Development and research of the methods for analysis of geodetic monitoring results for the subway tunnels

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ABSTRACT

In the presented paper, the different methods for analysis of the geodetic monitoring results for the subway tunnels were discussed. Using the results of the geodetic monitoring for the displacements of seven new subway tunnels in Kiev the traditional and new methods for measurements analysis were researched. The sections of these tunnels have a form of a circle with 5.5 m diameter. For analysis of the whole tunnel structure, the vertical displacements by the results of precise levelling were used. Two types of displacements were considered: vertical displacements of the tunnel surface and vertical displacements of the whole tunnel structure. For these displacements were carried out different types of analysis. Before data analysis, correlation relationships between displacements of the tunnel surface and the whole structure displacements were considered. These correlations were assessed using statistical criteria. It turned out that there is a high correlation between tunnel surface vertical displacements and structure vertical displacements in all. In order to smooth away possible geodetic measurements errors and approximate results of displacements measurements, Fourier analysis method was used. As an alternative approach for such an analysis neural networks method was considered. For quality assessment of the carried out analysis for both types of displacements the simplest deformation model which obeys to stress-strain condition was developed. This model is grounded on structural mechanics principles and allows to calculate tunnel surface displacements under specific construction conditions. The vertical displacements of the whole structure were analyzed both by Fourier analysis and neural networks method.

I. INTRODUCTION

Among different tasks of geodetic monitoring, the monitoring of underground structures is one of the most complicated (Kontogianni *et al.*, 1999). Besides traditional geodetic methods, e.g. levelling, observations by total station etc., there are many brand-new methods and approaches to perform such monitoring (Alba *et al.*, 2010; Jian *et al.*, 2012; Argüelles-Fraga *et al.*, 2013; Scaioni *et al.*, 2014; Protopapadakis *et al.*, 2016). Besides the complexity of such monitoring from a technological point of view, there is another one problem concerning data processing and analysis. Many factors that affect tunnels deformations lead to very complicated deformation process (Chrzanowski *et al.*, 1996). First of all, we have a deal with different types of deformations: tunnel surface deformation, displacement of the whole tunnel structure. Secondly, both of these deformations have three different meanings: deformation immediately after construction, deformation after tunnel construction accomplished and deformation during exploitation. The main aim of the accomplished research is study and simulation of deformations of subway tunnels at a stage of construction. It is clear, that in order to simulate these deformations, one needs to use complex math models (Heunecke *et al.*, 1998; Welsch *et al.*, 2001). Such models have to account different nature of deformation reasons, which in turn means, that we cannot use conventional models, e.g. polynomial, exponential, etc. Among state-of-the-art approaches for geodetic monitoring data simulation, one can emphasize the finite element method, random functions method and neural networks simulation. The goals of the research are a definition of an appropriate accuracy of geodetic monitoring, statistical data analysis and monitoring data simulation, using of Fourier analysis and neural networks simulation. As a data source for this research, the results of geodetic monitoring for new subway tunnels which were built thru the last five years in Kiev were chosen. These tunnels were built by using of tunnel boring machines, and concrete rings, with an inner diameter, equals to 5.5 m, that fixed tunnel surface.

Before to present results of the research, let us consider data for analysis and calculation and find out in which way they were got.

II. DATA

During tunnels construction, one performs geodetic measurements for tunnel surface just after construction and before tunnel begins functioning. The measurements were being performed for two perpendicular tunnel diameters; vertical displacements of tunnel vault; vertical displacements of tunnel bottom; horizontal displacement of tunnel axis. For diameters monitoring a comparison of design diameters and measured being performed (see Fig. 1).

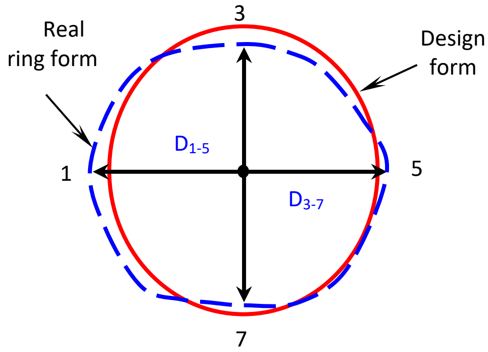

Figure 1. Scheme of diameters measurements

Below will be presented results of monitoring for a tunnel having length 1090 m and constructed at depth equals to 17 m.

There are many different methods, and approaches for tunnel monitoring have been presented the last ten years. Among them terrestrial laser scanning (Lindenbergh *et al*., 2005; van Gosliga *et al*., 2006) or total station measurements using a free stationing method. However, in this case, for diameter measurements, a simple tape with level was being used, but also a total station either in a prism or in reflectorless modes can be used. Diameters measurements during construction are presented in Fig. 2.

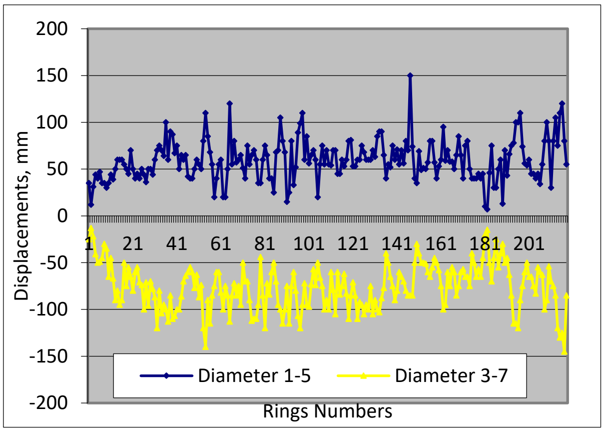

Figure 2. Diameters deviations

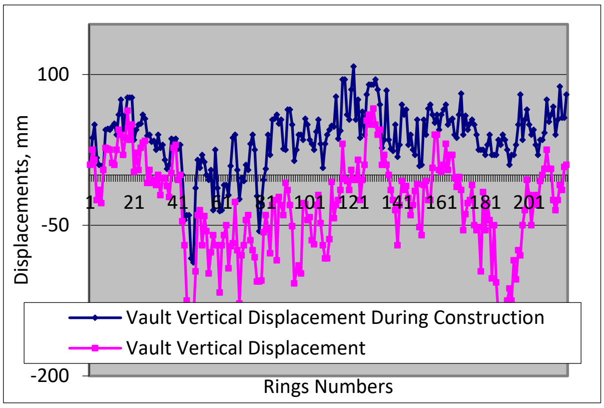

Figure 3. Vault vertical displacements

The vertical displacements of vault typically were being measured by levelling. Leveling with short sides of 5 m to 25 m and wooden or aluminum rods was used (see Fig. 3).

Horizontal displacements were being measured by precise traverses with using of precise total stations, by a scheme similar to (Trevor Greening *et al*.) along with levelling for vertical displacements of tunnel bottom (see Fig. 4).

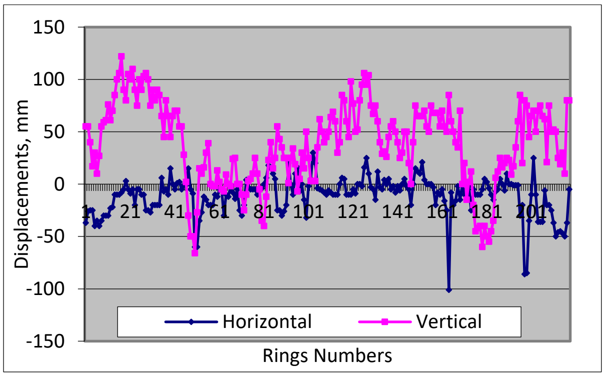

Figure 4. Displacements of tunnel axis

As a reference network for levelling and precise traverses, a spatial geodetic network on a ground surface was used. Totally, during five years monitoring measurements for seven tunnels were being performed.

Before measurements had been performed a task of necessary accuracy definition was solved. The method and appropriate calculations are presented in the next section.

III. Accuracy Requirements

One of the possible ways to define a necessary accuracy is using the value of tunnels breakthrough (Chrzanowski, 1981). According to the National Standards of Ukraine, the permissible deviations of the position of the tunnel rings in vertical and for diameters from the design value must be within δ = ± 50 mm. If we assume that the accuracy of geodetic observations is determined by expression (Chibiriakov *et al*., 2009)

$$m_g \leq 0.2\delta \,, \qquad (1)$$

then m_g ≤ ± 10 mm. Such accuracy of measurements can be achieved using traditional geodetic equipment and can be assigned for observation for the whole structure.

However, due to violations of the construction technology, low-quality assembling of the tunnel structure and the failure to take into account certain types of loads, additional deformations of the ring of the tunnel structure may occur, which may over time exceed the permissible values.

In this approach, the accuracy of observation is determined from the condition of detecting the maximum permissible deformation of the structure, which is calculated using the methods of structural mechanics.

A constant pressure of the structure weight leads to the consolidation of the soil in the bottom of the tunnel and subsidence of the whole structure. In addition to the pressure of the own structure weight, subsidence may occur as a result of changes in the level of groundwater, karst, landslide, and seismic phenomena, from the work of heavy mechanisms, etc.

The displacement of the structure in the horizontal plane may occur due to the lateral pressure of the soil or water. According to the results of geodetic observations, one determines the total value of the subsidence or displacement, which is the sum of pure subsidence and deformation of the structure itself. Therefore, for the correct assignment of the accuracy of observations and determination of "clean" subsidence, from the results of measurements, it is necessary to separately determine the accuracy of the observation of its deformation structures and the accuracy of observation for the subsidence in generally.

For the observations accuracy assignment, it is necessary to calculate the value of the own displacement of the structure.

To calculate the value of own displacement using a well-known approach from structural mechanics. The calculation is performed on the assumption of the maximum possible own displacement of the structure. The greatest effort is *N* and the bending moment *M*, which can accept this shell of the tunnel with a static load are $N^{\max}$ and $M^{\max}$. The magnitude of the stress is calculated as,

$$\sigma = (N/F) \pm (M/W),$$

where *F* = cross-sectional area; *W* = polar moment of inertia.

Insofar as in the shell calculation, the normative load is multiplied by the coefficient of working conditions, which for various conditions varies from 1.1 to 1.4, then the average value is approximately equal to 1.2. Then the shell load can exceed the standard by an average value of 20%.

$$\Delta M^{\max} = 0.2M \,;\; \Delta N^{\max} = 0.2N \tag{2}$$

By this approach, one calculates the values of the displacements of the ring elements Δ_1, Δ_2. Therefore, the errors permissible in geodetic measurements should not lead to additional efforts exceeding 20% of the calculated for the adopted cross-section. Based on these considerations, we will find the maximum displacements Δ_1, Δ_2 that will be caused by excessive loads.

The stress-strain state is characterized by two stiffness characteristics:

$$D = Eh^3 \big/ 12(1-\mu^2) \;;\quad H = Eh \big/ 1-\mu^2$$

where *D* = cylinder stiffness for bend
H = cylinder stiffness for strain-compression
E = modulus of rigidity, $E = 2.2 \cdot 10^6 \; \mathrm{t/m^2}$
μ = cross-expansion coefficient (Poisson coefficient) – 0.2
h = ring thickness – 0.3 m (Fig. 5)
R = mean ring radius - 2.90 m (Fig. 5)

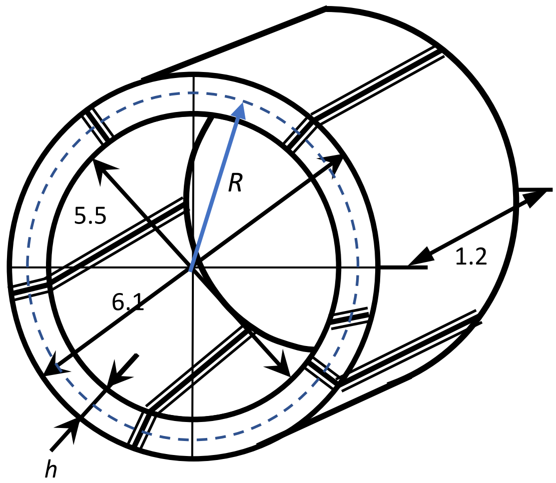

Figure 5. Main geometric characteristics of ring

Then for concrete in particular conditions,

$$D = 5.156 \cdot 10^4 \; \mathrm{kN{\times}m} \,;\; H = 6.875 \cdot 10^6 \; \mathrm{kN/m}$$

The largest effort *N* and bending moment *M* will equal:

$$M^{\max} = R_{flex} \cdot \frac{h^2}{6(1-\mu^2)} = 306.56\,\mathrm{kN} \,;$$

$$N^{\max} = R_{flex} \cdot h = 5886\,\mathrm{kN/m} \,,$$

and maximum load deviations:

$$\Delta M^{\max} = 61.7\,\mathrm{kN} \,;\; \Delta N^{\max} = 1177\,\mathrm{kN/m} \,.$$

Let us suppose that across the ring are placed n deformation targets, where *n* – even (*n* = 8) and Δ_1 is an error of normal displacements measurements and Δ_2 is an error of tangent displacements measurements. Let us consider the worst case when signs of the errors are alternately changing.

The largest values of the moment and the normal force will:

$$\left.\begin{aligned}\Delta M_2^{\max} &= \Delta_1 \left({D}/{R^2} \right) \cdot \left[-\left({n}/{2} \right)^2 + 1 \right], \\ \Delta N_2^{\max} &= \frac{H}{R} \left(\frac{n}{2} \Delta_2 + \left[1 - \frac{h^2}{12R^2} \left(\frac{n}{2} \right)^2 \right] \Delta_1 \right).\end{aligned}\right\} \quad (3)$$

From the expressions (3) we find Δ_1 and Δ_2.

$$\left.\begin{aligned}\Delta_1 &= \frac{\Delta M_2^{\max}}{{D}/{R^2} \left(-\left({n}/{2} \right)^2 + 1 \right)}; \\ \Delta_2 &= \frac{\Delta N_2^{\max} - {H}/{R} \left(1 - \frac{h^2}{12R^2} \left({n}/{2} \right)^2 \right) \Delta_1}{{H}/{R} \cdot {n}/{2}}\end{aligned}\right\} \quad (4)$$

By the expressions (4) we obtain the following values of displacements Δ_1 = 14 mm, Δ_2 = - 7mm. The resulting estimated displacement values allow establishing the required accuracy of observations. From expression (1) we have: $m_g \leq 3.1$ mm.

In addition, this accuracy can be used for assessment of data analysis quality. We will address to this accuracy during data analysis.

IV. Data Analysis

Statistical data analysis

The main aim of statistical analysis is to find a possible relationship between different types of displacements. If we find any relationship between different types of displacements, it will allow simplifying displacements simulation procedure insofar as will necessary to use the same math model for data analysis or even to perform analysis of only one type of displacements. The measure of the relationship between to parameters is a correlation coefficient.

Our task is to find the correlation between different types of displacements, e.g., between vertical diameter 3-7 (Diameter37), vertical displacement of a vault during assembling (VaultDispConst), vertical displacement of a vault after construction (VaultDisp) and vertical displacement of tunnel bottom (Vertical). As an example, let us consider statistical analysis of vertical displacements. The descriptive statistics of those data are presented in table 1.

Table 1. Descriptive Statistics

Displacement	Mean, mm	Std. Dev., mm
Diameter37	-75.89	24.294
VaultDisp	-30.11	47.559
VaultDispConst	36.13	30.919
Vertical	38.61	38.856

The next step of the analysis is a calculation of a correlation matrix. In table 2 are presented correlation coefficients and statistical checks for them.

Table 2. Correlations

		Diameter 37	Vault Disp	VaultDisp Const	Vertical
Diameter 37	PC	1	-0.040	-0.061	-0.130
	S2t		0.561	0.367	0.056
Vault Disp	PC	-0.040	1	0.647**	0.590**
	S2t	0.561		0.000	0.000
Vault Disp Const	PC	-0.061	0.647**	1	0.472**
	S2t	0.367	0.000		0.000
Vertical	PC	-0.130	0.590**	0.472**	1
	S2t	0.056	0.000	0.000	

PC - Pearson Correlation
S2t - Sig. (2-tailed)
** Correlation is significant at the 0.01 level (2-tailed).

By the coefficients analysis, we can infer about the relation between different displacements. As we have seen, there is no significant correlation between vertical diameter 3-7 deviations and other displacements. It means that we have to perform an analysis of those displacements separately from others.

From the other hand, there is a correlation between It means that we can use the same math models for those data simulation. Now, the last task, find a correct model for data simulation.

Displacements simulation

As an example, let us consider the procedure of opting of a better model for a vertical displacement of a vault during assembling. Due to the complex structure of deformation process, there is only one way to simulate that process, it is using of Fourier series. The general model for Fourier looks as:

$$f(x) = a_0 + \sum_1^i a_i \cos(i \cdot x \cdot w) + \sum_1^i b_i \sin(i \cdot x \cdot w)$$

Results of an application of that model are presented in Fig. 6. The quality of that model is described by adjusted R-square = 0.7358 and root mean square error = 19.97 mm. In this particular case, the model with 18 coefficients was used. It is clear that the accuracy of approximation six times worse than measurements accuracy.

Another possible model is a sinusoidal model:

$$f(x) = \sum_1^i a_i \sin(b_i \cdot x + c_i)$$

Results of an application of that model are presented in Fig. 7.

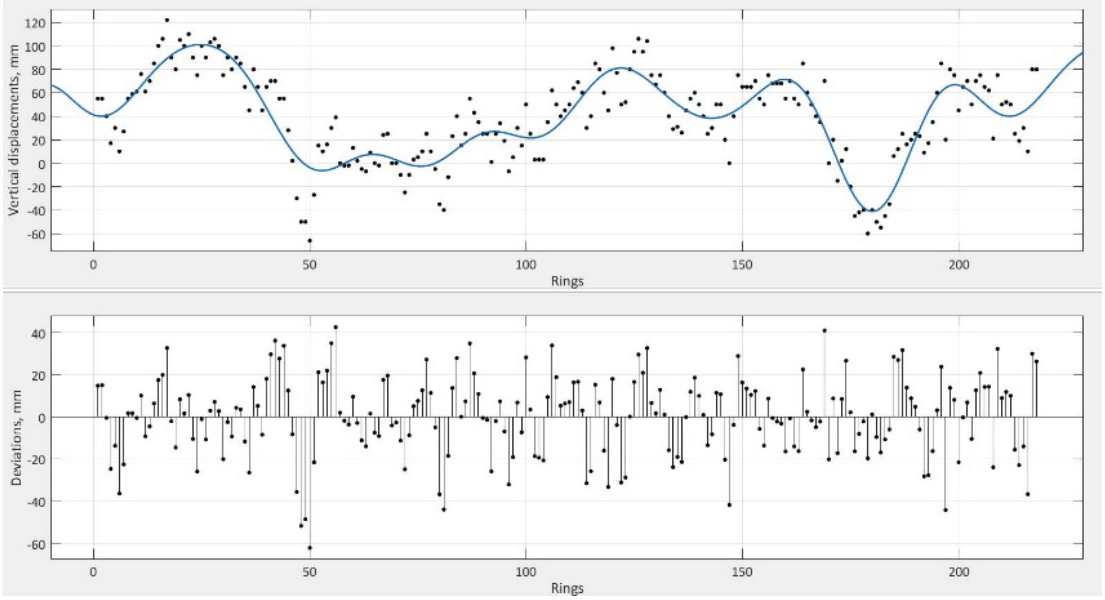

Figure 6. Results of Fourier approximation

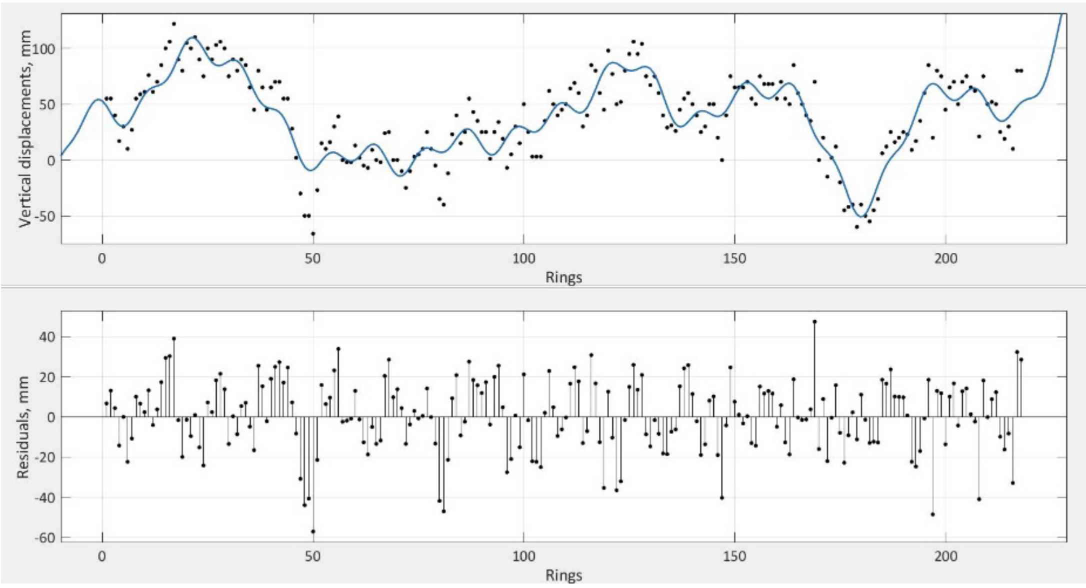

Figure 7. Results of sinusoidal approximation

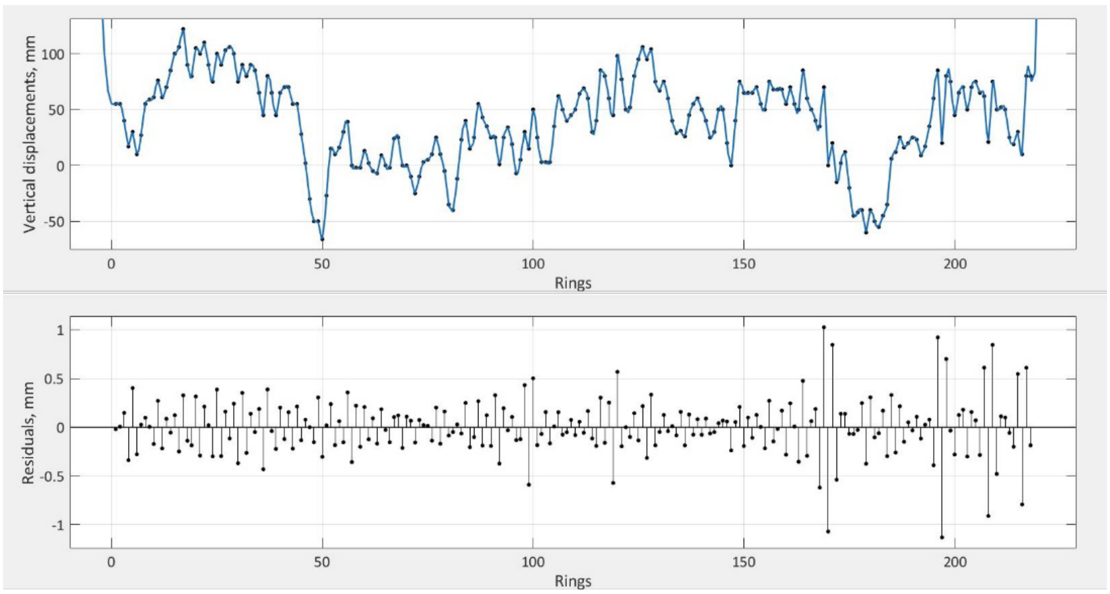

Figure 8. Results of smoothing spline application

The quality of that model is described by adjusted R-square = 0.759 and root mean square error = 19.07 mm. In this particular case, the model with 24 coefficients was used. General presentation of measured displacements looks better in comparison to Fourier approximation, however, an accuracy of the approximation is still considerably worse than measurements accuracy.

Of course, for both cases, we can increase the number of coefficients in models, but it will lead to bad reliability of those new coefficients definition.

Another possible way is using different smoothing models, e.g. splines. Below, the results of the smoothing spline application are presented (Fig. 8). The basic elements of a smoothing spline is a piecewise polynomial function and smoothing parameter. In our case p = 0.99876719. The quality of that model is described by adjusted R-square = 0.9967 and root mean square error = 2.24 mm. Such an accuracy satisfies our requirements. It points out that usage of smoothing models can be a possible solution of such a complex deformation process. However, a smoothing spline is just a math presentation of a deformation process and does not account physical factors, which were considered in Section III.

Among state-of-the-art models, a quite popular now are models based on artificial neural networks (Pantazis *et al.*, 2013; Miima *et al.*, 2004). Let us consider an application of neural networks for the same data set.

A number of neurons in a hidden layer can be defined by the expression:

$$\frac{mN}{1+\log_2 N} \le L_\omega \le m\left(\frac{N}{m}+1\right)\left(n+m+1\right)+m\,, \quad (5)$$

where n = number of input neurons (n = 1)
m = number of output neurons (m = 1)
N = quantity of elements in training sample (N = 218)
L_ω = quantity of synapsis weights.

Number of neurons in a hidden layer

$$L = \frac{L_\omega}{n+m} \Rightarrow 12 \le L \le 328\,.$$

As a basic structure of neural network was offered a quiet simple network consisted from two layers with one neuron in the input layer, from 12 up to 328 neurons in a hidden layer and one neuron in the output layer. The first attempt was made for a minimum number of neurons (12) in a hidden layer.

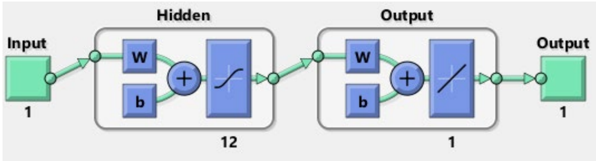

Figure 9. Scheme of neural network

In Fig. 10, the results of neural network application on 12 neurons are presented. The results of neural network application are presented in Fig. 11.

Results

	Samples	MSE	R
Training:	152	217.76363e-0	9.21942e-1
Validation:	33	0.00000e-0	0.00000e-0
Testing:	33	560.47975e-0	8.31356e-1

Figure 11. Results for 12 neurons

The quality of that model is described by correlation R = 0.922 and root mean square error = 14.8 mm for the training sample.

In Fig. 12, the results of neural network application on 328 neurons are presented. The results of a neural network for 328 neurons application are presented in Fig. 13.

Results

	Samples	MSE	R
Training:	196	17.34755e-0	9.94167e-1
Validation:	11	0.00000e-0	0.00000e-0
Testing:	11	201.42356e-0	9.60154e-1

Figure 13. Results for 328 neurons

The quality of that model is described by correlation R = 0.994 and root mean square error = 4.2 mm for the training sample.

The last study for 218 neurons with 25% for validation and testing data was made. In Fig. 14 the results of neural network application on 218 neurons with 25% for validation and testing data are presented. The quality neural network is presented in Fig. 15.

Results

	Samples	MSE	R
Training:	152	10.34622e-0	9.96684e-1
Validation:	33	0.00000e-0	0.00000e-0
Testing:	33	243.18117e-0	9.22691e-1

Figure 15. Results for 218 neurons (25% data for validation and testing)

The quality of that model is described by correlation R = 0.997 and root mean square error = 3.2 mm for the training sample. This model completely satisfies to preliminary requirements and if it is necessary, one can add additional parameters e.g. ground pressure, water level, etc. for a better simulation.

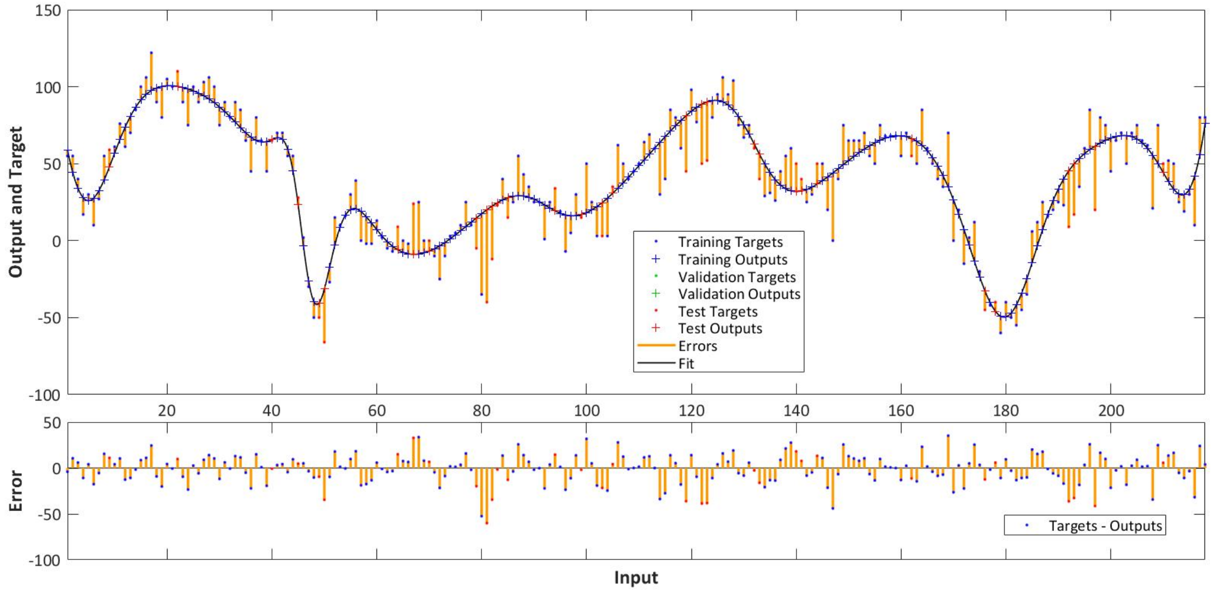

Figure 10. Results of neural network application on 12 neurons

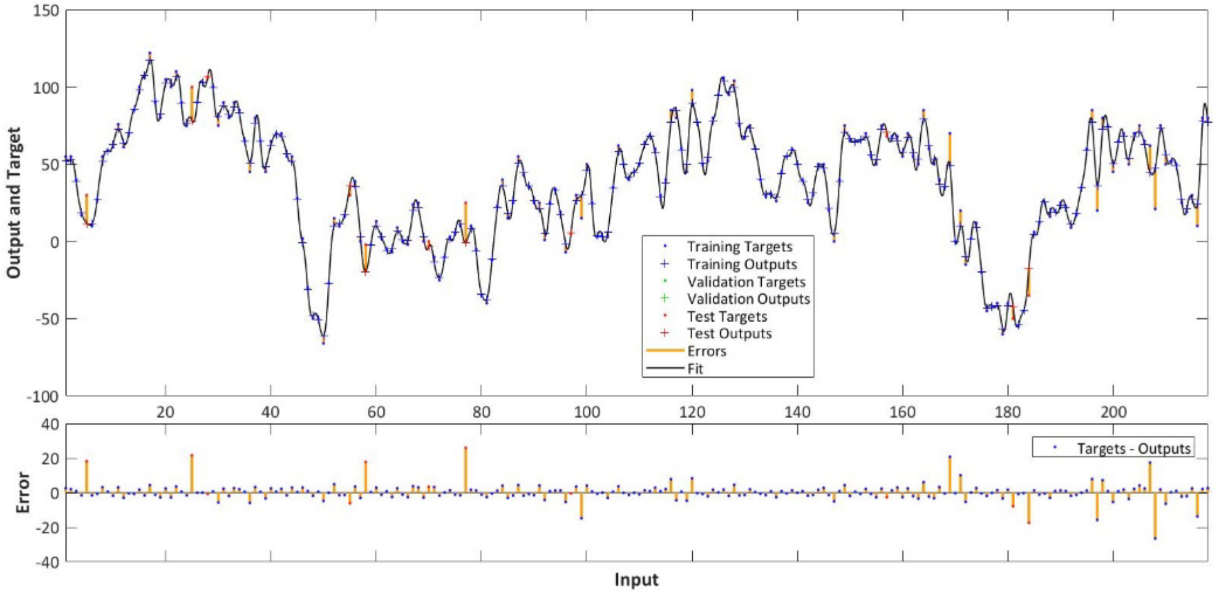

Figure 12. Results of neural network application on 328 neurons

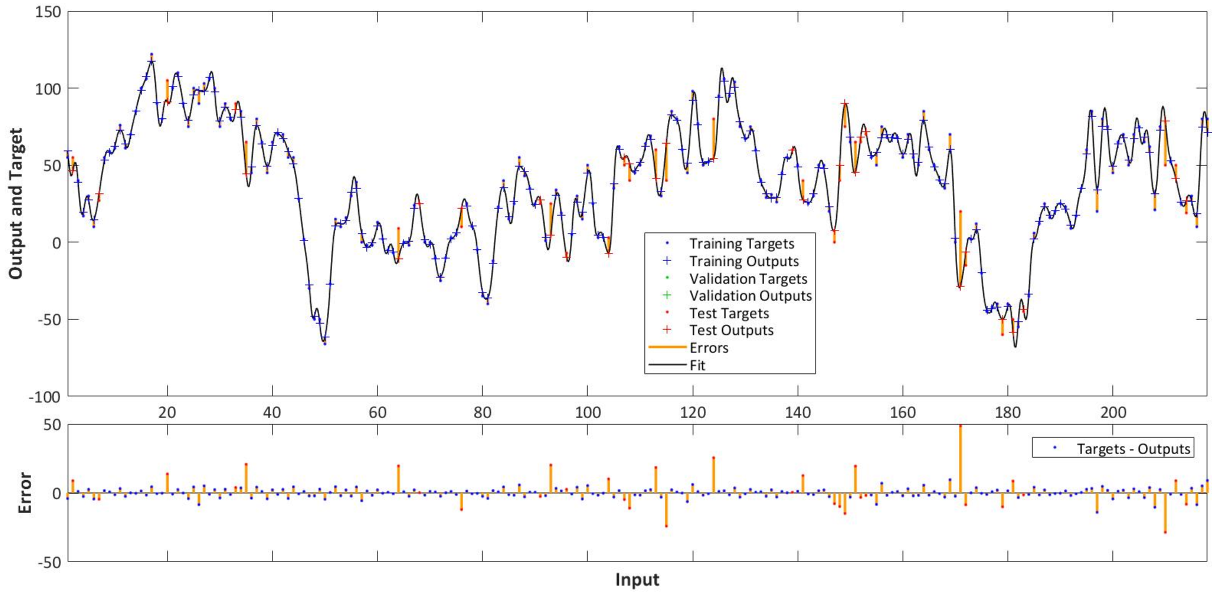

Figure 14. Results of neural network application on 218 neurons (25% data for validation and testing)

V. Conclusions

In the presented paper, a complex approach for the analysis of geodetic monitoring results for the subway tunnels has been presented. At the first step, the simplest deformation model, which obeys stress-strain condition, was developed. Based on this model a preliminary accuracy for monitoring was assigned. By that calculation, the accuracy should not be worse than 3 mm. This accuracy in following was used for quality assessment of the carried out analysis. At the second step, correlation relationships between displacements of the tunnel surface and the entire structure displacements were determined. These correlations allow simplifying data analysis and afford to find partial relationships between different displacements. It turned out that there is a high correlation (almost 0.65) between tunnel surface vertical displacements and tunnel vertical displacements.

At the third step, were carried out different types of analysis for vertical displacements. In order to smooth away possible geodetic measurements errors and to approximate results of displacements measurements least squares Fourier analysis method and neural networks analysis were used. It turned out that better result provides neural networks analysis. For the Fourier analysis method, root mean square error equals 20 mm, contrary to the neural network to which root mean square error equals 3 mm. By simulation analysis, it was found out that a better result provides the network with 218 neurons. In this particular case, the accuracy of the simulation best fits to the accuracy of measurements, as it has been pointed out in Section III. Further, it is recommended to perform a detailed analysis of monitoring data using neural networks. Of interest the analysis of vertical displacements with a set of input geometrical (vertical displacement of a vault during assembling, vertical displacement of a vault after construction and vertical displacement of tunnel bottom) and physical (pressure of the structure weight, consolidation of the soil in the bottom of the tunnel, changes in the level of groundwater, loads from the work of heavy mechanisms) parameters.

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