Deformation Monitoring of Objects of the Gabčíkovo Dam by the Terrestrial Surveying Methods and GPS Methods

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Key words:

ABSTRACT

The monitoring of the biggest Danube Gabčíkovo Water-work has been carried out by new geodetic procedures since 1996. The combination of modern terrestrial and GPS technology required new methodology for the determination of parameters of the displacement monitoring network. The deterministic and stochastic models data processing lead to new measurement procedures for GPS and automated tacheometric systems. Beside an overview of results of monitoring the Diversion Canal we discussed some details of automatic monitoring of the dam gate locks by a pair of integrated geodetic systems Leica TCA 1800.

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1. BASIC DATA OF THE GABČÍKOVO DAM

The second biggest European river Danube overflows across the territory of Slovakia in a length of 22 km and for about 149,5 km it creates a natural border: 7,5 km with Austria and 142 km with Hungary. Therefore Slovakia coordinates its activities on the Danube with their neighbours.

The construction of the Danube hydro system was a historical intention especially of Hungarian professionals. A rational basis for it was created in 1977 by international agreement between Hungary and Czechoslovakia about the common construction and operation of the hydro system Gabčíkovo - Nagymaros Water-work. After the interruption of construction by Hungary in 1987 decided Slovakia to finish the construction of Gabčíkovo Water-work on Slovak territory only by so-called substitute solution.

At present time Gabčíkovo Water work consists of the:

- **reservoir Hrušov,** which is created by the swell of Danube water surface, originate with the Dunakiliti water-gate, in present-day by the alternative dividing near Čuňovo,

- **objects of the alternative dividing dam near Čuňovo,** their task is to keep up the water surface on the required altitude and to ensure a necessary gradient for the Gabčíkovo Water Power Plant, at the same time these mentioned objects have to transmit conventional amount of water and during floods also Danube flows to the old Danube channel that Gabčíkovo Water-work is not possible to process,

- **diversion canal** that together with the Čuňovo water-gate centres the hydraulic gradient, supplies water to the Gabčíkovo Water-work and at the same time fulfils the task of he sea-way,

- **proper Gabčíkovo dam** that consists of the Gabčíkovo Water Power Plant and of the two tail bays, through these tail bays ships are rafting between the incoming and outlet canal, Gabčíkovo Water-work uses overflowed water for ecological electrical energy production and at the time of the floods flows helps with their safe taking away,

- **outlet canal** that takes away energetic used water from the Gabčíkovo Water Power Plant and water from the tail bays back to the river Danube, at the same time the outlet canal creates also the sea-way.

Fig. 1: Gabčíkovo Water work, general situation
1) reservoir Hrušov; 2) Čuňovo; 3) diversion canal; 4) Gabčíkovo dam; 5) outlet canal

2. CHARACTERISTIC OF THE DIVERSION CANAL AND A LONG PERIODICAL TECHNICAL AND SAFETY SUPERVISION

The diversion canal is situated on the left side embankment and fulfils the role of a power and navigation canal. It can also drain a part of the floods. Dikes with the slope 1:2 create it and its bottom level corresponds approx. the altitude of the surrounding terrain. The canal width changes from 540 m at the beginning, throughout 270 m up to 737 m at the end. By the depth of water of 7,3 m up to 14,3 m the canal flow capacity is up to 5,000 m^3 per second. Water volume at the maximum level is 87 million m^3. According to its parameters is the diversion canal the word No1.

The dikes are of gravel-sand, bituminous concrete and the bottom isolate their watersides by PVC foil sealing with protective gravel layer along both dikes they are the seepage canals. Maximal water level in the canal is 131,1 metres above sea level (Baltic datum) and the crest elevation is 133 metres above sea level (Baltic datum).

The tail bays of Gabčíkovo step are both on the left side. Their width of 34 m each and the lengths of 275 m enable the navigation of more ships at the same time.

Inseparable part of a trouble free operation of particular structures of the Water-work are the geodetic activities realised according to the Technical and Safety Supervision (TBD). TBD on the diversion canal consists of repeated planimetric and elevation measurement and processing of the selected points. The measurements of horizontal displacement are realised by a local control network (LGS) of the diversion canal since the October 1990 in regular six months intervals. Until 1996 the Surveying Section of the Hydro-construction Bratislava carried out the task. Due to large amount of measurements and time limits decided the Danube River Authority (the present administrator of presented Water-work) to shift these activities to a group of specialists according to a tender. Therefore the monitoring has been done in the last six years by a group under the headship of M.Sc. Š. Lukáč.

3. MEASUREMENT AND PROCESSING OF THE LGS OF THE DIVERSION CANAL

The trend of design and the inspection of precise LGS originated from a combined application of GPS and terrestrial methods based on a precise angular and length measurement by modern electronic tacheometers (total stations).

The LGS of the Gabčíkovo Diversion Canal consists of 236 points including 56 reference points. According to the configuration (1^{st} order design) it was originally intended to use **the classic terrestrial methods**. According to the measurement procedure and calculation (estimation) of effective parameters of the LGS (2^{nd} order design) the care of the network are 13 sets of the reference points (4 per set) situated with approximately 3 km equidistance parallel with both side of the canal.

Generally the LGS consists of 3 qualitative different groups of points:
- reference point mentioned are out side the canal dikes,
- monitoring-station points on the crowns of the dikes creating a regular quadratic chain with longitude sides (equidistance) about 500 m and cross-sides 270 – 750 m (according to the canal width),
- monitoring points – radians below both dikes at the beginning and at the end of the canal crown dike and in the area of the outlet canal.

The first 2 groups were constructed as high quality observation pillar-stations with forced centricity of instruments and prisms points have a form of small target pillars.

Measurement of the LGS included the following partial tasks (details are in [7]):
- measurement of horizontal directions on particular LGS points (Leica TC 1800),
- measurement of distances (Leica TC 1800),
- GPS measurement on a selected reference points (dual frequency TRIMBLE 4000 SSE and TRIMBLE 4000 SSI),
- monitoring of auxiliary factors: temperature, air, pressure, water level in the canal, etc.

The processing consists of the design of a theoretical (deterministic) model and an adequate stochastic model. Experimental verification of a theoretical model is based on the application of statistical methods with the important theory of estimation. Our main aim was to define an effective and statistic optimal procedure for processing of geodetic measurements realized by different geodetic technologies. The care of processing was in the application of a mixed model of measurement used for the estimation of parameters representing the standard scale factor of the distances used for a statistically optimal connection of the terrestrial and GPS measurements. The mixed linear model represents an instrument for modeling the measurement processing abut which we presume that they are loaded not only by an error component ε but also by another accidental component φ, the mean of which need not to be zero and the sum of which with the so called trend component represented by the mean of the observed random variable z we indicate as the effective part of measurement or a useful signal. A complex presentation of the statistical model mentioned is in [5] and its practical application is in [6].

4. APPLICATION OF NEW PROCEDURES BY MEASUREMENT AND PROCESSING OF THE LGS

From September 1996 till November 2001 we tailored gradually the methodology of measurement and processing during the 16^{th} -21^{st} stages according to qualities of instrumentation mentioned.

Suggested changing and their reasoning:

GPS measurement on selected reference LGS points. GPS methods are characterised by a high relative accuracy and a high stability of a geometric form and size of the network. Classical terrestrial methods reached the limits of their feasibility in the configuration of the LGS. Further improvement of the accuracy between the most distant LGS points was possible by the GPS technology only. We used the static GPS methods on 13 selected LGS points with the observation time between 1-6 hours per point. These points enabled to test the stability of the reference points not only with a high accuracy and repetition but also independently from the terrestrial measurements.

Adaptation of the observation plan for terrestrial measurement was aimed to better reduction of the atmospheric influence in the both side measurement of slant distances. Application of GPS and their optimal application for the definition of a control frame for terrestrial measurements required also the tailoring of the observation plan for angles and distances. The plan was supplemented by the measurement of directions on the observed points on the crown of the dikes. The aim of angular measurements was the improvement of the LGS homogeneity in the critical locations and to get higher relative accuracy among the LGS points. The increase of number redundant measurements enabled to indicate the possible positional changes of observed points – the sensitivity of the LGS according to the positional changes has been increased.

Definition of a new reference system for a common processing of the GPS and terrestrial measurement. The combination of technologies mentioned required defining a reference frame for their processing and mutual combination. According to the existing software and legislation we decided to use the Křovák conform conical projection and the coordinate system JTSK. In such way we had a good coincidence of the local coordinate system defined from the S-JTSK with the original system JTSK.

Definition of the statistic model for GPS processing and an effective procedure for the link of terrestrial measurements. The choice of the reference system mentioned defined indirectly also the procedure of a deterministic transformation of GPS results to the cartographic plane, without information loses. For the numerical solution we used the equations given in [3]. The following effective link of terrestrial surveys presumed the elimination of possible scale disharmony between the distances measured by the GPS and the instrument. Terrestrial measurements of the LGS were processed in one flow by a software system PLS ver.2.2 [2] by a finite methods, which gives the complex characteristics of accuracy from the global covariance matrix. The processing was completed by a statistic testing of measured values and their corrections with the intention to discover the values deviating significantly according to the statistical point of view.

Definition of a consistent statistically derived interpretation of horizontal displacement. The solution is based on the testing of statistical hypothesis of parameters, coordinate differences representing the positional changes. The application of such procedure supposed to know the complex characteristic of accuracy for the whole LGS. The comparison of the form and size coincidence of the GPS and terrestrial measurements for the testing of stability of the reference points was carried out by the comparison of invariant parameters. Some examples are given in Table 1.

Table 1: Comparison of invariant (reduced lengths) from terrestrial and GPS measurements

Stage	**Length**		**(1) Terrestrial Measurements**		**(2) GPS Measurements**		**(2-1)**
			Length	Mean Error	Length	Mean Error	
			[m]	[mm]	[m]	[mm]	[mm]
April 1997	**A**	**M**	**16146.788**	2.55	**16146.781**	0.93	**-7**
16th stage	**SB**	**L**	**15193.542**	4.32	**15193.560**	1.05	**18**
September 1997	**A**	**M**	**16146.792**	2.63	**16146.798**	0.87	**6**
17th stage	**SB**	**L**	**15193.543**	4.61	**15193.551**	0.95	**8**
September 1998	**A**	**M**	**16146.778**	3.11	**16146.777**	0.83	**-1**
19th stage	**SB**	**L**	**15193.548**	5.47	**15193.549**	0.82	**1**

Definition of the GPS observation plan for monitoring of the geodynamics of the whole region (realization since the 21st stage). According to the results achieved and the analyses of the GPS measurement it can be said that the quality and reliability of measurements increases with the prolongation of GPS observation. We have suggested a new technique for GPS measurements that assumed about forty-eight-hour observations measured at the five base points. Mentioned configuration of the five points was joined with help of the points (GABC = SB – Gabčíkovo, DLHO – Dlhá Hora and ZAVE – Záhorská Ves) to the SLOVGERENET and with help of the point MOPI – Modra Piesok to the net of the permanent stations (Figure 2), (Table 2).

Table 2: Lengths of vectors and their changes among stages concerning point MOPI

Vector (m)	**April 1997 (16th Stage)**	**September 1997 (17th Stage)**	**September 1998 (19th Stage)**	**Length's Changes of Vectors Among the Stages (m)**		
(1)	(2)	(3)	(4)	(3) - (2)	(4) - (2)	(4) - (3)
MOPI - A	57 572.565	57 572.562	57 572.571	-0.003	0.006	0.009
MOPI - M	44 178.946	44 178.938	44 178.965	-0.008	0.019	0.027
A - M	16 146.310	16 146.317	16 146.294	-0.007	-0.016	-0.023
MOPI - SB	58 254.322	58 254.297	58 254.314	-0.025	-0.008	0.017
MOPI - L	44 604.204	44 604.201	44 604.229	-0.003	0.025	0.028
L - SB	15 193.098	15 193.078	15 193.074	-0.020	-0.024	-0.004

5. DEFORMATION MONITORING OF TAIL BAYS BY AUTOMATED SYSTEM GEOMONITOR

Besides the classic geodetic methods for the complex deformation monitoring of tail bays there was suggested an automated monitoring of surface underground water change in the surrounding of the tail bays and also to locate leakage of expansion units of the tail bays. Monitoring of the surface and underground deformations together with hydraulic monitoring there was given a possibility to obtained a complex picture about behaviour of the tail bays in the time. Basically there was installed the automated system GeoMonitor in 1997 which has been already used for continuous monitoring of both tail bays for four years.

The main parts of the geotechnic monitoring automated system GeoMonitor that is used on the structures of the tail bays of the Gabčíkovo Water work are following:
- PC/software (system management, registration and representation of the measured values, their evaluation, correlation, alarm calling, graphic visualisation, automatic print of the reports,...)
- Data controller (sensor addressing, supplies by the electric current, signal incomes, ...)
- Measurement instruments (Leica TCA 1800, trajectory sensors, temperature sensors, water and atmospheric pressure sensors),
- Cable/interface (all of the measured instruments are connected with the one cable with help of the addressing interface),
- Modem (entrance to the current data and work with them in PC from far-away place).

Deformation monitoring intro-system GeoMonitor is insured by the two methods:
- Contact less (64 points) with help of the two integrated measurement systems Leica TCA 1800,
- Contact (80 sensors) for measurement of displacements under the surface and water.

From the geotechnic point of view it will be sufficient to measure by the automated geodetic methods only the vertical displacements of the each blocks of the tail bays. For this purpose it will be necessary to locate at least five automated levels in the surrounding of the tail bays, because these levels are able to measure with the sufficient precision only the points which are approximate fifty meters away [8]. Besides the difficult technical co-ordination of measurement by such number of the instruments inputs into the problem also inevitable need of the lighting of the rods in the night. From these reasons there were used only positioning measurements with help of the two integrated measurement systems Leica TCA 1800 which are able to measure points which are two hundred meters away without the lighting also in the night but of course at the expense of the less precision of measurement of the vertical elements of the displacements. Although the tacheometers were installed on the huge concrete pillars that are fixation into the left-handed bank (into the forth meters depth), they cannot be regarded as fixed because of marginal conditions of the building structure. For this purpose there were installed five base points that were located outside the structures of the tail bays. The height of the reflected prisms of the observed (sixty-four) points was artificial by the height of the protective banisters.

Because of the automated measurements there is a possibility to select a measurement interval, a number of the measured points and of course a measurement method. Before and after the each measurement of the observed points were always measured four base points. For a consideration of their position there was calculated a position of the tacheometers. This advance was to slow for a measurement but it was inevitable. Automated positioning measurements as were mentioned they were used for analysis of the short-time and long-time behaviour of the tail bays.

For the analysis of the short-time behaviour of the tail bays by their tapping and saturation it is impossible to measure all points at the dilatation in a one measurement cycle. Respectable measurement of the thirty-two points takes time more than the time for the saturation or tapping of the tails bay. Therefore it was measured a pair of the observed points on the appropriate dilatation and by the each measurement there was every time calculated a new position of the tacheometers. In the same time there was registrated a water surface in the tail bays every two minutes. By this way were obtained in an average four measurements during the change of the water surface in the tail bay. Each pair of the points on the dilatation was measured four-time like this way and then was evaluated deformation that depends of each blocks of the tail bays from the water surface in the tail bay in time.

For the long-time behaviour analysis of the tail bays is the measurement interval predetermined for every six hours where are measured all sixty-four observed points. From April 1997 till this day it is a huge data quantity. From the long-time point of view for the measurement precision is critical a stability of the base points. Only by the precision compliance we can for a certainty interpret the motions of the tail bay during the one or other years. By the long-time analysis plays the important role also a mode of the use (saturation) of the tail bays. Because for several months is used only one tail bay in this time there is a visible increase in tail bay deformation but this deformation returns step by step to the state from „the idle period“. The results from these mentioned measurements are graphical documented in [9].

6. CONCLUSION

In this presented article we introduce short outline of measurement and evaluation of the eighth stage measurements of the local geodetic network (LGS) of the incoming canal of the Gabčíkovo Water work (14^{th} – 21^{st} stage measurement of LGS). Mentioned measurements were measured in a period from April 1996 till November 1999. Our main aim was to evaluate a current state of the measurement of the observed points of LGS. For a consideration of the making analysis in this mentioned job description we have suggested and realised the changes that regard a current level of theoretical information in this problem and make use of technical possibilities of modern measurement instruments. Sequence of our steps ensures a continuity of the each repeated measurements of LGS also in spite of the limited financial possibilities from the hand of the work supplier. Our suggestion is that the realisation of the 21^{st} stage measurement is the best solution from the information aspect as well as from the economic aspect. From the practical point of view the important task plays the suggested advance of the analysis and interpretation of the horizontal displacements that uses the current possibilities of the hypothesis testing.

Installing and operation of the geotechnic monitoring automated system GeoMonitor on the tail bays of the Gabčíkovo Water work markedly contributed to the resumption of the complex picture about parallel deformation process of these structures as well as to the location of the leakages with help of the hydraulic measurements and underground deformation measurements in a subsoil.

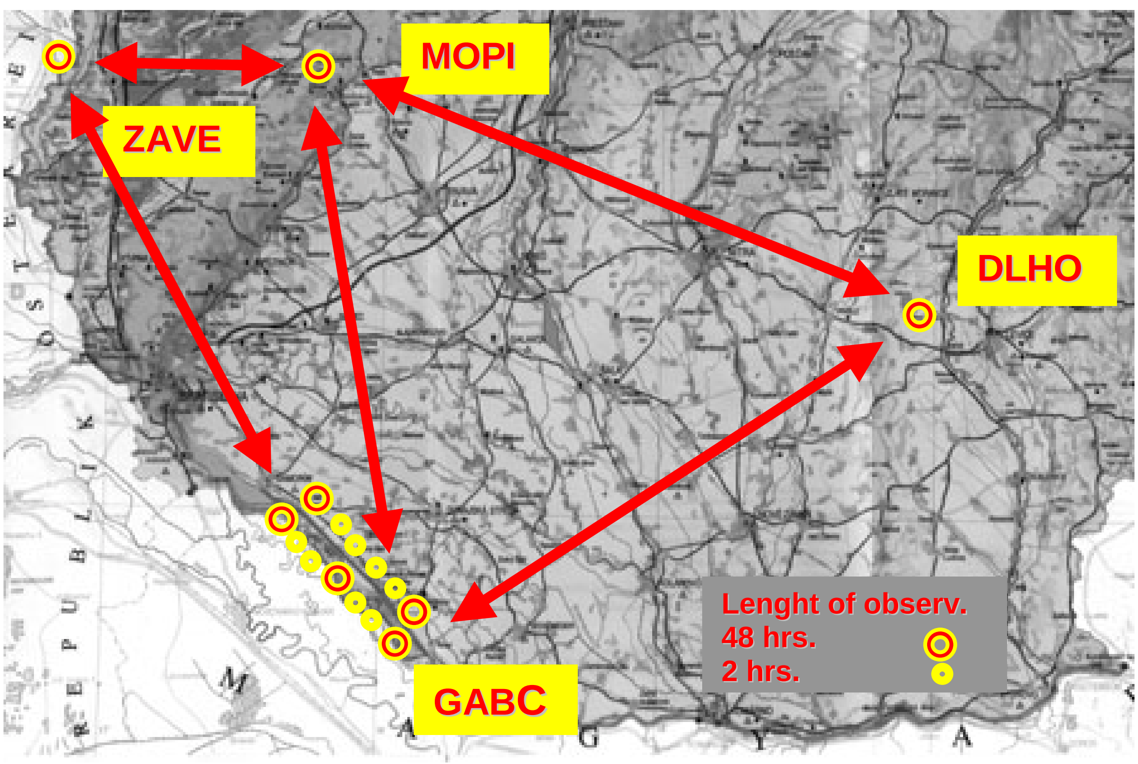

Fig. 2: GPS Measurement Incoming Canal of the Gabčíkovo Water work

By the evaluation of the automated short-time positioning measurements of the tail bays with help of the integrated measurement systems Leica TCA 1800 was proved that the vertical displacements in each dilatations don't achieve such values which could be the reason for the abuse of the dilatation sealing.

Measurement and interpretation of the structure deformations that is realised as a part of the Technical-safety-control is a demanding and long-time geodetic activity where we have to apply knowledge from the other theoretical and engineering disciplines. Carefully measured measurements, their documentation and capability to dynamically react at the newest information and development trends, make possible to effectively use the information (which are included in input data) also in the changing conditions.

REFERENCES

[1] DOBEŠ, J. et al.: Precision Local Geodetic Networks. OBIS VÚGK, Bratislava, 1989.

[2] KLOBUŠIAK, M.: Computer Aided Support of the Information Processing of the Precision Geodetic Networks that are constructed in the Stages without the Information Damage.

[3] KLOBUŠIAK, M.: Integrated Geodetic Network. Programs for the Stability and Non-Stability Analysis of the GPS Points, Effective Connection of the GPS Networks and Calculation of the Transformation Parameters. VÚGK, Bratislava, 1996.

[4] KOŽÁR, J.: Processing Methodology of the Geodetic Deformation Measurements. Project of the Academic Dissertation, Department of Surveying, STU Bratislava, 1999.

[5] KUBÁČKOVÁ, Lˇ.: Experimental Data Evaluation Methods. Bratislava, Veda 1990.

[6] LUKÁČ, Š. – KOŽÁR, J. – BALGOVÁ, Z.: Determination of Parameters of the Gabčíkovo Local Geodetic Network using the GPS Technology. In: 1st International Conference on Engineering Surveying INGEO' 98, Bratislava, STU, 1998.

[7] LUKÁČ, Š. – KOŽÁR, J. – BALGOVÁ, Z. – KALAFUT, M.: Report from the 21st Stage Measurement of the Positioning Local Geodetic Network of the Incoming Canal of the Gabčíkovo Water work. LIPG, Bratislava, 1999.

[8] GRÓF, V. – LUKÁČ, Š. – ŽÁK, M.: Application of the Measurement System GeoMonitor for the Measurement of the Vertical Displacements of the Constructions. In: 1st International Conference on Engineering Surveying INGEO' 98, Bratislava, STU, 1998.

[9] GRÓF, V. – KUBÍK, B.: The Three-Years Skills from the Operation of the Automated Measurement System on the Tail Bays of the Gabčíkovo Water work. In: Measurement, Monitoring and Evaluation of the Displacements at the Water-Trade Works. Gabčíkovo, Slovak Union of Surveyors 2000, pp. 69-76.