BIM AND FORECASTING DEFORMATIONS IN MONITORING STRUCTURES

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ABSTRACT

BIM technologies are becoming more widely used, mainly in the design and operation of buildings and structures, and in most cases this is enough for trouble-free operation. Nevertheless, there is a category of buildings for which the monitoring of the technical condition should be an integral part of the construction and operation. These are the so-called public large-span structures. Unfortunately, the development of BIM technology in the Russian Federation is not at such a level as to answer questions about the behaviour of objects under changing environmental conditions and reveal hidden patterns in the monitoring data. Based on the analysis of literary sources, the authors reviewed various methods for identifying hidden patterns in geodetic measurement data when monitoring buildings and structures. It is noted that modern analysis methods are based on statistical processing of measurement results and on the statistical method of forecasting. However, there are attempts to apply models that take into account the design features and the temperature regime of the object. This type includes the two proposed models, which are used to model the three-dimensional coordinates of the strain marks in the 3D model and only the elevations of the marks in the 1-Z model. The article presents the rationale for the simulated geometric elements and properties of the object. The solution of the equations of both models and the analysis of the results and parameters of the model for measurement epochs are shown. The simulation is shown on the example of a real object, which was monitored by the authors in 2015-2016. The authors believe that the monitoring of large-span structures and the search for patterns of their behaviour should be an integral part of the BIM system for such structures.

Keywords: geodetic measurement, environmental parameters, monitoring, thermal model, deformation forecast

1 INTRODUCTION

BIM technologies have been more widely applied in the design and use of buildings and constructions and in most cases it is enough for trouble-free operation. However, there is a category of buildings for which monitoring of technical condition must be the integral part of building and exploitation process. These are so-called public large-span constructions. Unfortunately, the development of BIM technologies in Russia has not yet reached the necessary level to answer the questions about the behaviour of objects in changing environmental conditions and reveal latent patterns in monitoring data. So far technical condition monitoring systems have not been integrated in BIM yet, and remain separate systems. This fact limits their sphere of application and makes the information from databases less useful, as this information is not correlated with calculation models which are an integral part of BIM.

Monitoring of different type objects in general implies the vertical displacement of particular strain marks, fixed in characteristic points of the object, or in the spots where critical strains might appear. Such measurements are carried out during long period of time and give a large volume of information. New methods of geodetic monitoring, such as laser scanning and digital photogrammetry, give the researcher huge volumes of data, from which one can get a lot of useful information about measurement accuracy, object deformation and its reaction to changing environmental conditions. The idea is not new, approximately 20 years ago there appeared the line of research which is called «data mining», the search of new patterns in data sets [1,2]. In the first turn, these methods were used to analyse customer databases of banks and shops to find out the categories of clients for service unification. Later appeared methods for intellectual analysis and classification of spatial information [3,4], and these methods concern geoinformation systems to a greater extent.

Under development now are the methods of searching, revealing, and taking into account systematic and non-systematic errors in multiple measurements [5]. Accuracy pre-calculation and deformation forecasting methods in monitoring tunnels [6,7], and opencast mining [8] are used more widely. The search for patterns in object monitoring is carried out together with modelling the processes which cause object deformation [9]. New tasks in monitoring require new schemes and methods of measurements [10] and deformation forecast: neural networks [11], final element method [12], etc. When modelling deformation it is suggested to take into account temperature deformations caused by environmental changes of temperature [13,14,15,16].

Now laser scanning is more often used to monitor and model historical buildings [17] and large span constructions [18]. Next, there is a very interesting approach in [19], where the authors imply joint data processing

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of satellite and geodetic observations in monitoring dams, and where the authors suggested that the object should be considered as geometrically combined observation points.

To model object behaviour in changing environmental conditions, researchers also use different approaches, e.g. general deterministic [20], where the author does not give a particular realization for real objects. One more approach is statistic modelling and forecasting of object's behaviour [21,22,23]. There is a lot of literature on this topic and the authors hope that they managed to highlight at least basic tendencies.

The authors consider that the monitoring of object condition cannot be complete and informative if the model does not take into account physical links among strain marks, placed on the object under research, and reaction of this object to changing parameters of environment.

The authors suggest to consider their approach on the example of the Novosibirsk aquapark, which is located in the flood land of the Ob river on the weak alluvial soil. In connection with this, the monitoring system did not imply the setting up of fundamental bench marks. The object of the research - the support ring has the diameter of 82 meters.

2 THERMAL MODEL OF SUPPORT RING DEFORMATION

In monitoring deformations and displacements of engineering objects the surveyors use the method of repeated geodetic measurements of coordinates of control bench marks fixed on the object. Their displacement in space characterizes the condition of the object under control. As a rule, the displacement of each bench mark is analysed separately and on this basis the surveyors draw the conclusion about the condition of the object.

When analysing the conditions of the object under investigation in this article (Fig. 1), we can point out its following peculiarities:

- the object, the support ring, is a monolithic steel-concrete construction, which does not contain any elements that could be displaced with respect to each other;
- the construction can change its position in space under the influence of gravity, but the elastic inner strain of the construction remains unchangeable;
- the sizes of the construction are by certain extent affected by changes under the temperature influence of environment.

All these displacements of bench marks, fixed on the support ring, follow some common pattern, the mathematical description of which is the model of changing object conditions in time. As long as the outside temperature influences the sizes of the support ring, this factor should be included in the model. That is why we can define it as a thermal model describing the object behaviour during the time.

Geodetic observations over the support ring behaviour should be divided into two variants: the first variant, when the spatial coordinates of bench marks z1…z10, fixed on the support ring, were measured (Fig. 1 and 2), and the second variant – was measured only the coordinate Z of all bench marks including points p1…p10, placed on the cap plate (Fig.2). Geodetic measurements were performed by the total station LeicaTM30, by special method, which provided determination of the coordinate Z with the accuracy 0.2 mm and 0.5 mm for the coordinates X and Y for points z1…z10. For points p1,…,p10 the coordinate Z was determined with the accuracy 0.5 mm. The geodetic monitoring of the object started 8 months after the concrete foundation plate had been poured.

Figure 1. Fragment of ring beam and strain marks stuck on it

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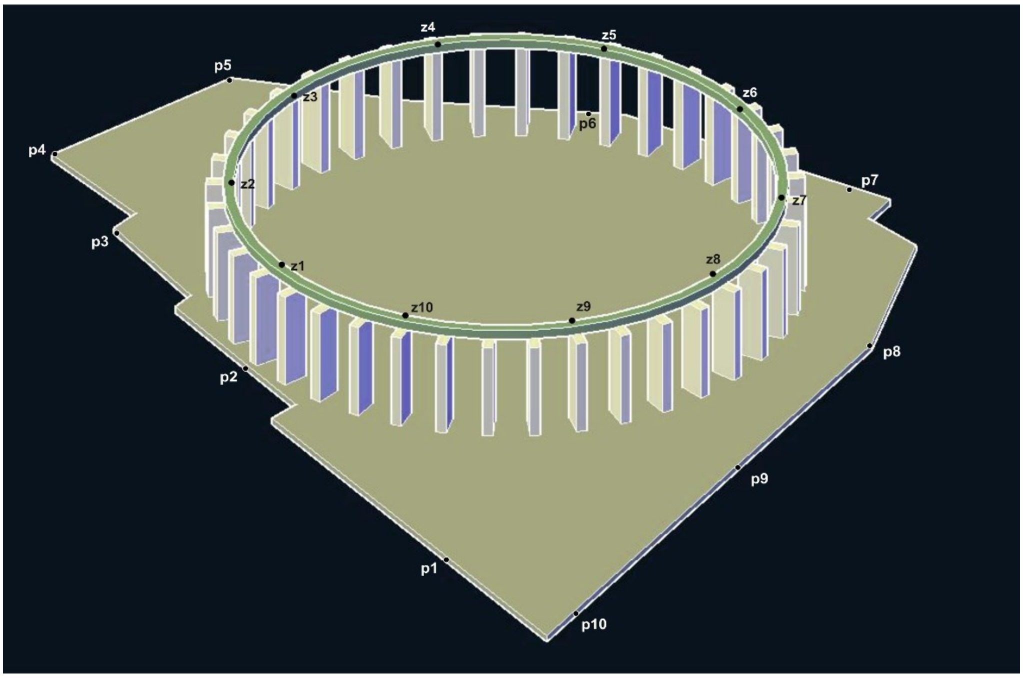

Figure 2. Strain marks position in 3D model

The first ten measurement cycles of the ring beam strain marks were carried out in the conditions which made it possible to define 3D coordinates of the points z1…z10 accurately and reliably. In the following measurement cycles, the bench marks were destroyed during mounting and finishing works, the inner geodetic network was getting more complicated and in the last measurement cycles the surveyors could reliably define only vertical settlements of the ring beam strain marks. For cap plate strain marks p1…p10 the form of geodetic network and measurement method did not make it possible to define the planned coordinates reliably, and that is why only their vertical displacements were taken into account in modelling. Figure 3 shows elevation changes of the ring beam strain marks for the entire period of observation.

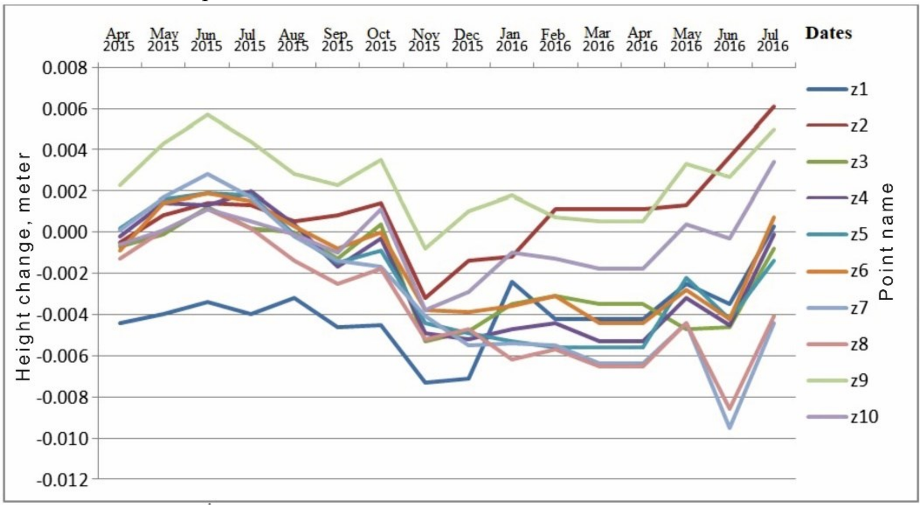

Figure 3. Bench mark settlement of steel-concrete ring beam

Visual analysis of graphs in Fig. 3 makes it possible to draw the conclusion about the existence of regular changes of height elevation of strain marks and changes of environmental temperature. The existence of such regularity can be checked by modelling object's behaviour in changing environmental parameters.

Model 3D. The first variant includes 10 cycles of geodetic observation. As long as all three geodetic coordinates were measured, they are included into the model, called 3D model. The model calculated the ring position change in the period from initial cycle to the current one.

Carrying the bench marks measurements to the initial epoch was performed on the basis of the following statements:

- the ring is a monolithic steel-concrete construction;
- within the construction the relative position of bench marks is unchangeable;

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- the construction can slant and displace in space as the whole thing;
- temperature expansion on Z axis goes from support plate of the ring;
- temperature expansion in horizontal plane goes from the ring centre along the radius;

Recalculation of the bench mark coordinates in measurement series is described in general view by the following equation:

$$X_{i,0} = A_j\left(X_{i,j} - \Delta_{i,j}^{(t)}\right) + C_j \tag{1}$$

where $X_{i,0}$ – coordinate vector of bench mark i in initial (zero) epoch;
$X_{i,j}$ – measured coordinate vector of bench mark i in current epoch j;
$\Delta_{i,j}^{(t)}$ – temperature displacement vector of bench mark i in epoch j;
$C_j = \begin{vmatrix} c_{x,j} \\ c_{y,j} \\ c_{z,j} \end{vmatrix}$ – central coordinate displacement vector in epoch j.
A_j – matrix of construction turning to Euler angles $\alpha_j, \beta_j, \gamma_j$ in epoch j, which is determined from expression

$$A_j = \begin{vmatrix} \cos\alpha_j\cos\beta_j & \cos\alpha_j\sin\beta_j\sin\gamma_j - \sin\alpha_j\cos\gamma_j & \cos\alpha_j\sin\beta_j\cos\gamma_j + \sin\alpha_j\sin\gamma_j \\ \sin\alpha_j\cos\beta_j & \sin\alpha_j\sin\beta_j\sin\gamma_j + \cos\alpha_j\cos\gamma_j & \sin\alpha_j\sin\beta_j\sin\gamma_j - \cos\alpha_j\sin\gamma_j \\ -\sin\beta_j & \cos\beta_j\sin\gamma_j & \cos\beta_j\cos\gamma_j \end{vmatrix} \tag{2}$$

where α_j– turning angle around axis Z, a β_j and γ_j inclination of, respectively, axes X и Y/
Parametric equations of corrections into measured coordinates in epoch j will have be:

$$V_{i,j} = A_j(X_{i,j} - \Delta_{i,j}^{(t)}) + C_j - X_{i,0}, \tag{3}$$

where $V_{i,j}$ – correction vector into measured coordinates of bench mark i in epoch j.
In linear view the equation (2) will be:

$$V_{i,j} = B_{i,j}\Omega_j - \alpha_t D_{i,j} + L_{i,j}, \tag{4}$$

where $B_{i,j}$ – coefficient matrix in correction parametric equations on bench mark i in epoch j;

$\Omega_j = \begin{vmatrix} \delta\alpha_j \\ \delta\beta_j \\ \delta\gamma_j \\ \delta c_{x,j} \\ \delta c_{y,j} \\ \delta c_{z,j} \end{vmatrix}$ – correction vector into construction inclination and displacement parameters in epoch j;

α_t – temperature coefficient of construction expansion;
$L_{i,j}=\hat{A}_j^T(X_{i,0} - \hat{C}_j) - \hat{\Delta}_{i,j}^{(t)} - X_{i,j}$ –vector of free terms on bench mark i, calculated by approximate values, noted by the sign «^».
Parametric equations for all bench marks in epoch j will be the following correction equation

$$V_j = B_j\Omega_j + \alpha_t D_j + L_j, \tag{5}$$

where matrixes B_j consist of the corresponding matrixes of equations (4).
Normal equations for parameters corrections will be:

$$\left.\begin{aligned} B_j^T B_j\Omega_j + \alpha_t B_j^T D_j + B_j^T L_j = 0; \\ D_j^T B_j\Omega_j + \alpha_t D_j^T D_j + D_j^T L_j = 0 \end{aligned}\right\}. \tag{6}$$

For reliable determination of temperature coefficient α_t it is necessary to integrate the equation systems for all epochs in one general system, which is represented by the following expression:

$$\left.\begin{aligned} B_1^T B_1\Omega_1 \qquad\qquad\qquad\qquad & + \alpha_t B_1^T D_1 + B_1^T L_1 = 0; \\ B_2^T B_2\Omega_2 \qquad\qquad & + \alpha_t B_2^T D_2 + B_2^T L_2 = 0; \\ \vdots \qquad\qquad & \\ B_n^T B_n\Omega_n & + \alpha_t B_n^T D_n + B_n^T L_n = 0; \\ D_1^T B_1\Omega_1 + D_2^T B_2\Omega_2 + \cdots + D_n^T B_n\Omega_n & + \alpha_t[D_j^T D_j] + [D_j^T L_j] = 0 \end{aligned}\right\}. \tag{7}$$

Having solved the system, we determine the parameters of all epochs and, thus, deformation and displacement of construction in time.

Vectors V_j characterize random error of geodetic measurements of coordinates, and on their basis we can determine μ– mean square error using the following formula:

$$\mu = \sqrt{\frac{[V_j^T V_j]}{3r(c-1)-p}} \tag{8}$$

where r – number of bench marks, c– number of observation cycles, p– number of parameters.

Estimation of RMS $-m_k$ of parameter k is determined by the expression [1]:

$$m_k = \mu\sqrt{Q_{k,k}} \quad (9)$$

where $Q_{k,k}$– diagonal element of reciprocal matrix of normal equations coefficients (7), corresponding to k - parameter.

When solving equation system (7) one should consider strength of casualty of coefficient matrix, which depends on network form and temperature changes. As strength of casualty is used the greatest and the least value ratio of proper numbers of matrix. [1]. If we calculate all unknown parameters, the strength of casualty is equal to 2500. It is explained by the fact that all bench marks are positioned almost in one horizontal plate in the upper part of the ring, that is why it is difficult to separate temperature influence and displacement on Z axis, as these parameters correlate.

If to admit that the displacement on the axis Z is caused only by the temperature factor, and parameter $c_{z,j}$ in all cycles is equal to zero, then the strength of casualty equals 300 and calculated parameters weakly correlate. Basic calculation results in determining all model parameters are shown in Table 1.

Table 1. Measurement processing results of the first observation variant

№ п/п	**Date (month, year)**	**Temperature °C**	**Inclination angles (")**			**Displacement $c_{z,j}$,мм**	**Slope line**	
			α_j	β_j	γ_j		**Inclination, sec**	**Azimuth, degree.**
1	05.2015	+15	0	0	0	0	0	0
2	06.2015	+18	-58.7	0.6	-2.8	+1.5	2.8	78.6
3	07.2015	+30	-67.2	5.0	-3.4	+0.8	6.0	34.4
4	08.2015	+18	-68.0	6.6	-2.0	+1.5	6.9	17.0
5	09.2015	+14	-43.3	8.3	-2.9	-0.5	8.8	19.5
6	10.2015	+2	-43.3	8.3	-3.3	-0.7	9.0	21.7
7	11.2015	-18	-66.4	5.9	-0.2	-17.1	5.9	2.2
8	12.2015	0	15.4	10.5	1.5	-7.8	10.7	8.2
9	01.2016	-7	70.9	12.0	-3.8	-11.4	12.6	17.7
10	02.2016	-7	-71.1	17.2	-2.5	-11.4	17.4	8.3

The error from formula (8) was equal to $\mu = \pm 3.4$мм, in this case RMS of angle parameters equals $\pm 7"$, temperature coefficient $\alpha_t = (0.56 \pm 0.02)10^{-5}$.

The correlation of angles β_j and γ_j depends on direction of coordinate system axes, that is why it will be more vivid to consider inclination angle of the slope line of coordinate axes plane X_jи Y_j in cycle j, normal to which is vector $\vec{n}_j$, consisting of elements from the third A matrix column, formula (2).

Inclination angle ε_j of the slope line is determined from expression

$$\varepsilon_j = \arcsin(\sqrt{1 - n_{j,z}^2}), \quad (10)$$

And its azimuth θ_j by formula

$$\theta_j = \mathrm{arctg}\left(\frac{n_{y,j}}{n_{x,j}}\right). \quad (11)$$

Model 1–Z. The second variant of observation over the ring position is conditioned by the fact that the conditions of construction site did not always provide opportunities to determine all three coordinates of bench marks, and that is why the surveyors determined only the elevation of points. This observation variant includes all measurement period and consists of 17 cycles.

Carrying bench marks measurements to initial epoch was performed on the basis of the following statements:

- the ring is a monolithic concrete construction;
- construction can slant, move up and down, as a whole thing;
- within the construction the relative position of bench marks is unchangeable;
- temperature expansion on Z axis goes from support plate of the ring (cap plate);
- temperature expansion in horizontal plane goes from the ring centre along the radius, but this model does not take this into account;
- bench marks slant as a whole thing, turning around the point with the coordinates equal to mean value of their coordinates.

Axes X and Y slant on small angles, relatively, γ and ε, in such a way that relative position of bench marks is not taken into account, but only the change of coordinate Z is analyzed.

The matrix of directing cosines of coordinate system inclination in accepted statements will be:

$$A_j = \begin{vmatrix} 1 & \sin\beta_j \sin\gamma_j & \sin\beta_j \cos\gamma_j \\ 0 & \cos\gamma_j & -\sin\gamma_j \\ -\sin\beta_j & \cos\beta_j \sin\gamma_j & \cos\beta_j \cos\gamma_j \end{vmatrix}, \quad (12)$$

as long as in the given model the angle α_j is considered to be equal to zero.

Because of small values of inclination angles β_j and γ_j, and also the analysis of only the coordinate Z, the equation (3) in linear view will be simplified as:

$$v_{z_{i,j}} = X_i \delta\beta_j + Y_i \delta\gamma_j + \delta c_{z,j} + \Delta Z_{i,j} - \alpha_t (Z_i - Z_{осн.})(T_j - T_0), \quad (13)$$

where $v_{z_{i,j}}$ – correction of random errors of elevation of bench mark i in epoch j;

X_i, Y_i, Z_i –bench mark coordinates i;

$\Delta Z_{i,j}$ –bench mark i elevation change in epoch j;

$Z_{осн.}$ –ring base height;

T_0, T_j – change in environmental temperature in measurements, corresponding to initial and j- observation cycles.

The equations (13) combined in one system were processed in accordance with the formulas (5) – (11). Calculation results are represented in Table 2, where measurements performed in May, 2015 were accepted as zero cycle. It allows to compare the results of the first and the second model variants in a more convenient way.

Random measurement error from formula (8) was equal to $\mu = \pm 2.6$мм, in this case RMS of angle parameters will be equal to $\pm 4''$, temperature coefficient $\alpha_t = (0.77 \pm 0.07)10^{-5}$.

Table 2. Processing results of the second observation variant

№ п/п	Date (month, year)	Temperature °C	Inclination angles (sec.)		Displacement $c_{z,j}$,мм	Slant line	
			β_j	γ_j		Inclination, sec.	Azimuth, degrees
1	03.2015	-18	1.7	6.2	3.4	6.4	74.4
2	04.2015	+5	-1.5	6.3	0.7	6.5	103.8
3	05.2015	+17.50	0	0	0	0	0
4	06.2015	+18	-8.8	-2.4	0.4	9.1	195.0
5	07.2015	+31	-8.7	-2.4	-2.0	9.0	195.5
6	08.2015	+19	-8.3	-2.3	-1.2	8.6	195.6
7	09.2015	+15	4.6	-1.3	-0.4	4.8	344.8
8	10.2015	+2	9.8	2.6	1.8	10.2	14.8
9	11.2015	-18	10.9	-1.1	-0.7	11.0	354.3
10	12.2015	0	10.7	2.0	-1.0	10.9	10.6
11	01.2016	-2	12.2	5.0	-0.7	13.2	22.2
12	02.2016	+1	8.2	1.7	-0.5	8.4	11.5
13	03.2016	+5	15.4	6.4	-2.6	16.7	22.7
14	04.2016	+8	16.3	4.8	-2.7	17.0	16.5
15	05.2016	+9	12.8	8.3	-2.5	15.2	32.8
16	06.2016	+17	15.6	4.1	-2.6	16.2	14.8
17	07.2016	+22	13.7	5.9	-1.0	14.9	23.2

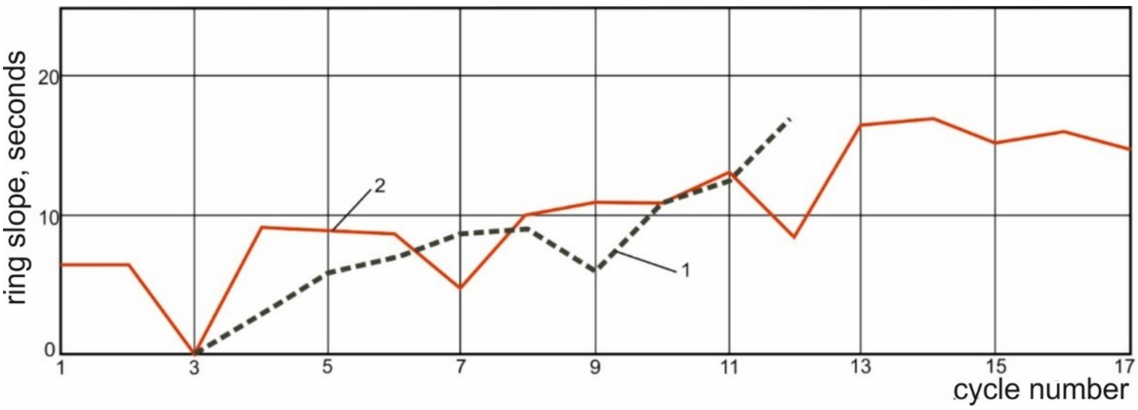

Figure 4. Graphs of ring inclination measurement results (1 – model 3D; 2 – model 1-Z)

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3 CONCLUSION

On the basis of the results of object's behaviour modelling in models 3D and 1-Z, we can draw the conclusion that, in addition to the settlement of ring beam caused by settlement of the ground and by increasing construction load, the temperature deformations and slants (Fig. 4) took place as well. Both models can determine general coefficient of linear temperature expansion because of object size change. In model 1-Z this coefficient is closer to the reference data for concrete, however, many researchers note that linear coefficients of temperature expansions for real objects can be very much different from reference values [24, 25, 26] and this difference is determined by a lot of factors of constructions and building conditions. In our case the difference of this coefficient in models 3D and 1-Z is explained by the fact that in model 3D all strain marks z1…z10 are placed on the same height and it is impossible to distinguish temperature deformations from settlements. And in model 1-Z the points z1…z 10 and p1… p10 are placed on different heights with level difference up to 15 m, that is why the coefficient was determined more accurately.

The analysis of ring beam inclination shows that ring inclination increased until the 13th measurement cycle, and then got stable and started to decrease, which is caused by the distribution of construction load during the construction process. Unfortunately, the authors do not possess information about the behaviour of the object during operation.

Of course, the models, shown in the work, are not universal – other objects with different constructive features might require the use of different equation systems, based on some other hypotheses, however, the given approach makes it possible to reveal object's behaviour patterns in different epochs and in different environmental parameters. On the given stage of BIM-technologies development such models can be additional for geotechnical monitoring system for searching for the first sight patterns of their changes and forecast of these changes in time.

The authors hope that geotechnical monitoring system of buildings and constructions will be integrated in BIM system together with calculating building models, which will give the opportunity to find more complex patterns of object's behaviour.

REFERENCES

[1] WITTEN, I. et al. *Data Mining. Practical Machine Learning Tools and Techniques*. Second Edition. Morgan Kaufmann, 2005.

[2] HAN, J. et al. *Data Mining: Concepts and Techniques*. Third Edition. Morgan Kaufmann Publishers, 2012. ISBN100123814790.

[3] LI, D. and S. WANG. Concepts, Principles and Applications of Spatial Data Mining and Knowledge Discovery. *ISSTM 2005, August, 27-29, 2005, Beijing, China, ISPRS*, XXXVI-2/W25, p.1-12.

[4] LI, D. S. WANG and D. LI. *Spatial Data Mining. Theory and Application*. Springer, Berlin, Heidelberg, 2015. https://doi.org/10.1007/978-3-662-48538-5.

[5] GERASIMENKO, M.D. and V.M. KAMORNYJ. Adjustment of repeated geodetic measurements in case the systematic errors presence. *Geodesy and cartography*. 2014, 9. pp. 7-8.

[6] AFONIN, D.A. et al. Preliminary calculation of the accuracy of geodetic measurements during the monitoring of deformation of gantry parts of transport tunnels. *Geodesy and cartography*. 2014, 1, pp. 7-11.

[7] GOROHOVA, E.I. Geomonitoringinzhenernyhsooruzhenijiprognozirovanie ih deforma-cij po dannym lazernogo skanirovanija (Geomonitoring of engineering constructions and forecast of their deformations based on laser scanning data). *Vestnik SGUGiT*. 2016, 34 (2), pp. 65-72.

[8] BROWN, N. et al. Monitoring of Open Pit Mines using Combined GNSS Satellite Receivers and Robotic Total Stations. *International Symposium on Rock Slope Stability in Open Pit Mining and Civil Engineering. Perth, Western Australia, 2007.*

[9] COSTANTINO, D. and M. G. ANGELINI. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences. In: *The Role of Geomatics in Hydrogeological Risk, 27 – 28 February 2013, Padua, Italy*, Volume XL-5/W3, pp. 179–187.

[10] CHRZANOWSKI, A. and A. SZOSTAK-CHRZANOWSKI. Reliability and Efficiency of Dam Deformation Monitoring Schemes. In: CDA *2011 Annual Conference, Congresannuel 2011 de l'ACB, Fredericton, NB, Canada,* October 12 – 20, 2011, pp.1-15.

[11] MIIMA, J.B. and W. NIEMEIER. Adapting neural networks for modelling structural behavior in geodetic deformation monitoring. *ZFV*. 2004, 129 (3), pp. 160-167.

[12] SHAN, A.C. Analytical Research on Deformation Monitoring of Large Span Continuous Rigid Frame Bridge during Operation. *Engineering*. 2015, 7, pp. 477-487. DOI: 10.4236/eng.2015.78044

[13] BLIUGER, F. Temperature Effects in Buildings with Panel Walls. *Building and Environment*. 1982, Vol. 17 (I), pp. 17-21.

[14] TIAN, Y. H. et al. Monitoring and analysis of ground temperature and deformation within Qinghai-Tibet

Highway subgrade in permafrost region. Sciences in Cold and Arid Regions, 2015, 7(4): 0370–0375. DOI: 10.3724/SP.J.1226.2015.00370

[15] ZHANG, P., Y. XIA and Y. Q. NI. Prediction of Temperature Induced Deformation of a Supertall Structure Using Structural Health Monitoring Data. In: *6th European Workshop on Structural Health Monitoring 2012-Tu.3. D.2*, pp.1-7.

[16] BUREŠ, J., O. ŠVÁBENSKÝ and M. KALINA. Long-term Deformation Measurements of atypical Roof Timber Structures. In: *INGEO 2014 – 6th International Conference on Engineering Surveying, TS 7 – Monitoring of structures.* Prague, Czech Republic, April 3-4, 2014, pp.249-254.

[17] VACCAA, G. et al. TERRESTRIAL LASER SCANNER FOR MONITORING THE DEFORMATIONS AND THE DAMAGES OF BUILDINGS. In: *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, Volume XLI-B5, 2016 XXIII ISPRS Congress, 12–19 July 2016, Prague, Czech Republic, pp. 453-460.

[18] MILL, T. and A. ELLMANN. Terrestrial Laser Scanning Technology for Deformation Monitoring of a Large Suspension Roof Structure. In: *INGEO 2014 – 6th International Conference on Engineering Surveying, TS 5 – Deformation measurement.* Prague, Czech Republic, April 3-4, 2014. pp.179- 186.

[19] JAGER, R. et al. Matematicheskiemodeliitehnicheskajarealizacija GOCA – onlajn sistemy geodezicheskogo monitoringa i opoveshhenija o deformacijah prirodnyh i tehnogennyh objektov, osnovannaja na tochnyh sputnikovyh (GNSS) i nazemnyh geodezicheskih nabljudenijah (LPS/LS) (Mathematical models and technical realization of GOGA – on-line system of geodetic monitoring and reporting deformations of natural and technogenic objects, based on accurate satellite (GNSS) and ground-based (LPS/LS)observations). *INTERJeKSPO GEO-SIBIR*. 2012, 5, pp. 9-32.

[20] BUGAKOVA, T.J. Modelirovanieizmenenijaprostranstvenno - vremennogosostojanijainzhe - nernyhsooruzhenijiprirodnyh objektovpogeodezicheskimdannym (Modelling of changes in spatial and temporal conditions of engineering construction and natural objects based on geodetic data). *VestnikSGUGiT*. 2015, 29 (1), pp. 34-42.

[21] KOBELEVA, N.N. and V.S. HOROSHILOV. Postroeniepogeodezicheskimdannym prognoznoj modeli processa peremeshhenij grebnja plotiny GJeS (na jetape jekspluatacii 2007–2009 godov) (Creation of forecast model of dam crest displacement of Sajano-Shushenskaja PS based on geodetic data, operation years 2007-2009). *Vestnik SGUGiT*. 2015, 32 (4), pp. 5-12.

[22] KOBELEVA, N.N. and V.S. HOROSHILOV. Postroeniematematicheskihmodelejdlja prognozirovanija gorizontal'nyh peremeshhenij plotiny Sajano-Shushenskoj GJeS dlja perioda jekspluatacii 2007–2009 gg. (Creation of mathematical models for forecast of horizontal displacements of Sajano-Shushenskaja dam for the operation period 2007–2009). *Vestnik SGUGiT*. 2016, 34 (2), pp. 73-86.

[23] KOBELEVA, N.N. Metodicheskieosobennostipostroenijaprognoznyhmatematicheskih mo-delej dlja izuchenija deformacij vysokih plotin. (Methodical aspects of mathematical forecast model creation for studying deformation of high dams). *Vestnik SGUGiT*. 2017, 22 (2), pp. 55-66.

[24] BEDOV, A.I. et al. *Ocenka tehnicheskogo sostojanija, vosstanovlenie i usilenie osnovanij i stroitel'nyh konstrukcij jekspluatiruemyh zdanij i soo-ruzheni (Estimation of technical conditions, reconstruction and reinforcement of foundations in engineering structures and buildings in operation).* Moscow: ASV, 2014.

[25] SIMONJAN, V.V. et al. *Geodezicheskij monitoring zdanijisooruzhe - nijkakosnovakontroljazabezopasnost'jupristroitel'stveijekspluataciiinzhenernyhsooruzhenij (Geodetic monitoring of buildings and constructions as a basis of safety control in building and exploitation of engineering structures).* Moscow: NIU MGSU, 2016.

[26] SNEGIREV, A.I. and A.I. AL'HIMENKO. Vlijanietemperaturyzamykanijaprivozvedeniinanaprjazhenija v nesushhihkonstrukcijah (Temperature influence onto bearing constructions strain). *Inzhenerno-stroitel'nyjzhurnal*. 2008, 2, pp. 8-16.

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