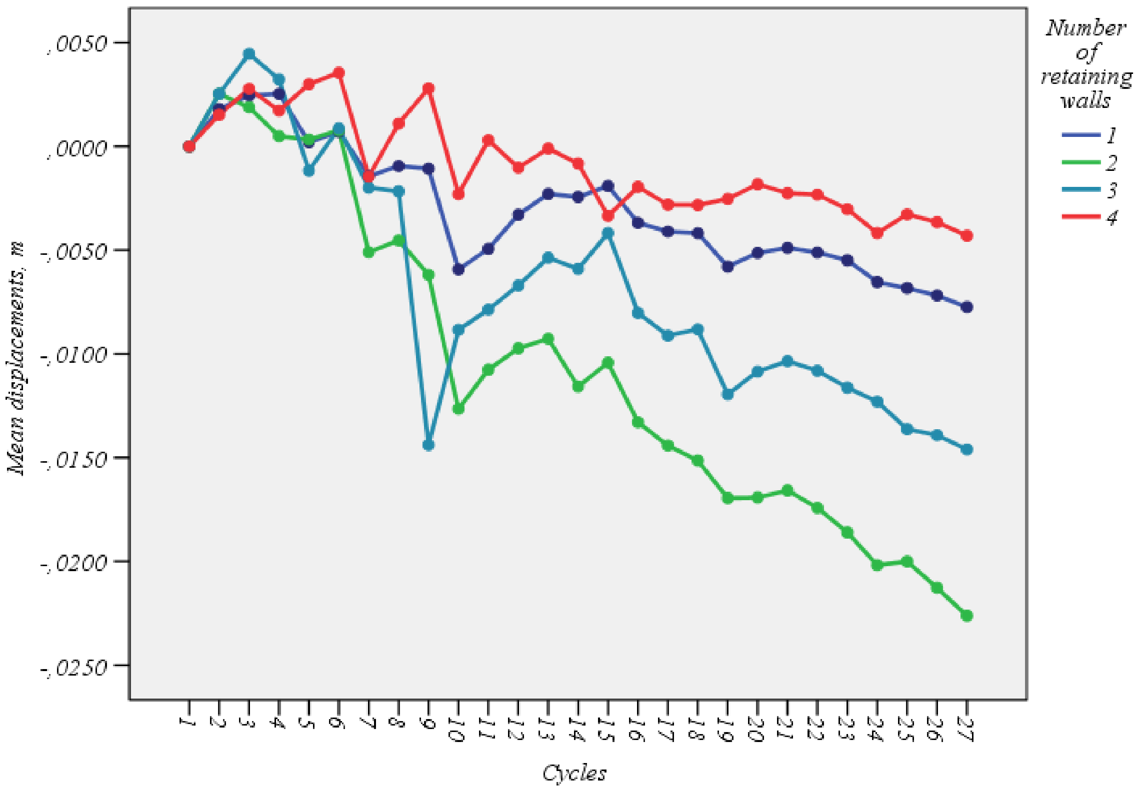

Fig. 7. Average displacement values for retaining walls in cycles

Table 7. Three-factor ANOVA (Displacement-Cycle-Number of retaining wall-Mark position)

Feature	DoF	The mean square	F	Significance level	η^2
α	26	0,001	21,40	0,000	0,364
β	3	0,004	145,42	0,000	0,310
γ	1	0,000	10,339	0,001	0,011
α * β	78	8E-5	2,686	0,000	0,177
α * γ	26	7E-6	0,259	1,000	0,007
β * γ	3	0,000	6,740	0,000	0,020
α * β * γ	78	5E-6	0,193	1,000	0,015
Error	972	3E-5			
Total	1188				

This result is very important, it confirms the complexity of the deformation process. From cycle to cycle different retaining walls change model of their displacement. Two-factor ANOVA (Displacement-Cycle-Number of retaining wall) shows the fundamental impossibility of the use of models deformation like a [3, 10], and speaks in favor of the use of models based on the theory of random functions.

At the analysis of the observations was paid a regard to circumstance that the displacement for marks, which is placed on the same vertical top and, bottom of each retaining wall differ. A hypothesis was pulled out that the displacement in the upper and lower parts of each retaining wall should be interpreted differently. According is pulled out hypothesis about necessity of verification a complex impact Displacement-Cycle-Number of retaining wall-Mark position. To test this hypothesis has been applied a three-factor ANOVA.

THREE-FACTOR ANOVA

When the three-factor analysis of variance implementation checkup the following dispersion relation by analogy with (8) and (22):

$$\left.\begin{aligned} &F_\alpha = \frac{m_\alpha^2}{m_r^2}, F_\beta = \frac{m_\beta^2}{m_r^2}, F_\gamma = \frac{m_\gamma^2}{m_r^2}, \\ &F_{\alpha\beta} = \frac{m_{\alpha\beta}^2}{m_r^2}, \quad F_{\alpha\gamma} = \frac{m_{\alpha\gamma}^2}{m_r^2}, \\ &F_{\beta\gamma} = \frac{m_{\beta\gamma}^2}{m_r^2}, F_{\alpha\beta\gamma} = \frac{m_{\alpha\beta\gamma}^2}{m_r^2}. \end{aligned}\right\} \quad (23)$$

In (23) factors are: α (cycle observation), β (number of retaining wall), γ (mark position).

Three-factor analysis showed that significant is the contribution of the following groups of factors: Displacement-Cycle – 36%, Displacement-Number of retaining wall – 31%, Displacement-Mark position – 1%, Displacement-Cycle-Number of retaining wall – 18% Displacement-Number of retaining wall-Mark position – 2%.

Summarizing the results it is possible to pass to the conclusions about the executed research.

CONCLUSIONS

Analysis of variance was a powerful instrument to explore the displacements. Using analysis of variance revealed the following features of the measurements were made:

1. When unclear picture of nature of displacement found that displacements occurs between cycles of the whole landslide,

2. In different parts of the landslide retaining walls respond differently to each of them should be built its deformation model,

3. It is necessary to execute the detailed analysis of observations after every cycle because there is dependence between the cycles of observations and displacement of retaining walls, which indicate on the possible different terms of operation between cycles for every wall,

4. It is necessary separately consider displacement deformation marks at the top and bottom of each retaining wall.

The obtained results are more fully explained to the results of geodetic measurements and perform a correct construction of a predictive model of the deformation process. In future we plan to use the results and observations of atmospheric parameters (air temperature, soil temperature and humidity, amount of precipitation) to build a model of deformations by the regression analysis.

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СТАТИСТИЧЕСКОЕ ИССЛЕДОВАНИЕ ПЕРЕМЕЩЕНИЙ ПОДПОРНЫХ СТЕНОК ПО РЕЗУЛЬТАТАМ ГЕОДЕЗИЧЕСКИХ ИЗМЕРЕНИЙ МЕТОДОМ ДИСПЕРСИОННОГО АНАЛИЗА

Аннотация. Выполнен анализ геодезических измерений за перемещениями подпорных стенок в жилом квартале города Киева. Для обработки наблюдений было предложено использовать метод дисперсионного анализа. Исследовано влияние изменения перемещений в зависимости от циклов наблюдений методом однофакторного дисперсионного анализа. Метод однофакторного дисперсионного анализа позволил также определить, что для различных подпорных стенок деформационный процесс имеет различную динамику. Зависимость между циклами наблюдений и размещением подпорных стенок было определено с помощью двухфакторного дисперсионного анализа.

Метод трехфакторного дисперсионного анализа позволил дополнительно определить влияние расположения деформационных марок на величину перемещений. Подтверждено, что метод дисперсионного анализа имеет большие перспективы при анализе геодезических измерений, особенно при больших объемах наблюдений.

Ключевые слова: дисперсионный анализ, перемещения, дисперсионное отношение, уровень значимости, подпорная стенка, оползень, прогнозирование деформаций.